The Hole Story

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What part do you play in the continuing saga of bolted connections?

IN THE WORLD OF STRUCTURAL STEEL CONSTRUCTION, THE STORY OF BOLTED CONNECTIONS IS AN EPIC AND GRAND TALE. It is a story that includes intrigue (fastener component selection), drama (design of the connection), mystery (pre-installation verification), action (installation), thrills (inspection), horror (arbitration), history (references), and the occasional miracle. The AISC *Specification for Structural Steel Buildings* (ANSI/AISC-360-05), the RCSC *Specification for Structural Joints Using ASTM A325 or A490 Bolts*, and numerous other publications provide a detailed account of the "hole" story from start (manufacture) to finish (recycling). The intent of this article is not to replicate those references, but to give you a clear view of your own chapter in the bolted connection story. So think of it not as a design guide, but as your handy set of crib notes for the tome that is Bolted Connections.

Chapter 1: Bolts

The choice between welded and bolted connections depends upon a variety of factors. A few of these factors include shop preference, connection geometry, and additional attachments that are to be placed on a structural steel member. When bolted connections are the choice, bolt holes are made as part of the automated fabrication of the structural steel pieces. These holes provide a method of locating pieces of structural steel quickly, as well as reduce the time necessary for the steel piece to be held in place by a crane at the erection site. In fact, OSHA requirements state that at least two bolts must be provided, as positive attachment of a steel member before the crane can be unhooked from it during erection.

The most commonly used high-strength bolts are those that are manufactured to ASTM A325, A490, F1852, and F2280 specifications. However, it should be noted that there are other high-strength bolts with unique characteristics that make them ideal for specific types of connections. Some of these high-strength bolts include:

ASTM A193 – for use in elevated-temperature service

ASTM A320 – for use in low-temperature service

ASTM A354 Grade BD – properties similar to A490, but can be obtained in larger diameters

ASTM A449 – properties similar to A325, but can be obtained in larger diameters

Chapter 2: Joint Selection

There are three types of joints that are available for bolted connections: snug-tightened, pretensioned, and slip-critical joint. The selection of which type of joint is required for a connection depends upon the application and loading conditions that the joint will experience. Table 1 illustrates some general guidelines for the three joint types.

The general cost of a bolted connection in a final structure includes the cost of the bolts, nuts, and washers (if required), the fabrication cost of

Table 1: Joint Type Requirements

Joint Type		
Snug-Tightened	**Pretensioned**	**Slip-Critical**
Applicable except when a pretensioned or slip-critical joint is required	As required by the AISC Specification *(see below)*	Joints that are subject to fatigue load with reversal of loading direction
	Joint subjected to significant load reversal	Joints with oversize holes
	Joint subjected to fatigue with no reversal of loading direction	Joints with slotted holes, except those with applied load approximately normal to the dimension of the long slot
	Joint with A325 or F1852 subjected to tensile fatigue	Joints in which slip of the joint would be detrimental to the performance of the structure
	Joints with A490 (or F2280) bolts with tension (tension or combined shear and tension, with or without fatigue)	
	Seismic connections in lateral force resisting systems when *R* is taken >3	

The AISC Specification requires that joints be pretensioned for the following circumstances:

- ➜ Column Splices in multi-story structures over 125 ft
- ➜ Connections of all girders and beams to columns and any other beams and girders on which the bracing of the columns is dependent in structures over 125 ft
- ➜ Connections in structures that support cranes with a capacity over 5 tons
- ➜ Connections for the support of machinery and other sources of impact or stress reversal
- ➜ End connections for built-up compression members (fabricated with Class A or B faying surfaces)

making the holes in all plies, the preparation of surfaces (if required), the installation of the bolts, and the inspection of the connection. These costs can increase significantly when comparing snug-tightened joints to slip-critical or pretensioned joints.

Snug-tightened joints are more economical when compared to pretensioned or slip critical joints. The reduction in the comparative cost of snug-tightened joints comes from the absence of faying surface preparation requirements and a reduction of inspection requirements. Therefore, if allowed, remember to specify snug-tightened joints whenever possible.

For applications in which seismic design is performed using $R = 3$, if given the choice, pretensioned joints are more economical than slip-critical joints. Slip-critical joints have special faying surface preparation requirements that do not apply to pretensioned joints. Thus, the reduction in the comparative cost of pretensioned joints results comes from the reduction in the overall fabrication cost of the connection.

The choice of faying surface selection in slip-critical joints may depend upon whether the steel member is (or is not) blast-cleaned and coated for other reasons. If the steel is to be blast-cleaned or blasted and coated with a coating rated for Class B slip resistance, then it is more economical to use a Class B faying surface. Otherwise, a Class A design may be a more appropriate choice.

