ARCHITECTURAL STRUCTURES:
FORM, BEHAVIOR, AND DESIGN
ARCH 331
DR. ANNE NICHOLS
SUMMER 2013

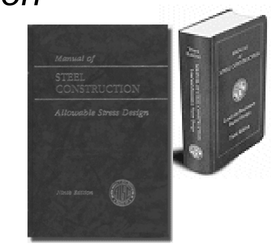
lecture
fifteen

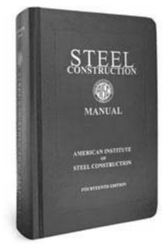
# steel construction: materials & beams



## Steel Beam Design

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

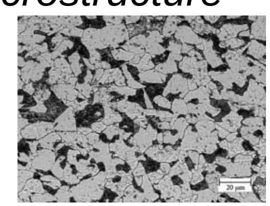





## Steel Materials

- *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*

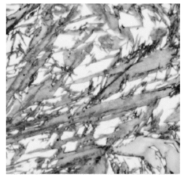
Hot Rolled

Cold Formed

AISC

# Steel Materials

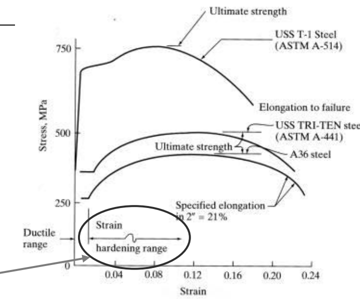
- steel grades
  - ASTM A36 – carbon
    - plates, angles
    - $F_y$ = 36 ksi & $F_u$ = 58 ksi
  - ASTM A572 – high strength low-alloy
    - some beams
    - $F_y$ = 60 ksi & $F_u$ = 75 ksi
  - ASTM A992 – for building framing
    - most beams
    - $F_y$ = 50 ksi & $F_u$ = 65 ksi



