Steel Design

Notation:

\( a \) = name for width dimension
\( A \) = name for area
\( A_b \) = area of a bolt
\( A_e \) = effective net area found from the product of the net area \( A_n \) by the shear lag factor \( U \)
\( A_g \) = gross area, equal to the total area ignoring any holes
\( A_{pv} \) = gross area subjected to shear for block shear rupture
\( A_n \) = net area, equal to the gross area subtracting any holes, as is \( A_{net} \)
\( A_{nt} \) = net area subjected to tension for block shear rupture
\( A_{nv} \) = net area subjected to shear for block shear rupture
\( A_w \) = area of the web of a wide flange section
\( AISC \) = American Institute of Steel Construction
\( ASD \) = allowable stress design
\( b \) = name for a (base) width
\( b_f \) = width of the flange of a steel beam cross section
\( B_l \) = factor for determining \( M_u \) for combined bending and compression
\( c \) = largest distance from the neutral axis to the top or bottom edge of a beam
\( c_l \) = coefficient for shear stress for a rectangular bar in torsion
\( C_b \) = modification factor for moment in ASD & LRFD steel beam design
\( C_c \) = column slenderness classification constant for steel column design
\( C_m \) = modification factor accounting for combined stress in steel design
\( C_v \) = web shear coefficient
\( d \) = calculus symbol for differentiation
\( d_b \) = nominal bolt diameter
\( D \) = shorthand for dead load
\( DL \) = shorthand for dead load
\( e \) = eccentricity
\( E \) = shorthand for earthquake load
\( f_c \) = axial compressive stress
\( f_b \) = bending stress
\( f_p \) = bearing stress
\( f_v \) = shear stress
\( f_{v-max} \) = maximum shear stress
\( f_y \) = yield stress
\( F \) = shorthand for fluid load
\( F_a \) = allowable axial (compressive) stress
\( F_b \) = allowable bending stress
\( F_c \) = critical unfactored compressive stress for buckling in LRFD
\( F_{cr} \) = flexural buckling stress
\( F_e \) = elastic critical buckling stress
\( F_{EXX} \) = yield strength of weld material
\( F_n \) = nominal strength in LRFD
\( F_p \) = allowable bearing stress
\( F_t \) = allowable tensile stress
\( F_u \) = ultimate stress prior to failure
\( F_v \) = allowable shear stress
\( F_y \) = yield strength
\( F_{yw} \) = yield strength of web material
\( F.S. \) = factor of safety
\( g \) = gage spacing of staggered bolt holes
\( h \) = name for a height
\( h_c \) = height of the web of a wide flange steel section
\( H \) = shorthand for lateral pressure load
\( I \) = moment of inertia with respect to neutral axis bending
\( I_{trial} \) = moment of inertia of trial section
\( I_{req'd} \) = moment of inertia required at limiting deflection
\( I_y \) = moment of inertia about the y axis
\( J \) = polar moment of inertia
\[ k = \text{distance from outer face of W flange to the web toe of fillet} \]
\[ K = \text{shape factor for plastic design of steel beams} \]
\[ l = \text{name for length} \]
\[ L = \text{name for length or span length} \]
\[ L_b = \text{unbraced length of a steel beam} \]
\[ L_c = \text{clear distance between the edge of a hole and edge of next hole or edge of the connected steel plate in the direction of the load} \]
\[ L_e = \text{effective length that can buckle for column design, as is } l_e \]
\[ L_r = \text{shorthand for live roof load} \]
\[ L_p = \text{maximum unbraced length of a steel beam in LRFD design for inelastic lateral-torsional buckling} \]
\[ L' = \text{length of an angle in a connector with staggered holes} \]
\[ LL = \text{shorthand for live load} \]
\[ LRFD = \text{load and resistance factor design} \]
\[ M = \text{internal bending moment} \]
\[ M_a = \text{required bending moment (ASD)} \]
\[ M_n = \text{nominal flexure strength with the full section at the yield stress for LRFD beam design} \]
\[ M_{\text{max}} = \text{maximum internal bending moment} \]
\[ M_{\text{max-adj}} = \text{maximum bending moment adjusted to include self weight} \]
\[ M_p = \text{internal bending moment when all fibers in a cross section reach the yield stress} \]
\[ M_u = \text{maximum moment from factored loads for LRFD beam design} \]
\[ M_y = \text{internal bending moment when the extreme fibers in a cross section reach the yield stress} \]
\[ n = \text{number of bolts} \]
\[ n.a. = \text{shorthand for neutral axis} \]
\[ N = \text{bearing length on a wide flange steel section} \]
\[ p = \text{bearing type connection with threads included in shear plane} \]
\[ P = \text{bolt hole spacing (pitch)} \]
\[ P_a = \text{required axial force (ASD)} \]
\[ P_c = \text{available axial strength} \]
\[ P_{el} = \text{Euler buckling strength} \]
\[ P_n = \text{nominal column load capacity in steel design} \]
\[ P_r = \text{required axial force} \]
\[ P_u = \text{factored column load calculated from load factors in LRFD steel design} \]
\[ Q = \text{first moment area about a neutral axis} \]
\[ q = \text{generic axial load quantity for LRFD design} \]
\[ r = \text{radius of gyration} \]
\[ r_y = \text{radius of gyration with respect to a y-axis} \]
\[ R = \text{generic load quantity (force, shear, moment, etc.) for LRFD design} \]
\[ R_{da} = \text{required strength (ASD)} \]
\[ R_n = \text{nominal value (capacity) to be multiplied by } \phi \text{ in LRFD and divided by the safety factor } \Omega \text{ in ASD} \]
\[ R_u = \text{factored design value for LRFD design} \]
\[ s = \text{longitudinal center-to-center spacing of any two consecutive holes} \]
\[ S = \text{shorthand for snow load} \]
\[ S = \text{section modulus} \]
\[ S_{\text{req'd}} = \text{allowable strength per length of a weld for a given size} \]
\[ S_{\text{req'd-adj}} = \text{section modulus required at allowable stress} \]
\[ SC = \text{slip critical bolted connection} \]
\[ t = \text{thickness of the connected material} \]
\[ t_f = \text{thickness of flange of wide flange} \]
### Steel Design

Structural design standards for steel are established by the *Manual of Steel Construction* published by the American Institute of Steel Construction, and uses **Allowable Stress Design** and **Load and Factor Resistance Design**. With the 13th edition, both methods are combined in one volume which provides common requirements for analyses and design and requires the application of the same set of specifications.

#### Materials

American Society for Testing Materials (ASTM) is the organization responsible for material and other standards related to manufacturing. Materials meeting their standards are guaranteed to have the published strength and material properties for a designation.
A36 – carbon steel used for plates, angles  \( F_y = 36 \text{ ksi}, F_u = 58 \text{ ksi}, E = 29,000 \text{ ksi} \)
A572 – high strength low-alloy used for some beams  \( F_y = 60 \text{ ksi}, F_u = 75 \text{ ksi}, E = 29,000 \text{ ksi} \)
A992 – for building framing used for most beams  \( F_y = 50 \text{ ksi}, F_u = 65 \text{ ksi}, E = 29,000 \text{ ksi} \)
(A572 Grade 50 has the same properties as A992)

**ASD**  \[ R_a \leq \frac{R_n}{\Omega} \]
where
- \( R_a = \text{required strength (dead or live; force, moment or stress)} \)
- \( R_n = \text{nominal strength specified for ASD} \)
- \( \Omega = \text{safety factor} \)

Factors of Safety are applied to the limit strengths for allowable strength values:

- **bending (braced, \( L_b < L_p \))** \( \Omega = 1.67 \)
- **bending (unbraced, \( L_p < L_b \) and \( L_b > L_r \))** \( \Omega = 1.67 \) (nominal moment reduces)
- **shear (beams)** \( \Omega = 1.5 \) or 1.67
- **shear (bolts)** \( \Omega = 2.00 \) (tabular nominal strength)
- **shear (welds)** \( \Omega = 2.00 \)

- \( L_b \) is the unbraced length between bracing points, laterally
- \( L_p \) is the limiting laterally unbraced length for the limit state of yielding
- \( L_r \) is the limiting laterally unbraced length for the limit state of inelastic lateral-torsional buckling

**LRFD**  \[ R_u \leq \phi R_n \]
where
- \( \phi = \text{resistance factor} \)
- \( \gamma = \text{load factor for the type of load} \)
- \( R = \text{load (dead or live; force, moment or stress)} \)
- \( R_u = \text{factored load (moment or stress)} \)
- \( R_n = \text{nominal load (ultimate capacity; force, moment or stress)} \)

*Nominal strength* is defined as the capacity of a structure or component to resist the effects of loads, as determined by computations using specified material strengths (such as yield strength, \( F_y \), or ultimate strength, \( F_u \)) and dimensions and formulas derived from accepted principles of structural mechanics or by field tests or laboratory tests of scaled models, allowing for modeling effects and differences between laboratory and field conditions.
Factored Load Combinations

The design strength, $\phi R_n$, of each structural element or structural assembly must equal or exceed the design strength based on the ASCE-7 (2010) combinations of factored nominal loads:

1.4D
1.2D + 1.6L + 0.5(L or S or R)
1.2D + 1.6(L or S or R) + L + 0.5W
1.2D + 0.5S
0.9D + 1.0W
0.9D + 1.0E

Criteria for Design of Beams

Allowable normal stress or normal stress from LRFD should not be exceeded:

Knowing $M$ and $F_b$, the minimum section modulus fitting the limit is:

$$ F_b \text{ or } \phi F_n \geq f_b = \frac{Mc}{I} $$

$$(M_a \leq M_n / \Omega \text{ or } M_a \leq \phi_b M_n)$$

Determining Maximum Bending Moment

Drawing V and M diagrams will show us the maximum values for design. Remember:

$$ V = \Sigma (-w)dx \quad M = \Sigma (V)dx \quad \frac{dV}{dx} = -w \quad \frac{dM}{dx} = V $$

Determining Maximum Bending Stress

For a prismatic member (constant cross section), the maximum normal stress will occur at the maximum moment.

For a non-prismatic member, the stress varies with the cross section AND the moment.

Deflections

If the bending moment changes, $M(x)$ across a beam of constant material and cross section then the curvature will change:

$$ R = \frac{1}{M(x)} $$

The slope of the n.a. of a beam, $\theta$, will be tangent to the radius of curvature, $R$:

$$ \theta = \text{slope} = \frac{1}{EI} \int M(x)dx $$

The equation for deflection, $y$, along a beam is:

$$ y = \frac{1}{EI} \int \theta dx = \frac{1}{EI} \int \int M(x)dx $$
Elastic curve equations can be found in handbooks, textbooks, design manuals, etc...Computer programs can be used as well. Elastic curve equations can be superimposed ONLY if the stresses are in the elastic range.

The deflected shape is roughly the same shape flipped as the bending moment diagram but is constrained by supports and geometry.

Allowable Deflection Limits

All building codes and design codes limit deflection for beam types and damage that could happen based on service condition and severity.

\[ y_{max}(x) = \Delta_{actual} \leq \Delta_{allowable} = \frac{L}{value} \]

<table>
<thead>
<tr>
<th>Use</th>
<th>LL only</th>
<th>DL+LL</th>
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</thead>
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<tr>
<td>Roof beams:</td>
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<tr>
<td>Industrial</td>
<td>L/180</td>
<td>L/120</td>
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<tr>
<td>Commercial</td>
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<td></td>
</tr>
<tr>
<td>plaster ceiling</td>
<td>L/240</td>
<td>L/180</td>
</tr>
<tr>
<td>no plaster</td>
<td>L/360</td>
<td>L/240</td>
</tr>
<tr>
<td>Floor beams:</td>
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<tr>
<td>Ordinary Usage</td>
<td>L/360</td>
<td>L/240</td>
</tr>
<tr>
<td>Roof or floor (damageable elements)</td>
<td>L/480</td>
<td></td>
</tr>
</tbody>
</table>

Lateral Buckling

With compression stresses in the top of a beam, a sudden “popping” or buckling can happen even at low stresses. In order to prevent it, we need to brace it along the top, or laterally brace it, or provide a bigger \( I_y \).

