Prying Action for Slip-Critical Connections with Bolt Tension and Shear Interaction

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ABSTRACT
Bolted connections subjected to both shear and tension must be checked for prying action and the interaction between tension, and shear must be considered. The 2010 AISC Specification for Structural Steel Buildings (AISC 360-10) presents interaction equations both for bearing connections and for slip-critical connections. This paper demonstrates two methods to account for tension and shear interaction when prying action must be considered in slip-critical connections. The prying action procedure outlined in the 14th edition Steel Construction Manual is assumed.

Keywords: bolt tension, bolt shear, prying action, slip-critical connections.

INTRODUCTION
When bolted connections subjected to both shear and tension must be checked for prying action, the interaction between tension and shear must be considered. The AISC Specification for Structural Steel Buildings (AISC, 2010) presents interaction equations for bearing connections and for slip-critical connections. However, little guidance for applying these equations to prying action analysis has been available. This paper will demonstrate how these interaction equations may be used in the prying action analysis presented in the 14th edition Steel Construction Manual (AISC, 2011) by comparing two methods. This paper is formulated in terms of Load and Resistance Factor Design (LRFD), but the principles are similar for Allowable Strength Design (ASD).

The 14th edition Steel Construction Manual outlines a design approach for prying action on pages 9-10 through 9-13. The quantity \( B \) is used to represent the available tension strength per bolt. When there is no applied shear,

\[
B = \phi r_t
\]

where \( \phi r_t \), the available tensile strength of the bolt, kips, is given in Table 7-2 of the Manual or is calculated from Specification Section J3.1 and Table J3.2.

BEARING-TYPE CONNECTIONS
For bearing connections, the presence of shear reduces the available tensile strength of the bolt. From Specification Section J3.7, Equation J3-3a (for LRFD; repeated here as Equation 2) calculates \( F'_{nt} \), the nominal tensile stress modified to include the effects of shear stress:

\[
F'_{nt} = 1.3F_{nt} - \frac{F_{nt}}{\phi F_{nv}} f_{rv} \leq F_{nt}
\]

where

- \( A_b \) = the area of the bolt, in.\(^2\)
- \( F_{nt} \) = nominal bolt tensile stress from Table J3.2, ksi
- \( F_{nv} \) = nominal bolt shear stress from Table J3.2, ksi
- \( f_{rv} \) = required bolt shear stress, ksi
- \( = \frac{V_u}{A_b} \)

Substituting terms in Equation 1 and expanding terms incorporates \( F'_{nt} \) (ksi) and the area of the bolt, \( A_b \) (in.), producing Equation 3:

\[
B' = \phi r'_t = \phi F'_{nt} A_b
\]

Note that \( \phi r'_t \) represents the reduced available tensile strength of the bolt, kips.

SLIP-CRITICAL CONNECTIONS
For slip-critical connections, the situation is somewhat different. When a tension is applied that reduces the net clamping force, the factor \( k_{sc} \) given by Specification Equation J3-5a is applied to the available slip resistance per bolt. Rewriting

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Equation J3-5a for \( k_{te} \) in terms of required tension force per bolt (rather than total tension force) and applying the factor to \( \phi_{ru} \) produces Equation 4 for \( \phi_{Bu} \), the shear strength per bolt reduced by the applied tension:

\[
\phi_{Bu} = \phi_{ru} \left( 1 - \frac{T_u}{T_e} \right) \quad \text{with} \quad T_u \leq \min \{ \phi_{ru}, T_e \}
\]  

(4)

where

\( T_e \) = the expected mean pretension per bolt, kips
\( = D_u T_b \)
\( T_u \) = required tension force per bolt, kips
\( \phi_{ru} \) = available shear strength per bolt for slip-critical connections, kips (Manual Table 7-3)
\( T_b \) = minimum bolt pretension, kips (Specification Table J3.1)
\( D_u \) = calibration factor, usually 1.13 (Specification Section J3.8)

In Equation 4, the limit on \( T_u \) is necessary because \( T_e \) is less than \( \phi_{ru} \) for ASTM A325 bolts with diameters larger than 1 in. This anomaly occurs because the 2010 Specification uses a minimum specified tensile strength of 120 ksi for all ASTM A325 bolt diameters. However, the ASTM A325 standard uses 120 ksi for bolts up to and including 1-in. diameter and then uses 105 ksi for larger bolts. The pretension values \( (T_b) \) in Specification Table J3.1 are based on the ASTM values, while Specification Table J3.2 uses 120 ksi “across-the-board” for all ASTM A325 bolt diameters. The difference occurs only for ASTM A325 bolts; for ASTM A490 bolts, both Table J3.1 and Table J3.2 are based on the ASTM minimum tensile strength value of 150 ksi.

