Tension
Available tensile strength is determined as given in RCSC Specification Section 5.1 and AISC Specification Section J3.6, with consideration of the effects of prying action, if any. Prying action is a phenomenon (in bolted construction only) whereby the deformation of a fitting under a tensile force increases the tensile force in the bolt. While the effect of prying action is relevant to the design of the bolts, it is primarily a function of the strength and stiffness of the connection elements. Prying action is addressed in Part 9.

Combined Shear and Tension
Available strength for combined shear and tension in bearing-type connections is determined as given in RCSC Specification Section 5.2 and AISC Specification Section J3.7.

Bearing Strength at Bolt Holes
Available bearing strength at bolt holes is determined as given in RCSC Specification Section 5.3 and AISC Specification Section J3.10.

Slip Resistance
The available strength of slip-critical connections is determined in accordance with AISC Specification Section J3.8. The available strength, \( \phi R_p \) or \( R/{\Omega} \), is determined by applying the resistance factor or safety factor appropriate for the hole type used.

ECCENTRICALLY LOADED BOLT GROUPS

Eccentricity in the Plane of the Faying Surface
When eccentricity occurs in the plane of the faying surface, the bolts must be designed to resist the combined effect of the direct shear, \( P_d \) or \( P_n \), and the additional shear from the induced moment, \( P_{g e} \) or \( P_{g e} \). Two analysis methods for this type of eccentricity are the instantaneous center of rotation method and the elastic method.

The instantaneous center of rotation method is more accurate, but generally requires the use of tabulated values or an iterative solution. The elastic method is simplified, but may be excessively conservative because it neglects the ductility of the bolt group and the potential for load redistribution.

Instantaneous Center of Rotation Method
Eccentricity produces both a rotation and a translation of one connection element with respect to the other. The combined effect of this rotation and translation is equivalent to a rotation about a point defined as the instantaneous center of rotation (IC), as illustrated in Figure 7-2(a). The location of the IC depends upon the geometry of the bolt group as well as the direction and point of application of the load.

The load-deformation relationship for one bolt is illustrated in Figure 7-3, where

\[
R = R_{ub}(1 - e^{-10\Delta})^{0.55}
\]

7-3
\[ M_E = A_b \left[ 2.5a \cdot F_y + 1.5a \left( \frac{3}{5} F_y \right) + 0.5a \left( \frac{1}{5} F_y \right) \right] 2 \] for them

\[ = 7A_b a F_y \]

\[ M_p = A_B \left[ 2.5a \cdot F_y + 1.5a F_y + 0.5a F_y \right] 2 \]

\[ = 9A_b a F_y \]
where
\[
R_m = \text{nominal shear strength of one bolt at a deformation } \Delta, \text{ kips}
\]
\[
R_{ult} = \text{ultimate shear strength of one bolt, kips (nominal)}
\]
\[
\Delta = \text{total deformation, including shear, bearing and bending deformation in the bolt and bearing deformation of the connection elements, in.}
\]
\[
e^* = 2.718..., \text{ base of the natural logarithm}
\]

The nominal shear strength of the bolt most remote from the IC can be determined by applying a maximum deformation, \(\Delta_{max}\), to that bolt. The load-deformation relationship is based upon data obtained experimentally for \(\frac{3}{4}\)-in.-diameter ASTM A325 bolts, where \(R_{ult} = 74\) kips, and \(\Delta_{max} = 0.34\) in.

The nominal shear strengths of the other bolts in the joint can be determined by applying a deformation \(\Delta\) that varies linearly with distance from the IC. The nominal shear strength of the bolt group is, then, the sum of the individual strengths of all bolts.

(a) Instantaneous center of rotation (IC)

(b) Forces on bolts in group for case of \(\theta = 0^\circ\) for simplicity

Fig. 7-2. Illustration for instantaneous center of rotation method.
The individual resistance of each bolt is assumed to act on a line perpendicular to a ray passing through the IC and the centroid of that bolt, as illustrated in Figure 7-2(b). If the correct location of the IC has been selected, the three equations of in-plane static equilibrium ($\Sigma F_x = 0$, $\Sigma F_y = 0$, and $\Sigma M = 0$) will be satisfied.

For further information, see Crawford and Kulak (1968).

**Elastic Method**

For a force applied as illustrated in Figure 7-4, the eccentric force, $P_u$ or $P_o$, is resolved into a direct shear, $P_u$ or $P_o$, acting through the center of gravity (CG) of the bolt group and a moment, $P_u e$ or $P_o e$, where $e$ is the eccentricity. Each bolt is then assumed to resist an equal share of the direct shear and a share of the eccentric moment proportional to its distance from the CG. The resultant vectorial sum of these forces is the required strength for the bolt, $r_u$ or $r_o$.

