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
    - $F_y = 36$ 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
  - 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

\[ \sigma_y = 50 \text{ksi} \]
\[ \epsilon_y = 0.001724 \]

LRFD Load Combinations

- 1.4(D + F)
- 1.2(D + F + T) + 1.6(L + H) + 0.5(L_r or S or R)
- 1.2D + 1.6(L_r or S or R) + (L or 0.8W)
- 1.2D + 1.6W + L + 0.5(L_r or S or 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

Shear in Web

- plate girders and stiffeners

Figure 2-5. Flange Local Bucking Limit State (Breuel, L. N., Christopher H. W., 1994)

Figure 2-7. Web Local Bucking Limit State (NAT Project)
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.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

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

Plastic Hinge Development

Plastic Hinge Examples

- stability can be effected

Plastic Section Modulus

- shape factor, \( k \) = \( \frac{M_p}{M_y} \)
  - \( \approx 3/2 \) for a rectangle
- plastic modulus, \( Z \)
  - \( k = \frac{Z}{S} \)
  - \( Z = \frac{M_p}{f_y} \)
LRFD – Shear (compact shapes)

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

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

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

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

Compact Sections

- plastic moment can form before any buckling
- criteria

Lateral Torsional Buckling

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

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

- \( M_{\text{max}} \) - \(|\text{max moment}|, \text{unbraced segment}\)
- \( M_A \) - \( |\text{moment}|, \) 1/4 point
- \( M_B \) - \( |\text{moment}|, \) center point
- \( M_C \) - \( |\text{moment}|, \) 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 $Z_{req'd}$

   \[ M_a \leq M_n / \Omega \]

   \[ M_u \leq \phi_b M_n \]

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

Beam Charts by $S_x$ (Appendix A)

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

6. Evaluate shear stresses - horizontal
   - $(V_a \leq V_n/\omega)$ or $(V_u \leq \phi V_n)$
   - rectangles and W's
     $$ f_{v_{\text{max}}} = \frac{3V}{2A} \approx \frac{V}{A_{\text{web}}} $$
     $$ V_n = 0.6 F_{yw} A_w $$
   - 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
- 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

http://nisee.berkeley.edu/godden