A Slightly Longer Look at Prying

By Carlo Lini, PE

The prying check procedure presented in Part 9 of the 14th Edition of the AISC *Steel Construction Manual* can be intimidating for first-time or infrequent users. There are many variables and equations, and the controlling limit state may not always be obvious. For those who have struggled with this procedure, this paper presents a different way to think about prying—and will hopefully provide a better understanding of the prying checks in Part 9.

Setting the Ground Rules

First, the assumptions must be defined. This paper adopts the model described in Part 9 of the *Manual*. This means that the paper considers only the ultimate strength of the connection and assumes fatigue is not a consideration. The model represents a lower-bound solution, which by definition predicts a strength that is less than—or at most equal to—the actual strength of the connection at ultimate loads. It is based on a set of forces that satisfies equilibrium. All applicable limit states are satisfied for the forces assumed in the model, and we know based on tests that it can safely be assumed that the connection has sufficient ductility to accommodate model.

The model does not consider the behavior of the connection as it reaches the force distribution assumed to exist at ultimate loads; it is not an elastic model. Prying can increase the stress range that must be considered under fatigue loading, a consideration that is beyond the scope of this paper.

The bolt force is shown as being applied at the edge of the bolt hole (Figure 1). This adjustment brings the theoretical and experimental results closer together (Kulak et al., 1987).

Fatigue

- Tensile fatigue in bolts is best avoided by configuring joints such that the bolts resist only shear.
- Though Appendix 3 of the *Specification* addresses snug-tight conditions, pretensioning is encouraged and greatly enhances fatigue behavior.
- Beam end shear connections should be flexible to allow rotation and prevent prying (Wilson, 1940).
- The AISC and RCSC *Specifications* address tensile fatigue in bolts somewhat differently, but both require accounting for prying.
- AASTO provides a simplified and conservative calculation to estimate prying.
- The calculation of the prying force, *q*, in the *Manual* is not appropriate for evaluating fatigue.

Prying for Strength

Prying may mistakenly be viewed as a flaw in a connection—a limit state that weakens the connection—but the opposite is actually true. As stated on page 9-11 of the 14th Edition *Manual*: “Alternatively, it is usually possible to determine a lesser required thickness by designing the connecting element and bolted joint for the actual effects of prying action with *q* greater than zero.” One can view prying as a way to increase the strength of a connection—i.e., a thinner part with prying can have the same strength as a thicker part without prying.

The Strength of the Plate without Prying

Before getting into how prying increases the strength of the connection, let's examine the condition without prying and how it is handled in the *Manual*.

Equation 9-20 in the *Manual* calculates the minimum thickness required to eliminate prying action:

$$t_{min} = \sqrt{\frac{4Tb'}{\phi p F_u}} \quad \text{(\textit{Manual} Eq. 9-20)}$$

This is the LRFD formulation, and the check assures that the flexural strength of the angle leg (Figure 1) is not exceeded. We can also think of this condition as a cantilevered beam with a length *b′* as idealized in Figure 2.

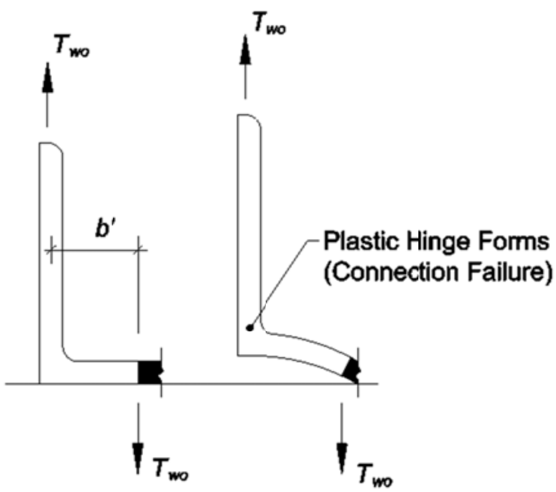


Figure 1: Angle loaded in tension without prying.

The Moment Arm

- Figure 1 shows a moment arm measured from the center of leg to the edge of the bolt hole. This is consistent with the model assumed for angles in the *Manual*.
- For tees and wide-flange shapes, the moment arm is generally measured from the face of the web.
- The February 2015 Steel Interchange (available at www.modernsteel.com) provides further discussion.