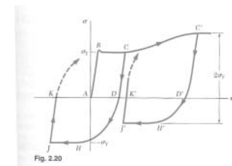


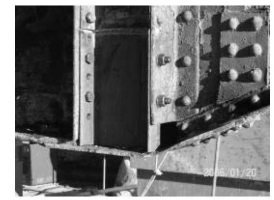
# Steel Properties

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




strain hardening



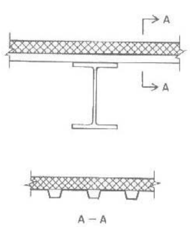


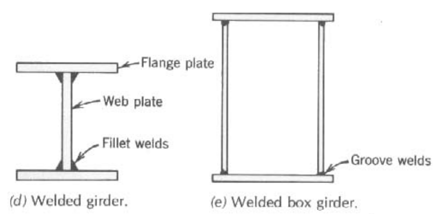
Winnepeg DOT

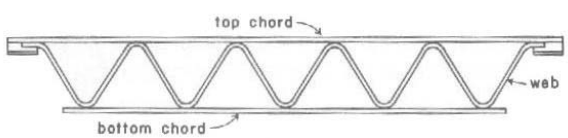


# Structural Steel

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



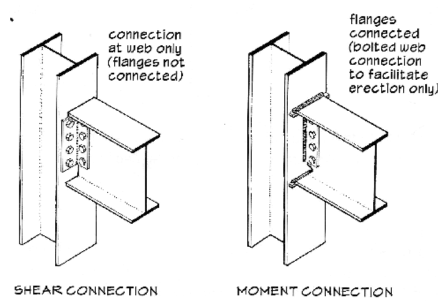



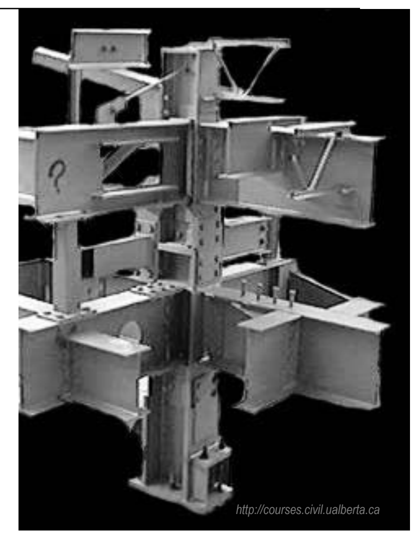






# Steel Construction

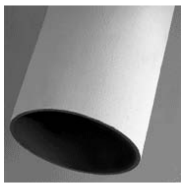
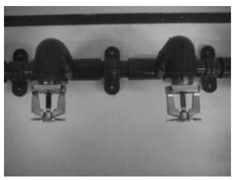
- welding
- bolts



## Steel Construction

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



## Unified Steel Design

- *ASD*

$$R_a \leq R_n / \Omega$$

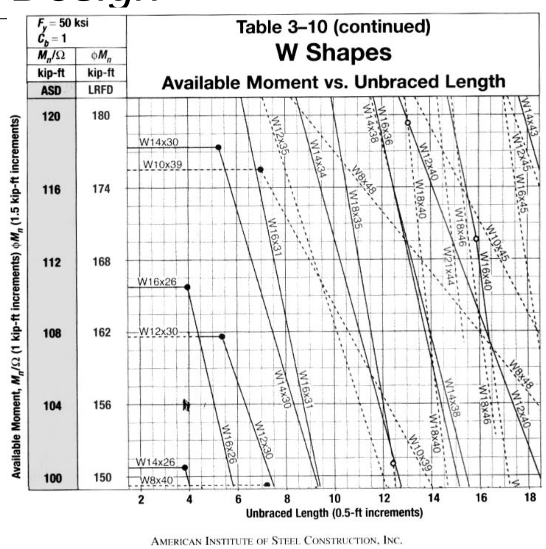
- *– bending (braced)* $\Omega = 1.67$
- *– bending (unbraced*)* $\Omega = 1.67$
- *– shear* $\Omega = 1.67$
- *– shear (bolts & welds)* $\Omega = 2.00$
- *– shear (welds)* $\Omega = 2.00$

** flanges in compression can buckle*



## Unified Steel Design

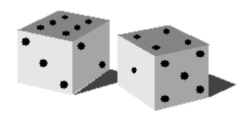
- *braced vs. unbraced*






## LRFD

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



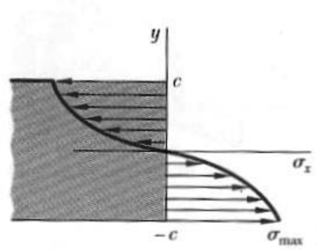
$$R_u = \gamma_D R_D + \gamma_L R_L \leq \phi R_n$$

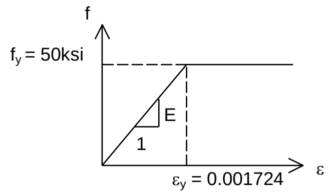
$\phi$ *- resistance factor*

$\gamma$ *- load factor for (D)ead & (L)ive load*

# LRFD Steel Beam Design

- *limit state is yielding <u>all across section</u>*
- *outside elastic range*
- *load factors & resistance factors*






# LRFD Load Combinations

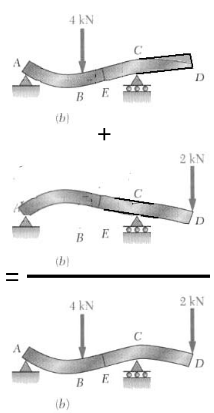
ASCE-7 (2010)

- *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)

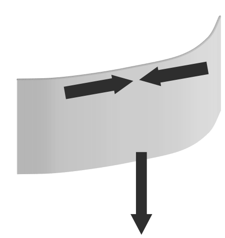
- *strength design*
  - *bending stresses predominate*
  - *shear stresses occur*
- *serviceability*
  - *limit deflection*
  - *stability*
- *superpositioning*
  - *use of beam charts*
  - *elastic range only!*
  - *"add" moment diagrams*
  - *"add" deflection CURVES (not maximums)*

