ENCE 455
Design of Steel Structures

II. Tension Members

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Introduction

Tension members are structural elements that are subjected to axial tensile forces. Examples include:
- Members in trusses
- Cables in cable-stayed and suspension bridges
- Bracing in frames to resist lateral forces from blast, wind, and earthquake

Forth Bridge
Queensferry, Scotland

Main sections: 5360 ft.
Maximum span: 1710(2), 4 spans total
Built: 1890

Introduction (cont.)

Stresses ($f$) in axially loaded members are calculated using the equation

\[ f = \frac{P}{A} \]

where $P$ is the load and $A$ is the cross-sectional area normal to the load.

Design of this component involves calculations for
- Tension member (gross area)
- Tension member at connection (net area)
- Gusset plate at connection (net area)
- Gusset plate at support
Design Strength

A tension member can fail by

- **Excessive deformation (yielding)** - Excessive deformation is prevented by limiting stresses on the gross section to less than the yield stress. For yielding on the gross section, the nominal strength is:
  \[ T_n = F_y A_g \quad \text{and} \quad \phi_t = 0.90 \]  
  \[ (3.2.1) \]

- **Fracture** - Fracture is avoided by limiting stresses on the net section to less than the ultimate tensile strength. For fracture on the net section, the nominal strength is:
  \[ T_n = F_u A_e = F_u (U A_n) \quad \text{and} \quad \phi_t = 0.75 \]  
  \[ (3.2.2) \]

  where \( A_e \) is the effective net area, \( A_n \) is the net area and \( U \) is the reduction coefficient (an efficient factor).

Net Area

**Net Area**

The performance of a tension member is often governed by the response of its connections. The AISC Steel Manual introduces a measure of connection performance known as joint efficiency, which is a function of:

- Material properties (ductility)
- Fastener spacing
- Stress concentrations
- Shear lag (Most important of the four and addressed specifically by the AISC Steel Manual)

Net Area (cont.)

The AISC Steel Manual introduces the concept of effective net area to account for shear lag effects.

- For bolted connections: \( A_e = U A_p \)  
  \[ (3.5.1) \]

- For welded connections: \( A_e = U A_g \)  
  \[ (3.5.3) \]

  where

  \[ U = 1 - \frac{x}{L} \leq 0.9 \]  
  \[ (3.5.2) \]

  and \( x \) is the distance from the plane of the connection to the centroid of the connected member and \( L \) is the length of the connection in the direction of the load.

  (Salmon & Johnson Example 3.5.1 for U)
For **bolted connections**, AISC Table D3.1 gives values for U that can be used in lieu of detailed calculation.

<table>
<thead>
<tr>
<th>Case</th>
<th>Description</th>
<th>U</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>With range connected with 3 or more fasteners per line in direction of loading</td>
<td>(U = 0.50)</td>
</tr>
<tr>
<td></td>
<td>With web connected with 4 or more fasteners in the direction of loading</td>
<td>(U = 0.85)</td>
</tr>
<tr>
<td>8</td>
<td>Single angles per Case 2, the larger value is permitted to be used</td>
<td>(U = 0.70)</td>
</tr>
<tr>
<td></td>
<td>With 4 or more fasteners per line in direction of loading</td>
<td>(U = 0.80)</td>
</tr>
<tr>
<td></td>
<td>With 2 or 3 fasteners per line in the direction of loading</td>
<td>(U = 0.60)</td>
</tr>
</tbody>
</table>

For **welded connections**, AISC Table D3.1 lists

- **Failure line** - When a member has staggered bolt holes, a different approach to finding \(A_e\) for the fracture limit state is taken. This is because the effective net area is different as the line of fracture changes due to the stagger in the holes. The test for the yielding limit state remains unchanged (the gross area is still the same).
- For calculation of the effective net area, the Section B2 of the AISC Steel Manual makes use of the product of the plate thickness and the net width. The net width is calculated as

\[
w_n = w_g - \sum d + \sum \frac{s^2}{4g}
\]
Block Shear

- Block shear is an important consideration in the design of steel connections. Consider the figure below that shows the connection of a single-angle tension member. The block is shown shaded.

