Introduction

Following subjects are covered:
- Introduction of Fasteners
- Failure modes of bolted shear connections
- LRFD - Fasteners
- LRFD of slip-critical connections
- High-strength bolts in tension
- Fasteners in combined shear and tension
- Basics of welding
- Fillet weld
- LRFD of welded connections

Reading:
- Chapter 7 of Segui
- AISC Steel Manual Specifications, Chapter J

Importance of Connections

- Beams and columns rarely fail
- Many catastrophic failure resulted from inadequate connection strength

What can go wrong?
- Hyatt Regency
- Kansas City, 1981
- 114 Dead
- 200+ Injured

The Culprit

http://www.rose-hulman.edu
http://www.taknosys.com
Problem and Solution

Problem -
- Lack of Understanding
- AISC Addresses “Typical” Details Only
- Failure Modes may be neglected

Solution -
- Develop Consistent Methodology
- Systematically Identify All Failure Modes
- Illustrate Applicable Failure Planes

Introduction of Fasteners

- Types of Fasteners: rivets (obsolete) and bolts (high-strength bolts: most common)
- Properties of bolts

<table>
<thead>
<tr>
<th>AISC designation</th>
<th>Bolt diameter in mm</th>
<th>Proof load yield strength method</th>
<th>Proof load* yield strength method</th>
<th>Minimum tensile strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>A24</td>
<td>6 (0.24)</td>
<td>--</td>
<td>--</td>
<td>120</td>
</tr>
<tr>
<td>A25</td>
<td>8 (0.31)</td>
<td>88.5</td>
<td>87</td>
<td>130</td>
</tr>
<tr>
<td>A325</td>
<td>10 (0.4)</td>
<td>(25)</td>
<td>(25)</td>
<td>(25)</td>
</tr>
<tr>
<td>A490</td>
<td>12 (0.47)</td>
<td>(30)</td>
<td>(30)</td>
<td>(30)</td>
</tr>
</tbody>
</table>

Ref: AISC LRFD p.16.4-46 thru -52

Introduction of Fasteners

- Two conditions of bolt installation are used with high-strength bolts
  - Snug-tight (producing a bearing connection)
    - Few impacts of an impact wrench
    - Full effort of a worker with an ordinary spud wrench
  - Tensioned (producing a slip-critical connection)
    - Turn-of-nut method: specified number of rotations of the nut from snug tight (nut rotations correlated to bolt elongation)
    - Calibrated wrench tightening
    - Alternate design bolts: specially design bolts whose tops twist off when the proper tension has been achieved
    - Direct tension indicators: compress washer (under bolt head or nut) with protrusions to a gap that is correlated to bolt tension

Ref: AISC LRFD p.16.4-46 thru -52

Introduction of Fasteners

- When high-strength bolts are to be tensioned, minimum limits are set on the bolt tension. See AISC Table J3.1
- Tension equal to 70% of the minimum tensile strength of the bolt
- Purpose of tensioning is to achieve the clamping force between connected parts.

<table>
<thead>
<tr>
<th>Table J3.1 Minimum Bolt Pretension, kips*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bolt Size, in.</td>
</tr>
<tr>
<td>---------------</td>
</tr>
<tr>
<td>1/4</td>
</tr>
<tr>
<td>1/2</td>
</tr>
<tr>
<td>5/8</td>
</tr>
<tr>
<td>3/4</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>1-1/2</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
</tbody>
</table>

*Equal to 3.33 times minimum tensile strength of bolts, rounded off to nearest kip, as specified in AISC specification for A250 and A490 bolts with UNC threads.
LRFD - Fasteners

- \( \Phi R_u \geq \Sigma \gamma_i Q_i \)
- General
- Where \( \Phi \) = resistance factor (strength reduction factor)
- \( R_u \) = nominal resistance (strength)
- \( \gamma_i \) = overload factors (LRFD-A4.1)
- \( Q_i \) = loads (such as dead load, live load, wind load, earthquake load) of load effects (such as bending moment, shear, axial force, and torsional moment resulting from the various loads)
- \( \Phi R_u \geq P_u \)
- Fasteners
- Where \( \Phi \) = resistance factor, 0.75 for fracture in tension, shear on high-strength bolts, and bearing of bolt against side of hole
- \( R_u \) = nominal strength of one fastener
- \( P_u \) = factored load on one fastener

Failure Mode of Bolted Shear Connections

Two types of bolted connector failure are considered in this section

- Failure of the connector
- Failure of the connected parts

Failure Mode of Bolted Shear Connections (cont.)