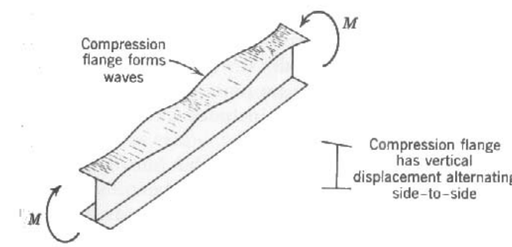





# Steel Beams

- *lateral stability - bracing*
- *local buckling – stiffen, or bigger $I_y$*

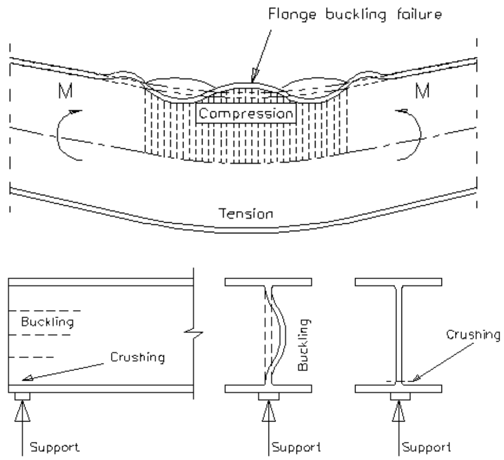





Local buckling of compression flange.

# Local Buckling

- *steel I beams*
- *flange*
  - *buckle in direction of smaller radius of gyration*
- *web*
  - *force*
  - *"crippling"*






# Local Buckling

- *flange*

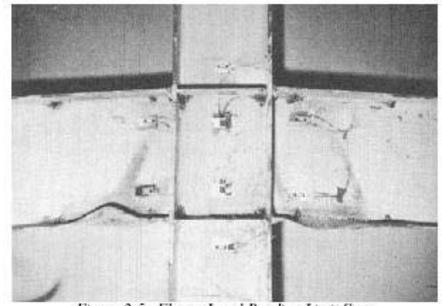


*Figure 2-5. Flange Local Bending Limit State (Beedle, L.S., Christopher, R., 1964)*

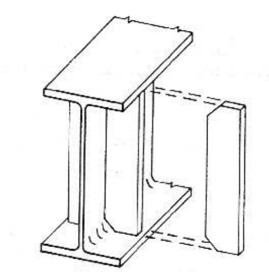
- *web*

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

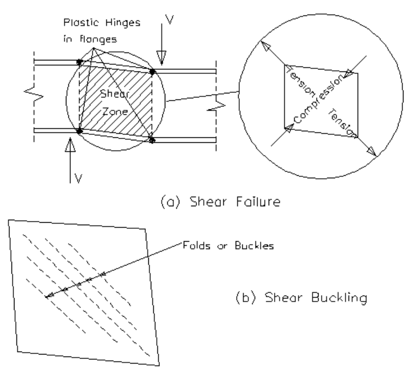


# Shear in Web

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



stiffeners to prevent lateral buckling






# Shear in Web

- *plate girders and stiffeners*


*http:// nisee.berkeley.edu/godden*

# Steel Beams

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

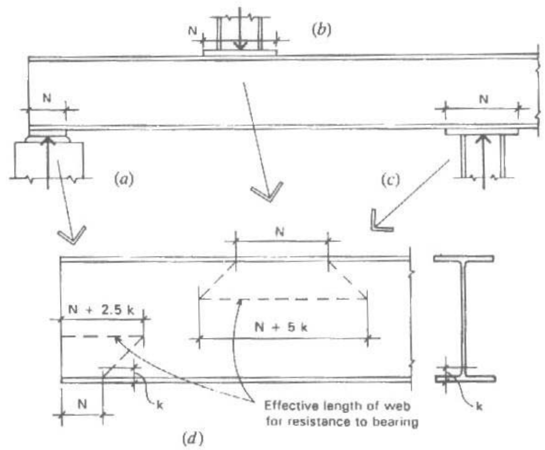



**Figure 9.10** Considerations for bearing in beams with thin webs, as related to web crippling (buckling of the thin web in compression).