Figure 3.8.2 Load distribution in plate A (Example 3.8.1)
Block Shear (cont.)

- In this example, the block will fail in shear along ab and tension on bc. The AISC Steel Manual procedure is based on one of the two failure surfaces yielding and the other fracturing.
  - Fracture on the shear surface is accompanied by yielding on the tension surface
  - Fracture on the tension surface is accompanied by yielding on the shear surface
  - Both surfaces contribute to the total resistance.

The nominal strength in tension is $F_{yA_{nt}}$ for fracture and $F_{yA_{nt}}$ for yielding where the second subscript t denotes area on the tension surface (bc in the figure above).

- The yield and ultimate stresses in shear are taken as 60% of the values in tension. The AISC Steel Manual considers two failure modes:
  - Shear yield - tension fracture: $T_n = 0.6F_{yA_{nt}} + F_{uA_{nt}}$ (3.6.1)
  - Shear fracture - tension yield: $T_n = 0.6F_{uA_{nv}} + F_{uA_{nt}}$ (3.6.2)
- One equation to cover all
  $T_n = 0.6F_{yA_{nv}} + U_{bs}F_{uA_{nt}} \leq 0.6F_{yA_{nv}} + U_{bs}F_{uA_{nt}}$ (AISC J4-5)
- Because the limit state is fracture, the equation with the larger of the two fracture values controls where $\phi_t = 0.75$.
  (Example 3.9.2 for block shear)

Design of Tension Members

- The design of a tension member involves selecting a member from the AISC Steel Manual with adequate
  - Gross area
  - Net area
  - Slenderness ($L/r \leq 300$ to prevent vibration, etc; does not apply to cables.)
- If the member has a bolted connection, the choice of cross section must account for the area lost to the bolt holes.
- Because the section size is not known in advance, the default values of $U$ are generally used for preliminary design.

Design of Tension Members (cont.)

- Detailing of connections is a critical part of structural steel design. Connections to angles are generally problematic if there are two lines of bolts.
- Consider the Gages for Angle figure shown earlier that provides some guidance on sizing angles and bolts.
  - Gage distance $g_1$ applies when there is one line of bolts
  - Gage distances $g_2$ and $g_3$ apply when there are two lines
Threaded Rod -
- Tension on the effective net area
  \[ T_n = A_s F_u = 0.75 A_b F_u \]
- Tension on the gross section
  \[ T_n = 0.9 A_g F_y (D1-1) \]
- Shear on the effective area
  \[ \varphi T_n = 0.75(0.6A_{sf} F_u) = 0.75(0.6[2t (a + d/2)] F_u) \]
  \[ (D5-2) \]
- Bearing on projected area
  \[ \varphi T_n = 0.75(1.8 A_pb F_y) = 0.75[1.8 (d t) F_y] \]
  \[ (J8-1) \]
- Embedded length
  \[ \varphi T_n = 0.75(2 t b_{eff} F_u) \]
  \[ (D5-1) \]
- Bearing on projected area
  \[ \varphi T_n = 0.75(1.8 A_pb F_y) = 0.75[1.8 (d t) F_y] \]
  \[ (D1-1) \]

Threaded Rod -
- Tension on the effective net area
\[ T_n = A_s F_u = 0.75 A_b F_u \]
where \( A_s \) is the stress area (threaded portion), \( A_b \) is the nominal (unthreaded area), and 0.75 is a lower bound (conservative) factor relating \( A_s \) and \( A_b \). See Section J3.6 of the AISC Steel Manual Specification for details.

The design strength of a threaded rod is calculated as
\[ \varphi T_n = 0.75 T_n \]
(Example 3.10.2 for Rod Design)