Local Buckling in Steel I Beams–Web Crippling or Flange Buckling

Concentrated forces on a steel beam can cause the web to buckle (called web crippling). Web stiffeners under the beam loads and bearing plates at the supports reduce that tendency. Web stiffeners also prevent the web from shearing in plate girders.
The maximum support load and interior load can be determined from:

\[ P_{n(\text{max-end})} = (2.5k + N)F_{yw}t_w \]
\[ P_{n(\text{interior})} = (5k + N)F_{yw}t_w \]

where \( t_w \) = thickness of the web
\( F_{yw} \) = yield strength of the web
\( N \) = bearing length
\( k \) = dimension to fillet found in beam section tables

\( \phi = 1.00 \) (LRFD) \hspace{1cm} \( \Omega = 1.50 \) (ASD)

**Beam Loads & Load Tracing**

In order to determine the loads on a beam (or girder, joist, column, frame, foundation...) we can start at the top of a structure and determine the *tributary area* that a load acts over and the beam needs to support. Loads come from material weights, people, and the environment. This area is assumed to be from half the distance to the next beam over to halfway to the next beam.

The reactions must be supported by the next lower structural element *ad infinitum*, to the ground.

**LRFD - Bending or Flexure**

For determining the flexural design strength, \( \phi_b M_u \), for resistance to pure bending (no axial load) in most flexural members where the following conditions exist, a single calculation will suffice:

\[ \Sigma \gamma_i R_i = M_u \leq \phi_b M_n = 0.9 F_y Z \]

where \( M_u \) = maximum moment from factored loads
\( \phi_b \) = resistance factor for bending = 0.9
\( M_n \) = nominal moment (ultimate capacity)
\( F_y \) = yield strength of the steel
\( Z \) = plastic section modulus

**Plastic Section Modulus**

Plastic behavior is characterized by a yield point and an increase in strain with no increase in stress.
Internal Moments and Plastic Hinges

Plastic hinges can develop when all of the material in a cross section sees the yield stress. Because all the material at that section can strain without any additional load, the member segments on either side of the hinge can rotate, possibly causing instability.

For a rectangular section:

- Elastic to $f_y$: $M_y = \frac{I}{c} f_y = \frac{bh^2}{6} f_y = \frac{b}{6} \left(2c\right)^2 f_y = \frac{2bc^2}{3} f_y$

- Fully Plastic: $M_{ub}$ or $M_p = bc^2 f_y = \frac{3}{2} M_y$

For a non-rectangular section and internal equilibrium at $\sigma_y$, the n.a. will not necessarily be at the centroid. The n.a. occurs where $A_{tension} = A_{compression}$. The reactions occur at the centroids of the tension and compression areas.

Instability from Plastic Hinges

Shape Factor:

The ratio of the plastic moment to the elastic moment at yield:

$$k = \frac{M_p}{M_y}$$

$\text{k} = 3/2$ for a rectangle

$\text{k} \approx 1.1$ for an I beam

Plastic Section Modulus

$$Z = \frac{M_p}{f_y} \quad \text{and} \quad k = \frac{Z}{S}$$
Design for Shear

\[ V_a \leq V_n / \Omega \text{ or } V_a \leq \phi_b V_n \]

The nominal shear strength is dependent on the cross section shape. Case 1: With a thick or stiff web, the shear stress is resisted by the web of a wide flange shape (with the exception of a handful of W’s). Case 2: When the web is not stiff for doubly symmetric shapes, singly symmetric shapes (like channels) (excluding round high strength steel shapes), inelastic web buckling occurs. When the web is very slender, elastic web buckling occurs, reducing the capacity even more:

Case 1) For \( h/t_w \leq 2.24 \sqrt{\frac{E}{F_y}} \quad V_n = 0.6 F_{yw} A_w \quad \phi_v = 1.00 \text{ (LRFD)} \quad \Omega = 1.50 \text{ (ASD)} \)

where \( h \) equals the clear distance between flanges less the fillet or corner radius for rolled shapes
\( V_n \) = nominal shear strength
\( F_{yw} \) = yield strength of the steel in the web
\( A_w = t_w d = \text{area of the web} \)

Case 2) For \( h/t_w > 2.24 \sqrt{\frac{E}{F_y}} \quad V_n = 0.6 F_{yw} A_w C_v \quad \phi_v = 0.9 \text{ (LRFD)} \quad \Omega = 1.67 \text{ (ASD)} \)

where \( C_v \) is a reduction factor (1.0 or less by equation)

Design for Flexure

\[ M_a \leq M_n / \Omega \text{ or } M_a \leq \phi_b M_n \quad \phi_b = 0.90 \text{ (LRFD)} \quad \Omega = 1.67 \text{ (ASD)} \]

The nominal flexural strength \( M_n \) is the lowest value obtained according to the limit states of

1. yielding, limited at length \( L_p = 1.76 r_y \sqrt{\frac{E}{F_y}} \), where \( r_y \) is the radius of gyration in \( y \)
2. lateral-torsional buckling (inelastic) limited at length \( L_r \)
3. flange local buckling
4. web local buckling

Beam design charts show available moment, \( M_n/\Omega \) and \( \phi_b M_n \), for unbraced length, \( L_{bn} \) of the compression flange in one-foot increments from 1 to 50 ft. for values of the bending coefficient \( C_b = 1 \). For values of \( 1 < C_b \leq 2.3 \), the required flexural strength \( M_u \) can be reduced by dividing it by \( C_b \). \( C_b = 1 \) when the bending moment at any point within an unbraced length is larger than that at both ends of the length. \( C_b \) of 1 is conservative and permitted to be used in any case. When the free end is unbraced in a cantilever or overhang, \( C_b = 1 \). The full formula is provided below.

**NOTE:** the self weight is not included in determination of \( M_n/\Omega \) or \( \phi_b M_n \)
Compact Sections
For a laterally braced compact section (one for which the plastic moment can be reached before local buckling) only the limit state of yielding is applicable. For unbraced compact beams and non-compact tees and double angles, only the limit states of yielding and lateral-torsional buckling are applicable.

Compact sections meet the following criteria:
\[ \frac{b_f}{2t_f} \leq 0.38 \sqrt[3]{\frac{E}{F_y}} \quad \text{and} \quad \frac{h_c}{t_w} \leq 3.76 \sqrt[3]{\frac{E}{F_y}} \]

where:
- \( b_f \) = flange width in inches
- \( t_f \) = flange thickness in inches
- \( E \) = modulus of elasticity in ksi
- \( F_y \) = minimum yield stress in ksi
- \( h_c \) = height of the web in inches
- \( t_w \) = web thickness in inches

With lateral-torsional buckling the nominal flexural strength is
\[ M_n = C_b \left( M_p - (M_p - 0.7F_yS_x) \left( \frac{L_\| - L_p}{L_r - L_p} \right) \right) \leq M_p \]

where \( C_b \) is a modification factor for non-uniform moment diagrams where, when both ends of the beam segment are braced:

- \( M_{max} \) = absolute value of the maximum moment in the unbraced beam segment
- \( M_A \) = absolute value of the moment at the quarter point of the unbraced beam segment
- \( M_B \) = absolute value of the moment at the center point of the unbraced beam segment
- \( M_C \) = absolute value of the moment at the three quarter point of the unbraced beam segment length.

Available Flexural Strength Plots
Plots of the available moment for the unbraced length for wide flange sections are useful to find sections to satisfy the design criteria of \( M_a \leq M_n / \Omega \) or \( M_u \leq \phi_p M_n \). The maximum moment that can be applied on a beam (taking self weight into account), \( M_a \) or \( M_u \), can be plotted against the unbraced length, \( L_\| \). The limit \( L_\| \) is indicated by a solid dot (●), while \( L_r \) is indicated by an open dot (○). Solid lines indicate the most economical, while dashed lines indicate there is a lighter section that could be used. \( C_b \), which is a modification factor for non-zero moments at the ends, is 1 for simply supported beams (0 moments at the ends). (see figure)
Design Procedure

The intent is to find the most lightweight member (which is economical) satisfying the section modulus size.

1. Determine the unbraced length to choose the limit state (yielding, lateral torsional buckling or more extreme) and the factor of safety and limiting moments. Determine the material.

2. Draw V & M, finding $V_{\text{max}}$ and $M_{\text{max}}$ for unfactored loads (ASD, $V_a$ & $M_a$) or from factored loads (LRFD, $V_u$ & $M_u$).

3. Calculate $Z_{\text{req'd}}$ when yielding is the limit state. This step is equivalent to determining if

$$f_b = \frac{M_{\text{max}}}{S} \leq F_b, \quad Z_{\text{req'd}} = \frac{M_{\text{max}}}{F_y} / \Omega$$

and $Z \geq \frac{M_u}{\phi_b F_y}$ to meet the design criteria that

$$M_a \leq M_n / \Omega \text{ or } M_u \leq \phi_b M_n$$

If the limit state is something other than yielding, determine the nominal moment, $M_n$, or use plots of available moment to unbraced length, $L_b$.

4. For steel: use the section charts to find a trial $Z$ and remember that the beam self weight (the second number in the section designation) will increase $Z_{\text{req'd}}$. The design charts show the lightest section within a grouping of similar $Z$'s.

**** Determine the “updated” $V_{\text{max}}$ and $M_{\text{max}}$ including the beam self weight, and verify that the updated $Z_{\text{req'd}}$ has been met.*****
5. Consider lateral stability.

6. Evaluate horizontal shear using \( V_{\text{max}} \). This step is equivalent to determining if \( f_v \leq F_v \) is satisfied to meet the design criteria that \( V_a \leq V_n / \Omega \) or \( V_a \leq \phi V_n \)

For I beams: \[ f_{v-\text{max}} = \frac{3V}{2A} \approx \frac{V}{A_{\text{web}}} = \frac{V}{t_w d} \quad V_n = 0.6F_{yw} A_w \quad \text{or} \quad V_n = 0.6F_{yw} A_w C_v \]

Others: \[ f_{v-\text{max}} = \frac{VQ}{lb} \]

7. Provide adequate bearing area at supports. This step is equivalent to determining if \( f_p = \frac{P}{A} \leq F_p \)

is satisfied to meet the design criteria that \( P_a \leq P_n / \Omega \) or \( P_a \leq \phi P_n \)

8. Evaluate shear due to torsion \[ f_v = \frac{T_d}{J} \text{ or } \frac{T}{c_{\text{ref}} ab^2} \leq F_v \] (circular section or rectangular)

9. Evaluate the deflection to determine if \( \Delta_{\text{max LL}} \leq \Delta_{\text{LL-allowed}} \) and/or \( \Delta_{\text{max Total}} \leq \Delta_{\text{Total allowed}} \)

**** note: when \( \Delta_{\text{calculated}} > \Delta_{\text{limit}} \) \( I_{\text{req'd}} \) can be found with: and \( Z_{\text{req'd}} \) will be satisfied for similar self weight ****

\[ I_{\text{req'd}} \geq \frac{\Delta_{\text{too big}}}{\Delta_{\text{limit}}} I_{\text{trial}} \]

FOR ANY EVALUATION:

Redesign (with a new section) at any point that a stress or serviceability criteria is NOT satisfied and re-evaluate each condition until it is satisfactory.

Load Tables for Uniformly Loaded Joists & Beams

Tables exist for the common loading situation of uniformly distributed load. The tables either provide the safe distributed load based on bending and deflection limits, they give the allowable span for specific live and dead loads including live load deflection limits.