# LRFD - Flexure

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

$M_u$ - maximum moment

$\phi_b$ - resistance factor for bending = 0.9

$M_n$ - nominal moment (ultimate capacity)

$F_y$ - yield strength of the steel

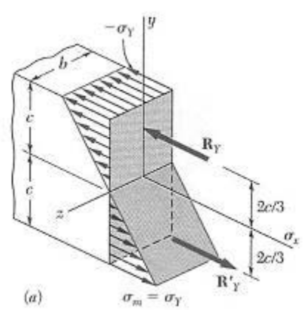
$Z$ - plastic section modulus*



# Internal Moments - at yield

- *material hasn't failed*

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

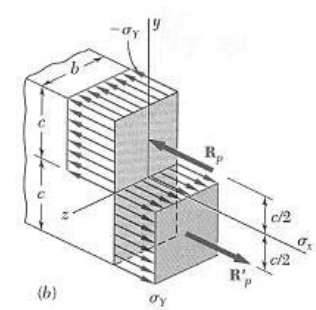



$$= \frac{b(2c)^2}{6} f_y = \frac{2bc^2}{3} f_y$$

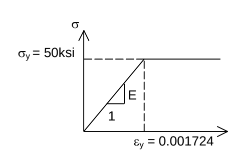


# Internal Moments - ALL at yield

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

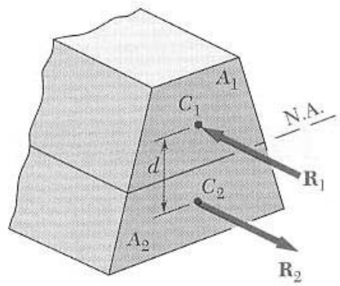



$$M_p = bc^2 f_y = \frac{3}{2} M_y$$



## n.a. of Section at Plastic Hinge

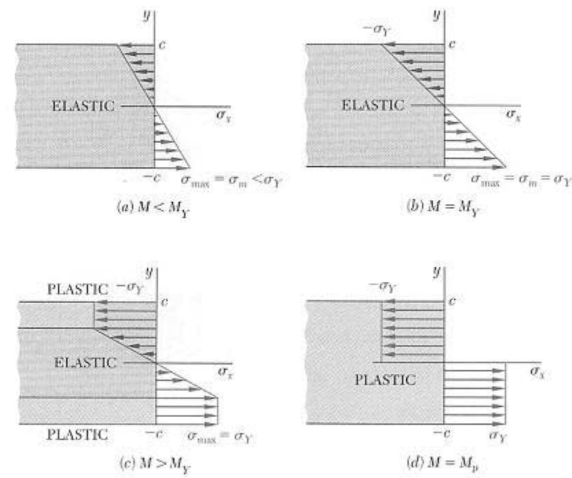
- cannot guarantee at centroid
- $f_y A_1 = f_y A_2$
- moment found from yield stress times <u>moment area</u>




