Prying Action—a General Treatment*

WILLIAM A. THORNTON

INTRODUCTION

The 8th Edition AISC Manual[1] uses a model (Fig. 1) for predicting the prying force which was recommended in the book by Fisher and Struik.[2] Unlike the approach taken in the 7th Edition Manual, this method is not restricted to specific bolt-plate combinations, since all major parameters which influence the prying action are included in the model. The Q denotes the prying force per bolt and is assumed to act as a line load at the edge of the flange. Test results have shown this to be a reasonable assumption for conditions near ultimate, as long as the edge distance a is within certain limits. The tensile load in the fastener is B_c, and the corresponding applied load per bolt is equal to T. The bending moment at the interface between the web and the flange is taken as M_c, and the moment at the bolt line due to prying force Q is taken equal to $\delta\alpha M_c$ where δ is equal to the ratio of the net area (at the bolt line section bb) and the gross area (at the web face section aa) of the flange. The α represents the ratio between the moment per unit width at the centerline of the bolt line and the flange moment at the web face. When $\alpha = 0$, it corresponds to the case of single curvature bending, i.e., no prying action, and $\alpha = 1$ corresponds to double curvature bending and maximum prying action. Note that, from physical considerations, $0 \leq \alpha \leq 1$.

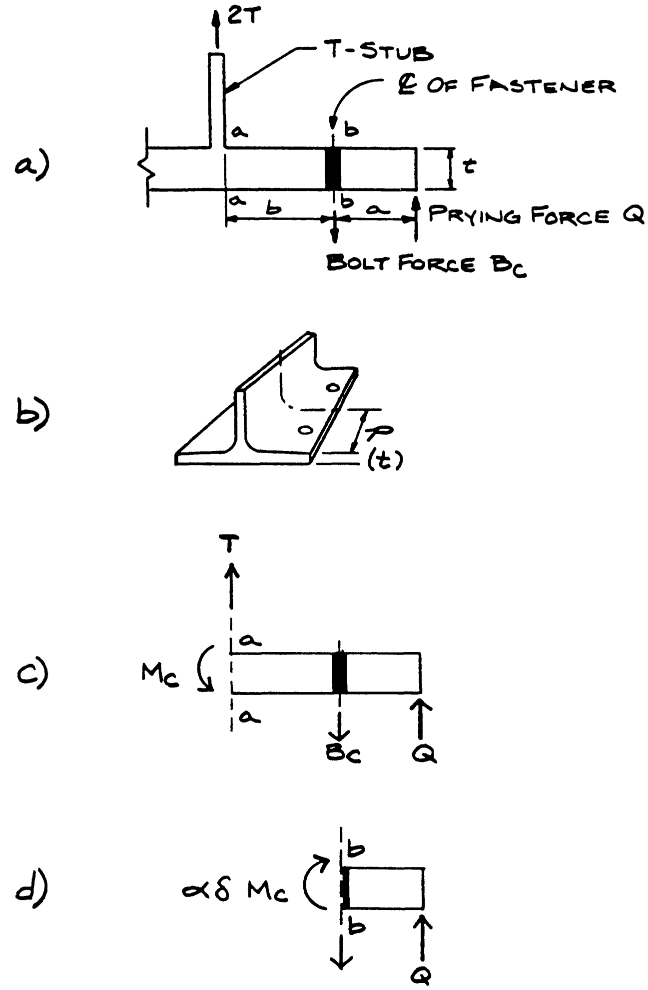

Fig. 1. Prying action analytical model

GENERAL DEVELOPMENT

Considering equilibrium of the portions of the flange shown in Figs. 1c and 1d, the following independent equilibrium equations result:

$$M_c - Tb + Qa = 0$$

$$T + Q - B_c = 0$$

$$Qa - \delta\alpha M_c = 0$$

William A. Thornton, PhD, is Chief Engineer, Cives Corporation, Atlanta, Georgia.

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If T is taken as a known applied load, M_c, Q, B_c and α are unknowns. The problem is statically indeterminate and no elastic solution is possible without recourse to compatibility and constitutive relationships. Alternately, limit analysis can be used. This is the approach taken in Ref. 2. Reference 2 also proposed an adjustment in the position of the bolt force as shown in Fig. 2 to bring the theoretical and experimental results closer together. Replacing b with $b' = b - d/2$ and a with $a' = a + d/2$, the equilibrium equations can be rearranged into the following two equations:

$$\frac{Tb'}{1 + \delta\alpha} = M_c$$

$$T\left(1 + \frac{\delta\alpha}{1 + \delta\alpha}\rho\right) = B_c$$

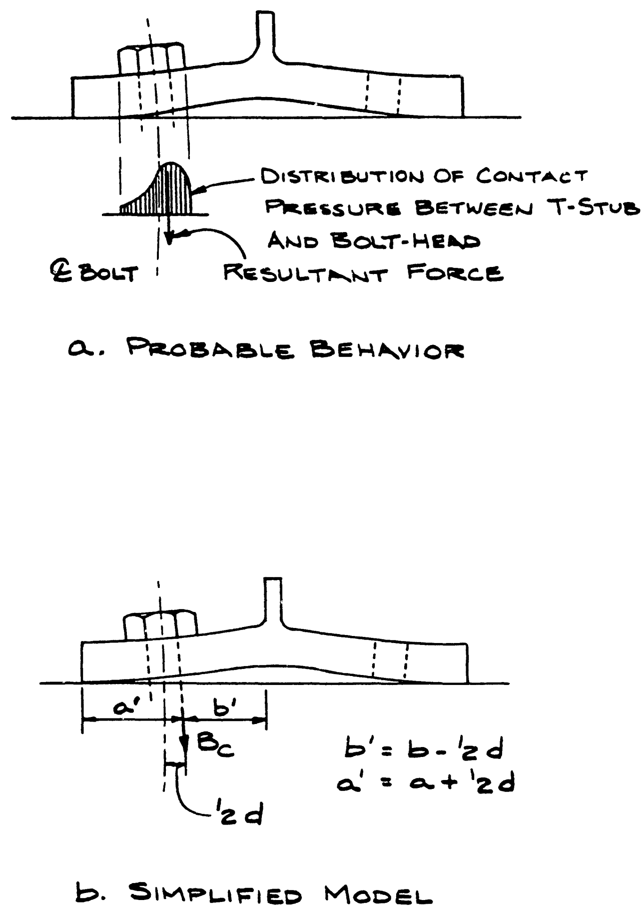

Fig. 2. Influence of flange deformations on location of resultant bolt force

where $\rho = b'/a'$. These are the basic equations for prying analysis. A third equation which provides an explicit result for Q is:

$$Q = T\left(\frac{\delta\alpha}{1 + \delta\alpha}\rho\right)$$

Next, introducing the limit state conditions:

$$M_c \leq M$$

where

$$M = \frac{1}{8}pt^2F_y$$

and

$$B_c \leq B$$

where B = specified allowable bolt tension, any solution to the following two inequalities:

$$\frac{Tb'}{1 + \delta\alpha} \leq \frac{1}{8}pt^2F_y$$

$$T\left(1 + \frac{\delta\alpha}{1 + \delta\alpha}\rho\right) \leq B$$

is a valid solution to the prying action problem.

The solution space for these inequalities is shown in Fig. 3 in dimensionless form by introducing the parameter t_c, where:

$$t_c = \sqrt{\frac{8Bb'}{pF_y}}$$

In terms of T/B and t/t_c, the above two inequalities can be rewritten as:

$$\frac{T}{B} \leq (1 + \delta\alpha)\left(\frac{t}{t_c}\right)^2 \qquad (1)$$

$$\frac{T}{B} \leq \frac{1 + \delta\alpha}{1 + \delta\alpha(1 + \rho)} \qquad (2)$$

The family of curves labeled a in Fig. 3 is obtained from the Inequality 1 above with the inequality sign replaced by the equality sign. The family of curves labeled b in Fig. 3 is obtained from the prying force equation:

$$\frac{Q}{B} = \frac{T}{B}\left(\frac{\delta\alpha}{1 + \delta\alpha}\right)\rho$$

with:

$$\frac{T}{B} = (1 + \delta\alpha)\left(\frac{t}{t_c}\right)^2 \qquad (3)$$

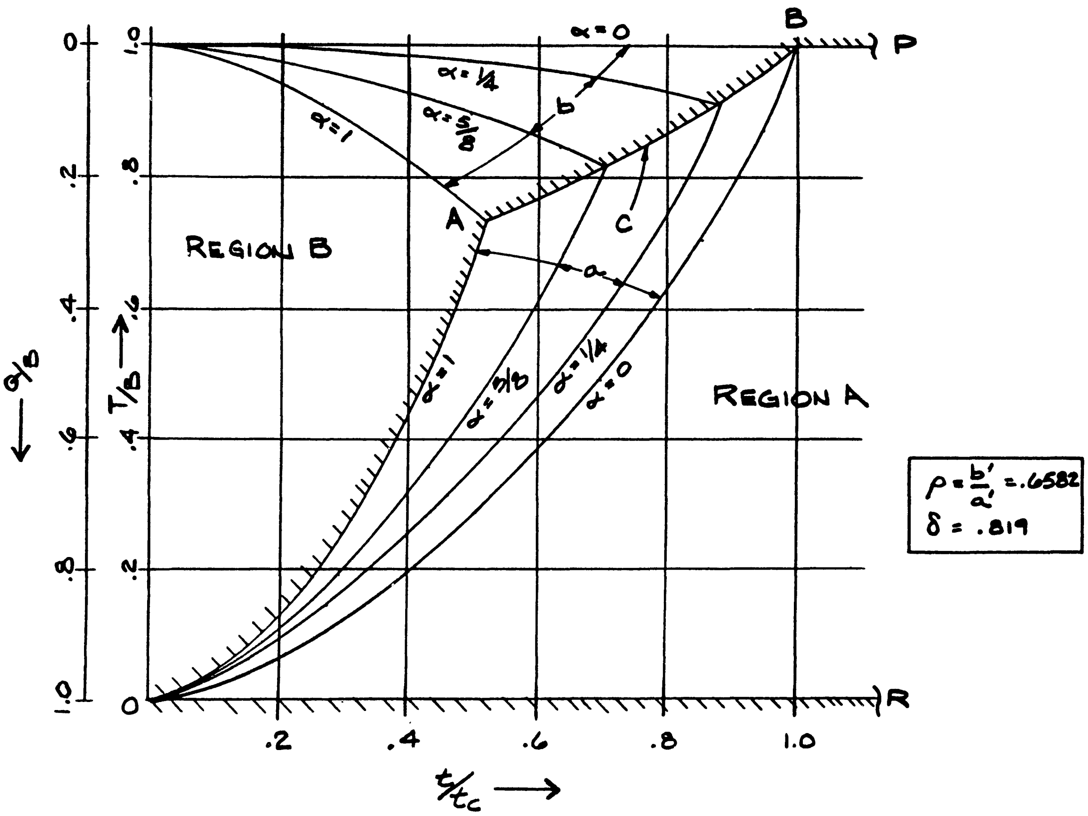

Fig. 3. Solution space for prying action analysis

Thus, curves b are given by:

$$\frac{Q}{B} = \delta\alpha\rho\left(\frac{t}{t_c}\right)^2 \tag{4}$$

The curve c in Fig. 3 is the locus of points for which:

$$\frac{T}{B} + \frac{Q}{B} = 1$$

and is given by:

$$\frac{T}{B} = \frac{1}{1+\rho}\left[1 + \rho\left(\frac{t}{t_c}\right)^2\right]$$

The boundary between the region of solutions to Inequalities 1 and 2, Region A and the remainder of the solution space, Region B, is denoted by the cross-hatched curve ROABP of Fig. 3. It will be apparent from Fig. 3 that there is no unique solution to the prying action problem. For instance, if the applied tension is given, T/B is known and any value of t/t_c from curve OAB to $t/t_c \rightarrow \infty$ is a solution. Likewise, if t is given, t/t_c is known, and any value of T/B from 0 to curve OABP is a solution. Obviously, efficient solutions are those that lie on curve OAB. Points on this curve give the least required material thickness t for a given applied tension T, or the largest allowable applied load T for a given material thickness. Thus, methods for achieving points which are on or close to curve OAB will be developed.

METHODS OF SOLUTION

Method 1.

This method solves the problem:

Given: T, a', b', p, F_y, and B
Find: the smallest value of t
Such that: Inequalities 1 and 2 are satisfied

It can be verified that the solution to this problem is given by the following algorithm:

1. Check $T \leq B$; if so proceed, if not use more or stronger bolts
2. Then calculate $\beta = \frac{1}{\rho}\left(\frac{B}{T} - 1\right)$

3. If $\beta \geq 1$ set $\alpha = 1$

4. If $0 \leq \beta < 1$, $\alpha = \min\left\{\frac{1}{\delta}\left(\frac{\beta}{1-\beta}\right), 1\right\}$

5. With the determined value of α, calculate:

$$t_{reqd} = \sqrt{\frac{8Tb'}{pF_y(1 + \delta\alpha)}}$$

In using this method, an initial choice of WT or angles will probably have to be made because of the geometry involved in calculating a' and b'. Let this initial choice for t be denoted t_{act}. Then, if $t_{act} \geq t_{reqd}$ calculated above, the initial choice is satisfactory.

Note that, if $t_{act} > t_{reqd}$, the design point will not lie on curve OAB, but will be to the right of OAB. Thus, the actual value of α will be less than the value calculated above. This reduced value of α, say α_{act}, can be calculated from Eq. 3 above, as:

$$\alpha_{act} = \frac{1}{\delta}\left(\frac{T/B}{(t_{act}/t_c)^2} - 1\right)$$

$$\text{if} \quad \alpha_{act} < 0, \text{ set} \quad \alpha_{act} = 0$$

and this value of α should be used if the true value of the prying force is required. The latter can be calculated from Eq. 4, as:

$$\left(\frac{Q}{B}\right)_{act} = \delta\alpha_{act}\rho\left(\frac{t_{act}}{t_c}\right)^2$$