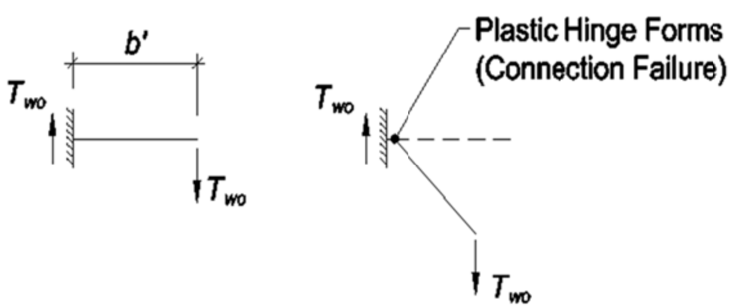


Figure 2: Without prying, viewed as a cantilever beam.

The Effective Width

- The effective width, *p*, can be conservatively taken as 3.5*b* but cannot exceed the spacing between the bolts.
- Larger effective widths can be justified through rational analysis. The *Manual* provides further guidance.

The available flexural strength of the angle leg near the heel of the angle is equal to

$$\phi M_{wo} = \phi F_u Z = \phi F_u \left(\frac{p\,t^2}{4}\right) \quad \text{(Eq. 1)}$$

where *p* is equal to the tributary width and *t* is equal the angle thickness.

The moment at this location is equal to

$$M_u = T_{wo}\ x\ b' \quad \text{(Eq. 2)}$$

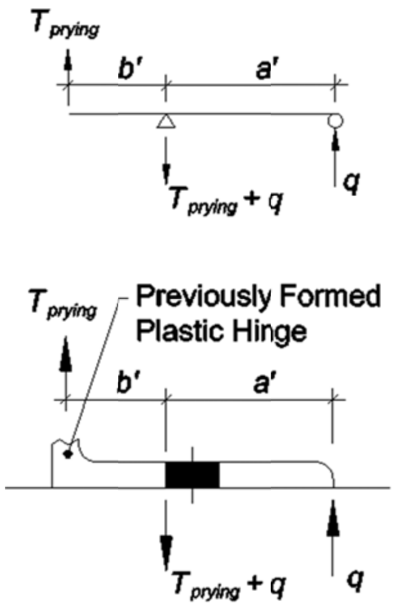
Setting M_u equal to ϕM_{wo} and solving for T_{wo} results in

$$T_{wo} = \frac{\phi M_{wo}}{b'} \quad \text{(Eq. 3)}$$

T_{wo} refers to the amount of load that can be applied to the angle before creating a plastic hinge near the heel of the angle. Note that one can substitute Eq. 2 into Eq. 1 and solve for the required thickness, *t*, which would result in the same expression as *Manual* Eq. 9-20 presented earlier. This can be viewed as the minimum thickness required to provide sufficient strength without having to account for prying and the additional strength that result from prying. For cases where the applied load, *T*, is less than T_{wo}, the α calculated in *Manual* Eq. 9-29 is less than 0. This is equivalent to *t* being less than t_{min}.

Additional Strength of the Plate with Prying

It might be possible to squeeze more strength from the connection if a more complex model is chosen. Prying action can be accounted for. As mentioned previously, the case without prying can be envisioned as a cantilever beam. To account for the additional strength from prying, a model, as shown in Figure 3, can be used. The addition of a hinge at the bolt line increases the flexural strength of the flange (which might be intuitively surmised). Recognizing additional restraint that was previously ignored cannot weaken the system. This is in fact a corollary to the lower bound theorem.

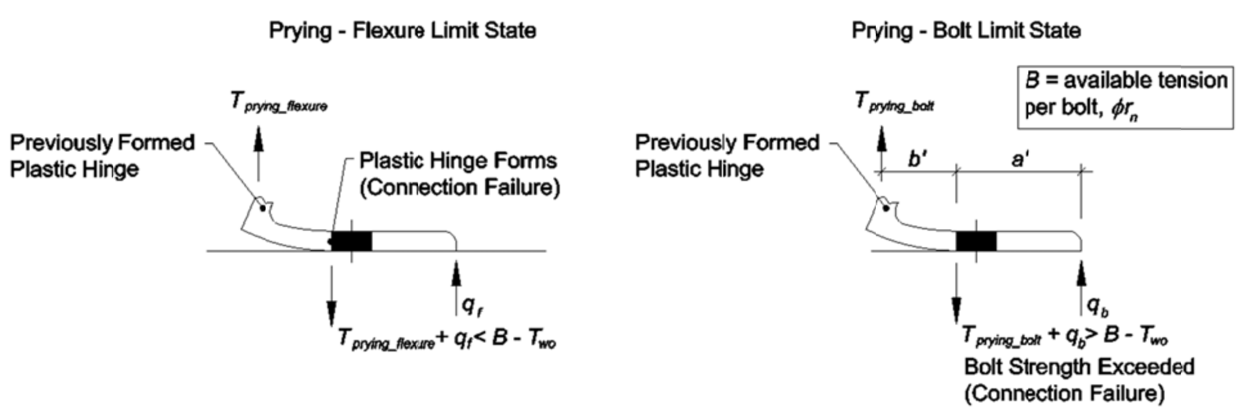


Cantilever Model

Note that the strength gain shown from considering prying is superimposed onto the strength without prying case (see Eq. 11). That is why no moment is shown at the cantilever end in Figure 3 and 4. Since the case without prying develops the flexural strength near the angle heel, no additional moment can be taken at this location.