Table 2: Joint Design Requirements

Limit States	Joint Type		
	Snug-Tightened	Pretensioned	Slip-Critical
Design shear or tensile strength of a bolt	X	X	X
Strength of the bolt when subject to combined shear and tension	X	X	X
Design Bearing strength at bolt holes of connected material and bolt	X	X	X
Design Slip Resistance (faying surfaces and bolt pretension)			X

Additional considerations for the design of the joint include:

- ➜ shear and/or tension yielding
- ➜ shear and/or tension rupture
- ➜ block shear rupture
- ➜ shear lag
- ➜ prying action

Chapter 3: Connection Design

After you have selected the joint type, the next step is to design the connection itself. Table 2 illustrates some general design guidelines for each of the three joint types.

In general, the type of bolt hole selected for a joint should be based upon constructability. Standard holes and short-slotted holes can be used in each of the joint types. Long-slotted holes are permitted in each of the joint types with the approval of the Engineer of Record, while oversized holes can be used only in slip-critical joints. The selection of the type of bolt hole selected is a great topic of conversation with a steel fabricator. It is considered good practice, when using standard and oversized holes, to specify the same hole type in all plies so that the plies can be aligned using a spud wrench and drift pins during erection.

OSHA requires at least two bolts (or an equivalent attachment) in all connections, and these bolts must remain in place after the member has been released from the crane. It is considered good practice to have connections that do not share bolts through a support. If this is not possible, a discussion with the steel fabricator should occur to determine a solution. Some examples of typical solutions to this situation can include providing temporary erection seats, offsetting connections, making one connection deeper than the other to make sure that some bolts are not shared by both connections, or another solution that will address erection safety.

Washers are required for all joint types that have sloped surfaces or use slotted holes in the outer ply. For pretensioned and slip-critical joints, washers are required for the following types of connections:

- ➜ when using ASTM A490 bolts and the connection material is less than 40ksi (not required under the head for the ASTM F2280 bolts)
- ➜ under the turned element when using the calibrated wrench pretensioning method
- ➜ under the nut when the twist-off-type tension-control bolt pretensioning method is used in certain bolt configurations (reference Section 6.2.4 and Figure C-8.1 in the RCSC Specification)
- ➜ when the direct-tension-indicator pretensioning method is used
- ➜ when oversized holes are used in the outer ply

Table 6.1 in the RCSC Specification illustrates the conditions that require thick or plate washers for bolted joints with oversized and slotted holes in the outer ply.

When designing bolted connections it is always best to limit the number of different bolt strengths and diameters being used on the entire project. It is also advisable to use different diameters of bolts when different bolt strengths (for example ASTM A325 and A490) are mixed on a project. This reduces the chances of the wrong bolt strength being placed in the wrong connection during erection, and simplifies the purchasing, installation, and quality assurance functions.

Chapter 4: Fabrication and Installation

During fabrication of structural steel members, bolt holes are generally created via drilling, punching, or thermal cutting. Additionally, bolt holes can be created by sub-punching, reaming, and hole-sawing.

Bolts, nuts, and washers must be stored properly when delivered to the job site and during construction of the structure. Proper storage of bolts is particularly important for assemblies that will be pretensioned. Containers should be used to protect the fastener components from dirt and moisture. In addition, the containers should be kept in a protected shelter to ensure accidental exposure does not occur. The fastener components should only be removed from the protected storage when installation of those necessary parts will occur. Fastener components that are not used right away should be returned to protective storage as soon as possible.

Table 3 illustrates the current accepted bolt installation requirements and methods. Tightening of the bolts in a joint should begin with the bolt at the most rigid part of the connection being installed. Subsequently, the additional bolts of the connection are systematically tightened in a manner that will minimize the relaxation of the previously installed bolts.

Chapter 5: Inspection

The AISC Specification references the RCSC Specification for bolted joint inspection requirements. When inspection of the bolted joints is required in the contract documents, an inspector is responsible for assuring that the installation of the bolted connections meets the requirements of the RCSC Specification. When Inspection of the bolted joints is not required, the contractor is responsible for assuring that the installation of the bolted connections meets the requirements of the RCSC Specification.

Prior to the actual installation of the bolts, a visual inspection should verify that all mandatory markings are present. All manufacturers or suppliers of high-strength bolts and components should provide certification documenting their conformance with the ASTM Specifications.

