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

**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

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**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

**Local Buckling**
- web

**Shear in Web**
- plate girders and stiffeners

http://nisee.berkeley.edu/godden

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

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

LRFD - Flexure

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

- $M_u$ - 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
- $A_{tension} = A_{compression}$

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

$$n_i = 50 ksi$$

$$\varepsilon = 0.001724$$
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

\[
M_p = f_y A_1 d = f_y \sum A_i d_i
\]

Plastic Hinge Development

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, \( Z \)

\[
Z = \frac{M_p}{f_y}
\]
LRFD – Shear (compact shapes)

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

- \( V_u \): 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 \( L_p = 1.76 r_y \frac{F_y}{E} \)
  2. lateral-torsional buckling*
  3. flange local buckling
  4. web local buckling

- minimum \( M_n \) governs

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

Compact Sections

- plastic moment can form before any buckling
- criteria

\[ - \frac{b_f}{2 t_f} \leq 0.38 \sqrt{\frac{E}{F_y}} \]

\[ - \text{and} \frac{h_c}{t_w} \leq 3.76 \sqrt{\frac{E}{F_y}} \]

Lateral Torsional Buckling

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

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

- \( C_b \): modification factor
- \( M_{\text{max}} \): |max moment|, unbraced segment
- \( M_A \): |moment|, 1/4 point
- \( M_B \): |moment|, center point
- \( M_C \): |moment|, 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 $M_{max}$

3. Calculate $S_{req'd}$ ($M_a \leq M_n/\Omega$)
   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)**

<table>
<thead>
<tr>
<th>Allowable Stress Design—Selected beam shapes $S_x$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Section</strong></td>
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</tbody>
</table>

**Beam Charts by $S_x$ (Appendix)**

<table>
<thead>
<tr>
<th>Table A9</th>
<th>Elastic Section Modulus—U.S. and S.I. Metric.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Section</td>
<td>$S_x$—U.S. (lb/in$^2$)</td>
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<tr>
<td>418</td>
<td>W32 x 141</td>
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<tr>
<td>439</td>
<td>W36 x 135</td>
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<td>W27 x 146</td>
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<td>W26 x 144</td>
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<td>380</td>
<td>W32 x 132</td>
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<td>W23 x 146</td>
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<tr>
<td>425</td>
<td>W21 x 131</td>
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<tr>
<td>395</td>
<td>W20 x 134</td>
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<tr>
<td>329</td>
<td>W30 x 156</td>
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<td>329</td>
<td>W25 x 131</td>
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</table>
Beam Charts by $Z_x$ (Appendix)

<table>
<thead>
<tr>
<th>Load Resistance Factor Design (LRFD) Selection Table for Beams – $Z_x$ ($F_y = 50$ ksi; $f_y = 0.90$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z_x$</td>
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</tbody>
</table>

Beam Design (revisited)

4*. Include self weight for $M_{max}$

- 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

6. Evaluate shear stresses - horizontal

- $V_a \leq V_n / \Omega$ or $V_u \leq \phi V_n$
- rectangles and $W$'s $f_{v-max} = \frac{3V}{2A} \approx \frac{V}{A_{web}}$
- $V_n = 0.6 F_{yw} A_w$
- general $f_{v-max} = \frac{VQ}{I_b}$

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
  \[ f_v = \frac{T}{c_1ab^2} \]

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