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,

$$B = \phi r_t \tag{1}$$

where ϕr_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.

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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:

$$F'_{nt} = 1.3F_{nt} - \frac{F_{nt}}{\phi F_{nv}} f_{rv} \le F_{nt} \tag{2}$$

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 shear stress, ksi

= 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:

$$B' = \phi r'_t = \phi F'_{nt} A_b \tag{3}$$

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

Equation J3-5a for k_{sc} in terms of required tension force per bolt (rather than total tension force) and applying the factor to ϕr_v produces Equation 4 for $\phi r_v'$, the shear strength per bolt reduced by the applied tension:

$$\phi r_v' = \phi r_v \left(1 - \frac{T_u}{T_e}\right) \text{ with } T_u \le \min\{\phi r_t, T_e\} \tag{4}$$

where

T_e = the expected mean pretension per bolt, kips

= $D_u T_b$

T_u = required tension force per bolt, kips

ϕr_v = 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 ϕr_t 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_{nt} are 75% of the bolt tensile strength F_u. Thus, for ASTM A325 bolts, $F_{nt} = 0.75 \times 120$ ksi = 90 ksi and for ASTM A490 bolts, $F_{nt} = 0.75 \times 150$ ksi = 113 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, $\phi r_t'$, due to the presence of shear, V_u. For slip-critical connections, Equation 4 produces a reduced shear strength, $\phi r_v'$, 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:

$$\phi r_t' = T_e \left(1 - \frac{V_u}{\phi r_v}\right) \le \min\{\phi r_t, T_e\} \text{ with } V_u \le \phi r_v \tag{5}$$

where V_u is the applied shear per bolt, kips, and all other terms are as previously defined. Similar to Equation 3, $B' = \phi r_t'$; 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:

$$B' = \phi r_t' = T_e \left(1 - \frac{V_u}{\phi r_v}\right) \le \min\{\phi r_t, T_e\}$$

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 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:

$$\phi r_v' = \phi r_v \left(1 - \frac{T_u}{T_e}\right) \text{ with } T_u \le \min\{\phi r_t, T_e\}$$

Step 2 If $\phi r'_v < V_u$, the slip-critical shear strength is insufficient and the connection fails.

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

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

$$F'_{nt} = 1.3F_{nt} - \frac{F_{nt}}{\phi F_{nv}} f_{rv} \le F_{nt}$$

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, ⅞-in. diameter, slip-critical, Class A faying surface, oversize holes, threads included in the shear plane. $V_u = 5.56$ kips/bolt and $T_u = 22.0$ kips/bolt.

$D_u = 1.13$ from *Specification* Section J3.8

$T_b = 39$ kips from *Specification* Table J3.1

$T_e = D_u \times T_b = 1.13 \times 39 = 44.1$ kips

$\phi r_v = 11.2$ kips from *Manual* Table 7-3

$F_{nv} = 54$ ksi from *Specification* Table J3.2

$\phi r_t = 40.6$ kips from *Manual* Table 7-2

$F_{nt} = 90$ ksi from *Specification* Table J3.2

Solution A:

From Equation 5,

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

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

$$= 22.2 \text{ kips/bolt} \le \phi r_t = 40.6 \text{ kips/bolt} \quad \textbf{OK}$$

Use $B' = 22.2$ kips/bolt.

Solution B:

Step 1 Check Equation 4:

$$\phi r'_v = \phi r_v \left(1 - \frac{T_u}{T_e}\right) \text{ with } T_u \le \min\{\phi r_t, T_e\}$$

$$T_u \le \min\{\phi r_t, T_e\}$$

$$\le \min\{40.6 \text{ kips}, 44.1 \text{ kips}\} = 40.6 \text{ kips}$$

$$T_u = 22.0 \text{ kips} \le 40.6 \text{ kips} \quad \textbf{OK}$$

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

$$= 5.56 \text{ kips/bolt}$$

Step 2 $\phi r'_v = 5.56 \text{ kips} \ge V_u = 5.56 \text{ kips}$ **OK to proceed**

Step 3 Calculate F'_{nt} using Equation 3:

$$F'_{nt} = 1.3F_{nt} - \frac{F_{nt}}{\phi F_{nv}} f_{rv} \le F_{nt}$$

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

$$= 96.4 \text{ ksi}$$

$$F'_{nt} = 96.4 \text{ ksi} > F_{nt} = 90 \text{ ksi}$$

Use $F'_{nt} = 90$ ksi.

Calculate B' using Equation 2:

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

$$= (90 \text{ ksi})(0.75)\left(0.601 \text{ in.}^2\right)$$

$$= 40.6 \text{ kips/bolt} \le \phi r_t = 40.6 \text{ kips/bolt} \quad \textbf{OK}$$

Use $B' = 40.6$ kips/bolt.

SUMMARY AND CONCLUSIONS

Method A gives $B' = 22.2$ kips/bolt while Method B gives $B' = 40.6$ 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:

$$T_a \le \frac{R_n}{\Omega} = \frac{F_{nt} A_b}{\Omega} = \frac{0.75 F_u A_b}{2.00} = 0.375 F_u A_b$$

The specified pretension values from *Specification* Table J3.1 are approximately 70% of the tensile strength of the bolt: $T_b \approx 0.70F_uA_b$. 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.

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