Example 1

Consider Ex. 1 of the 8th Edition AISC Manual, p. 4-91. Given the data $B = 19.4$ kips, $T = 11$ kips, $p = 4.5$ and 4-in. cross-centers, an initial choice of WT section must be made to determine a and b. The Manual provides a Preliminary Selection Table on p. 4-98 which is based on Eq. 1 with $\delta = \alpha = 1$, and $b' = b$. Thus,

$$t_{prelim} = 2\sqrt{\frac{Tb}{pF_y}}$$

and we have, with $b = \frac{4 - t_w}{2} = \frac{4 - .5}{2} = 1.75$, assuming a .5-in. web thickness,

$$t_{prelim} = 2\sqrt{\frac{11 \times 1.75}{4.5 \times 36}} = .6894$$

On the basis of $t_{prelim} = .6894$, a tee cut from a W18×60, with $t_{act} = .695$, is chosen, and the following geometric parameters ensue: $b = 1.792$, $a = 1.778 < 1.25 \times 1.792$, $b' = 1.417$, $a' = 2.153$, $\delta = .819$, $\rho = b'/a' = .6582$. Then:

$$\beta = \frac{1}{.6582}\left(\frac{19.4}{11} - 1\right) = 1.16$$

and $\quad \alpha = 1$

Thus

$$t_{reqd} = \sqrt{\frac{8 \times 11 \times 1.417}{4.5 \times 36 \times 1.819}} = .651 \text{ in.}$$

Since $t_{act} = .695 > t_{reqd} = .651$, the W18×60 is o.k. To calculate the prying force:

$$t_c = \sqrt{\frac{8 \times 19.4 \times 1.417}{4.5 \times 36}} = 1.1651$$

$$\alpha_{act} = \frac{1}{.819}\left(\frac{11/19.4}{(.695/1.1651)^2} - 1\right) = .7246$$

$$Q_{act} = 19.4 \times .819 \times .7246 \times .6582 \times \left(\frac{.695}{1.1651}\right)^2$$

$$= 2.696 \text{ kips}$$

Example 2

This example is also drawn from the Manual. It is Ex. 2 on p. 4-92, and involves the same situation as Ex. 1, but with a fatigue loading of more than 20,000 but less than 500,000 cycles. Section B3 of the AISC Specification has a provision for reducing the allowable bolt tension B to .6 B, exclusive of prying force if $Q/T > .10$. In this example, $Q/T = 2.696/11 = .2451 > .10$, thus $B = .6 \times 19.4 = 11.64$. Since $11.64 > 11.0$, the connection is satisfactory.

Example 3

This is Ex. 4, pp. 4-92 and 4-93 of the Manual, and it serves to demonstrate the solution to problems in which the bolts are subjected to both tension and shear. The bolts are A325N ¾-dia. Skipping the preliminary selection routine which is performed here exactly as it was in Ex. 1, as a ⅝-angle is chosen and the geometric data are $a' = 1.875$, $b' = 1.50$, $\delta = .819$, $\rho = .8000$, $T = 8.95$, and the shear per bolt $V = 26.8/6 = 4.47$. Interaction enters this problem as (see Table 1):

$$B = .4418 \times 55 - 1.8 \times 4.47 = 16.253 \text{ kips}$$

Since $16.253 > 8.95$, we proceed to calculate:

$$\beta = \frac{1}{.8}\left(\frac{16.253}{8.95} - 1\right) = 1.02 \quad \text{and} \quad \alpha = 1$$

Table 1. Interaction Expressions for Bearing Connections

Bolt Type	Value of B	
	Threads Included	Threads Excluded
A325	$55A_b - 1.8V \leq 44A_b$	$55 - 1.4V \leq 44A_b$
A490	$68A_b - 1.8V \leq 54A_b$	$68A_b - 1.4V \leq 54A_b$
A307	$26A_b - 1.8V \leq 20A_b$	

Thus

$$t_{reqd} = \sqrt{\frac{8 \times 8.95 \times 1.5}{4.5 \times 36 \times 1.819}} = .605 < .625 \quad \textbf{o.k.}$$

The $^5/_8$-angle is therefore satisfactory. The prying force, if required, can be calculated in the same manner as explained in Ex. 1, as follows:

$$t_c = \sqrt{\frac{8 \times 16.253 \times 1.5}{4.5 \times 36}} = 1.0972$$

$$\alpha_{act} = \frac{1}{.819}\left[\frac{8.95/16.253}{(.625/1.0972)^2} - 1\right] = .8513$$

$$Q_{act} = 16.253 \times .819 \times .8513 \times .8 \times \left(\frac{.625}{1.0972}\right)^2$$

$$= 2.942 \text{ kips}$$

Example 4

Suppose the connection of Ex. 3 above is required to be a friction type connection. Let the faying surfaces be blast cleaned and coated with inorganic zinc primer, thus producing surface class F. Let the holes be standard holes and assume that threads are not necessarily excluded from shear planes. Then, the allowable bolt shear stress is $F_v = 21$ ksi.