If the load is not uniform, an equivalent uniform load can be calculated from the maximum moment equation:

\[ M_{\text{max}} = \frac{w_{\text{equivalent}} L^2}{8} \]

If the deflection limit is less, the design live load to check against allowable must be increased, ex.

\[ W_{\text{adjusted}} = w_{\text{table limit}} \left( \frac{L}{360} \right) \quad \text{table limit} \]

\[ W_{\text{adjusted}} = w_{\text{wanted}} \left( \frac{L}{400} \right) \quad \text{wanted} \]

Criteria for Design of Columns

If we know the loads, we can select a section that is adequate for strength & buckling.

If we know the length, we can find the limiting load satisfying strength & buckling.
Allowable Stress Design

The allowable stress design provisions prior to the combined design of the 13th edition of the AISC Steel Construction Manual had relationships for short and intermediate length columns (crushing and the transition to inelastic buckling), and long columns (buckling) as shown in the figure. The transition slenderness ratio is based on the yield strength and modulus of elasticity and are 126.1 ($F_y = 36$ ksi) and 107.0 ($F_y = 50$ ksi) with a limiting slenderness ratio of 200.

Design for Compression

American Institute of Steel Construction (AISC) Manual 14th ed:

$$P_u = \frac{P_n}{\Omega} \quad \text{or} \quad P_u \leq \phi V_n$$

where

- $P_u = \sum \gamma_i P_i$
- $\gamma$ is a load factor
- $P$ is a load type
- $\phi$ is a resistance factor
- $P_n$ is the nominal load capacity (strength)

$\phi =$ 0.90 (LRFD) \hspace{1cm} $\Omega =$ 1.67 (ASD)

For compression $P_n = F_{cr} A_g$

where \(A_g\) is the cross section area and \(F_{cr}\) is the flexural buckling stress

The flexural buckling stress, \(F_{cr}\), is determined as follows:

when \(\frac{KL}{r} \leq 4.71 \sqrt{\frac{E}{F_y}}\) \hspace{1cm} or \(F_e \geq 0.44F_y\):

$$F_{cr} = \left[ 0.658 \frac{F_y}{F_e} \right] F_y$$

when \(\frac{KL}{r} > 4.71 \sqrt{\frac{E}{F_y}}\) \hspace{1cm} or \(F_e < 0.44F_y\):

$$F_{cr} = 0.877 F_e$$

where \(F_e\) is the elastic critical buckling stress:

$$F_e = \frac{\pi^2 E}{(KL/r)^2}$$
Design Aids

Tables exist for the value of the flexural buckling stress based on slenderness ratio. In addition, tables are provided in the AISC Manual for Available Strength in Axial Compression based on the effective length with respect to least radius of gyration, \( r_y \). If the critical effective length is about the largest radius of gyration, \( r_x \), it can be turned into an effective length about the y axis by dividing by the fraction \( r_x / r_y \).

**Procedure for Analysis**

1. Calculate \( KL/r \) for each axis (if necessary). The largest will govern the buckling load.
2. Find \( F_{cr} \) as a function of \( KL/r \) from the appropriate equation (above) or table.
3. Compute \( P_n = F_{cr}A \) or alternatively compute \( f_c = P/A \) or \( P_u/A \)
4. Is the design satisfactory?
   - \( P_a \leq P_n/\Omega \) or \( P_a \leq \phi P_n \)? \( \Rightarrow \) yes, it is; no, it is no good
   - \( f_c \leq F_{cr}/\Omega \) or \( \phi F_{cr} \)? \( \Rightarrow \) yes, it is; no, it is no good

**Procedure for Design**

1. Guess a size by picking a section.
2. Calculate \( KL/r \) for each axis (if necessary). The largest will govern the buckling load.
3. Find $F_{cr}$ as a function of $KL/r$ from appropriate equation (above) or table.
4. Compute $P_n = F_{cr} A_g$ or alternatively compute $f_c = P/A$ or $P_u/A$
5. Is the design satisfactory?
   Is $P_a \leq P_u/\Omega$ or $P_a \leq \phi_c P_u$? yes, it is; no, pick a bigger section and go back to step 2.
   Is $f_c \leq F_{cr}/\Omega$ or $\phi_c F_{cr}$? \Rightarrow yes, it is; no, pick a bigger section and go back to step 2.
6. Check design efficiency by calculating percentage of capacity used:
   \[ \frac{P_a}{P_n} \cdot 100\% \text{ or } \frac{P_a}{\phi_c P_n} \cdot 100\% \]
   If value is between 90-100%, it is efficient.
   If values is less than 90%, pick a smaller section and go back to step 2.

**Columns with Bending (Beam-Columns)**

In order to design an adequate section for allowable stress, we have to start somewhere:

1. Make assumptions about the limiting stress from:
   - buckling
   - axial stress
   - combined stress
2. See if we can find values for $r$ or $A$ or $Z$
3. Pick a trial section based on if we think $r$ or $A$ is going to govern the section size.
4. Analyze the stresses and compare to allowable using the allowable stress method or interaction formula for eccentric columns.
5. Did the section pass the capacity adequacy test?
   - If not, do you increase $r$ or $A$ or $Z$?
   - If so, is the difference really big so that you could decrease $r$ or $A$ or $Z$ to make it more efficient (economical)?
6. Change the section choice and go back to step 4. Repeat until the section meets the stress criteria.

**Design for Combined Compression and Flexure:**

The interaction of compression and bending are included in the form for two conditions based on the size of the required axial force to the available axial strength. This is notated as $P_r$ (either $P$ from ASD or $P_u$ from LRFD) for the axial force being supported, and $P_c$ (either $P_u/\Omega$ for ASD or $\phi_c P_u$ for LRFD). The increased bending moment due to the P-\Delta effect must be determined and used as the moment to resist.
For \( \frac{P_r}{P_c} \geq 0.2 \):
\[
\frac{P}{P_n} + \frac{8}{9} \left( \frac{M_x}{M_{nx}} + \frac{M_y}{M_{ny}} \right) \leq 1.0
\]
(ASD)
\[
\frac{P_u}{\phi_e P_n} + \frac{8}{9} \left( \frac{M_{ux}}{\phi_b M_{nx}} + \frac{M_{uy}}{\phi_b M_{ny}} \right) \leq 1.0
\]
(LRFD)

For \( \frac{P_r}{P_c} < 0.2 \):
\[
\frac{P}{2P_n} + \left( \frac{M_x}{M_{nx}} + \frac{M_y}{M_{ny}} \right) \leq 1.0
\]
(ASD)
\[
\frac{P_u}{2\phi_e P_n} + \left( \frac{M_{ux}}{\phi_b M_{nx}} + \frac{M_{uy}}{\phi_b M_{ny}} \right) \leq 1.0
\]
(LRFD)

where:
for compression \( \phi_c = 0.90 \) (LRFD) \( \Omega = 1.67 \) (ASD)
for bending \( \phi_b = 0.90 \) (LRFD) \( \Omega = 1.67 \) (ASD)

For a braced condition, the moment magnification factor \( B_1 \) is determined by
\[
B_1 = \frac{C_m}{1 - \left( \frac{P_u}{P_{el}} \right)} \geq 1.0
\]
where \( C_m \) is a modification factor accounting for end conditions

When not subject to transverse loading between supports in plane of bending:
\[
\Omega = 0.6 - 0.4 \left( \frac{M_1}{M_2} \right) \text{ where } M_1 \text{ and } M_2 \text{ are the end moments and } M_1 < M_2. \quad M_1/M_2 \text{ is positive when the member is bent in reverse curvature (same direction), negative when bent in single curvature.}
\]

When there is transverse loading between the two ends of a member:
\[
\Omega = 0.85, \text{ members with restrained (fixed) ends}
\]
\[
\Omega = 1.00, \text{ members with unrestrained ends}
\]
\[ P_{el} = \frac{\pi^2 EA}{(Kl/r)^2} \]

Criteria for Design of Connections

Connections must be able to transfer any axial force, shear, or moment from member to member or from beam to column.

Connections for steel are typically high strength bolts and electric arc welds. Recommended practice for ease of construction is to specified shop welding and field bolting.

Fig. C-44.1. Failure by shear rupture limit state.
Fig. C-44.2. Block shear rupture in tension.
Bolted and Welded Connections

The limit state for connections depends on the loads:

1. tension yielding
2. shear yielding
3. bearing yielding
4. bending yielding due to eccentric loads
5. rupture

Welds must resist tension AND shear stress. The design strengths depend on the weld materials.

Bolted Connection Design

Bolt designations signify material and type of connection where
SC: slip critical
N: bearing-type connection with bolt threads included in shear plane
X: bearing-type connection with bolt threads excluded from shear plane

A307: similar in strength to A36 steel (also known as ordinary, common or unfinished bolts)
A325: high strength bolts (Group A)
A490: high strength bolts (higher than A325) (Group B)

Bearing-type connection: no frictional resistance in the contact surfaces is assumed and slip between members occurs as the load is applied. (Load transfer through bolt only).

Slip-critical connections: bolts are torqued to a high tensile stress in the shank, resulting in a clamping force on the connected parts. (Shear resisted by clamping force). Requires inspections and is useful for structures seeing dynamic or fatigue loading.

Class A indicates the faying (contact) surfaces are clean mill scale or adequate paint system, while Class B indicates blast cleaning or paint for $\mu = 0.50$.

Bolts rarely fail in bearing. The material with the hole will more likely yield first.

For the determination of the net area of a bolt hole the width is taken as $1/16''$ greater than the nominal dimension of the hole. Standard diameters for bolt holes are $1/16''$ larger than the bolt diameter. (This means the net width will be $1/8''$ larger than the bolt.)

Design for Bolts in Bearing, Shear and Tension

Available shear values are given by bolt type, diameter, and loading (Single or Double shear) in AISC manual tables. Available shear value for slip-critical connections are given for limit states of serviceability or strength by bolt type, hole type (standard, short-slotted, long-slotted or oversized), diameter, and loading. Available tension values are given by bolt type and diameter in AISC manual tables.
Allowable bearing force values are given by bolt diameter, ultimate tensile strength, $F_u$, of the connected part, and thickness of the connected part in AISC manual tables.

For shear OR tension (same equation) in bolts: \[ R_n \leq R_n / \Omega \quad \text{or} \quad R_n \leq \phi R_n \]

where \( R_n = \Sigma \gamma_i R_i \)

- single shear (or tension) \[ R_n = F_n A_b \]
- double shear \[ R_n = F_n 2A_b \]

where \( \phi = \) the resistance factor
\( F_n = \) the nominal tension or shear strength of the bolt
\( A_b = \) the cross section area of the bolt

\( \phi = 0.75 \) (LRFD) \quad \Omega = 2.00 \) (ASD)

For bearing of plate material at bolt holes: \[ R_n \leq R_n / \Omega \quad \text{or} \quad R_n \leq \phi R_n \]

where \( R_n = \Sigma \gamma_i R_i \)

- deformation at bolt hole is a concern \[ R_n = 1.2L_c tF_u \leq 2.4dtF_u \]
- deformation at bolt hole is not a concern \[ R_n = 1.5L_c tF_u \leq 3.0dtF_u \]
- long slotted holes with the slot perpendicular to the load \[ R_n = 1.0L_c tF_u \leq 2.0dtF_u \]

where \( R_n = \) the nominal bearing strength
\( F_u = \) specified minimum tensile strength
\( L_c = \) clear distance between the edges of the hole and the next hole or edge in the direction of the load
\( d = \) nominal bolt diameter
\( t = \) thickness of connected material

\( \phi = 0.75 \) (LRFD) \quad \Omega = 2.00 \) (ASD)

The minimum edge distance from the center of the outer most bolt to the edge of a member is generally 1¾ times the bolt diameter for the sheared edge and 1¼ times the bolt diameter for the rolled or gas cut edges.

The maximum edge distance should not exceed 12 times the thickness of thinner member or 6 in.