![Graph showing load-deformation relationship for one 3/4-in.-diameter ASTM A325 bolt in single shear.](image)

**Fig. 7-3. Load-deformation relationship for one 3/4-in.-diameter ASTM A325 bolt in single shear.**

![Illustration for elastic method.](image)

**Fig. 7-4. Illustration for elastic method.**
The shear per bolt due to the concentric force, $P_u$ or $P_{du}$, is $r_{pu}$ or $r_{pa}$, where

<table>
<thead>
<tr>
<th>LRFD</th>
<th>ASD</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_{pu} = \frac{P_u}{n}$ (7-2a)</td>
<td>$r_{pa} = \frac{P_u}{n}$ (7-2b)</td>
</tr>
</tbody>
</table>

and $n$ is the number of bolts. To determine the resultant forces on each bolt when $P_u$ or $P_{du}$ is applied at an angle $\theta$ with respect to the vertical, $r_{pu}$ or $r_{pa}$ must be resolved into horizontal component, $r_{pxu}$ or $r_{pxa}$, and vertical component, $r_{pyu}$ or $r_{pya}$, where

$$r_{pxu} = r_{pu} \sin \theta \text{ (LRFD)}$$
$$r_{pxa} = r_{pa} \sin \theta \text{ (ASD)}$$
$$r_{pyu} = r_{pu} \cos \theta \text{ (LRFD)}$$
$$r_{pya} = r_{pa} \cos \theta \text{ (ASD)}$$

(7-3a) (7-3b) (7-4a) (7-4b)

The shear on the bolt most remote from the CG due to the moment, $P_u e$ or $P_{du} e$, is $r_{nu}$ or $r_{ma}$, where

<table>
<thead>
<tr>
<th>LRFD</th>
<th>ASD</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_{nu} = \frac{P_u e c}{I_p}$ (7-5a)</td>
<td>$r_{ma} = \frac{P_{du} e c}{I_p}$ (7-5b)</td>
</tr>
</tbody>
</table>

where

- $c$ = radial distance from CG to center of bolt most remote from CG, in.
- $I_p = I_x + I_y$ = polar moment of inertia of the bolt group, in$^4$ per in$^2$.

To determine the resultant force on the most highly stressed bolt, $r_{nu}$ or $r_{ma}$ must be resolved into horizontal component $r_{nxu}$ or $r_{nxa}$ and vertical component $r_{nyu}$ or $r_{nya}$, where

<table>
<thead>
<tr>
<th>LRFD</th>
<th>ASD</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_{nxu} = \frac{P_u e c x}{I_p}$ (7-6a)</td>
<td>$r_{nxa} = \frac{P_{du} e c x}{I_p}$ (7-6b)</td>
</tr>
<tr>
<td>$r_{nyu} = \frac{P_u e c y}{I_p}$ (7-7a)</td>
<td>$r_{nya} = \frac{P_{du} e c y}{I_p}$ (7-7b)</td>
</tr>
</tbody>
</table>

In the above equations, $c_x$ and $c_y$ are the horizontal and vertical components of the diagonal distance $c$. Thus, the required strength per bolt is $r_u$ or $r_a$, where

<table>
<thead>
<tr>
<th>LRFD</th>
<th>ASD</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_u = \sqrt{(r_{pxu} + r_{nxu})^2 + (r_{pyu} + r_{nyu})^2}$ (7-8a)</td>
<td>$r_a = \sqrt{(r_{pxa} + r_{nxa})^2 + (r_{pya} + r_{nya})^2}$ (7-8b)</td>
</tr>
</tbody>
</table>

For further information, see Higgins (1971).
Eccentricity Normal to the Plane of the Faying Surface

Eccentricity normal to the plane of the faying surface produces tension above and compression below the neutral axis for a bracket connection as shown in Figure 7-5. The eccentric force, \( P_u \) or \( P_a \), is resolved into a direct shear, \( P_u \) or \( P_a \), acting at the faying surface of the joint and a moment normal to the plane of the faying surface, \( P_u e \) or \( P_a e \), where \( e \) is the eccentricity. Each bolt is then assumed to resist an equal share of the concentric force, \( P_u \) or \( P_a \), and the moment is resisted by tension in the bolts above the neutral axis and compression below the neutral axis.

Two design approaches for this type of eccentricity are available: Case I, in which the neutral axis is not taken at the center of gravity (CG), and Case II, in which the neutral axis is taken at the CG.

Case I—Neutral Axis Not at Center of Gravity

The shear per bolt due to the concentric force, \( r_{av} \) or \( r_{av} \), is determined as

<table>
<thead>
<tr>
<th>LRFD</th>
<th>ASD</th>
</tr>
</thead>
<tbody>
<tr>
<td>( r_{av} = \frac{P_u}{n} ) \hspace{1cm} (7-9a)</td>
<td>( r_{av} = \frac{P_u}{n} ) \hspace{1cm} (7-9b)</td>
</tr>
</tbody>
</table>

where \( n \) is the number of bolts in the connection.