From AISC Specification Sect. 1.6.3, the interaction equation for friction type connections is:

$$F'_v = \left(1 - \frac{f_t A_b}{T_b}\right) F_v$$

where F'_v is the reduced allowable bolt shear stress, f_t is the bolt tensile stress due to a direct load applied to all of the bolts in the connection, A_b is the nominal bolt cross-sectional area and T_b is the specified bolt pretension load from Specification Table 1.23.5. It will be noticed this interaction equation is expressed in a form inverse to the interaction equations for bearing type connections. This inverse form is not convenient for use in the prying equations because these require an expression which gives the allowable bolt tension B as a function of the applied shear. Thus, inverting the above friction type interaction expression to the required form, we get:

$$B = T_b\left(1 - \frac{V}{A_b F_v}\right) \leq A_b F_t$$

where F_t is the allowable bolt tensile stress in the absence of shear, and the applied bolt shear V must satisfy the inequality:

$$V \leq A_b F_v$$

Table 2. Interaction Expressions for Friction Connections

Bolt Type	Value of B (or B_r)
A325	$T_b\left(1 - \frac{V}{A_b F_v}\right) \leq 44 A_b$
A490	$T_b\left(1 - \frac{V}{A_b F_v}\right) \leq 54 A_b$

The interaction equations for friction type connections are summarized in Table 2. Proceeding now with Ex. 4:

$$B = 28\left(1 - \frac{4.47}{9.3}\right) = 14.542 \text{ kips} < 19.4 \text{ kips} \quad \textbf{o.k.}$$

$$V = 4.47 \text{ kips} < 9.3 \text{ kips} \quad \text{o.k.}$$

Then:

$$\beta = \frac{1}{.8}\left(\frac{14.542}{8.95} - 1\right) = .7810$$

$$\alpha = \min\left\{\frac{1}{.819}\left(\frac{.7810}{1 - .7810}\right), 1\right\}$$

$$= \min\{4.3543, 1\} = 1$$

$$t_{reqd} = \sqrt{\frac{8 \times 8.95 \times 1.5}{4.5 \times 36 \times 1.819}} = .605 < .625 \quad \textbf{o.k.}$$

The $^5/_8$-angles and $^3/_4$-dia. bolts are satisfactory for a friction-type connection.

The prying force is calculated, as before, by calculating t_c, α_{act} and Q_{act} as:

$$t_c = \sqrt{\frac{8 \times 14.542 \times 1.5}{4.5 \times 36}} = 1.0379$$

$$\alpha_{act} = \frac{1}{.819}\left[\frac{8.95/14.542}{(.625/1.0379)^2} - 1\right] = .8514$$

$$Q_{act} = 14.542 \times .819 \times .8514 \times .8 \times \left(\frac{6.25}{1.0379}\right)^2$$

$$= 2.942 \text{ kips}$$

Alternate formulation for the friction-type connection

As is well known, there is no interaction between tension and shear in friction-type connections when the tension is not applied to all the bolts of the group. This situation occurs when the bolt tension is caused by a moment due to eccentric shear, such as occurs, for instance, in bracket connections. In this case, the reduction in shear capacity due to unloading of the faying surfaces in the vicinity of the tension bolts is picked up by an increase in shear capacity due to increased loading of the faying surfaces in the compression zone. Something akin to this occurs in prying connections. The faying surfaces adjacent to the bolt are unloaded by the prying force Q, but the faying surface compression near the toes of the angles or tee flanges is increased due to the Q force. For this reason, interaction need not be applied to the total bolt tension $T + Q$, but only to that part T caused by the direct load.

Introducing the notation:

$$B_r = T_b \left(1 - \frac{V}{A_b F_v}\right) \leq A_b F_t$$

where B_r is called the reduced allowable bolt tension, and letting B now represent the unreduced bolt tension ($= A_b F_t$), the solution to this alternate formulation is exactly the previous Method 1 solution with Step 1 changed to:

1a. Check $T \leq B_r$

In all remaining steps and subsidiary calculations, when B appears, it is the unreduced value.

Applying this algorithm to Ex. 4:

$$B_r = 28 \left(1 - \frac{4.47}{9.3}\right) = 14.542 \text{ kips } (<19.4 \text{ kips})$$

Since $T = 8.95$ kips < 14.542 kips, the solution may proceed. If $T > B_r$, more or larger bolts would have to be used to proceed. Continuing:

$$\beta = \frac{1}{.8}\left(\frac{19.4}{8.95} - 1\right) = 1.4595$$

Since $\beta > 1$, set $\alpha = 1$, and:

$$t_{reqd} = \sqrt{\frac{8 \times 8.95 \times 1.5}{4.5 \times 36 \times 1.819}} = .605 < .625 \quad \textbf{o.k.}$$

Thus the $^5/_8$-angle and A325F $^3/_4$-dia. bolts are satisfactory. The alternate formulation does not, for this example, yield a different result, but it is a much more liberal solution which can yield significantly reduced angle or tee flange thicknesses. Reductions in thickness of 10% to 15%, when compared to those obtained from the initial solution method presented for friction-type connections, can be obtained.

Completing the solution, the actual prying force is calculated as follows:

$$t_c = \sqrt{\frac{8 \times 19.4 \times 1.5}{4.5 \times 36}} = 1.1988$$

$$\alpha_{act} = \frac{1}{.819}\left[\frac{8.95/19.4}{(.625/1.1988)^2} - 1\right] = .8514$$

$$Q_{act} = 19.4 \times .819 \times .8514 \times .8 \times \left(\frac{.625}{1.1988}\right)^2$$

$$= 2.942 \text{ kips}$$

Method 2.