$$M_p = f_y A_1 d = f_y \sum_{n.a} A_i d_i$$



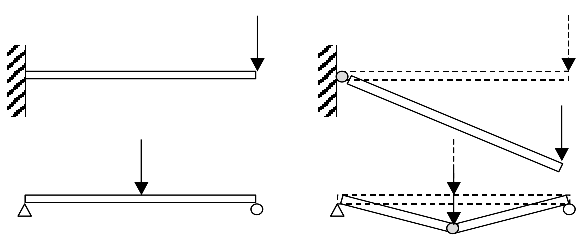
## Plastic Hinge Development






## Plastic Hinge Examples

- stability can be effected





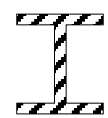
## Plastic Section Modulus

- shape factor, k

$$k = M_p / M_y$$

= 3/2 for a rectangle

≈ 1.1 for an I



$$k = Z / S$$

- plastic modulus, Z

$$Z = \frac{M_p}{f_y}$$

# LRFD – Shear (compact shapes)

$$\Sigma\gamma_i R_i = V_u \le \phi_v V_n = 1.0(0.6F_{yw}A_w)$$

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

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

$$\Sigma\gamma_i R_i = M_u \le \phi_b M_n$$



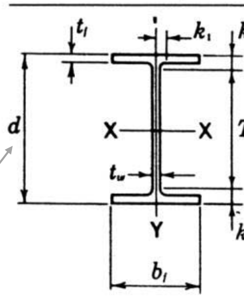
# Compact Sections

- plastic moment can form before any buckling
- criteria

– $\frac{b_f}{2t_f} \le 0.38\sqrt{\frac{E}{F_y}}$

– and $\frac{h_c}{t_w} \le 3.76\sqrt{\frac{E}{F_y}}$

**TABLE A.3 Properties of W Shapes**






# Lateral Torsional Buckling

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

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

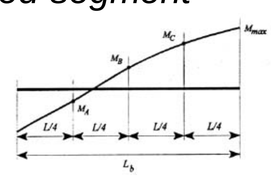
$C_b$ = modification factor

$M_{max}$ - |max moment|, unbraced segment

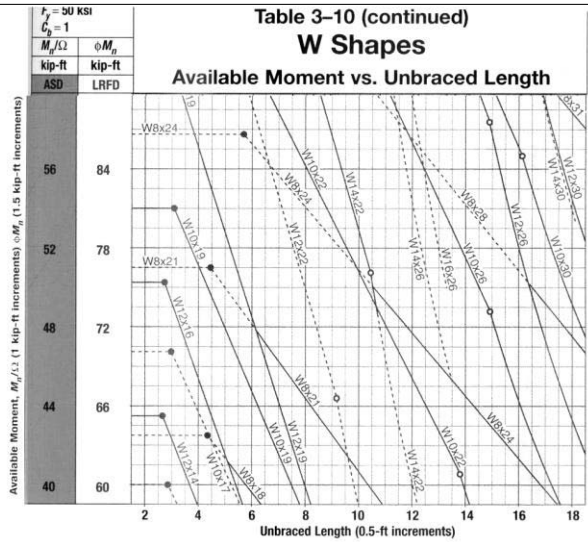
$M_A$ - |moment|, 1/4 point

$M_B$ = |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*



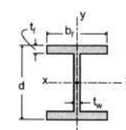
# Design Procedure (revisited)

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 A)

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




$S_x$ **Allowable Stress Design—Selected Beam Shapes** $S_x$

| $S_x$—US (in.³) | Section | $S_x$—SI (10³ × mm³) | $S_x$—US (in.³) | Section | $S_x$—SI (10³ × mm³) |
|---|---|---|---|---|---|
| **448** | **W33 × 141** | **7350** | 188 | W18 × 97 | 3080 |
| 439 | W36 × 135 | 7200 | | | |
| 411 | W27 × 146 | 6740 | **176** | **W24 × 76** | **2890** |
| | | | 175 | W16 × 100 | 2870 |
| **406** | **W33 × 130** | **6660** | 173 | W14 × 109 | 2840 |
| 380 | W30 × 132 | 6230 | 171 | W21 × 83 | 2800 |
| 371 | W24 × 146 | 6080 | 166 | W18 × 86 | 2720 |
| | | | 157 | W14 × 99 | 2570 |
| **359** | **W33 × 118** | **5890** | 155 | W16 × 89 | 2540 |
| 355 | W30 × 124 | 5820 | | | |
| | | | **154** | **W24 × 68** | **2530** |
| **329** | **W30 × 116** | **5400** | 151 | W21 × 73 | 2480 |
| 329 | W24 × 131 | 5400 | 146 | W18 × 76 | 2390 |
| 329 | W21 × 147 | 5400 | 143 | W14 × 90 | 2350 |
| | | | | | |
| **299** | **W30 × 108** | **4900** | **140** | **W21 × 68** | **2300** |
| 299 | W27 × 114 | 4900 | 134 | W16 × 77 | 2200 |

