Steel construction: materials & beams
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

A36 steel, JOM 1998

AISC
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

Strain hardening

Winnepeg DOT
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 \( \Omega = 1.67 \)
- 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

- 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”
Local Buckling

- **flange**

- **web**

*Figure 2-5. Flange Local Bending Limit State (Beedle, L.S., Christopher, R., 1964)*

*Figure 2-7. Web Local Buckling Limit State (SAC Project)*
Shear in Web

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

![Diagram](image.png)

- (a) Shear Failure
- (b) Shear Buckling

stiffeners to prevent lateral buckling
Shear in Web

• plate girders and stiffeners
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
- $A_{\text{tension}} = A_{\text{compression}}$

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

$\sigma_y = 50\text{ksi}$
$\varepsilon_y = 0.001724$
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

(a) $M < M_Y$

(b) $M = M_Y$

(c) $M > M_Y$

(d) $M = M_p$
Plastic Hinge Examples

- stability can be effected
Plastic Section Modulus

• shape factor, \( k \)

\[ k = \frac{M_p}{M_y} \]

= 3/2 for a rectangle

\[ k \approx 1.1 \text{ for an } I \]

• plastic modulus, \( Z \)

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

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

- $V_u$ - 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
  2. lateral-torsional buckling*
  3. flange local buckling
  4. web local buckling
- minimum $M_n$ governs

$$L_p = 1.76 r_y \sqrt{\frac{F_y}{E}}$$

$$\sum \gamma_i R_i = M_u \leq \phi_b M_n$$
Compact Sections

- Plastic moment can form before any buckling

- Criteria

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

- \( h \leq 3.76 \sqrt{\frac{E}{F_y}} \)
Lateral Torsional Buckling

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

\[ C_b = \frac{12.5 M_{\text{max}}}{2.5 M_{\text{max}} + 2M_A + 4M_B + 3M_C} \]

- \( C_b \) = 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

Table 3-10 (continued)

W Shapes

Available Moment vs. Unbraced Length

Available Moment, $M_{u}/\Omega$ (1 kip-ft increments) vs. $\phi M_{u}$ (1.5 kip-ft increments)

<table>
<thead>
<tr>
<th>ASD</th>
<th>LRFD</th>
</tr>
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<tbody>
<tr>
<td>56</td>
<td>84</td>
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<td>52</td>
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<td>48</td>
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<td>44</td>
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<tr>
<td>40</td>
<td>60</td>
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Unbraced Length (0.5-ft increments)
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 $Z_{\text{req'd}}$ 
   \[ (M_a \leq M_n / \Omega) \]
   \[ (M_u \leq \phi_b M_n) \]

4. Choose (economical) section from section or beam capacity charts
Beam Charts by $S_x$ (Appendix A)

Table 11: Listing of W Shapes in Descending Order of $S_x$ for Beam Design.

<table>
<thead>
<tr>
<th>$S_x$—US (in.$^3$)</th>
<th>Section</th>
<th>$S_x$—SI ($10^3 \times \text{mm}^3$)</th>
<th>$S_x$—US (in.$^3$)</th>
<th>Section</th>
<th>$S_x$—SI ($10^3 \times \text{mm}^3$)</th>
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<tr>
<td>448</td>
<td>W33 × 141</td>
<td>7350</td>
<td>188</td>
<td>W18 × 97</td>
<td>3080</td>
</tr>
<tr>
<td>439</td>
<td>W36 × 135</td>
<td>7200</td>
<td>176</td>
<td>W24 × 76</td>
<td>2890</td>
</tr>
<tr>
<td>411</td>
<td>W27 × 146</td>
<td>6740</td>
<td>175</td>
<td>W16 × 100</td>
<td>2870</td>
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<td>406</td>
<td>W33 × 130</td>
<td>6660</td>
<td>173</td>
<td>W14 × 109</td>
<td>2840</td>
</tr>
<tr>
<td>380</td>
<td>W30 × 132</td>
<td>6230</td>
<td>171</td>
<td>W21 × 83</td>
<td>2800</td>
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<tr>
<td>371</td>
<td>W24 × 146</td>
<td>6080</td>
<td>166</td>
<td>W18 × 86</td>
<td>2720</td>
</tr>
<tr>
<td>359</td>
<td>W33 × 118</td>
<td>5890</td>
<td>157</td>
<td>W14 × 99</td>
<td>2570</td>
</tr>
<tr>
<td>355</td>
<td>W30 × 124</td>
<td>5820</td>
<td>155</td>
<td>W16 × 89</td>
<td>2540</td>
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<td>329</td>
<td>W30 × 116</td>
<td>5400</td>
<td>154</td>
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<td>W21 × 147</td>
<td>5400</td>
<td>146</td>
<td>W18 × 76</td>
<td>2390</td>
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<td></td>
<td></td>
<td></td>
<td>143</td>
<td>W14 × 90</td>
<td>2350</td>
</tr>
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</table>
# Beam Charts by $Z_x$