A trial position for the neutral axis can be selected at one-sixth of the total bracket depth, measured upward from the bottom (line X-X in Figure 7-6(a)). To provide for reasonable proportions and to account for the bending stiffness of the connection elements, the effective width of the compression block, \( b_{ef} \), should be taken as

\[ b_{ef} = 8t_f \leq b_f \] \hspace{1cm} (7-10)

![Fig. 7-5. Tee bracket subject to eccentric loading normal to the plane of the faying surface.](image)

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where
\[ t_f = \text{lesser connection element thickness, in.} \]
\[ b_f = \text{connection element width, in.} \]

This effective width is valid for bracket flanges made from W-shapes, S-shapes, welded plates and angles. Where the bracket flange thickness is not constant, the average flange thickness should be used.

The assumed location of the neutral axis can be evaluated by checking static equilibrium assuming an elastic stress distribution. Equating the moment of the bolt area above the neutral axis with the moment of the compression block area below the neutral axis,

\[ (\Sigma A_b) y = b_{eff} d (d/2) \quad (7-11) \]

where
\[ \Sigma A_b = \text{sum of the areas of all bolts above the neutral axis, in.}^2 \]
\[ y = \text{distance from line X-X to the CG of the bolt group above the neutral axis, in.} \]
\[ d = \text{depth of compression block, in.} \]

The value of \( d \) may then be adjusted until a reasonable equality exists.

Once the neutral axis has been located, the tensile force per bolt, \( r_{ut} \) or \( r_{at} \), as illustrated in Figure 7-6(b), may be determined as

<table>
<thead>
<tr>
<th>LRFD</th>
<th>ASD</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ r_{ut} = \left( \frac{P_{net}}{I_x} \right) A_b ] (7-12a)</td>
<td>[ r_{at} = \left( \frac{P_{net}}{I_x} \right) A_b ] (7-12b)</td>
</tr>
</tbody>
</table>

where
\[ c = \text{distance from neutral axis to the most remote bolt in the group, in.} \]
\[ I_x = \text{combined moment of inertia of the bolt group and compression block about the neutral axis, in.}^4 \]

![Diagram](image)

Fig. 7-6. Location of neutral axis (NA) for out-of-plane eccentric loading using Case I.
Bolts above the neutral axis are subjected to the shear force, the tensile force, and the effect of prying action (see Part 9); bolts below the neutral axis are subjected to the shear force, \( r_{uv} \) or \( r_{av} \), only.

**Case II—Neutral Axis at Center of Gravity**

This method provides a more direct, but also a more conservative result. As for Case I, the shear force per bolt, \( r_{uv} \) or \( r_{av} \), due to the concentric force, \( P_h \) or \( P_d \), is determined as

\[
\begin{align*}
LRFD & & ASD \\
\frac{P_h}{n} = r_{uv} & & \sqrt{3} \frac{P_d}{n} = r_{av} \\
(7-13a) & & (7-13b)
\end{align*}
\]

where \( n \) is the number of bolts in the connection.

The neutral axis is assumed to be located at the CG of the bolt group as illustrated in Figure 7-7. The bolts above the neutral axis are in tension and the bolts below the neutral axis are said to be in "compression." To obtain a more accurate result, a plastic stress distribution is assumed; this assumption is justified because this method is still more conservative than Case I. Accordingly, the tensile force in each bolt above the neutral axis, \( r_{ut} \) or \( r_{at} \), due to the moment, \( P_h e \) or \( P_d e \), is determined as

\[
\begin{align*}
LRFD & & ASD \\
\frac{P_h e}{n'd_m} = r_{ut} & & \frac{P_d e}{n'd_m} = r_{at} \\
(7-14a) & & (7-14b)
\end{align*}
\]

![Diagram showing the location of neutral axis (NA) for out-of-plane eccentric loading using Case II.](image)

**Fig. 7-7. Location of neutral axis (NA) for out-of-plane eccentric loading using Case II.**

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\[ n' = \text{number of bolts above the neutral axis} \]
\[ d_m = \text{moment arm between resultant tensile force and resultant compressive force, in.} \]

Bolts above the neutral axis are subjected to the shear force, the tensile force, and the effect of prying action (see Part 9); bolts below the neutral axis are subjected to the shear force, \( r_{uv} \) or \( r_{av} \), only.