# Beam Charts by $Z_x$

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

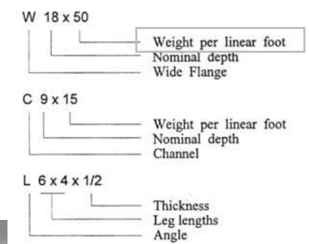
| | | $F_y$ = 36 ksi | | | | $F_y$ = 50 ksi | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Designation | $Z_x$ in.$^3$ | $L_p$ ft | $L_r$ ft | $M_p$ kip-ft | $M_r$ kip-ft | $L_p$ ft | $L_r$ ft | $M_p$ kip-ft | $M_r$ kip-ft | $r_y$ in. | $b_f/2t_f$ | $h/t_w$ | $X_1$ ksi | $X_2 \times 10^6$ (1/ksi)$^2$ |
| **W 33 × 141** | **514** | **10.1** | **30.1** | **1,542** | **971** | **8.59** | **23.1** | **2,142** | **1,493** | **2.43** | **6.01** | **49.6** | **1,800** | **17,800** |
| W 30 × 148 | 500 | 9.50 | 30.6 | 1,500 | 945 | 8.06 | 22.8 | 2,083 | 1,453 | 2.28 | 4.44 | 41.6 | 2,310 | 6,270 |
| W 24 × 162 | 468 | 12.7 | 45.2 | 1,404 | 897 | 10.8 | 32.4 | 1,950 | 1,380 | 3.05 | 5.31 | 30.6 | 2,870 | 2,260 |
| W 24 × 146 | 418 | 12.5 | 42.0 | 1,254 | 804 | 10.6 | 30.6 | 1,742 | 1,237 | 3.01 | 5.92 | 33.2 | 2,590 | 3,420 |
| **W 33 × 118** | **415** | **9.67** | **27.8** | **1,245** | **778** | **8.20** | **21.7** | **1,729** | **1,197** | **2.32** | **7.76** | **54.5** | **1,510** | **37,700** |
| W 30 × 124 | 408 | 9.29 | 28.2 | 1,224 | 769 | 7.88 | 21.5 | 1,700 | 1,183 | 2.23 | 5.65 | 46.2 | 1,930 | 13,500 |
| W 21 × 147 | 373 | 12.3 | 46.4 | 1,119 | 713 | 10.4 | 32.8 | 1,554 | 1,097 | 2.95 | 5.44 | 26.1 | 3,140 | 1,590 |
| W 24 × 131 | 370 | 12.4 | 39.3 | 1,110 | 713 | 10.5 | 29.1 | 1,542 | 1,097 | 2.97 | 6.70 | 35.6 | 2,330 | 5,290 |
| W 18 × 158 | 356 | 11.4 | 56.5 | 1,068 | 672 | 9.69 | 38.0 | 1,483 | 1,033 | 2.74 | 3.92 | 19.8 | 4,410 | 403 |
| **W 30 × 108** | **346** | **8.96** | **26.3** | **1,038** | **648** | **7.60** | **20.3** | **1,442** | **997** | **2.15** | **6.89** | **49.6** | **1,680** | **24,200** |
| W 27 × 114 | 343 | 9.08 | 28.2 | 1,029 | 648 | 7.71 | 21.3 | 1,429 | 997 | 2.18 | 5.41 | 42.5 | 2,100 | 9,220 |
| W 24 × 117 | 327 | 12.3 | 37.1 | 981 | 631 | 10.4 | 27.9 | 1,363 | 970 | 2.94 | 7.53 | 39.2 | 2,090 | 8,190 |
| W 21 × 122 | 307 | 12.2 | 41.0 | 921 | 592 | 10.3 | 29.8 | 1,279 | 910 | 2.92 | 6.45 | 31.3 | 2,630 | 3,160 |
| W 18 × 130 | 290 | 11.3 | 47.7 | 870 | 555 | 9.55 | 32.8 | 1,208 | 853 | 2.7 | 4.65 | 23.9 | 3,680 | 810 |
| **W 30 × 90** | **283** | **8.71** | **24.8** | **849** | **531** | **7.39** | **19.4** | **1,179** | **817** | **2.09** | **8.52** | **57.5** | **1,410** | **49,600** |
| W 24 × 103 | 280 | 8.29 | 27.0 | 840 | 531 | 7.04 | 20.0 | 1,167 | 817 | 1.99 | 4.59 | 39.2 | 2,390 | 5,310 |
| W 27 × 94 | 278 | 8.83 | 25.9 | 834 | 527 | 7.50 | 19.9 | 1,158 | 810 | 2.12 | 6.70 | 49.5 | 1,740 | 19,900 |
| W 14 × 145 | 260 | 16.6 | 81.6 | 780 | 503 | 14.1 | 54.7 | 1,083 | 773 | 3.98 | 7.11 | 16.8 | 4,400 | 348 |
| W 24 × 94 | 254 | 8.25 | 25.9 | 762 | 481 | 7.00 | 19.4 | 1,058 | 740 | 1.98 | 5.18 | 41.9 | 2,180 | 7,800 |