Standard bolt hole spacing is 3 in. with the minimum spacing of \( 2 \frac{1}{3} \) times the diameter of the bolt, \( d_b \). Common edge distance from the center of last hole to the edge is 1¼ in..
In steel tension members, there may be bolt holes which reduce the size of the cross section.

- $g$ refers to the row spacing or gage
- $p$ refers to the bolt spacing or pitch
- $s$ refers to the longitudinal spacing of two consecutive holes

**Effective Net Area:**

The smallest effective area must be determined by subtracting the bolt hole areas. With staggered holes, the shortest length must be evaluated.

A series of bolts can also transfer a portion of the tensile force, and some of the effective net areas see reduced stress.

The effective net area, $A_e$, is determined from the net area, $A_n$, multiplied by a shear lag factor, $U$, which depends on the element type and connection configuration. If a portion of a connected member is not fully connected (like the leg of an angle), the unconnected part is not subject to the full stress and the shear lag factor can range from 0.6 to 1.0: $A_e = A_n U$

For tension elements: $R_u \leq R_n / \Omega$ or $R_u \leq \Phi R_n$

where $R_n = \Sigma \gamma_i R_i$

1. yielding $R_n = F_y A_g$
   
   $\phi = 0.90$ (LRFD)  $\Omega = 1.67$ (ASD)

2. rupture $R_n = F_u A_e$
   
   $\phi = 0.75$ (LRFD)  $\Omega = 2.00$ (ASD)

where  $A_g =$ the gross area of the member (excluding holes)  
$A_e =$ the effective net area (with holes, etc.)
\[ F_y = \text{the yield strength of the steel} \]
\[ F_u = \text{the tensile strength of the steel (ultimate)} \]

When holes are staggered in a chain of holes (zigzagging) at diagonals, the length of each path from hole edge to edge is taken as the net area less each bolt hold area and the addition of \( \frac{s^2}{4g} \) for each gage space in the chain:

\[ A_n = bt - \Sigma ht - \Sigma \left( \frac{s^2}{4g} \right) \]

where:
- \( b \) is the plate width
- \( t \) is the plate thickness
- \( h \) is the standard hole diameter of each hole
- \( s \) is the staggered hole spacing
- \( g \) is the gage spacing between rows

### Welded Connections

Weld designations include the strength in the name, i.e. E70XX has \( F_y = 70 \, \text{ksi} \). Welds are weakest in shear and are assumed to always fail in the shear mode.

The throat size, \( T \), of a fillet weld is determined by trigonometry:

\[ T = 0.707 \times \text{weld size*} \]

* When the submerged arc weld process is used, welds over 3/8" will have a throat thickness of 0.11 in. larger than the formula.

Weld sizes are limited by the size of the parts being put together and are given in AISC manual table J2.4 along with the allowable strength per length of fillet weld, referred to as \( S \).

The maximum size of a fillet weld:
- a) can’t be greater than the material thickness if it is \( \frac{1}{4} \)" or less
- b) is permitted to be 1/16" less than the thickness of the material if it is over \( \frac{1}{4} \)"

The minimum length of a fillet weld is 4 times the nominal size. If it is not, then the weld size used for design is \( \frac{1}{4} \) the length.

Intermittent fillet welds cannot be less than four times the weld size, not to be less than \( 1 \frac{1}{2} \)".

### Table J2.4

<table>
<thead>
<tr>
<th>Material Thickness of Thicker Part Joined (in.)</th>
<th>Minimum Size of Fillet Weld (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>To ( \frac{1}{4} ) inclusive</td>
<td>( \frac{1}{8} )</td>
</tr>
<tr>
<td>Over ( \frac{1}{4} ) to ( \frac{1}{2} )</td>
<td>( \frac{3}{8} )</td>
</tr>
<tr>
<td>Over ( \frac{1}{2} ) to ( \frac{3}{4} )</td>
<td>( \frac{1}{4} )</td>
</tr>
<tr>
<td>Over ( \frac{3}{4} )</td>
<td>( \frac{3}{16} )</td>
</tr>
</tbody>
</table>

*Leg dimension of fillet welds. Single-pass welds must be used.
For fillet welds:

\[ R_u \leq R_n / \Omega \text{ or } R_u \leq \phi R_n \]

where \( R_u = \Sigma \gamma_i R_i \)

for the weld metal: \( R_n = 0.6F_{EXX} Tl = S_l \)

\[ \phi = 0.75 \text{ (LRFD)} \quad \Omega = 2.00 \text{ (ASD)} \]

where:
- \( T \) is throat thickness
- \( l \) is length of the weld

For a connected part, the other limit states for the base metal, such as tension yield, tension rupture, shear yield, or shear rupture must be considered.

| Available Strength of Fillet Welds per inch of weld (\( \phi S \)) |
|-----------------|-----------------|-----------------|
| Weld Size       | E60XX           | E70XX           |
| (in. )          | (k/in.)         | (k/in.)         |
| \( \frac{3}{16} \) | 3.58            | 4.18            |
| \( \frac{1}{4} \) | 4.77            | 5.57            |
| \( \frac{5}{16} \) | 5.97            | 6.96            |
| \( \frac{3}{8} \) | 7.16            | 8.35            |
| \( \frac{7}{16} \) | 8.35            | 9.74            |
| \( \frac{1}{2} \) | 9.55            | 11.14           |
| \( \frac{5}{8} \) | 11.93           | 13.92           |
| \( \frac{3}{4} \) | 14.32           | 16.70           |

(not considering increase in throat with submerged arc weld process)

Framed Beam Connections

Coping is the term for cutting away part of the flange to connect a beam to another beam using welded or bolted angles.

AISC provides tables that give bolt and angle available strength knowing number of bolts, bolt type, bolt diameter, angle leg thickness, hole type and coping, and the wide flange beam being connected.

Group A bolts include A325, while Group B includes A490.

There are also tables for bolted/welded double-angle connections and all-welded double-angle connections.
Sample AISC Table for Bolt and Angle Available Strength in All-Bolted Double-Angle Connections

Limiting Strength or Stability States

In addition to resisting shear and tension in bolts and shear in welds, the connected materials may be subjected to shear, bearing, tension, flexure and even prying action. Coping can significantly reduce design strengths and may require web reinforcement. All the following must be considered:

- shear yielding
- shear rupture
- block shear rupture - failure of a block at a beam as a result of shear and tension
- tension yielding
- tension rupture
- local web buckling
- lateral torsional buckling
Block Shear Strength (or Rupture):

\[ R_u \leq R_n / \Omega \quad \text{or} \quad R_u \leq \phi R_n \]

where \( R_u = \sum \gamma_i R_i \)

\[ R_n = 0.6F_u A_{nv} + U_{bs} F_u A_{nt} \leq 0.6F_y A_{gv} + U_{bs} F_u A_{nt} \]

\[ \phi = 0.75 \text{ (LRFD)} \quad \Omega = 2.00 \text{ (ASD)} \]

where:
- \( A_{nv} \) is the net area subjected to shear
- \( A_{nt} \) is the net area subjected to tension
- \( A_{gv} \) is the gross area subjected to shear
- \( U_{bs} = 1.0 \) when the tensile stress is uniform (most cases)
  \( = 0.5 \) when the tensile stress is non-uniform

Gusset Plates

Gusset plates are used for truss member connections where the geometry prevents the members from coming together at the joint “point”. Members being joined are typically double angles.

Decking

Shaped, thin sheet-steel panels that span several joists or evenly spaced support behave as continuous beams. Design tables consider a “1 unit” wide strip across the supports and determine maximum bending moment and deflections in order to provide allowable loads depending on the depth of the material.

The other structural use of decking is to construct what is called a diaphragm, which is a horizontal unit tying the decking to the joists that resists forces parallel to the surface of the diaphragm.

When decking supports a concrete topping or floor, the steel-concrete construction is called composite.
Example 1 (pg 290)

Example 2. A simple beam consisting of a W 21 × 57 is subjected to bending. Find the limiting moments (a) based on elastic stress conditions and a limiting stress of $F_y = 36$ ksi, and (b) based on full development of the plastic moment.

Example 2 (pg 300)

Example 7. Design a simply supported floor beam to carry a superimposed load of 2 kips per ft [29.2 kN/m] over a span of 24 ft [7.3 m]. (The term superimposed load is used to denote any load other than the weight of a structural member itself.) The superimposed load is 25 percent dead load and 75 percent live load. The yield stress is 36 ksi [250 MPa]. The floor beam is continuously supported along its length against lateral buckling.
Example 3

Given:
Select an ASTM A992 W-shape beam with a simple span of 35 feet. Limit the member to a maximum nominal depth of 18 in. Limit the live load deflection to \( L/360 \). The nominal loads are a uniform dead load of 0.45 kip/ft and a uniform live load of 0.75 kip/ft. Assume the beam is continuously braced. Use ASD of the Unified Design method.

![Beam Loading & Bracing Diagram (full lateral support)](image)

Solution:

Material Properties:
ASTM A992 \( F_y = 50 \text{ ksi} \) \( F_u = 65 \text{ ksi} \)

1. The unbraced length is 0 because it says it is fully braced.

2. Find the maximum shear and moment from unfactored loads: \( w_a = 0.450 \text{ kft} + 0.750 \text{ kft} = 1.20 \text{ kft} \)

\[
V_a = 1.20 \text{ kft}(35 \text{ ft})/2 = 21 \text{ k}
\]

\[
M_a = 1.20 \text{ kft}(35 \text{ ft})^2/8 = 184 \text{ k-ft}
\]

If \( M_a \leq M_{\text{max}}/\Omega \), the maximum moment for design is \( M_{\text{max}} \):

\[
M_{\text{max}} = 184 \text{ k-ft}
\]

3. Find \( Z_{\text{reqd}} \):

\[
Z_{\text{reqd}} \geq M_{\text{max}}/F_y = M_{\text{max}}(1.67)(12 \text{ in/ft})/50 \text{ ksi} = 73.75 \text{ in}^3 \quad (F_y \text{ is the limit stress when fully braced})
\]

4. Choose a trial section, and also limit the depth to 18 in as instructed:

W18 x 40 has a plastic section modulus of 78.4 in\(^3\) and is the most light weight (as indicated by the bold text) in Table 9.1

Include the self weight in the maximum values:

\[
w_{a\text{-adjusted}} = 1.20 \text{ kft} + 0.04 \text{ kft} = 1.24 \text{ kft}
\]

\[
V_{a\text{-adjusted}} = 1.24 \text{ kft}(35 \text{ ft})/2 = 21.7 \text{ k}
\]

\[
M_{a\text{-adjusted}} = 1.24 \text{ kft}(35 \text{ ft})^3/8 = 189.9 \text{ k-ft}
\]

\[
Z_{\text{reqd}} \geq 189.9 \text{ k-ft}(1.67)(12 \text{ in/ft})/50 \text{ ksi} = 76.11 \text{ in}^3 \quad \text{And the Z we have (78.4) is larger than the Z we need (76.11), so OK.}
\]

6. Evaluate shear (is \( V_a \leq V_u/\Omega \)): \( A_w = d t_w \) so look up section properties for W18 x 40: \( d = 17.90 \text{ in} \) and \( t_w = 0.315 \text{ in} \)

\[
V_u/\Omega = 0.6F_y A_w/\Omega = 0.6(50 \text{ ksi})(17.90 \text{ in})(0.315 \text{ in})/1.5 = 112.8 \text{ k} \quad \text{which is much larger than 21.7 k, so OK.}
\]