Figure 3: Prying contribution viewed as a cantilever resulting from the forces at the bolt and angle toe locations, forming a moment couple.

This additional cantilever support would prevent the failure mode depicted in Figure 1 and 2—i.e., we are going from a model that allows only one plastic hinge to one that allows two plastic hinges to form. An additional flexure check near the bolt line can be made to determine the strength increase due to the presence of the second plastic hinge (Figure 4a). This new model requires an additional force, *q*, to maintain equilibrium. The T_{prying} term can simply be viewed as the additional strength gained from taking prying into account. That is, the total strength of the connection, *T*, would be $T = T_{wo}+T_{prying}$.



a.) $T_{prying\_flexure}$ limited by flexural yielding limit state at bolt hole location. b.) T_{prying_bolt} limited by bolt tension rupture limit state.

Figure 4: Prying contribution limit states.

The flexure limit state looks at bending along the bolt line. This check can be expressed as follows:

$$\phi M_{prying} = \phi F_u Z = \phi F_u \left(\frac{\left(p-(d')\right) t^2}{4} \right) \quad \text{(Eq. 4)}$$

Where $d' = d_b + {}^{1}\!/_{16}\, in$

Equation 4 is similar to Equation 1 except the plate width that is checked is adjusted to account for the material removed to account for the bolt hole. Similar to Equation 3, we can say that the maximum additional prying force based on the flexure limit state, $T_{prying\_flexure}$, is equal to

$$T_{prying\_flexure} = \frac{\phi M_{prying}}{b'} \quad \text{(Eq. 5)}$$

Bolt Tension Rupture Limit State

Whether or not prying is accounted for, the force on the bolt cannot exceed the available tensile rupture strength of the bolt. For the condition without prying, the force on the bolt is simply the applied tension per bolt. For the condition with prying, the force on the bolt is the applied tension per bolt plus the prying force, q.

From Figure 4b, based on sum of the forces equaling zero in the y-direction, we can say the additional force on the bolt due to prying is equal to $T_{prying\_bolt}+q_b$. By solving for the sum of the moments about the hole location, we can determine the value for q_b:

$$q_b = \frac{T_{prying\_bolt}\, b'}{a'} \quad \text{(Eq. 6)}$$

From the case without prying, we already have a load on the bolt equal to T_{wo} (Figure 1). As shown in Figure 4, the maximum additional load that can be placed on the bolt would have to be less than the bolt capacity, B, minus the existing load on the bolt without prying, T_{wo}.

$$T_{prying\_bolt} + q_b \le B - T_{wo} \quad \text{(Eq. 7)}$$

Combining Equations 6 and 7 results in the following expression:

$$T_{prying\_bolt} + \frac{T_{prying\_bolt}\, b'}{a'} \le B - T_{wo} \quad \text{(Eq. 8)}$$

Simplifying Equation 8 yields

$$T_{prying\_bolt} \left(1 + \frac{b'}{a'}\right) \le B - T_{wo} \quad \text{(Eq. 9)}$$

Solving for T_{prying_bolt}, the maximum additional force that can be added to the angle based on the bolt limit state is equal to

$$T_{prying\_bolt} = \frac{B - T_{wo}}{\left(1 + \frac{b'}{a'}\right)} \quad \text{(Eq. 10)}$$

Overall Connection Strength with Prying

Remember that accounting for prying increases the strength of the flange and may increase the strength of the connection. As stated earlier, the strength of the flange when prying is considered can be expressed as

$$T_{total} = T_{wo} + T_{prying} \quad \text{(Eq. 11)}$$

The maximum additional load that can be added to a connection when prying is considered will be limited by either bolt tension rupture or flexural yielding of the angle leg at the bolt hole. Therefore, T_{prying} is equal to

$$T_{pyring} = min\begin{cases} T_{prying\_flexure} \\ T_{prying\_bolt} \end{cases} \quad \text{(Eq. 12)}$$