## TABLE 9.1 Load Factor Resistance Design Selection for Shapes Used as Beams

<table>
<thead>
<tr>
<th>Designation</th>
<th>$Z_x$ in.$^3$</th>
<th>$L_p$ ft</th>
<th>$L_r$ ft</th>
<th>$M_p$ kip-ft</th>
<th>$M_r$ kip-ft</th>
<th>$F_y = 36$ ksi</th>
<th>$F_y = 50$ ksi</th>
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<tbody>
<tr>
<td>W 33 × 141</td>
<td>514</td>
<td>10.1</td>
<td>30.1</td>
<td>1,542</td>
<td>971</td>
<td>8.59</td>
<td>23.1</td>
</tr>
<tr>
<td>W 30 × 148</td>
<td>500</td>
<td>9.50</td>
<td>30.6</td>
<td>1,500</td>
<td>945</td>
<td>8.06</td>
<td>22.8</td>
</tr>
<tr>
<td>W 24 × 162</td>
<td>468</td>
<td>12.7</td>
<td>45.2</td>
<td>1,404</td>
<td>897</td>
<td>10.8</td>
<td>32.4</td>
</tr>
<tr>
<td>W 24 × 146</td>
<td>418</td>
<td>12.5</td>
<td>42.0</td>
<td>1,254</td>
<td>804</td>
<td>10.6</td>
<td>30.6</td>
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<tr>
<td>W 33 × 118</td>
<td>415</td>
<td>9.67</td>
<td>27.8</td>
<td>1,245</td>
<td>778</td>
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<td>21.7</td>
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<td>W 30 × 124</td>
<td>408</td>
<td>9.29</td>
<td>28.2</td>
<td>1,224</td>
<td>769</td>
<td>7.88</td>
<td>21.5</td>
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<tr>
<td>W 21 × 147</td>
<td>373</td>
<td>12.3</td>
<td>46.4</td>
<td>1,119</td>
<td>713</td>
<td>10.4</td>
<td>32.8</td>
</tr>
<tr>
<td>W 24 × 131</td>
<td>370</td>
<td>12.4</td>
<td>39.3</td>
<td>1,110</td>
<td>713</td>
<td>10.5</td>
<td>29.1</td>
</tr>
<tr>
<td>W 18 × 158</td>
<td>356</td>
<td>11.4</td>
<td>56.5</td>
<td>1,068</td>
<td>672</td>
<td>9.69</td>
<td>38.0</td>
</tr>
<tr>
<td>W 30 × 108</td>
<td>346</td>
<td>8.96</td>
<td>26.3</td>
<td>1,038</td>
<td>648</td>
<td>7.60</td>
<td>20.3</td>
</tr>
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<td>W 27 × 114</td>
<td>343</td>
<td>9.08</td>
<td>28.2</td>
<td>1,029</td>
<td>648</td>
<td>7.71</td>
<td>21.3</td>
</tr>
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<td>W 24 × 117</td>
<td>327</td>
<td>12.3</td>
<td>37.1</td>
<td>981</td>
<td>631</td>
<td>10.4</td>
<td>27.9</td>
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<tr>
<td>W 21 × 122</td>
<td>307</td>
<td>12.2</td>
<td>41.0</td>
<td>921</td>
<td>592</td>
<td>10.3</td>
<td>29.8</td>
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<tr>
<td>W 18 × 130</td>
<td>290</td>
<td>11.3</td>
<td>47.7</td>
<td>870</td>
<td>555</td>
<td>9.55</td>
<td>32.8</td>
</tr>
</tbody>
</table>

### Steel Beams 37
### Lecture 18
### Architectural Structures
### ARCH 331
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 \((V_u \leq \phi_v V_n)\)
- 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

\[ P_a \leq \frac{P_n}{\Omega} \]
\[ P_u \leq \phi P_n \]
Beam Design (revisited)

8. Evaluate torsion

\( f_v \leq F_v \)

- **circular cross section**

\[
f_v = \frac{T \rho}{J}
\]

- **rectangular**

\[
f_v = \frac{T}{c_1 a b^2}
\]

**TABLE 3.1. Coefficients for Rectangular Bars in Torsion**

<table>
<thead>
<tr>
<th>a/b</th>
<th>c_1</th>
<th>c_2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>0.208</td>
<td>0.1406</td>
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<tr>
<td>1.2</td>
<td>0.219</td>
<td>0.1661</td>
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<td>1.5</td>
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<td>0.1958</td>
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<td>2.0</td>
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<td>2.5</td>
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<td>0.249</td>
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<td>3.0</td>
<td>0.267</td>
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<td>4.0</td>
<td>0.282</td>
<td>0.281</td>
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<td>10.0</td>
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<tr>
<td>(\infty)</td>
<td>0.333</td>
<td>0.333</td>
</tr>
</tbody>
</table>
Beam Design (revisited)

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” \( M_{\text{max}} = \frac{W_{\text{equivalent}} L^2}{8} \)

<table>
<thead>
<tr>
<th>Joint Designation</th>
<th>10K1</th>
<th>12K1</th>
<th>12K3</th>
<th>12K5</th>
<th>14K1</th>
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<tr>
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<td>14</td>
<td>14</td>
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<td>Approx. Wt (lbf./ft)</td>
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load for live load deflection limit
in RED, total in BLACK
Sloped Beams

- stairs & roofs
- projected live load
- dead load over length

- perpendicular load to beam:
  \[ W_\perp = w \cdot \cos \alpha \]

- equivalent distributed load:
  \[ W_{adj.} = \frac{w}{\cos \alpha} \]
Steel Arches and Frames

- solid sections
  or open web

http://nisee.berkeley.edu/godden
Approximate Depths

<table>
<thead>
<tr>
<th>Structure</th>
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<td>Decking</td>
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<td>Wide flanges</td>
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<td>Plate girders</td>
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<td>Open-web joists</td>
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<td>Arches</td>
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<td>Ribbed domes</td>
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<td>Cables</td>
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<td>Space frame (column-supported)</td>
<td>L/12-L/20</td>
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<td>Space frame (wall-supported)</td>
<td>L/12-L/20</td>
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