9. Evaluate the deflection with respect to the limit stated of \( L/360 \) for the live load. (If we knew the total load limit we would check that as well). The moment of inertia for the W18 x 40 is needed. \( I_x = 612 \text{ in}^4 \)

\[
\Delta \text{ live load limit} = 35 \text{ ft}(12 \text{ in/ft})/360 = 1.17 \text{ in}
\]

\[
\Delta = 5wL^4/384EI = 5(0.75 \text{ kft})(35 \text{ ft})^4(12 \text{ in/ft})^3/384(29 \times 10^3 \text{ ksi})(612 \text{ in}^4) = 1.42 \text{ in!} \quad \text{This is TOO BIG (not less than the limit.}
\]

Find the moment of inertia needed:

\[
I_{\text{reqd}} \geq \Delta_{\text{too big}}/(\Delta_{\text{limit}}) = 1.42 \text{ in}(612 \text{ in}^4)/(1.17 \text{ in}) = 742.8 \text{ in}^4
\]

From Table 9.1, a W16 x 45 is larger (by Z), but not the most light weight (efficient), as is W10 x 68, W14 x 53, W18 x 46, (W21 x 44 is too deep) and W18 x 50 is bolded (efficient). (Now look up I's). (In order: \( I_x = 586, 394, 541, 712 \) and \( 800 \text{ in}^4 \))

Choose a W18 x 50.
Example 4
A steel beam with a 20 ft span is designed to be simply supported at the ends on columns and to carry a floor system made with open-web steel joists at 4 ft on center. The joists span 28 feet and frame into the beam from one side only and have a self weight of 8.5 lb/ft. Use A992 (grade 50) steel and select the most economical wide-flange section for the beam. Floor loads are 50 psf LL and 14.5 psf DL.
Example 5
Select a A992 W shape flexural member \( (F_y = 50 \text{ ksi}, F_u = 65 \text{ ksi}) \) for a beam with distributed loads of 825 lb/ft (dead) and 1300 lb/ft (live) and a live point load at midspan of 3 k using the Available Moment tables. The beam is simply supported, 20 feet long, and braced at the ends and midpoint only \( (L_b = 10 \text{ ft}) \). The beam is a roof beam for an institution without plaster ceilings. (LRFD)

\[ S_{1.6}(3k) = 4.8k \]

\[ w = 1.2(825 \text{ lb/ft}) + 1.6(1300 \text{ lb/ft}) = 3.07k/ft \]

\[ S^{\text{ SOLUTION:}} \]

To use the Available Moment tables, the maximum moment required is plotted against the unbraced length. The first solid line with capacity or unbraced length above what is needed is the most economical.

**DESIGN LOADS** (load factors applied on figure):

\[ M_v = \frac{wl^2}{2} + Pb = \frac{3.07 F_y (20 \text{ ft})^2}{2} + 4.8k(10 \text{ ft}) = 662k-ft \]

\[ V_v = wI + P = 3.07 F_u (20 \text{ ft}) + 4.8k = 66.2k \]

Plotting 662 k-ft vs. 10 ft lands just on the capacity of the W21x83, but it is dashed (and not the most economical) AND we need to consider the contribution of self weight to the total moment. Choose a trial section of W24 x 76. Include the new dead load:

\[ \frac{M^*_v \text{ adjusted}}{10 \text{ ft}} = \frac{662k-ft + 1.2(76lb/ft)(20\text{ ft})^2}{2(1000 lb/ft)} = 680.2k-ft \]

\[ V^*_v \text{ adjusted} = 66.2k + 1.2(0.076lb/ft)(20 \text{ ft}) = 68.0k \]

Replot 680.2 k-ft vs. 10 ft, which lands above the capacity of the W21x83. We can’t look up because the chart ends, but we can look for that capacity with a longer unbraced length. This leads us to a W24 x 84 as the most economical. (With the additional self weight of 84 - 76 lb/ft = 8 lb/ft, the increase in the factored moment is only 1.92 k-ft; therefore, it is still OK.)

Evaluate the shear capacity:

\[ \phi V_v = 0.6 F_y A_v = 1.0(0.6)(50 \text{ ksi})(24.10 \text{ in}) = 338.4k \text{ lbs} \]

so yes, \( 68k \leq 338.4k \quad \text{OK} \)

Evaluate the deflection with respect to the limits of L/240 for live (unfactored) load and L/180 for total (unfactored) load:

\[ \Delta_{\text{total}} = \frac{Pb^2(3l-b)}{6EI} + \frac{wL^4}{24EI} = \frac{3k(10 \text{ ft})^2(3 \cdot 20 - 10 \text{ ft})}{6(30\times10^3 \text{ ksis})2370in^3} = 0.06 + 0.36 = 0.42\text{ in} \]

\[ \Delta_{\text{limit}} = \frac{2.209k}{24(30\times10^3 \text{ ksis})2370in^3} = 0.06 \text{ in} \]

So, \( \Delta_{\text{total}} \leq \Delta_{\text{limit}} \) and \( \Delta_{\text{total}} \leq \Delta_{\text{limit}} \):

\[ 0.06 \text{ in} \leq 1 \text{ in.} \quad \text{and} \quad 0.42 \text{ in} \leq 1.33 \text{ in.} \]

(This section is so big to accommodate the large bending moment at the cantilever support that it deflects very little.)

\[ \therefore \text{FINAL SELECTION IS W24x84} \]
Example 6
A floor is to be supported by trusses spaced at 5 ft. on center and spanning 60 ft. having a dead load of 53 lb/ft$^2$ and a live load of 100 lb/ft$^2$. With 3 ft.-long panel points, the depth is assumed to be 3 ft with a span-to-depth ratio of 20. With 6 ft.-long panel points, the depth is assumed to be 6 ft with a span-to-depth ratio of 10. Determine the maximum force in a horizontal chord and the maximum force in a web member. Assume a self weight of 40 lb/ft.

<table>
<thead>
<tr>
<th>Truss</th>
<th>Area loads</th>
<th>tributary widths</th>
<th>Floor loads</th>
<th>Factored loads</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$W_{\text{dead}}$</td>
<td>$W_{\text{live}}$</td>
<td>$P_{\text{dead}}$</td>
<td>$P_{\text{live}}$</td>
</tr>
<tr>
<td></td>
<td>(#/ft$^2$)</td>
<td>(#/ft$^2$)</td>
<td>(ft)</td>
<td>(K)</td>
</tr>
<tr>
<td>3 ft deep</td>
<td>53</td>
<td>0.053</td>
<td>100</td>
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<tr>
<td>6 ft deep</td>
<td>53</td>
<td>0.053</td>
<td>100</td>
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</tbody>
</table>

**NOTE** – end panels only have half the tributary width of interior panels

**FBD 1** for 3 ft deep truss

**FBD 2** of cut just to the left of midspan

**FBD 3** of cut just to right of left support

**FBD 4** for 6 ft deep truss

**FBD 5** of cut just to the left of midspan

**FBD 6** of cut just to right of left support

**FBD 1**

Maximum web force will be in the end diagonal (just like maximum shear in a beam)

$$\Sigma F_Y = 10P_1 - 0.5P_1 - F_{AB} \cdot \sin45^\circ = 0$$

$$F_{AB} = 9.5P_1 / \sin45^\circ = 9.5(3.49 k) / 0.707 = 46.9 k$$

**FBD 2**

Maximum chord force (top or bottom) will be at midspan

$$\Sigma M_G = 9.5P_1(30^\circ) - P_1(27^\circ) - P_1(24^\circ) - P_1(21^\circ) - P_1(18^\circ) - P_1(15^\circ) - P_1(12^\circ) - P_1(9^\circ) - P_1(6^\circ) - P_1(3^\circ) - T_1(3^\circ) = 0$$

$$T_1 = P_1(150^\circ) / 3^\circ = 3.49 k(50) = 174.5 k$$

$$\Sigma F_Y = 10P_1 - 9.5P_1 - D_1 \cdot \sin45^\circ = 0$$

$$D_1 = 0.5(3.49 k) / 0.707 = 2.5 k \text{ (minimum near midspan)}$$

$$\Sigma F_x = -C_1 + T_1 + D_1 \cdot \cos45^\circ = 0$$

$$C_1 = 176.2 k$$

**FBD 3**

Maximum web force will be in the end diagonal

$$\Sigma F_Y = 5P_2 - 0.5P_2 - F_{AB} \cdot \sin45^\circ = 0$$

$$F_{AB} = 4.5P_2 / \sin45^\circ = 4.5(7 k) / 0.707 = 44.5 k$$

**FBD 4**

Maximum chord (top or bottom) force will be at midspan

$$\Sigma M_G = 4.5P_2(30^\circ) - P_2(27^\circ) - P_2(24^\circ) - P_2(21^\circ) - P_2(18^\circ) - P_2(15^\circ) - P_2(12^\circ) - P_2(9^\circ) - P_2(6^\circ) - T_2(3^\circ) = 0$$

$$T_2 = P_2(75^\circ) / 6^\circ = 7 k(12.5) = 87.5 k$$

$$\Sigma F_Y = 5P_2 - 4.5P_1 - D_2 \cdot \sin45^\circ = 0$$

$$D_2 = 0.5(7 k) / 0.707 = 4.9 k \text{ (minimum near midspan)}$$

$$\Sigma F_x = -C_2 + T_2 + D_2 \cdot \cos45^\circ = 0$$

$$C_2 = 92.4 k$$
Example 7 (pg 339)

**Example 14.** Open web steel joists are to be used for a floor with a unit live load of 75 psf [3.59 kN/m²] and a unit dead load of 40 psf [1.91 kN/m²] (not including the joist weight) on a span of 30 ft [9.15 m]. Joists are 2 ft [0.61 m] on center, and deflection is limited to 1/240 of the span under total load and 1/360 of the span under live load only. Determine the lightest possible joist and the lightest joist of least depth possible.

---

**TABLE 9.5 (Continued)**

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<td>(180)</td>
<td>(219)</td>
<td>(287)</td>
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</tbody>
</table>

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Example 8 (pg 353)

**Example 3.** Figure 10.5a shows an elevation of the steel framing at the location of an exterior wall. The column is laterally restrained but rotationally free at the top and bottom in both directions. (The end condition is as shown for Case (d) in Figure 10.3.) With respect to the x-axis of the section, the column is laterally braced for its full height. However, the existence of the horizontal framing in the wall plane provides lateral tracing with respect to the y-axis of the section; thus, the buckling of the column in this direction takes the form shown in Figure 10.5b. If the column is a W 12 × 53 of A36 steel, *L*₁ is 30 ft [9.15 m], and *L*₂ is 18 ft [5.49 m], what is the maximum factored compression load?
Example 9 (pg 361)

Example 6. Using Table 10.4, select a standard weight steel pipe to carry a dead load of 15 kips [67 kN] and a live load of 26 kips [116 kN] if the unbraced height is 12 ft [3.66 m].

SOLUTION

DESIGN LOADS (shown on figure):
Axial load = 1.2(0.25)(350k)+1.6(0.75)(350k)=525k
Moment at joint = 1.2(0.25)(60 k) + 1.6(0.75)(60 k) = 90 k-ft

Determine column capacity and fraction to choose the appropriate interaction equation:

\[ \frac{KL}{r_y} = \frac{15\text{ ft}(12\gamma_p)}{6.96\text{in}} = 25.9 \quad \text{and} \quad \frac{KL}{r_y} = \frac{15\text{ ft}(12\gamma_p)}{2.46\text{in}} = 73 \quad \text{(governs)} \]

\[ P_c = \phi_c P_a = \phi_c F_y A_y = (30.5\text{ksi})(9.7\text{in}^2) = 600.85k \]

\[ \frac{P}{P_c} = \frac{525k}{600.85k} = 0.87 > 0.2 \quad \text{so use} \quad \frac{P}{P_c} = \frac{8}{9} \left( \frac{M_m}{M_m} + \frac{M_w}{M_w} \right) \leq 1.0 \]

There is no bending about the y axis, so that term will not have any values.