Connector failure

- Single shear connection – Single shear plane. \( P = f_s A \), where \( f_s \) is the average shearing stress and \( A \) is the connector’s cross-sectional area.
- Double shear connection – Double shear plane. \( P = 2f_s A \)
Failure Mode of Bolted Shear Connections (cont.)

2. Failure of the connected part because of bearing exerted by the fastener (average bearing stress is $f_p = P/d_t$)
   - If the hole is slightly larger than the fastener and the fastener is assumed to be placed loosely in the hole (rarely the case), contact between the fastener and the connected part will exist over approximately 50% of the circumference of the fastener.
   - The bearing problem is affected by the edge distance and bolt spacing.

LRFD – Fasteners (cont)

Design shear strength - no threads in shear planes
- $\Phi R_n = 0.75(0.50 F_u^b)m A_b$
  - where $\Phi = 0.75$, the standard value for shear
  - $F_u^b$ = tensile strength of the bolt material (120 ksi for A325 bolts; 150 ksi for A490 bolts)
  - $m$ = the number of shear planes participating [usually one (single shear) or two (double shear)]
  - $A_b$ = gross cross-sectional area across the unthreaded shank of the bolt

Design shear strength - threads in shear planes
- $\Phi R_n = 0.75(0.40 F_u^b)m A_b$

Sequi Examples 7.1 & 7.2

Design bearing strength
1. Usual conditions based on the deformation limit state, according to LRFD-Formula (J3-1a). This applies for all holes except long-slotted holes perpendicular to the line of force, where end distance is at least $1.5d$, the center-to-center spacing $s$ is at least $3d$, and there are two or more bolts in the line of force.
- $\Phi R_n = \Phi(1.2L_d F_u) < \Phi(2.4d t F_u)$
  - where $\Phi = 0.75$
  - $d$ = nominal diameter of bolt at unthreaded area
  - $t$ = thickness of part against which bolt bears
  - $F_u$ = tensile strength of connected part against which bolt bears
  - $L_d$ = distance along line of force from the edge of the connected part to the center of a standard hole or the center of a short- and long-slotted hole perpendicular to the line of force.

Ref: AISC LRFD p. 16.1-61

![Table of Design Strength of Fasteners](image)
LRFD – Fasteners (cont)

- Minimum edge distance requirement (AISC J3.4)

<table>
<thead>
<tr>
<th>Nominal Bolt or</th>
<th>All Sheared Edges</th>
<th>All Sheared Edges, Ø</th>
<th>Edge of Connected Part</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/8 in.</td>
<td>1/8 in.</td>
<td>1/8 in.</td>
<td></td>
</tr>
<tr>
<td>1/4 in.</td>
<td>1/4 in.</td>
<td>1/4 in.</td>
<td></td>
</tr>
<tr>
<td>1/2 in.</td>
<td>1/2 in.</td>
<td>1/2 in.</td>
<td></td>
</tr>
<tr>
<td>3/4 in.</td>
<td>3/4 in.</td>
<td>3/4 in.</td>
<td></td>
</tr>
<tr>
<td>1 in.</td>
<td>1 in.</td>
<td>1 in.</td>
<td></td>
</tr>
<tr>
<td>1-1/2 in.</td>
<td>1-1/2 in.</td>
<td>1-1/2 in.</td>
<td></td>
</tr>
<tr>
<td>2 in.</td>
<td>2 in.</td>
<td>2 in.</td>
<td></td>
</tr>
<tr>
<td>Over 2 in.</td>
<td>Over 2 in.</td>
<td>Over 2 in.</td>
<td></td>
</tr>
</tbody>
</table>

Ref: AISC LRFD p. 16.1-63

LRFD – Fasteners (cont)

Maximum edge distance - \( \leq 12 \, t \leq 6" \), where \( t \) is the thickness of the connected part.

Maximum spacing of connectors

(a) For painted members or unpainted members not subject to corrosion, \( \leq 24t \leq 12" \)

(b) For unpainted members of weathering steel subject to atmospheric corrosion, \( \leq 14t \leq 7" \)

LRFD Slip-critical Connections

- A connection with high-strength bolts is classified as either a bearing or slip-critical connection.

- Bearing connections - the bolt is brought to a snug-tight condition so that the surfaces of the connected parts are in firm contact.
  - Slippage is acceptable
  - Shear and bearing on the connector

- Slip-critical connections - no slippage is permitted and the friction force described earlier must not be exceeded.
  - Slippage is not acceptable (Proper installation and tensioning is key)
  - Must have sufficient shear and bearing strength in the event of overload that causes slip. AISC J3.8 for details.