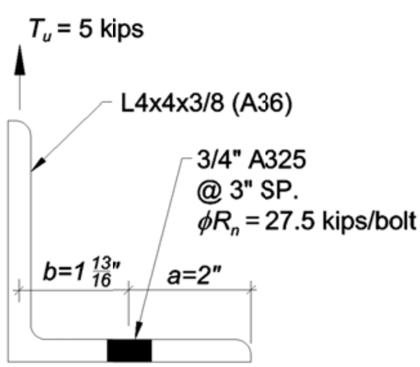
Similar to Equation (9-28) in the *Manual*, if one wants to solve for the actual prying force in the bolt, *q*, the following equation can be used:

$$q = \frac{(T_u - T_{wo})b'}{a'} \quad \text{(Eq. 13)}$$

Examples

The following examples compare the results from the procedure in Part 9 to those obtained using the approach discussed in this article.

Example 1



Given:
p = 3 in
B = 27.5 kips

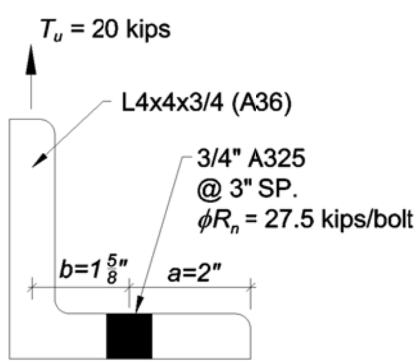
Use the equations in Part 9 of the 14th Edition *Manual* to solve for the following variables:

b′ = 1 7/16 in
a′ = 2 3/8 in
d′ = 13/16 in

Article Approach	*Manual* Procedure
Without Prying Check	
Check Bolt Tensile Strength without Prying *T_u = 5 kips < B = 27.5 kips* Calculate T_{wo} Eq. 1: $\phi M_{wo} = 0.9x58\ ksi\left(\frac{3in\ x\ ^{3}/_{8}in^2}{4}\right)$ $\phi M_{wo} = 5.51\ kip - in$ Eq. 3: $T_{wo} = \frac{5.51\ kip-in}{1^{7}/_{16}in}$ *= 3.83 kips < 5 kips* Consider Prying	Check Bolt Tensile Strength without Prying *T_u = 5 kips < B = 27.5 kips* Calculate t_{min} to eliminate prying *Manual* Eq. 9-20a: t_{min}*= 0.43 in > 3/8 in* Consider Prying

Article Approach	*Manual* Procedure
Consider Prying	
Flexure Limit State at Bolt Hole	*Manual* Eq. 9-30a: $t_c = 1.0$
Eq. 4: $\phi M_{prying} = 0.9x58\ ksi \left(\frac{(3in - {}^{13}/_{16}in)\ {}^{3}/_{8}in^2}{4}\right)$	*Manual* Eq. 9-24: $\delta = 0.73$
$\phi M_{prying} = 4.01\ kip - in$	*Manual* Eq. 9-26: $\rho = 0.61$
Eq. 5: $T_{prying\_flexure} = \frac{4.01\ kip-in}{1{}^{7}/_{16}in} = 2.79\ kips$	*Manual* Eq. 9-35: $\alpha' = 5.28$
Check Bolt Tensile Strength for Prying	$\alpha' > 1$. Use Equation 9-34
Eq. 10: $T_{pyring\_bolt} = \frac{27.5\ kip - 3.83\ kip}{\left(1+\frac{1\ {}^{7}/_{16}in}{2\ {}^{3}/_{8}in}\right)} = 14.7\ kips$	*Manual* Eq. 9-34: $Q = 0.24$
Eq. 12: $T_{pyring} = min \begin{cases} 2.79\ kips \\ 14.7\ kips \end{cases}$	*Manual* Eq. 9-31: $T_{avail} = 6.62\ kips$
Eq. 11: $T_{total} = 3.83\ kip + 2.79\ kip = 6.62\ kips$	6.62 kips > 5 kips. Connection is adequate.
6.62 kips > 5 kips. Connection is adequate.	
Note: When $\alpha' > 1$, the *Manual* states that the fitting has insufficient strength to develop the full bolt. This makes sense since the prying contribution is limited by the flexure limit state at the bolt holes.	