Determine the bending moment capacity in the x direction:

The unbraced length to use the full plastic moment (L_p) is listed as 8.69 ft, and we are over that so we don’t want to determine it from formula, we can find the beam in the Available Moment vs. Unbraced Length tables. The value of \( \phi M_u \) at \( L_p = 15 \text{ ft} \) is 422 k-ft.

Determine the magnification factor when \( M_1 = 0 \), \( M_2 = 90 \text{ k-ft} \):

\[ C_n = 0.6 - 0.4 \frac{M_2}{M_1} = 0.6 - 0.4 \frac{90}{90} = 0.6 \leq 1.0 \]

\[ B_t = \frac{C_n}{1 - (P_c/P_a)} = \frac{0.6}{1 - (525k/8695.4k)} = 0.64 \leq 1.0 \]

\[ P_{el} = \frac{\pi^2 E I}{(K L / r_y)^2} = \frac{\pi^2 (30 \times 10^3 \text{ksi})(9.7\text{in}^2)}{(25.9)^2} = 8.695.4k \]

Finally, determine the interaction value:

\[ \frac{P}{\phi_c P_a} + \frac{8}{9} \left( \frac{M_m}{\phi_c M_m} + \frac{M_w}{\phi_c M_w} \right) = 0.87 + \frac{8}{9} \left( \frac{90}{422} \right) = 1.06 \leq 1.0 \]

This is NOT OK. (and outside error tolerance). The section should be larger.

Example 10

Investigate the acceptability of a W16 x 67 used as a beam-column under the unfactored loading shown in the figure. It is A992 steel (\( F_y = 50 \text{ ksi} \)). Assume 25% of the load is dead load with 75% live load.

SOLUTION:

DESIGN LOADS (shown on figure):
Axial load = 1.2(0.25)(350k)+1.6(0.75)(350k)=525k
Moment at joint = 1.2(0.25)(60 k) + 1.6(0.75)(60 k) = 90 k-ft

Determine column capacity and fraction to choose the appropriate interaction equation:

\[ \frac{KL}{r_y} = \frac{15\text{ ft}(12\gamma_p)}{6.96\text{in}} = 25.9 \quad \text{and} \quad \frac{KL}{r_y} = \frac{15\text{ ft}(12\gamma_p)}{2.46\text{in}} = 73 \quad \text{(governs)} \]

\[ P_c = \phi_c P_a = \phi_c F_y A_y = (30.5\text{ksi})(9.7\text{in}^2) = 600.85k \]

\[ \frac{P}{P_c} = \frac{525k}{600.85k} = 0.87 > 0.2 \quad \text{so use} \quad \frac{P}{P_c} = \frac{8}{9} \left( \frac{M_m}{M_m} + \frac{M_w}{M_w} \right) \leq 1.0 \]

There is no bending about the y axis, so that term will not have any values.

Determine the bending moment capacity in the x direction:

The unbraced length to use the full plastic moment (L_p) is listed as 8.69 ft, and we are over that so we don’t want to determine it from formula, we can find the beam in the Available Moment vs. Unbraced Length tables. The value of \( \phi M_u \) at \( L_p = 15 \text{ ft} \) is 422 k-ft.

Determine the magnification factor when \( M_1 = 0 \), \( M_2 = 90 \text{ k-ft} \):

\[ C_n = 0.6 - 0.4 \frac{M_2}{M_1} = 0.6 - 0.4 \frac{90}{90} = 0.6 \leq 1.0 \]

\[ B_t = \frac{C_n}{1 - (P_c/P_a)} = \frac{0.6}{1 - (525k/8695.4k)} = 0.64 \leq 1.0 \]

\[ P_{el} = \frac{\pi^2 E I}{(K L / r_y)^2} = \frac{\pi^2 (30 \times 10^3 \text{ksi})(9.7\text{in}^2)}{(25.9)^2} = 8.695.4k \]

Finally, determine the interaction value:

\[ \frac{P}{\phi_c P_a} + \frac{8}{9} \left( \frac{M_m}{\phi_c M_m} + \frac{M_w}{\phi_c M_w} \right) = 0.87 + \frac{8}{9} \left( \frac{90}{422} \right) = 1.06 \leq 1.0 \]

This is NOT OK. (and outside error tolerance). The section should be larger.
**Example 11 (pg 371)**

*Example 7.* It is desired to use a 10-in. W shape for a column in a situation such as that shown in Figure 10.7. The factored axial load from above on the column is 175 kips [778 kN], and the factored beam load at the column face is 35 kips [156 kN]. The column has an unbraced height of 16 ft [4.88 m] and a K factor of 1.0. Select a trial section for the column. Evaluate the trial W10x45 chosen in the text of A36 steel with \( d = 10.1 \) in and \( f_y M_n = 133.4 \) k-ft (16 ft unbraced length).

---

**Example 12**

**10.5** Using the AISC framed beam connection bolt shear in Table 7-1, determine the shear adequacy of the connection shown in Figure 10.28. What thickness and angle length are required? Also determine the bearing capacity of the wide flange sections.

Factored end beam reaction = 90 k.

---

*Figure 10.28 Typical beam-column connection.*
Example 13

10.2 The butt splice shown in Figure 10.22 uses two 8 × 3/8” plates to “sandwich” in the 8 × 1/2” plates being joined. Four 3/8” φ A325-SC bolts are used on both sides of the splice. Assuming A36 steel and standard round holes, determine the allowable capacity of the connection.

SOLUTION:

Shear, bearing and net tension will be checked to determine the critical conditions that govern the capacity of the connection. (The edge distance to the holes is presumed to be adequate.)

**Shear:** Using the AISC available shear in Table 7-3 (Group A):

\[ \phi R_n = 26.4 \text{k/bolt} \times 4 \text{ bolts} = 105.6 \text{k} \]

**Bearing:** Using the AISC available bearing in Table 7-4:

There are 4 bolts bearing on the center (1/2”) plate, while there are 4 bolts bearing on a total width of two sandwich plates (3/4” total). The thinner bearing width will govern.

Assume 3 in. spacing (center to center) of bolts. For A36 steel, \( F_u = 58 \text{ ksi} \).

\[ \phi R_n = 91.4 \text{k/bolt/in.} \times 0.5 \text{ in.} \times 4 \text{ bolts} = 182.8 \text{k} \]

**Tension:** The center plate is critical, again, because its thickness is less than the combined thicknesses of the two outer plates. We must consider tension yielding and tension rupture:

\[ \phi R_n = \phi F_y A_g \] and \[ \phi R_n = \phi F_u A_e \] where \( A_e = A_{\text{net}} U \)

\[ A_g = 8 \text{ in.} \times \frac{1}{2} \text{ in.} = 4 \text{ in}^2 \]

The holes are considered 1/8 in. larger than the nominal bolt diameter = 7/8 + 1/8 = 1 in.

\[ A_v = (8 \text{ in.} - 2 \text{ holes x 1 in.}) \times \frac{1}{2} \text{ in.} = 3 \text{ in}^2 \]

The whole cross section sees tension, so the shear lag factor \( U = 1 \)

\[ \phi F_y A_g = 0.9 \times 36 \text{ ksi x 4 in}^2 = 129.6 \text{k} \]

\[ \phi F_u A_e = 0.75 \times 58 \text{ ksi x (1) x 3 in}^2 = 130.5 \text{k} \]

**Block Shear Rupture:** It is possible for the center plate to rip away from the sandwich plates leaving the block (shown hatched) behind:

\[ \phi R_n = \phi (0.6F_y A_{uv} + U_{bs}F_u A_{vt}) \leq \phi (0.6F_y A_{gv} + U_{bs}F_u A_{nt}) \]

where \( A_{uv} \) is the area resisting shear, \( A_{vt} \) is the area resisting tension, \( A_{gv} \) is the gross area resisting shear, and \( U_{bs} = 1 \) when the tensile stress is uniform.

\[ A_{gv} = (4 \times 2 \text{ in.}) \times \frac{1}{2} \text{ in.} = 3 \text{ in}^2 \]

\[ A_{uv} = A_{gv} - 1 \frac{1}{2} \text{ holes area} = 3 \text{ in}^2 - 1.5 \times 1 \text{ in.} \times \frac{1}{2} \text{ in.} = 2.25 \text{ in}^2 \]

\[ A_{vt} = 3.5 \text{ in.} \times t - 1 \text{ holes} = 3.5 \text{ in.} \times \frac{1}{2} \text{ in.} - 1 \times 1 \text{ in.} \times \frac{1}{2} \text{ in.} = 1.25 \text{ in}^2 \]

\[ \phi (0.6F_y A_{uv} + U_{bs}F_u A_{vt}) = 0.75 \times (0.6 \times 58 \text{ ksi x 2.25 in}^2 + 1 \times 58 \text{ ksi x 1.25 in}^2) = 113.1 \text{k} \]

\[ \phi (0.6F_y A_{gv} + U_{bs}F_u A_{nt}) = 0.75 \times (0.6 \times 36 \text{ ksi x 3 in}^2 + 1 \times 58 \text{ ksi x 1.25 in}^2) = 103.0 \text{k} \]

The maximum connection capacity is governed by block shear rupture.

\[ \phi R_n = 103.0 \text{k} \]
Example 14

10.9 Determine the maximum load carrying capacity of this lap joint, assuming A36 steel with E60XX electrodes.

Example 15

10.7 Determine the capacity of the connection in Figure 10.44 assuming A36 steel with E70XX electrodes.

Solution:

Capacity of weld:

For a 3/16" fillet weld, $\phi S = 6.96$ k/in

Weld length = 22"

Weld capacity = 22" x 6.96 k/in = 153.1 k

Capacity of plate:

$P_n = \phi F_y A_g$  $\phi = 0.9$

Plate capacity = 0.9 x 36 k/in² x 3/8" x 6" = 72.9 k

: Plate capacity governs, $P_{allow} = 72.9$ k

The weld size used is obviously too strong. What size, then, can the weld be reduced to so that the weld strength is more compatible to the plate capacity? To make the weld capacity = plate capacity:

$22" \times (\text{weld capacity per in.}) = 72.9$ k

Weld capacity per inch = $\frac{72.9}{22\text{in.}} = 3.31$ k/in.

From Available Strength table, use 3/16" weld ($\phi S = 4.18$ k/in.)

Minimum size fillet = 3/16" based on a 3/8" thick plate.
Example 16

The steel used in the connection and beams is A992 with $F_y = 50$ ksi, and $F_u = 65$ ksi. Using A490-N bolt material, determine the maximum capacity of the connection based on shear in the bolts, bearing in all materials and pick the number of bolts and angle length (not staggered). Use A36 steel for the angles.

W21x93: $d = 21.62$ in, $t_w = 0.58$ in, $t_f = 0.93$ in
W10x54: $t_f = 0.615$ in

SOLUTION:

The maximum length the angles can be depends on how it fits between the top and bottom flange with some clearance allowed for the fillet to the flange, and getting an air wrench in to tighten the bolts. This example uses 1” of clearance:

Available length = beam depth – both flange thicknesses – 1” clearance at top & 1” at bottom
= 21.62 in – 2(0.93 in) – 2(1 in) = 17.76 in.

With the spaced at 3 in. and 1 ¼ in. end lengths (each end), the maximum number of bolts can be determined:

Available length ≥ 1.25 in. + 1.25 in. + 3 in. x (number of bolts – 1)
number of bolts ≤ (17.76 in – 2.5 in. - (-3 in.))/3 in. = 6.1, so 6 bolts.

It is helpful to have the All-bolted Double-Angle Connection Tables 10-1. They are available for ¾”, 7/8”, and 1” bolt diameters and list angle thicknesses of ¼”, 5/16”, 3/8”, and ½”. Increasing the angle thickness is likely to increase the angle strength, although the limit states include shear yielding of the angles, shear rupture of the angles, and block shear rupture of the angles.