Overview of Theory for Design

- Plate A
- Plate B
- High-Strength Bolt
- Plate A (Free Body)
- Plate B (Free Body)

Where:
- \( T \) = Tensile Force
- \( \mu T \) = Frictional Resistance
- \( \mu \) = Coefficient of Friction
- \( P \) = Load
**LRFD Slip-critical Connections (cont)**

\[ \Phi R_{str} = 0.13 \mu T \]

(4.9.1)

- Where \( R_{str} \) = nominal slip resistance per bolt at factored loads
- \( m \) = number of slip (shear) planes
- \( T \) = minimum fastener initial tension given in AISC Table J3.1
- \( \mu \) = mean slip coefficient, as applicable, or as established by tests
- \( \Phi \) = 0.35 for Class A surface condition
  - 0.50 for Class B surface condition
  - 0.40 for Class C surface condition
  - 1.0 for standard holes
- \( m_t \) = 0.85 for oversize and short-slotted holes
  - 0.70 for long-slotted holes transverse to load
  - 0.60 for long-slotted holes parallel to load

Sequi Example 7.4

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**High-Strength Bolts in Tension**

\( T_0 + \Delta T = F \)

\[ \Delta T = \frac{A_b E_b \delta_{b}}{L_0} = \frac{A_b E_b \delta_{b}}{L_0} \]

where \( \delta_{b} = \frac{N_0 L_0}{A_b E_b} \)

Figures 7-24 & 7-25

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**LRFD – Fasteners (cont)**

**Design tensile strength**

\[ \Phi R_n = 0.75(0.75 F_{u}^h) A_b \]

- where \( \Phi = 0.75 \), a value for the tensile fracture mode
- \( F_{u}^h = \) tensile strength of the bolt material (120 ksi for A325 bolts; 150 si for A490 bolts)
- \( A_b = \) gross cross-sectional area across the unthreaded shank of the bolt

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**Prying Action**

- Bolt tension \( B_0 \rightarrow B \)
- Prying force \( Q \)
- The corresponding bolt force, including the effects of prying, is \( B_c \)

Before external load

After external load

Maximum prying force

Figure 7.27
Prying Action

\[ Tb - M_{a-a} = Qa \]

\[ M_{b-b} = Qa \]

\[ B_c = T + Q \]

Figure 7.28

Combined Shear and Tension

Bearing-type connections

- \( M_{a-a} = \text{design} \cdot \text{strength} = \phi_h M_b = \phi_h \left( \frac{pt_f F_u}{4} \right) \)

- \( B_c = T + Q \)  \( \rightarrow \)  \( B_c = T \left[ 1 + \frac{\delta \alpha}{1 + \delta \alpha} \right] \)

- \( \delta = 1 - \frac{d}{p} = \frac{\text{net area at bolt line}}{\text{gross area at stem face}} \)

For Evaluation:

\[ \alpha = \frac{M_{b-b}}{\delta M_{a-a}} \]

For back checking:

\[ \alpha = \frac{1}{\delta} \left[ \frac{4.44 Tb'}{\phi_h p F_u (1 + \delta \alpha)} - 1 \right] \]

Sequi Example 7.8

Sequi Example 7.9
Basic of welding

- Structural welding is a process whereby the parts to be connected are heated and fused with a molten filler metal.
- Upon cooling, the structural steel (parent metal) and weld or filler metal will act as one continuous part. The filler metal is deposited from a special electrode. A number of welding processes are used, depending on the application:
  - Field welds
  - Shop welds

Basic of welding (cont)

Basic process:

1. Shielded Metal Arc Welding (SMAW):
   - Normally done manually and is widely used for field welding
   - Current arcs across the gap between the electrode and the base metal
   - Connected parts are heated and part of the filler metal is deposited into the molten base metal
   - Coating on the electrode vaporizes and forms a protective gaseous shield, preventing the molten metal from oxidizing before it solidifies
   - The electrode is moved across the joint and a weld bead is deposited. Size of the weld bead depends on the rate of travel
   - As the weld cools, impurities rise to the surface and form a coating called slag. Slag must be removed before the next pass or the weld is painted.

