Steel Beam Design

- American Institute of Steel Construction
  - Manual of Steel Construction
  - ASD & LRFD
  - combined in 2005

Steel Materials

- smelt iron ore
- add alloying elements
- heat treatments
- iron, carbon
- microstructure

Steel Materials

- cast into billets
- hot rolled
- cold formed
- residual stress
- corrosion-resistant “weathering” steels
- stainless
Steel Materials

- **steel grades**
  - ASTM A36 – carbon
    - plates, angles
    - $F_y = 36 \text{ ksi} \; \& \; F_u = 58 \text{ ksi}$
  - ASTM A572 – high strength low-alloy
    - some beams
    - $F_y = 60 \text{ ksi} \; \& \; F_u = 75 \text{ ksi}$
  - ASTM A992 – for building framing
    - most beams
    - $F_y = 50 \text{ ksi} \; \& \; F_u = 65 \text{ ksi}$

Steel Properties

- **high strength to weight ratio**
- elastic limit – yield ($F_y$)
- inelastic – plastic
- ultimate strength ($F_u$)
- ductile
- strength sensitive to temperature
- can corrode
- fatigue

Structural Steel

- **standard rolled shapes (W, C, L, T)**
- open web joists
- plate girders
- decking

Steel Construction

- **welding**
- **bolts**
Steel Construction

- fire proofing
  - cementicious spray
  - encasement in gypsum
  - intumescent – expands with heat
  - sprinkler system

Unified Steel Design

- ASD
  \[ R_a \leq \frac{R_n}{\Omega} \]
  - bending (braced) \( \Omega = 1.67 \)
  - bending (unbraced) \( \Omega = 1.67 \)
  - shear \( \Omega = 1.5 \) or \( 1.67 \)
  - shear (bolts & welds) \( \Omega = 2.00 \)
  - shear (welds) \( \Omega = 2.00 \)

* flanges in compression can buckle

Unified Steel Design

- braced vs. unbraced

LRFD

- loads on structures are
  - not constant
  - can be more influential on failure
  - happen more or less often
  - UNCERTAINTY

\[ R_u = \gamma_D R_D + \gamma_L R_L \leq \phi R_n \]

\( \phi \) - resistance factor
\( \gamma \) - load factor for (D)ead & (L)ive load
**LRFD Steel Beam Design**

- limit state is yielding all across section
- outside elastic range
- load factors & resistance factors

\[ f_y = 50 \text{ksi} \]
\[ \varepsilon_y = 0.001724 \]

**LRFD Load Combinations**

ASCE-7 (2005)

- \[ 1.4(D + F) \]
- \[ 1.2(D + F + T) + 1.6(L + H) + 0.5(L_r, S, R) \]
- \[ 1.2D + 1.6(L_r, S, R) + (L + 0.8W) \]
- \[ 1.2D + 1.6W + L + 0.5(L_r, S, R) \]
- \[ 1.2D + 1.0E + L + 0.2S \]
- \[ 0.9D + 1.6W + 1.6H \]
- \[ 0.9D + 1.0E + 1.6H \]

**Beam Design Criteria (revisited)**

- strength design
  - bending stresses predominate
  - shear stresses occur
- serviceability
  - limit deflection
  - stability
- superpositioning
  - use of beam charts
  - elastic range only!
  - “add” moment diagrams
  - “add” deflection CURVES (not maximums)

**Steel Beams**

- lateral stability - bracing
- local buckling – stiffen, or bigger \( I_y \)
Local Buckling

• steel I beams
• flange
  – buckle in direction of smaller radius of gyration
• web
  – force
  – “crippling”

Shear in Web

• panels in plate girders or webs with large shear
• buckling in compression direction
• add stiffeners

Figure 2-5. Flange Local Buckling Limit State
(Buckling, L.S., Christopher W., 1964)

http://nisee.berkeley.edu/godden
Steel Beams

• bearing
  – provide adequate area
  – prevent local yield of flange and web

LRFD - Flexure

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

- $M_u$ - maximum moment
- $\phi_b$ - resistance factor for bending = 0.9
- $M_n$ - nominal moment (ultimate capacity)
- $F_y$ - yield strength of the steel
- $Z$ - plastic section modulus*

Internal Moments - at yield

• material hasn’t failed

\[ M_y = I f_y = \frac{bh^2}{6} f_y \]

\[ = \frac{b(2c)^2}{6} f_y = \frac{2bc^2}{3} f_y \]

Internal Moments - ALL at yield

• all parts reach yield
• plastic hinge forms
• ultimate moment
• $A_{tension} = A_{compression}$

\[ M_p = bc^2 f_y = \frac{3}{2} M_y \]

\[ n_s = 0.001724 \]
n.a. of Section at Plastic Hinge

- cannot guarantee at centroid
- \( f_y A_1 = f_y A_2 \)
- moment found from yield stress times moment area

\[
M_p = f_y A_1 d = f_y \sum n.a. A_i d_i
\]

Plastic Hinge Development

Plastic Hinge Examples

- stability can be effected

Plastic Section Modulus

- shape factor, \( k \)
  \[
  k = \frac{M_p}{M_y}
  \]
  - \( = 3/2 \) for a rectangle
  - \( \approx 1.1 \) for an \( I \)
  \[
  k = \frac{Z}{S}
  \]

- plastic modulus, \( Z \)
  \[
  Z = \frac{M_p}{f_y}
  \]
**LRFD – Shear (compact shapes)**

\[
\Sigma \gamma_i R_i = V_u \leq \phi_v V_n = 1.0(0.6 F_{yw} A_w)
\]