Let us now proceed to the second method of solution to the prying action problem which yields points which are on or near curve OAB.

Consider the problem:

Given: t, a', b', p, F_y and B
Find: the largest value of T
Such that: Inequalities 1 and 2 are satisfied

It can be verified the solution to this problem is given by the following algorithm:

1. Check $T \leq B$; if so, proceed; if not use more or stronger bolts
2. Then, calculate:
   $$\alpha = \frac{1}{\delta(1 + \rho)}\left[\frac{8Bb'}{pt^2 F_y} - 1\right]$$
3. If $\alpha < 0$, set $\alpha = 0$ (bolts control), and
   $$T_{allow} = \frac{B(1 + \delta\alpha)}{1 + \delta\alpha(1 + \rho)} = B$$
4. If $\alpha > 1$, set $\alpha = 1$ (material thickness controls), and
   $$T_{allow} = \frac{pt^2 F_y}{8b'}(1 + \delta\alpha)$$
5. If $0 \leq \alpha \leq 1$ (bolts and material thickness *both* control), and
   $$T_{allow} = \frac{B(1 + \delta\alpha)}{1 + \delta\alpha(1 + \rho)}$$
   or
   $$T_{allow} = \frac{pt^2 F_y}{8b'}(1 + \delta\alpha)$$
   The two values given for T_{allow} for the latter case will always be equal. The designer can choose which one he prefers to calculate.

As in Method 1, an initial choice of section is made to get t, a' and b'. The initial choice can be based, as before, on:

$$t_{prelim} = 2\sqrt{\frac{Tb}{pF_y}}$$

Once a section is chosen, T_{allow} is calculated. If $T_{allow} > T$, the choice is adequate. If $T_{allow} < T$, choose a thicker t, reduce cross-centers, use more or stronger bolts, and try again.

When a satisfactory section is found, the prying force Q can be found using the same formulas developed in Method 1, i.e.,

$$\alpha_{act} = \frac{1}{\delta}\left[\frac{T/B}{(t_{act}/t_c)^2} - 1\right]$$

$$\left(\frac{Q}{B}\right)_{act} = \delta\alpha_{act}\rho\left(\frac{t_{act}}{t_c}\right)^2$$

As pointed out in the examples for Method 1, the quantity B must be reduced when shear is present in bearing connections. For friction connections, two alternatives were given, the second being more liberal while still satisfying code requirements.

In the first (or basic) friction connection method, the reduced value of B is substituted for B in every formula in which B appears. In the second (or alternate) friction connection method, the reduced value B_r is used *only* in Step 1 of the solution algorithm. The unreduced value of B is used in every other step of the algorithm and in all subsidiary calculations, such as the determination of the actual prying force Q.

Example 5

Using the same data as Ex. 1 of Method 1, the preliminary selection calculation is performed as in Ex. 1. Then with $t_{act} = .695$, $a' = 2.153$, $b' = 1.417$, $p = 4.5$, $\delta = .819$, $\rho = .6582$, $T = 11 < B = 19.4$

$$\alpha = \frac{1}{.819 \times 1.6582}\left[\frac{8 \times 19.4 \times 1.417}{4.5 \times .695^2 \times 36} - 1\right] = 1.333$$

Since $\alpha = 1.333 > 1$, set $\alpha = 1$, and

$$T_{allow} = \frac{4.5 \times .695^2 \times 36}{8 \times 1.417} \times 1.819 = 12.56 \text{ kips}$$

Since 12.56 kips > 11.0 kips, the W18×60 tee and ³/₄-dia. bolts are **o.k.** To calculate the prying force:

$$t_c = \sqrt{\frac{8 \times 19.4 \times 1.417}{4.5 \times 36}} = 1.1651$$

$$\alpha_{act} = \frac{1}{.819}\left[\frac{11/19.4}{(.695/1.1651)^2} - 1\right] = .7246$$

$$Q_{act} = 19.4 \times .819 \times .7246 \times .6582 \times \left(\frac{.695}{1.1651}\right)^2$$
$$= 2.696 \text{ kips}$$

As expected (and obvious from the equations used), this is the same result obtained by Method 1.

Example 6

This is the same as Ex. 3 of Method 1. Given the data of Ex. 3, $T = 8.95 < B = 16.253$, so proceed to calculate α as:

$$\alpha = \frac{1}{.819(1.8)}\left[\frac{8 \times 16.253 \times 1.5}{4.5 \times .625^2 \times 36} - 1\right] = 1.4123$$

Since $\alpha = 1.4123 > 1$, set $\alpha = 1$, and

$$T_{allow} = \frac{4.5 \times .625^2 \times 36}{8 \times 1.5} \times 1.819 = 9.59 \text{ kips}$$

Since 9.59 kips > 8.95 kips, the ⁵/₈-angle and ³/₄-dia. A325N bolts are **o.k.** As will be obvious from previous calculations, $\alpha_{act} = .8513$ and $Q_{act} = 2.942$ kips.