For these diameters, the available shear (double) from Table 7-1 for 6 bolts is (6)45.1 k/bolt = 270.6 kips, (6)61.3 k/bolt = 367.8 kips, and (6)80.1 k/bolt = 480.6 kips.
Tables 10-1 (not all provided here) list a bolt and angle available strength of 271 kips for the ¾” bolts, 296 kips for the 7/8" bolts, and 281 kips for the 1” bolts. It appears that increasing the bolt diameter to 1” will not gain additional load. Use 7/8” bolts.

ϕRn = 367.8 kips for double shear of 7/8” bolts  
ϕRn = 296 kips for limit state in angles

We also need to evaluate bearing of bolts on the beam web, and column flange where there are bolt holes. Table 7-4 provides available bearing strength for the material type, bolt diameter, hole type, and spacing per inch of material thicknesses.

a) Bearing for beam web: There are 6 bolt holes through the beam web. This is typically the critical bearing limit value because there are two angle legs that resist bolt bearing and twice as many bolt holes to the column. The material is A992 ( Fu = 65 ksi), 0.58” thick, with 7/8” bolt diameters at 3 in. spacing.

ϕRn = 6 bolts * (102 k/bolt/inch) * (0.58 in) = 355.0 kips

b) Bearing for column flange: There are 12 bolt holes through the column. The material is A992 ( Fu = 65 ksi), 0.615” thick, with 1” bolt diameters.

ϕRn = 12 bolts * (102 k/bolt/inch) * (0.615 in) = 752.8 kips

Although, the bearing in the beam web is the smallest at 355 kips, with the shear on the bolts even smaller at 324.6 kips, the maximum capacity for the simple-shear connector is 296 kips limited by the critical capacity of the angles.
Beam Design Flow Chart

1. Collect data: L, ϕ, γ, Δ_limit; find beam charts for load cases and Δ_actual equations.

   ASD: Allowable Stress Design
   LRFD: Load and Resistance Factor Design

2. Collect data: F_y, F_u, and safety factors Ω.

   Find V_max & M_max from constructing diagrams or using beam chart formulas.

3. Find Z_{req}'d and pick a section from a table with Z_x greater or equal to Z_{req}'d.

   Determine ω_{self wt} (last number in name) or calculate ω_{self wt} using A found. Find M_{max-adj} & V_{max-adj}.

4. No: Calculate Z_{req}'d-adj using M_{max-adj}.

   Is Z_{picked} ≥ Z_{req}'d-adj?

5. Yes: Is V_{max-adj} ≤ (0.6F_{yweb}A_{web})/Ω?

   No: Is V_u ≤ φ(V_{max-adj})? Yes: pick a new section with a larger web area.

   Yes: Calculate Δ_max (no load factors!) using superpositioning and beam chart equations with the I_x for the section.

6. Is Δ_max ≤ Δ_limit? This may be both the limit for live load deflection and total load deflection.

   No: pick a section with a larger I_x.

   Yes: I_{req}'d ≥ Δ_{max-big}/Δ_{limit} I_{trial}

   Yes: (DONE)
## Listing of W Shapes in Descending order of Z\textsubscript{x} for Beam Design

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<th>Z\textsubscript{x} – US (in.\textsuperscript{3})</th>
<th>I\textsubscript{x} – US (in.\textsuperscript{4})</th>
<th>Section</th>
<th>I\textsubscript{x} – SI (10\textsuperscript{6} mm\textsuperscript{4})</th>
<th>Z\textsubscript{x} – SI (10\textsuperscript{6} mm\textsuperscript{3})</th>
<th>Z\textsubscript{x} – US (in.\textsuperscript{3})</th>
<th>I\textsubscript{x} – US (in.\textsuperscript{4})</th>
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<td>73</td>
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<td>113</td>
<td>17.7</td>
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<td>154</td>
<td>9.53</td>
<td>194</td>
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</tr>
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<td>75</td>
<td>29.8</td>
<td>115</td>
<td>17.1</td>
<td>155</td>
<td>9.40</td>
<td>195</td>
<td>5.94</td>
</tr>
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<td>76</td>
<td>29.5</td>
<td>116</td>
<td>16.8</td>
<td>156</td>
<td>9.28</td>
<td>196</td>
<td>5.88</td>
</tr>
<tr>
<td>37</td>
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<td>77</td>
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<td>117</td>
<td>16.5</td>
<td>157</td>
<td>9.17</td>
<td>197</td>
<td>5.82</td>
</tr>
<tr>
<td>38</td>
<td>40.5</td>
<td>78</td>
<td>28.8</td>
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<td>16.2</td>
<td>158</td>
<td>9.05</td>
<td>198</td>
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</tr>
<tr>
<td>39</td>
<td>40.3</td>
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<td>119</td>
<td>16.0</td>
<td>159</td>
<td>8.94</td>
<td>199</td>
<td>5.70</td>
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<td>80</td>
<td>28.2</td>
<td>120</td>
<td>15.7</td>
<td>160</td>
<td>8.82</td>
<td>200</td>
<td>5.65</td>
</tr>
</tbody>
</table>
### Bolt Strength Tables

#### Table 7-1
**Available Shear Strength of Bolts, kips**

<table>
<thead>
<tr>
<th>Nominal Bolt Diameter, $d$, in.</th>
<th>$\frac{f_{y}}{\Omega}$</th>
<th>$\frac{f_{y}}{\Omega}$</th>
<th>$\frac{f_{y}}{\Omega}$</th>
<th>$\frac{f_{y}}{\Omega}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.307</td>
<td>0.442</td>
<td>0.601</td>
<td>0.785</td>
<td></td>
</tr>
<tr>
<td><strong>ASTM Desig.</strong></td>
<td><strong>Thread Cond.</strong></td>
<td><strong>$P_{u}$ (kips)</strong></td>
<td><strong>$P_{r}$ (kips)</strong></td>
<td><strong>Loading</strong></td>
</tr>
<tr>
<td><strong>ASD</strong></td>
<td><strong>LRFD</strong></td>
<td><strong>ASD</strong></td>
<td><strong>LRFD</strong></td>
<td><strong>ASD</strong></td>
</tr>
<tr>
<td><strong>Group A</strong></td>
<td>N</td>
<td>27.0</td>
<td>40.5</td>
<td>S</td>
</tr>
<tr>
<td></td>
<td>X</td>
<td>34.0</td>
<td>51.0</td>
<td>S</td>
</tr>
<tr>
<td><strong>Group B</strong></td>
<td>N</td>
<td>34.0</td>
<td>51.0</td>
<td>S</td>
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<tr>
<td></td>
<td>X</td>
<td>42.0</td>
<td>63.0</td>
<td>S</td>
</tr>
<tr>
<td><strong>A307</strong></td>
<td>–</td>
<td>13.5</td>
<td>20.3</td>
<td>S</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Nominal Bolt Diameter, $d$, in.</th>
<th>$f_{y}$</th>
<th>$f_{y}$</th>
<th>$f_{y}$</th>
<th>$f_{y}$</th>
</tr>
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<tbody>
<tr>
<td>0.994</td>
<td>1.23</td>
<td>1.48</td>
<td>1.77</td>
<td></td>
</tr>
<tr>
<td><strong>ASTM Desig.</strong></td>
<td><strong>Thread Cond.</strong></td>
<td><strong>$P_{u}$ (kips)</strong></td>
<td><strong>$P_{r}$ (kips)</strong></td>
<td><strong>Loading</strong></td>
</tr>
<tr>
<td><strong>ASD</strong></td>
<td><strong>LRFD</strong></td>
<td><strong>ASD</strong></td>
<td><strong>LRFD</strong></td>
<td><strong>ASD</strong></td>
</tr>
<tr>
<td><strong>Group A</strong></td>
<td>N</td>
<td>27.0</td>
<td>40.5</td>
<td>S</td>
</tr>
<tr>
<td></td>
<td>X</td>
<td>34.0</td>
<td>51.0</td>
<td>S</td>
</tr>
<tr>
<td><strong>Group B</strong></td>
<td>N</td>
<td>34.0</td>
<td>51.0</td>
<td>S</td>
</tr>
<tr>
<td></td>
<td>X</td>
<td>42.0</td>
<td>63.0</td>
<td>S</td>
</tr>
<tr>
<td><strong>A307</strong></td>
<td>–</td>
<td>13.5</td>
<td>20.3</td>
<td>S</td>
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</tbody>
</table>

**ASD** | **LRFD**
---

For end loaded connections greater than 36 in., see ASD Specification Table 32.2 footnote b.

$\Omega = 2.00$  $\sigma = 0.75$

#### Table 7-2
**Available Tensile Strength of Bolts, kips**

<table>
<thead>
<tr>
<th>Nominal Bolt Diameter, $d$, in.</th>
<th>$f_{y}$</th>
<th>$f_{y}$</th>
<th>$f_{y}$</th>
<th>$f_{y}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.307</td>
<td>0.442</td>
<td>0.601</td>
<td>0.785</td>
<td></td>
</tr>
<tr>
<td><strong>ASTM Desig.</strong></td>
<td><strong>$P_{u}$ (kips)</strong></td>
<td><strong>$P_{r}$ (kips)</strong></td>
<td><strong>Loading</strong></td>
<td><strong>$f_{y}$</strong></td>
</tr>
<tr>
<td><strong>ASD</strong></td>
<td><strong>LRFD</strong></td>
<td><strong>ASD</strong></td>
<td><strong>LRFD</strong></td>
<td><strong>ASD</strong></td>
</tr>
<tr>
<td><strong>Group A</strong></td>
<td>A307</td>
<td>45.0</td>
<td>67.5</td>
<td>13.8</td>
</tr>
<tr>
<td></td>
<td>Group B</td>
<td>56.5</td>
<td>84.9</td>
<td>17.3</td>
</tr>
<tr>
<td></td>
<td>A307</td>
<td>22.5</td>
<td>33.8</td>
<td>6.90</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Nominal Bolt Diameter, $d$, in.</th>
<th>$f_{y}$</th>
<th>$f_{y}$</th>
<th>$f_{y}$</th>
<th>$f_{y}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.994</td>
<td>1.23</td>
<td>1.48</td>
<td>1.77</td>
<td></td>
</tr>
<tr>
<td><strong>ASTM Desig.</strong></td>
<td><strong>$P_{u}$ (kips)</strong></td>
<td><strong>$P_{r}$ (kips)</strong></td>
<td><strong>Loading</strong></td>
<td><strong>$f_{y}$</strong></td>
</tr>
<tr>
<td><strong>ASD</strong></td>
<td><strong>LRFD</strong></td>
<td><strong>ASD</strong></td>
<td><strong>LRFD</strong></td>
<td><strong>ASD</strong></td>
</tr>
<tr>
<td><strong>Group A</strong></td>
<td>A307</td>
<td>45.0</td>
<td>67.5</td>
<td>44.7</td>
</tr>
<tr>
<td></td>
<td>Group B</td>
<td>56.5</td>
<td>84.9</td>
<td>56.2</td>
</tr>
<tr>
<td></td>
<td>A307</td>
<td>22.5</td>
<td>33.8</td>
<td>22.4</td>
</tr>
</tbody>
</table>