2. Submerged Arc Welding (SAW)
3. Gas Metal Arc Welding (GMAW)
   - End of the electrode and the arc are submerged in a granular flux that melts and forms a gaseous shield.
4. Flux Cored Arc Welding (FCAW)
5. Electro Gas Welding (FGW)
6. Electroslag Welding (ESW)
Basic of welding (cont)

Minimum weld size, maximum weld size, and minimum length:

- The minimum size of a fillet weld is a function of the thickness of the thicker connected part. See AISC Table J2.4 for details.
- The maximum size of a fillet weld is as follows:
  - Along the edge of a connected part less than ¼-inch thick, the maximum fillet weld size (w) equals the plate thickness.
  - For other values of plate thickness, t, the maximum weld size is t - 1/16 in.

<table>
<thead>
<tr>
<th>Minimum Size of Fillet Welds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material Thickness of Thicker Part (in., min.)</td>
</tr>
<tr>
<td>(Note: Thicker part must be at least twice the thickness of the thinner part.)</td>
</tr>
<tr>
<td>1/8 in.</td>
</tr>
<tr>
<td>1/4 in.</td>
</tr>
<tr>
<td>1/2 in.</td>
</tr>
</tbody>
</table>

The minimum permissible length of a fillet weld is 4 times its size. If only a shorter length is available, \( w = \frac{L}{4} \). For the welds in the connection shown below, \( L \geq W \) to address shear lag in such connections.

- When a weld extends to the corner of a member, it must be continued around the corner (an end return).
  - Prevent stress concentrations at the corner of the weld.
  - Minimum length of return is 2w.

Common types of welds are:
- Fillet welds - Welds placed in a corner formed by two parts in contact.
- Groove welds - Welds deposited in a gap between two parts.
- Plug welds - Circular or slotted hole that is filled with weld metal. Used sometimes when more weld length is needed than is available.

Basic of welding (cont)

Fillet Weld

- The design and analysis of fillet welds is based on the assumption that the geometry of the weld is a 45-degree right triangle.
- Standard weld sizes are expressed in sixteenths of an inch.
- Failure of fillet welds is assumed to occur in shear on the throat.
The strength of a fillet weld depends on the strength of the filler or electrode metal used. The strength of an electrode is given in terms of its tensile strength in ksi. Strengths of 60, 70, 80, 90, 100, 110, and 120 ksi are available.

The standard notation for an electrode is E**XX where ** indicate the tensile strength in ksi and XX denotes the type of coating used.

- Usually XX is the focus of design
- E70XX is an electrode with a tensile strength of 70 ksi
- Electrodes should be chosen to match the base metal.
  - Use E70XX electrodes for use with steels that have a yield stress less than 60 ksi
  - Use E80XX electrodes that have a yield stress of 60 ksi or 65 ksi

The critical shearing stress on a weld of length \( L \) is given by
\[
f = \frac{P}{(0.707wL)}
\]
If the ultimate shearing stress in the weld is termed \( F_w \), the nominal design strength of the weld can be written as
\[
\phi R_n = 0.707wL(\phi F_w) = 0.707wL(0.75(0.6F_{EXX})) = 0.32wL F_{EXX}
\]
For E70XX and E80XX electrodes, the design stresses are \( \phi F_w \), or 31.5 ksi and 36 ksi, respectively.

In addition, the factored load shear on the base metal shall not produce a stress in excess of \( \phi F_{BM} \) where \( F_{BM} \) is the nominal shear strength of the connected material. The factored load on the connection is thus subjected to the limit of
\[
\phi R_n = \phi F_{BM} A_y = 0.90(0.6F_{EXX})A_y = 0.54F_{EXX} A_y
\]

### LRFD of Welded Connections

#### TABLE 22.5

<table>
<thead>
<tr>
<th>Type of Weld and Stress Condition</th>
<th>W</th>
<th>F_{BM}</th>
<th>R_{BM}</th>
<th>( \phi R_n )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile normal to effective axis</td>
<td>Base</td>
<td>90 ksi</td>
<td>0.90</td>
<td>0.54F_{EXX}</td>
</tr>
<tr>
<td>Tensile normal to effective axis</td>
<td>Base</td>
<td>65 ksi</td>
<td>0.90</td>
<td>0.36F_{EXX}</td>
</tr>
<tr>
<td>Shear on effective area</td>
<td>Base</td>
<td>65 ksi</td>
<td>0.90</td>
<td>0.36F_{EXX}</td>
</tr>
<tr>
<td>Shear on effective area</td>
<td>Base</td>
<td>65 ksi</td>
<td>0.90</td>
<td>0.36F_{EXX}</td>
</tr>
</tbody>
</table>

Sequi Examples 7.11 & 7.15