Note that in Specification Table J3.2, the values of \( F_{nrt} \) are 75% of the bolt tensile strength \( F_{nt} \). Thus, for ASTM A325 bolts, \( F_{nrt} = 0.75 \times 120 \text{ ksi} = 90 \text{ ksi} \) and for ASTM A490 bolts, \( F_{nrt} = 0.75 \times 150 \text{ ksi} = 113 \text{ ksi} \). The factor 0.75 is the ratio of the threaded area to the shank area.

For bearing connections, Equation 3 produces a reduced available tensile strength, \( \phi_{rt} \), due to the presence of shear, \( V_u \). For slip-critical connections, Equation 4 produces a reduced shear strength, \( \phi_{Bu} \), due to the presence of applied bolt tension, \( T_u \).

Note that in Equation 4, \( T_u \) does not include the prying force, \( q \). The reason for this is that the total faying surface compression force is not reduced by \( q \). The bolt tension, \( T_u \), is increased by \( q \), but an equal and opposite \( q \) acts as an additional compression force on the faying surface. Thus, the slip-critical shear resistance—while reduced by the applied tension, \( T_u \)—is unaffected by the prying force, \( q \).

The slip-critical interaction Equation 4 may be mathematically rearranged to produce Equation 5:

\[
\phi_{Bu} = T_e \left( 1 - \frac{V_u}{\phi_{ru}} \right) \leq \min \{ \phi_{ru}, T_e \} \quad \text{with} \quad V_u \leq \phi_{ru}
\]  

(5)

where \( V_u \) is the applied shear per bolt, kips, and all other terms are as previously defined. Similar to Equation 3, \( B' = \phi_{Bu} \); thus, Equation 5 produces the value \( B' \) required for prying action calculations.

In spite of its mathematical relationship to Equation 4, Equation 5 does not accurately represent the physical behavior of slip-critical connections. The reason that Specification Equation J3-5a (Equation 4 of this paper) is written in terms of a reduced shear stress is as follows: while \( T_u \) affects slip-critical connection shear strength per bolt as shown in Equation 4, applied shear, \( V_u \), does not affect the tensile strength of the bolt in quite the same manner, even though Equation 5 would indicate otherwise. The reason for this lies in the physical behavior of slip-critical connections. Connection shear \( V_u \) is carried by the faying surface through friction—rather than by the bolt shank as Equation 5 appears to indicate—until slip occurs. Thus, the bolt itself “sees” no shear until the connection slips, and its tensile strength is consequently unaffected until slip. Once slip occurs, bearing interaction Equation J3-3a from the Specification and Equations 2 and 3 of this paper must be used.

**SOLUTION STRATEGIES**

**Method A.** Use the mathematically inverted Specification Equation J3-5a, rearranged as Equation 5, to solve for \( B' \) for use in prying action calculations:

\[
B' = \phi_{Bu} = T_e \left( 1 - \frac{V_u}{\phi_{ru}} \right) \leq \min \{ \phi_{ru}, T_e \}
\]  

As previously discussed, this approach does not capture the physical behavior of the connection because it does not account for the pre-slip condition. However, Equation 5 provides a conservative solution. This approach has been previously presented in the literature by Thornton (1985), Brockenbrough (2006) and Tamboli (2010).

**Method B.** Account for pre-slip and post-slip behavior as follows:

**Step 1** Calculate the slip-critical shear strength as reduced by the applied tension, using Equation 4:

\[
\phi_{Bu} = \phi_{ru} \left( 1 - \frac{T_u}{T_e} \right) \quad \text{with} \quad T_u \leq \min \{ \phi_{ru}, T_e \}
\]
**Step 2** If \( \phi r' < V_u \), the slip-critical shear strength is insufficient and the connection fails.

**Step 3** If \( \phi r' \geq V_u \), the connection is in the “pre-slip” state. Use Equations 2 and 3 to calculate \( B' \) for the post-slip state (bearing):

\[
B' = \phi r' = \frac{F_{nt} A_b}{T_u}
\]

\[
F_{nt} = 1.3F_{nt} - \frac{F_{nt}}{\phi r_v} f_{rv} \leq F_{nt}
\]

Once the value \( B' \) is determined, the calculations follow the process outlined in the 14th edition *Manual* for both methods.