Example 7

This is the same as Ex. 4 of Method 1. The first (basic) method given in Ex. 4 proceeds as follows:

$\beta = 14.542 > T = 8.95$, so calculate α as:

$$\alpha = \frac{1}{.819(1.8)}\left[\frac{8 \times 14.524 \times 1.5}{4.5 \times .625^2 \times 36} - 1\right] = 1.1922$$

Since $\alpha = 1.1922 > 1$, set $\alpha = 1$, and:

$T_{allow} = 9.59$ kips > 8.95 kips **o.k.**

From the calculations of Ex. 3, $\alpha_{act} = .8514$ and $Q_{act} = 2.942$ kips. The second (alternate) method given in Ex. 4 proceeds as follows:

$B_r = 14.542$ kips > 8.95 kips, so calculate α as:

$$\alpha = \frac{1}{.819(1.8)}\left[\frac{8 \times 19.4 \times 1.5}{4.5 \times .625^2 \times 36} - 1\right] = 1.8171$$

Since $\alpha = 1.8171 > 1$, set $\alpha = 1$, then

$T_{allow} = 9.59$ kips > 8.95 kips **o.k.**

From the calculations of Ex. 3, $\alpha_{act} = .8514$, $Q_{act} = 2.942$ kips.

As mentioned earlier, the alternate method for friction connections can yield significantly lighter (cheaper) connections than the first method, but the above examples, which are taken from the AISC Manual, do not show this. Consider then the following example:

Example 8

The framed connection shown in Fig. 4 is subjected to 65 kips of shear. The shop and field bolts are A325 ³/₄-dia. A friction-type connection is required and the surface class is A− clean mill scale. Standard holes are used, so $F_v = 17.5$ ksi. Determine the maximum tension this connection can carry.

The fundamental parameters can be calculated from the given information. Thus:

$$b = 3 - .625 = 2.3750$$

$$b' = 2.3750 - .3750 = 2.0$$

$$a = \frac{8.5 - 6.5}{2} = 1.0 \ (< 1.25 \times 2.3750 \quad \textbf{o.k.})$$

$$a' = 1.375$$

$$\rho = 2/1.375 = 1.4545$$

$$\delta = 1 - \frac{13/16}{3} = .7292$$

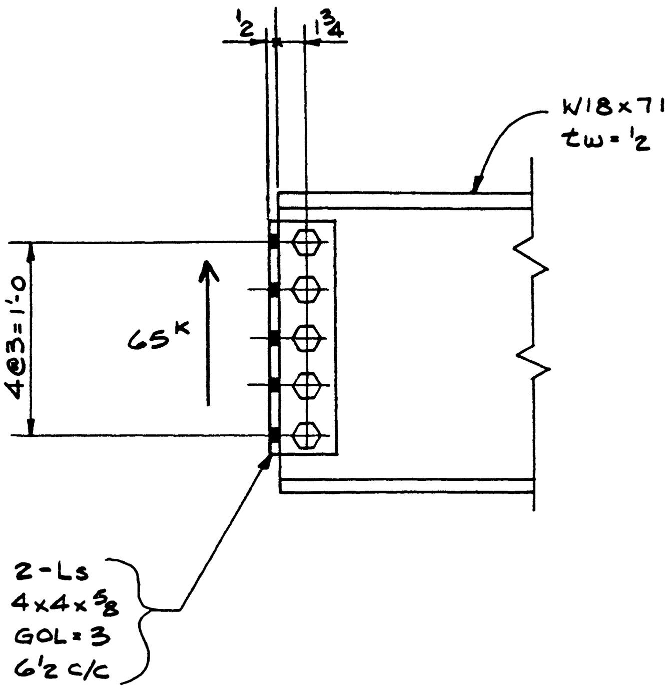

Figure 4

$p = 3$

$V = 65/10 = 6.5$ kips

Solution by "basic" Method:

$$B = 28\left(1 - \frac{6.5}{7.73}\right) = 4.4554 < 19.4 \quad \textbf{o.k.}$$

$$\alpha = \frac{1}{.7292 \times 2.4545}\left[\frac{8 \times 4.4554 \times 2.0}{3 \times .625^2 \times 36} - 1\right]$$

$$= .3854$$

$$T_{allow} = \frac{3 \times .625^2 \times 36}{8 \times 2.0}(1 + .7292 \times .3854)$$

$$= 3.3777 \text{ kips}$$

Since there are 10 bolts, the total allowable applied tension is:

$$T_{total} = 3.3777 \times 10 = 33.78 \text{ kips}$$

Solution by "Alternate" Method:

$B = 19.4$

$B_r = 4.4554$

$$\alpha = \frac{1}{.7292 \times 2.4545}\left[\frac{8 \times 19.4 \times 2.0}{3 \times .625^2 \times 36} - 1\right] = 3.5521$$

Since $\alpha = 3.5521 > 1$, set $\alpha = 1$, and

$$T_{allow} = \frac{3 \times .625^2 \times 36}{8 \times 2.0}(1 + .7292) = 4.559$$

Remembering that the applied tension cannot exceed B_r:

$$T_{allow} = \min\{4.559, B_r\} = 4.4554 \text{ kips}$$

and the total allowable applied tension is:

$$T_{total} = 4.4554 \times 10 = 44.55 \text{ kips}$$

which is 32% greater than the previously obtained value of 33.78 kips. It can be seen that the alternate method is the significantly more economical method of the two.