**ASD** | **LRFD**
---

$\Omega = 2.00$  $\sigma = 0.75$
<table>
<thead>
<tr>
<th>Hole Type</th>
<th>Loading</th>
<th>1/3</th>
<th>3/4</th>
<th>Minimum Group A Bolt Pretension, kips</th>
<th>Nominal Diameter, d, in.</th>
<th>1/4</th>
<th>1/2</th>
<th>Group B Bolts</th>
</tr>
</thead>
<tbody>
<tr>
<td>A325/A325M</td>
<td>4.29</td>
<td>6.38</td>
<td>9.49</td>
<td>12.9</td>
<td>19.0</td>
<td>26.4</td>
<td>39.1</td>
<td>4.64</td>
</tr>
<tr>
<td>A354 Grade BC</td>
<td>4.82</td>
<td>6.99</td>
<td>10.1</td>
<td>14.2</td>
<td>20.3</td>
<td>28.5</td>
<td>41.7</td>
<td>5.10</td>
</tr>
<tr>
<td>A449</td>
<td>5.00</td>
<td>7.14</td>
<td>11.3</td>
<td>16.5</td>
<td>23.6</td>
<td>32.8</td>
<td>46.0</td>
<td>5.28</td>
</tr>
<tr>
<td>A490, A490M</td>
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<td>11.6</td>
<td>17.7</td>
<td>24.8</td>
<td>34.0</td>
<td>48.2</td>
<td>5.46</td>
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<tr>
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<td>5.37</td>
<td>7.52</td>
<td>12.0</td>
<td>18.0</td>
<td>26.0</td>
<td>35.1</td>
<td>49.3</td>
<td>5.65</td>
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<tr>
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<td>27.1</td>
<td>36.2</td>
<td>50.6</td>
<td>5.84</td>
</tr>
</tbody>
</table>

### Notes
- **Table 7-3 (continued)**
- **Available Shear Strength, kips**
  - Class A Faying Surface, $\mu = 0.30$
- **Group A Bolts**
  - A255, A325M
  - A354 Grade BC
  - A449
- **Group B Bolts**
  - A490, A490M
- **Stock Sizes**
  - D = 1.00
  - F = 0.85
  - S = 0.65
  - M = 0.50

### Definitions
- **STD** (standard hole)
- **SSS** (short-staged hole, parallel to the line of force)
- **SSJ** (short-staged hole, perpendicular to the line of force)
- **LSL** (long-sized hole, parallel to the line of force)
- **LJS** (long-sized hole, perpendicular to the line of force)
- **D** (double shear)
- **S** (single shear)
### Table 7-4

**Available Bearing Strength at Bolt Holes Based on Bolt Spacing**

<table>
<thead>
<tr>
<th>Bolt Type</th>
<th>Bolt Spacing, s, in.</th>
<th>F_{b}, ksi</th>
<th>( \frac{F_{b}}{\sigma} )</th>
<th>( \frac{F_{b}}{2F_{t}} )</th>
<th>( \frac{F_{b}}{2F_{l}} )</th>
<th>( \frac{F_{b}}{1\omega} )</th>
<th>( \frac{F_{b}}{1\varepsilon} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>STD</td>
<td>2( \frac{2d_{p}}{3} )</td>
<td>58</td>
<td>34.1</td>
<td>51.1</td>
<td>41.3</td>
<td>62.0</td>
<td>48.6</td>
</tr>
<tr>
<td></td>
<td>3 in.</td>
<td>58</td>
<td>38.2</td>
<td>57.3</td>
<td>46.3</td>
<td>69.5</td>
<td>54.4</td>
</tr>
<tr>
<td>SSLT</td>
<td>2( \frac{2d_{p}}{3} )</td>
<td>58</td>
<td>43.5</td>
<td>65.3</td>
<td>52.2</td>
<td>78.3</td>
<td>60.9</td>
</tr>
<tr>
<td></td>
<td>3 in.</td>
<td>58</td>
<td>48.8</td>
<td>73.1</td>
<td>59.5</td>
<td>87.8</td>
<td>68.3</td>
</tr>
<tr>
<td>OVS</td>
<td>2( \frac{2d_{p}}{3} )</td>
<td>58</td>
<td>29.7</td>
<td>44.6</td>
<td>37.0</td>
<td>55.5</td>
<td>44.2</td>
</tr>
<tr>
<td></td>
<td>3 in.</td>
<td>58</td>
<td>33.3</td>
<td>50.0</td>
<td>41.4</td>
<td>62.2</td>
<td>48.6</td>
</tr>
<tr>
<td>LSLP</td>
<td>2( \frac{2d_{p}}{3} )</td>
<td>58</td>
<td>43.5</td>
<td>65.3</td>
<td>52.2</td>
<td>78.3</td>
<td>60.9</td>
</tr>
<tr>
<td></td>
<td>3 in.</td>
<td>58</td>
<td>48.8</td>
<td>73.1</td>
<td>59.5</td>
<td>87.8</td>
<td>68.3</td>
</tr>
<tr>
<td>STD, SSLT, OVS, LSLP</td>
<td>( s \geq 5d_{p} )</td>
<td>58</td>
<td>43.5</td>
<td>65.3</td>
<td>52.2</td>
<td>78.3</td>
<td>60.9</td>
</tr>
<tr>
<td>STD, SSLT</td>
<td>2( \frac{2d_{p}}{3} )</td>
<td>58</td>
<td>38.2</td>
<td>57.3</td>
<td>46.3</td>
<td>69.5</td>
<td></td>
</tr>
<tr>
<td>OVS</td>
<td>2( \frac{2d_{p}}{3} )</td>
<td>58</td>
<td>43.5</td>
<td>65.3</td>
<td>52.2</td>
<td>78.3</td>
<td></td>
</tr>
<tr>
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<td>2( \frac{2d_{p}}{3} )</td>
<td>58</td>
<td>33.3</td>
<td>50.0</td>
<td>41.4</td>
<td>62.2</td>
<td></td>
</tr>
<tr>
<td>SSLT</td>
<td>2( \frac{2d_{p}}{3} )</td>
<td>58</td>
<td>48.8</td>
<td>73.1</td>
<td>59.5</td>
<td>87.8</td>
<td></td>
</tr>
<tr>
<td>OVS</td>
<td>2( \frac{2d_{p}}{3} )</td>
<td>58</td>
<td>29.7</td>
<td>44.6</td>
<td>37.0</td>
<td>55.5</td>
<td></td>
</tr>
<tr>
<td>LSLP</td>
<td>2( \frac{2d_{p}}{3} )</td>
<td>58</td>
<td>33.3</td>
<td>50.0</td>
<td>41.4</td>
<td>62.2</td>
<td></td>
</tr>
<tr>
<td>Minimum Spacing* = 2( \frac{2d_{p}}{3} ), in.</td>
<td>58</td>
<td>38.2</td>
<td>57.3</td>
<td>46.3</td>
<td>69.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

**Table 7-4 (continued)**

**Available Bearing Strength at Bolt Holes Based on Bolt Spacing**

<table>
<thead>
<tr>
<th>Bolt Type</th>
<th>Bolt Spacing, s, in.</th>
<th>F_{b}, ksi</th>
<th>( \frac{F_{b}}{\sigma} )</th>
<th>( \frac{F_{b}}{2F_{t}} )</th>
<th>( \frac{F_{b}}{2F_{l}} )</th>
<th>( \frac{F_{b}}{1\omega} )</th>
<th>( \frac{F_{b}}{1\varepsilon} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>STD</td>
<td>2( \frac{2d_{p}}{3} )</td>
<td>58</td>
<td>63.1</td>
<td>94.6</td>
<td>70.3</td>
<td>105</td>
<td>77.6</td>
</tr>
<tr>
<td></td>
<td>3 in.</td>
<td>58</td>
<td>70.7</td>
<td>106</td>
<td>78.8</td>
<td>116</td>
<td>89.9</td>
</tr>
<tr>
<td>SSLT</td>
<td>2( \frac{2d_{p}}{3} )</td>
<td>58</td>
<td>52.2</td>
<td>78.3</td>
<td>59.5</td>
<td>89.2</td>
<td>66.7</td>
</tr>
<tr>
<td></td>
<td>3 in.</td>
<td>58</td>
<td>58.5</td>
<td>88.3</td>
<td>69.7</td>
<td>98.9</td>
<td>74.9</td>
</tr>
<tr>
<td>OVS</td>
<td>2( \frac{2d_{p}}{3} )</td>
<td>58</td>
<td>52.2</td>
<td>78.3</td>
<td>59.5</td>
<td>89.2</td>
<td>66.7</td>
</tr>
<tr>
<td></td>
<td>3 in.</td>
<td>58</td>
<td>58.5</td>
<td>88.3</td>
<td>69.7</td>
<td>98.9</td>
<td>74.9</td>
</tr>
<tr>
<td>LSLP</td>
<td>2( \frac{2d_{p}}{3} )</td>
<td>58</td>
<td>54.4</td>
<td>81.0</td>
<td>61.6</td>
<td>92.4</td>
<td>68.9</td>
</tr>
<tr>
<td></td>
<td>3 in.</td>
<td>58</td>
<td>60.9</td>
<td>91.4</td>
<td>69.1</td>
<td>104</td>
<td>72.2</td>
</tr>
<tr>
<td>SSLT</td>
<td>2( \frac{2d_{p}}{3} )</td>
<td>58</td>
<td>60.9</td>
<td>91.4</td>
<td>69.1</td>
<td>104</td>
<td>72.2</td>
</tr>
<tr>
<td>OVS</td>
<td>2( \frac{2d_{p}}{3} )</td>
<td>58</td>
<td>60.9</td>
<td>91.4</td>
<td>69.1</td>
<td>104</td>
<td>72.2</td>
</tr>
<tr>
<td>LSLP</td>
<td>2( \frac{2d_{p}}{3} )</td>
<td>58</td>
<td>60.9</td>
<td>91.4</td>
<td>69.1</td>
<td>104</td>
<td>72.2</td>
</tr>
<tr>
<td>Minimum Spacing* = 2( \frac{2d_{p}}{3} ), in.</td>
<td>58</td>
<td>60.9</td>
<td>91.4</td>
<td>69.1</td>
<td>104</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

Notes:
- **STD** = standard hole
- **SSLT** = short-slotted hole oriented transverse to the line of force
- **SSLP** = short-slotted hole oriented parallel to the line of force
- **OVS** = oversized hole
- **LSLP** = long-slotted hole oriented parallel to the line of force
- **LST** = long-slotted hole oriented transverse to the line of force
- ASD = available bearing strength
- LFDF = long-fastener oriented deflection

*Minimum Spacing = \( 2 \omega d_{p} \), in.*

*Spacing indicated is from the center of the hole or slot to the center of the adjacent hole or slot in the line of force. Hole deformation is considered. When hole deformation is not considered, see **Table** 3.10.*

*Decimal values have been rounded to the nearest sixteenth of an inch.*
Table 7-5: Available Bearing Strength at Bolt Holes Based on Edge Distance

### Available Bearing Strength at Bolt Holes Based on Edge Distance

**kips/in. thickness**

<table>
<thead>
<tr>
<th>Hole Type</th>
<th>Edge Distance $L_h$, in.</th>
<th>$F_b$, ksi</th>
<th>Nominal Bolt Diameter, $d$, in.</th>
<th>$r_p/2L_h$</th>
<th>$r_0/2L_h$</th>
<th>$r_1/2L_h$</th>
<th>$r_2/2L_h$</th>
<th>$r_3/2L_h$</th>
<th>$r_4/2L_h$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ASD</strong></td>
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**Edge distance for full bearing strength**

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**Std = standard hole**

**SLLT = short-slotted hole oriented transverse to the line of force**

**SSLP = short-slotted hole parallel to the line of force**

**OVS = oversized hole**

**LSLT = long-slotted hole oriented parallel to the line of force**

**LSLP = long-slotted hole oriented transverse to the line of force**

--- indicates spacing less than minimum spacing required per ASC Specification Section J.3.3.

Note: Spacing indicated is from the center of the hole or slot to the center of the adjacent hole or slot in the line of force. Hole deformation is considered. When hole deformation is not considered, see ASC Specification Section J.3.10.

* Decimal value has been rounded to the nearest sixteenth of an inch.

--- indicates spacing less than minimum spacing required per ASC Specification Section J.3.3.

Note: Spacing indicated is from the center of the hole or slot to the center of the adjacent hole or slot in the line of force. Hole deformation is considered. When hole deformation is not considered, see ASC Specification Section J.3.10.

* Decimal value has been rounded to the nearest sixteenth of an inch.