During the inspection of all joint connection types, the fastener components, connection plies, bolt holes, faying surface conditions, and proper bolt storage/usage procedures need to be evaluated. Note that there is no requirement for the inspection of each bolt, but rather that the bolt installation procedure in place results in required processes being met. For snug-tightened joints, only a visual inspection is required to determine that the correct bolt types are in their specified holes and that the plies are drawn into firm contact. For pretensioned and slip-critical joints the RCSC Specification specifies that the following inspection procedures are required:

- ➜ When the turn-of-nut pretensioning installation method is used, it is necessary to observe that the bolting crew properly rotates the turned element relative to the unturned element by the specified amount.
- ➜ When the calibrated wrench pretensioning installation method is used, pre-installation verification procedures are performed daily for the calibration of the installation wrench. In addition, routine observation that the bolting crew properly applies the calibrated wrench to the turned element is necessary.
- ➜ When twist-off-type tension-controlled bolts are used, it is necessary to observe that the splined ends are properly severed during installation by the bolting crew.
- ➜ When the direct tension indicator method is used, the inspector shall observe the pre-installation verification testing. Furthermore, prior to pretensioning, routine observation is necessary to verify that the appropriate feeler gage is accepted in at least half of the spaces between the protrusions of the direct tension indicator, and that the protrusions are properly oriented

Table 3: Detailed Bolt Installation Requirements

Joint Type	Installation Methods
Snug-Tightened	A few impacts with an impact wrench or the full effort of an ironworker using an ordinary spud wrench to bring the plies into firm contact.
Pretensioned and Slip-Critical	**Turn-of-Nut**: Installed first as snug-tight, then additional rotation of the nut or head is applied ranging from 1/3 to 1 turn based on grip geometry and bolt aspect ratio.
	Calibrated Wrench: Installed first as snug-tight. Subsequently, a predetermined torque (calibrated daily to provide the required pretension) is applied with a wrench that indicates the torque applied to the nut or head. The nut or head does not need to be rotated greater than specified limits (for turn-of-nut method).
	Twist-Off-Type Tension-Control Bolt: Bolts meeting F1852 or F2280 are used and installed as an assembly. Installed first as snug-tight without severing the spline. Subsequently, all bolts are pretensioned with the twist-off-type tension-control bolt installation wrench.
	Direct Tension Indicator: Direction tension indicators must meet ASTM F959. Bolts (with washers) are first installed as snug-tight, making sure the gap is not less than the job installation gap. Subsequently, the bolts are pretensioned until the direct tension indicator protrusions have been compressed and the gap is less than the job inspection gap.
	If alternative design fastener or alternative washer-type indicating devices are used, install per manufacturer (and as approved by the Engineer of Record).

away from the work. After pretensioning, routine observation is necessary to verify that the appropriate feeler gage is refused entry into at least half of the spaces between the protrusions.

Pre-installation verification is used to check that the fastener assemblies and pretensioned installation procedures perform as required prior to installation. The RCSC Specification provides detailed procedures for the pre-installation verifications methods available for each of the installation types. It should be noted that pre-installation verification is required onsite daily for the calibrated wrench pre-tensioning procedure. In addition, it should be noted that detailed inspection instructions should be provided by the manufacturer(s) for the chosen fastener components.

Chapter 6: Arbitration

In the instance where there is valid reason to believe that the installed bolts do not have the required pretension, arbitration may be required. The RCSC Specification provides a detailed procedure for arbitration of pretensioned and slip-critical joints.

During arbitration it should be noted that reliability concerns may occur due to the nature of the testing procedure used. Conditions that are present at the installation site are not wholly present at the arbitration testing site. These conditions can include the use of hardened washers, the lubrication condition, and the effect of the passage of time/exposure of the joints. If it is found that the RCSC procedure is not appropriate for the specific situation of the joint(s) in question, an alternative arbitration procedure from the one described may be permitted. MSC

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References

Research Council on Structural Connections (RCSC): *Specification for Structural Joints Using ASTM A325 or A490 Bolts*, dated June 30, 2004.

ANSI/AISC 360-05: *Specification for Structural Steel Buildings*, dated March 9, 2005.

ANSI/AISC 341-05: *Seismic Provisions for Structural Steel Buildings*, dated March 9, 2005, and *Supplement No. 1*, dated November 16, 2005.

AISC 303-05: *Code of Standard Practice for Steel Buildings and Bridges*, dated March 18, 2005.

AISC *Steel Design Guide 17: High Strength Bolts, A Primer for Structural Engineers.*

Kulak, Geoffrey L., Fisher, John W., and Struik, John H.A., *Guide to Design Criteria for Bolted and Riveted Joints*, second edition.

Steel Structures Technology Center, Inc. (SSTC): *Structural Bolting Handbook.*