Steel Beam Design

- American Institute of Steel Construction
  - Manual of Steel Construction
  - ASD & LRFD
  - combined in 13th ed.

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
    - $F_y = 36$ ksi & $F_u = 58$ ksi
  - ASTM A572 – high strength low-alloy
    - some beams
    - $F_y = 60$ ksi & $F_u = 75$ ksi
  - ASTM A992 – for building framing
    - most beams
    - $F_y = 50$ ksi & $F_u = 65$ 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
  - cementious 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 \( \Omega = 1.67 \)
  - 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

LRFD Load Combinations

- 1.4D
- 1.2D + 1.6L + 0.5(L_r or S or R)
- 1.2D + 1.6(L_r or S or R) + (L or 0.5W)
- 1.2D + 1.0W + L + 0.5(L_r or S or R)
- 1.2D + 1.0E + L + 0.2S
- 0.9D + 1.0W
- 0.9D + 1.0E
  * F has same factor as D in 1-5 and 7
  * H adds with 1.6 and resists with 0.9 (permanent)

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

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

- bearing
  - provide adequate area
  - prevent local yield of flange and web

LRFD - Flexure

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

- \( M_u \) - 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

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

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

Internal Moments - ALL at yield

- all parts reach yield
- plastic hinge forms
- ultimate moment
- \( A_{\text{tension}} = A_{\text{compression}} \)

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

$$M_p = f_y A_1 d = f_y \sum A_i d_i$$

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

- plastic modulus, $Z$

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

\( V_u \) - 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 = \( t_w d \)

**Compact Sections**

- plastic moment can form before any buckling
- criteria
  \[- \frac{b_f}{2t_f} \leq 0.38 \sqrt{\frac{E}{F_y}} \]
  - and
  \[- \frac{h_c}{t_w} \leq 3.76 \sqrt{\frac{E}{F_y}} \]

**LRFD – Shear (compact shapes)**

**LRFD - Flexure Design**

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

**Lateral Torsional Buckling**

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

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

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

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 $M_{\text{max}}$

3. Calculate $S_{\text{req'd}}$ ($M_a \leq M_n/\Omega$)
   or $Z$ ($M_u \leq \phi_b M_n$)

4. Choose (economical) section from section or beam capacity charts

Beam Charts by $S_x$ (Appendix A)

Table 31  Listing of W Shapes in Descending Order of $S_x$ for Beam Design.

<table>
<thead>
<tr>
<th>$S_x$—US (in2)</th>
<th>Section</th>
<th>$S_{\text{req'd}}$—SL (bf x in)</th>
<th>$S_x$—US (in2)</th>
<th>Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>410</td>
<td>W33 x 141</td>
<td>7150</td>
<td>198</td>
<td>W18 x 97</td>
</tr>
<tr>
<td>459</td>
<td>W36 x 155</td>
<td>7200</td>
<td>176</td>
<td>W24 x 76</td>
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<tr>
<td>611</td>
<td>W22 x 146</td>
<td>6740</td>
<td>175</td>
<td>W18 x 100</td>
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<tr>
<td>646</td>
<td>W33 x 130</td>
<td>6560</td>
<td>173</td>
<td>W18 x 109</td>
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<tr>
<td>380</td>
<td>W30 x 132</td>
<td>6230</td>
<td>171</td>
<td>W21 x 83</td>
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<tr>
<td>371</td>
<td>W24 x 146</td>
<td>6080</td>
<td>166</td>
<td>W18 x 86</td>
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<td>359</td>
<td>W33 x 118</td>
<td>5890</td>
<td>159</td>
<td>W18 x 89</td>
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<tr>
<td>359</td>
<td>W30 x 124</td>
<td>5820</td>
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<tr>
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<td>W30 x 116</td>
<td>5400</td>
<td>154</td>
<td>W24 x 68</td>
</tr>
<tr>
<td>329</td>
<td>W24 x 131</td>
<td>5400</td>
<td>146</td>
<td>W18 x 76</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
     \[ f_{v-\text{max}} = \frac{VQ}{I_b} \]

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
  \[ f_v = \frac{T \rho}{J} \]
- rectangular
  \[ f_v = \frac{T}{c_1 ab^2} \]

**Load Tables & Equivalent Load**

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

**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