It must be kept in mind there are other checks, involving the shop bolts and beam web, that must be made to assess the capacity of this joint. Thus, 44.55 kips calculated above may *not* be the tensile capacity of the joint. The reader can verify that the maximum allowable tension, at 65 kips shear, is 41.84 kips, based on resultant shear in the shop bolts.

Methods 1 and 2 for the solution to the prying action problem provide optimal solutions from the point of view of least material thickness or maximum capacity, respectively. Any other method of solution which achieves a point (t/t_c, T/B) in region A of Fig. 3, is an acceptable method. Method 3, which follows, is just such a method. It is an organized version of the method given on pp. 4-89 and 4-90 of the Manual.

Method 3.

An initial choice of thickness t is required for this method. Note that in Methods 1 and 2, an initial t was *not* required except that it was needed to estimate a' and b'. After choosing number, type and arrangement of bolts, proceed as follows:

Choose $t = t_{act}$, calculate a', b', p, T, V, B, δ.
Then

1. Check $T \leq B$; if not increase number of bolts or use larger or stronger bolts.
2. Calculate $\alpha = \dfrac{1}{\delta}\left[\dfrac{T/B}{(t_{act}/t_c)^2} - 1\right] \equiv \dfrac{1}{\delta}\left(\dfrac{Tb'}{M} - 1\right)$ (AISC Eq. 3)
3. If $\alpha > 1$, set $\alpha = 1$

   $$t_{reqd} = \sqrt{\frac{8Tb'}{pF_y(1 + \delta)}} > t_{act} \quad \textbf{n.g.}$$

   Choose a new $t_{act} > t_{reqd}$, or increase number of bolts; go to Step 1.
4. If $\alpha < 0$, set $\alpha = 0$

   $$t_{reqd} = \sqrt{\frac{8Tb'}{pF_y}} < t_{act} \quad \textbf{o.k.}$$

Choice of bolts and t_{act} is satisfactory, no further calculations are required; go to Step 6.

5. If $0 \leq \alpha \leq 1$:

$$t_{reqd} = \sqrt{\frac{8Tb'}{pF_y(1 + \delta\alpha)}} = t_{act} \quad \textbf{o.k.}$$

Check $B_c = T\left(\frac{1 + \delta\alpha(1 + p)}{1 + \delta\alpha}\right) \leq B$ (AISC Eq. 4)

If **o.k.**, go to Step 6, otherwise choose more or stronger bolts, or increase t_{act}, and go to Step 1.

6. Solution is complete. Prying force, if required, is calculated from:

$$Q_{act} = B\delta\alpha\rho\left(\frac{t_{act}}{t_c}\right)^2$$

In the above algorithm, when shear is present, B is determined from the interaction equation for bearing connections or friction connections. In the alternative method for friction connections B is replaced by the reduced $B = B_r$ only in Step 1. Everywhere else B appears it is the unreduced tension value.

The above algorithm will seem to differ from the Manual procedure in that AISC Eq. 5 (Manual p. 4-89) does not appear. Actually, AISC Eq. 5 can be written as:

$$reqd\ t_f = \sqrt{\frac{8Tb'}{pF_y(1 + \delta\alpha)}} \quad \text{(AISC Eq. 5)}$$

which can be verified by direct substitution of AISC Eq. 4 into AISC Eq. 5, thereby eliminating the appearance of B and simplifying the expression. In this simplified form, it can be seen that AISC Eq. 5 does indeed appear in Steps 3, 4 and 5 of the above algorithm.

As a final comment on this method, it will be noticed in Steps 3, 4 and 5 that the result of the comparison of t_{reqd} with t_{act} is known in advance. This occurs because the same equation is being used to calculate α in Step 2 and t_{reqd} in Steps 3, 4 and 5. Thus, there is no need actually to calculate t_{reqd} in Steps 4 and 5. In Step 3, t_{reqd} is calculated to provide a new guess for t_{act} if a thicker angle or tee is decided upon rather than more bolts.

REFERENCES

1. *American Institute of Steel Construction, Inc.* Manual of Steel Construction *8th Ed., 1980, Chicago, Ill., pp. 4-88 through 4-93.*
2. *Fisher, J. W. and J. H. A. Struik* Guide to Design Criteria for Bolted and Riveted Joints *Wiley-Interscience, New York, N.Y., 1974, pp. 270–279.*