Example 2



Given:
p = 3 in
B = 27.5 kips

Use the equations in Part 9 of the 14th Edition *Manual* to solve for the following variables:

b' = 1 1/4 in
a' = 2 3/8 in
d' = 13/16 in

<table>
<tr><td>Article Approach</td><td>Manual Procedure</td></tr>
<tr><td colspan="2">Without Prying Check</td></tr>
<tr><td>Check Bolt Tensile Strength without Prying

$T_u = 20\ kips < B = 27.5\ kips$

Calculate T_{wo}

Eq. 1: $\phi M_{wo} = 0.9x58\ ksi\left(\frac{3in\ x\ ^3/_4 in^2}{4}\right)$

$\phi M_{wo} = 22.0\ kip - in$

Eq. 3: $T_{wo} = \frac{22.0\ kip-in}{1^1/_4 in} = 17.6\ kips < 20\ kips$

Consider Prying</td><td>Check Bolt Tensile Strength without Prying

$T_u = 20\ kips < B = 27.5\ kips$

Calculate t_{min} to eliminate prying

Manual Eq. 9-20a: $t_{min} = 0.80\ in > 3/4\ in$

Consider Prying</td></tr>
<tr><td colspan="2">Consider Prying</td></tr>
<tr><td>Flexure Limit State at Bolt Hole

Eq. 4: $\phi M_{prying} = 0.9x58\ ksi\left(\frac{(3in - ^{13}/_{16}in)\ ^3/_4 in^2}{4}\right)$

$\phi M_{prying} = 16.1\ kip - in$

Eq. 5: $T_{prying\_flexure} = \frac{16.1\ kip-in}{1^1/_4 in} = 12.9\ kips$</td><td rowspan="3">Manual Eq. 9-30a: $t_c = 0.94$

Manual Eq. 9-24: $\delta = 0.73$

Manual Eq. 9-26: $\rho = 0.53$

Manual Eq. 9-35: $\alpha' = 0.5$

$0 < \alpha' < 1$. Use Equation 9-33

Manual Eq. 9-33: $Q = 0.876$

Manual Eq. 9-31: $T_{avail} = 24.1\ kips$

$24.1\ kips > 20\ kips$. Connection is adequate.</td></tr>
<tr><td>Check Bolt Tensile Strength for Prying

Eq. 10: $T_{pyring\_bolt} = \frac{27.5\ kip - 17.6\ kip}{\left(1+\frac{1\ ^1/_4 in}{2\ ^3/_8 in}\right)} = 6.49\ kips$</td></tr>
<tr><td>Eq. 12: $T_{pyring} = min\begin{cases}12.9\ kips\\ 6.49\ kips\end{cases}$

Eq. 11: $T_{total} = 17.6\ kip + 6.49\ kip = 24.1\ kips$

$24.1\ kips > 20\ kips$. Connection is adequate.</td></tr>
<tr><td colspan="2">Note: When $0 < \alpha' < 1$, the manual states that the fitting has sufficient strength to develop the full bolt, but insufficient stiffness to prevent prying action. This makes sense since the prying contribution is limited by the bolt tension rupture limit</td></tr>
</table>

Example 1 Revisited

This example looks at Example 1 in the more traditional limit state checks format.

Bolt Tensile Strength without Prying

$T_u = 5\ kips < B = 27.5\ kips$ Bolt Check OK

Check Flexural Yielding at Angle Leg Near Heel

Eq. 2: $M_u = 5\ kip\ x\ 1\ {}^{7}/_{16}\ in = 7.19\ kip\text{-}in$

Eq. 1: $\phi M_{wo} = 5.51\ kip - in < 7.19\ kip - in$

Prying needs to be considered.

Eq. 3: $T_{wo} = 3.83\ kips$

Angle can only transfer 3.83 kips without prying. Check to see if angle is adequate to transfer the remaining load per the two prying limit states. The remaining load is equal to 5 kips – 3.83 kips =1.17 kips.

Check Flexural Yielding at Bolt Hole

$M_u = 1.17\ kips\ x\ 1\ {}^{7}/_{16}\ in = 1.68\ kip - in$

Eq. 4: $\phi M_{prying} = 4.01\ kip - in > 1.68\ kip - in$ Flexural Check OK

Check Bolt Tensile Strength with Prying

Eq. 13: $q = \frac{1.17\ kips\ x\ 1\ {}^{7}/_{16} in}{2\ {}^{3}/_{8}} = 0.71$ kips

Force on bolt = 5 kips + 0.71 kips = 5.71 kips < 27.5 kips Bolt Check OK

Connection is adequate.

Referenced and Useful Documents

- AISC (2010a), *Specification for Structural Steel Buildings*, ANSI/AISC 360-10, American Institute of Steel Construction, Chicago, IL.
- AISC (2010b), *Steel Construction Manual*, 14th Ed., American Institute of Steel Construction, Chicago, IL.
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An abbreviated version of this paper appears as the July 2016 SteelWise article "A Quick Look at Prying," available at www.modernsteel.com.

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