- \(V_u\) - maximum shear
- \(\phi_v\) - resistance factor for shear = 1.0
- \(V_n\) - nominal shear
- \(F_{yw}\) - yield strength of the steel in the web
- \(A_w\) - area of the web = \(t_w d\)

**LRFD - Flexure Design**

- **limit states for beam failure**
  1. yielding \(L_p = 1.76 r_y \sqrt{\frac{F_y}{E}}\)
  2. lateral-torsional buckling*
  3. flange local buckling
  4. web local buckling
- **minimum \(M_n\) governs**

\[
\Sigma \gamma_i R_i = M_u \leq \phi_b M_n
\]

**Compact Sections**

- **plastic moment can form before any buckling**
- **criteria**

\[
- \frac{b_f}{2t_f} \leq 0.38 \left( \frac{E}{F_y} \right) \sqrt{\frac{E}{F_y}}
\]

- and \(\frac{h_c}{t_w} \leq 3.76 \left( \frac{E}{F_y} \right) \sqrt{\frac{E}{F_y}}\)

**Lateral Torsional Buckling**

\[
M_n = C_b \left[ \text{moment based on lateral buckling} \right] \leq M_p
\]

\[
C_b = \frac{12.5 M_{max}}{2.5 M_{max} + 3M_A + 4M_B + 3M_C}
\]

- \(C_b\) = modification factor
- \(M_{max}\) - \(|\text{max moment}|, \text{unbraced segment}\)
- \(M_A\) - \(|\text{moment}|, 1/4 \text{ point}\)
- \(M_B\) = \(|\text{moment}|, \text{center point}\)
- \(M_C\) = \(|\text{moment}|, 3/4 \text{ point}\)
Beam Design Charts

<table>
<thead>
<tr>
<th>Unbraced Length (L, ft)</th>
<th>Available Moment (F ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
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<tr>
<td>2</td>
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<td>8</td>
<td>200</td>
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<td>9</td>
<td>225</td>
</tr>
<tr>
<td>10</td>
<td>250</td>
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Charts & Deflections

- **beam charts**
  - solid line is most economical
  - dashed indicates there is another more economical section
  - self weight is NOT included in $M_n$
- **deflections**
  - no factors are applied to the loads
  - often governs the design

Design Procedure (revisited)

1. Know unbraced length, material, design method ($\Omega$, $\phi$)
2. Draw V & M, finding $M_{max}$
3. Calculate $Z_{req'd}$ ($M_a \leq M_n/\Omega$)
   
   $(M_u \leq \phi_b M_n)$
4. Choose (economical) section from section or beam capacity charts

Beam Charts by $S_x$ (Appendix A)

<table>
<thead>
<tr>
<th>$S_x$</th>
<th>Section</th>
<th>$S_{x-US}$</th>
<th>$S_{x-MI}$</th>
<th>$S_{x-US}$</th>
<th>Section</th>
<th>$S_{x-MI}$</th>
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<tbody>
<tr>
<td>410</td>
<td>W33 x 141</td>
<td>7300</td>
<td>188</td>
<td>W13 x 97</td>
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<td>7700</td>
<td>176</td>
<td>W24 x 76</td>
<td>2890</td>
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<tr>
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<td>W27 x 146</td>
<td>6700</td>
<td>177</td>
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<td>6460</td>
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<td>W14 x 109</td>
<td>2840</td>
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<td>6200</td>
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<td>134</td>
<td>W16 x 77</td>
<td>2200</td>
<td></td>
</tr>
</tbody>
</table>
Beam Design (revisited)

4. Include self weight for $M_{\text{max}}$
   - it’s dead load
   - and repeat 3 & 4 if necessary

5. Consider lateral stability
   
   Unbraced roof trusses were blown down in 1999 at this project in Moscow, Idaho.
   
   Photo: Ken Carper

Beam Design (revisited)

6. Evaluate shear stresses - horizontal
   
   • $(V_a \leq V_n/\Omega)$ or $(V_u \leq \phi V_n)$
   
   • rectangles and W’s
     
     $$f_{v-\text{max}} = \frac{3V}{2A} \approx \frac{V}{A_{\text{web}}}$$

   • general
     
     $$f_{v-\text{max}} = \frac{VQ}{Ib}$$

Beam Design (revisited)

7. Provide adequate bearing area at supports
   
   $(P_a \leq P_n/\Omega)$
   $(P_u \leq \phi P_n)$
Beam Design (revisited)

8. Evaluate torsion

\[ (f_v \leq F_v) \]

- circular cross section
  \[ f_v = \frac{T}{J} \rho \]
- rectangular
  \[ f_v = \frac{T}{c_1 a b^2} \]

9. Evaluate deflections – NO LOAD FACTORS

\[ y_{\text{max}}(x) = \Delta_{\text{actual}} \leq \Delta_{\text{allowable}} \]

Load Tables & Equivalent Load

- uniformly distributed loads
- equivalent “w”
  \[ M_{\text{max}} = \frac{W_{\text{equivalent}} L^2}{8} \]

Sloped Beams

- stairs & roofs
- projected live load
- dead load over length
- perpendicular load to beam:
  \[ W_{\perp} = W \cdot \cos \alpha \]
- equivalent distributed load:
  \[ W_{\text{adj.}} = \frac{W}{\cos \alpha} \]
Steel Arches and Frames

- solid sections
- or open web

Steel Shell and Cable Structures

Approximate Depths