**SPECIAL CONSIDERATIONS FOR HOLLOW STRUCTURAL SECTIONS**

**Through-Bolting to HSS**
Long bolts that extend through the entire HSS are satisfactory for shear connections that do not require a pretensioned installation. The flexibility of the walls of the HSS precludes installation of pretensioned bolts. Standard structural bolts may be used, although ASTM A449 bolts may be required for longer lengths. The bolts are designed for static shear and the only limit-state involving the HSS is bolt bearing. The available bearing strength is determined as \( \phi R_n \) or \( R_n / \Omega \), where

\[ R_n = 1.8 \phi F_y t_{\text{design}} \]  \hfill (7-15)

where
\[ \phi = 0.75 \] \[ \Omega = 2.00 \]
\[ n = \text{number of fasteners} \]
\[ d = \text{fastener diameter, in.} \]
\[ F_y = \text{specified minimum yield strength of HSS, ksi} \]
\[ t_{\text{design}} = \text{design wall thickness of HSS, in.} \]

**Blind Bolts**
Special fasteners are available that eliminate the need for access to install a nut (Koro et al., 1993; Henderson, 1996). The shank of the fastener is inserted through holes in the parts to be connected until the head bears on the outer ply (see Figure 7-8). In some cases, a special wrench is used on the open end to keep the outer part of the shank from rotating and simultaneously turn the threaded part of the shank. A wedge or other mechanism on the blind side causes the fixed part of the shank to expand and form a contact with the inside of the HSS. Some fasteners contain a break-off mechanism when the fastener is pretensioned. Recent versions of these fasteners meet the requirements for a pretensioned ASTM A325 bolt (Henderson, 1996) and could be used in slip-critical or tension conditions. HSS limit states are bolt bearing in shear, tear-out of the bolt in tension, and wall distortion. Manufacturers’ literature must be consulted to determine the available strength of blind bolts.

**Flow-Drilling**
Flow-drilling is a process that can be used to produce a threaded hole in an HSS to permit blind bolting when the inside of the HSS is inaccessible (Sherman, 1995; Henderson, 1996). The process is to force a hole through the HSS with a carbide conical tool rotating at sufficient speed to produce high rapid heating, which softens the material in a local area. The material...
The critical fastener force is 21.7 kips. Inspection of the magnitudes and directions of the horizontal and vertical components of the forces confirms the earlier conclusion that the fastener selected is indeed the critical one.

**Ultimate Strength Analysis**

The foregoing procedure is relatively easy to apply but is inaccurate — on the conservative side. The major flaw in the analysis is the implied assumption that the fastener load–deformation relationship is linear and that the yield stress is not exceeded. Experimental evidence shows that this is not the case and that individual fasteners do not have a well-defined shear yield stress. The procedure to be described here determines the ultimate strength of the connection by using an experimentally determined nonlinear load–deformation relationship for the individual fasteners.

The experimental study reported in Crawford and Kulak (1971) used \( \frac{3}{4} \)-inch-diameter A325 bearing-type bolts and A36 steel plates, but the results can be used with little error for A325 bolts of different sizes and steels of other grades. The procedure gives conservative results when used with slip-critical bolts and with A490 bolts (AISC, 1994).

The bolt force \( R \) corresponding to a deformation \( \Delta \) is

\[
R = R_{ult} (1 - e^{-\mu \Delta})^\lambda
\]

\[
= 74 (1 - e^{-10 \Delta})^{0.55}
\]

where

\( R_{ult} \) = bolt shear force at failure = 74 kips

\( e \) = base of natural logarithms

\( \mu \) = a regression coefficient = 10

\( \lambda \) = a regression coefficient = 0.55

The ultimate strength of the connection is based on the following assumptions:

1. At failure, the fastener group rotates about an instantaneous center (IC).
2. The deformation of each fastener is proportional to its distance from the IC and acts perpendicularly to the radius of rotation.
3. The capacity of the connection is reached when the ultimate strength of the fastener farthest from the IC is reached. (Figure 8.7 shows the bolt forces as resisting forces acting to oppose the applied load.)
4. The connected parts remain rigid.

As a consequence of the second assumption, the deformation of an individual fastener is

\[
\Delta = \frac{r_{max} \Delta_{max}}{r_{max} \Delta_{max}} = \frac{r_{max} \text{bolt}}{0.34}
\]

where

\( \Delta \) = deformation of any

\( r \) = distance from the IC to the fastener

\( r_{max} \) = distance to the farthest fastener

\( \Delta_{max} \) = deformation of the farthest fastener at ultimate = 0.34 in. (determined experimentally)
Plastic N.A. ②

Elastic N.A. ①

① \( \bar{y} = \frac{(A_1y_1 + A_2y_2)}{(A_1 + A_2)} \)

\( f_{\text{max}} = F_y \) in bottom fiber
All stresses elastic

② \( \bar{y} = \text{when } A_{\text{above}} = A_{\text{below}} \)
\( f_{\text{max}} = F_y \) everywhere

Elastic centroid

① \( \bar{y} = \text{as above} \)

② \( \bar{y} = \text{when equilibrium reached & first bolt reaches } 72.6k \)