**EXAMPLE**

**Given:** ASTM A325 bolts, \( \frac{3}{4} \)-in. diameter, slip-critical, Class A faying surface, oversize holes, threads included in the shear plane. \( V_u = 5.56 \text{kips/bolt} \) and \( T_u = 22.0 \text{kips/bolt} \).

\[
D_u = 1.13 \text{ from Specification Section J3.8}
\]

\[
T_b = 39 \text{ kips from Specification Table J3.1}
\]

\[
T_e = D_u \times T_b = 1.13 \times 39 = 44.1 \text{kips}
\]

\[
\phi r_v = 11.2 \text{kips from Manual Table 7-3}
\]

\[
F_{nv} = 54 \text{ ksi from Specification Table J3.2}
\]

\[
\phi r_i = 40.6 \text{kips from Manual Table 7-2}
\]

\[
F_{nt} = 90 \text{ ksi from Specification Table J3.2}
\]

**Solution A:**

From Equation 5,

\[
B' = \phi r' = T_e \left( 1 - \frac{V_u}{\phi r_v} \right)
\]

\[
B' = 44.1 \text{kips} \left( 1 - \frac{5.56 \text{kips}}{11.2 \text{kips}} \right)
\]

\[
= 22.2 \text{kips/bolt} \leq \phi r_i = 40.6 \text{kips/bolt} \text{ OK}
\]

Use \( B' = 22.2 \text{kips/bolt} \).

**Solution B:**

**Step 1** Check Equation 4:

\[
\phi r' = \phi r_i \left( 1 - \frac{T_u}{T_e} \right) \text{ with } T_u \leq \min \{ \phi r_i, T_e \}
\]

\[
T_u \leq \min \{ \phi r_i, T_e \}
\]

\[
\leq \min \{ 40.6 \text{kips}, 44.1 \text{kips} \} = 40.6 \text{kips}
\]

\[
T_u = 22.0 \text{kips} \leq 40.6 \text{kips} \text{ OK}
\]

\[
\phi r' = 11.2 \text{kips} \left( 1 - \frac{22.0 \text{kips}}{44.1 \text{kips}} \right)
\]

\[
= 5.56 \text{kips/bolt}
\]

**Step 2** \( \phi r' = 5.56 \text{kips} \geq V_u = 5.56 \text{kips} \text{ OK to proceed}

**Step 3** Calculate \( F_{nt} \) using Equation 3:

\[
F_{nt} = 1.3F_{nt} - \frac{F_{nt}}{\phi r_v} f_{rv} \leq F_{nt}
\]

\[
= 1.3(90 \text{ksi}) \frac{90 \text{ksi}}{0.75}(54 \text{ksi}) \left( \frac{5.56 \text{kips/bolt}}{0.601 \text{in}^2} \right)
\]

\[
= 96.4 \text{ksi}
\]

\[
F_{nt} = 96.4 \text{ksi} > F_{nt} = 90 \text{ksi}
\]

Use \( F_{nt} = 90 \text{ksi} \).

Calculate \( B' \) using Equation 2:

\[
B' = \phi r' = \phi r' A_b
\]

\[
= (90 \text{ksi})(0.75)(0.601 \text{in}^2)
\]

\[
= 40.6 \text{kips/bolt} \leq \phi r_i = 40.6 \text{kips/bolt} \text{ OK}
\]

Use \( B' = 40.6 \text{kips/bolt} \).

**SUMMARY AND CONCLUSIONS**

Method A gives \( B' = 22.2 \text{kips/bolt} \) while Method B gives \( B' = 40.6 \text{kips/bolt} \). Method A is conservative but does not capture the pre-slip/post-slip phenomenon. Method B captures the pre-slip/post-slip phenomenon and is less conservative. The authors recommend the use of Method B because it is based on a mathematical model that more closely resembles the connection behavior.

Kulak et al. (1987) indicate that, at ultimate loads, the effects of prying will be the same regardless of whether the bolts are pretensioned or not. This observation further supports the use of Method B. Another observation by the authors of this paper suggests that Method B may also prove to be overly conservative in practice. This point is easiest to see if we transition to ASD and look at service loads. *Specification* Equation J3-1 calculates the tensile strength of bolts using \( \Omega = 2.00 \). Tension service loads, \( T_a \), must satisfy the following:

\[
T_a \leq \frac{R_m}{\Omega} = \frac{F_{nt} A_b}{\Omega} = \frac{0.75F_{nt} A_b}{2.00} = 0.375F_{nt} A_b
\]

The specified pretension values from *Specification* Table J3.1 are approximately 70% of the tensile strength of the
bolt: \( T_b = 0.70F_{uA_b} \). Thus, at service loads the applied tension—limited to \( 0.375F_{uA_b} \)—is less than the tensile strength of the bolt—\( 0.70F_{uA_b} \)—and the bearing behavior reflected in Equation 3 will never occur. This is true for both the ASD and LRFD design approaches. Further study is necessary to establish how—or if—this reality should be incorporated into the design process.

REFERENCES

AISC (2010), Specification for Structural Steel Buildings, ANSI/AISC 360-10, American Institute of Steel Construction, Chicago, IL.