# Beam Design (revisited)

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

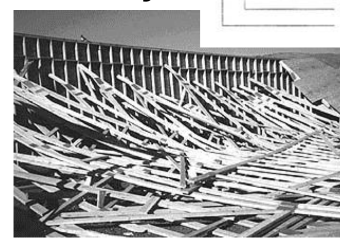
- it's dead load
- and repeat 3 & 4 if necessary




5. Consider lateral stability

*Unbraced roof trusses were blown down in 1999 at this project in Moscow, Idaho.*

*Photo: Ken Carper*





# Beam Design (revisited)

6. Evaluate shear stresses - horizontal

- $(V_a \le V_n/\Omega)$ or $(V_u \le \phi_v V_n)$
- rectangles and W's $\quad f_{v-max} = \dfrac{3V}{2A} \approx \dfrac{V}{A_{web}}$

$$V_n = 0.6\, F_{yw} A_w$$

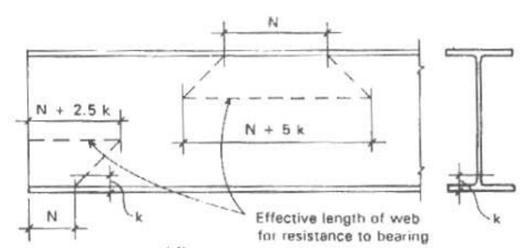
- general $\quad f_{v-max} = \dfrac{VQ}{Ib}$



# Beam Design (revisited)

7. Provide adequate bearing area at supports

$$(P_a \le P_n/\Omega)$$
$$(P_u \le \phi P_n)$$

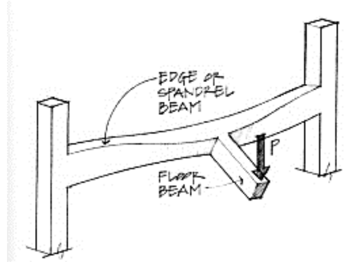



(d)

# Beam Design (revisited)

8. Evaluate torsion

$$\left( f_v \le F_v \right)$$




- circular cross section

$$f_v = \frac{T\rho}{J}$$

- rectangular

$$f_v = \frac{T}{c_1 ab^2}$$

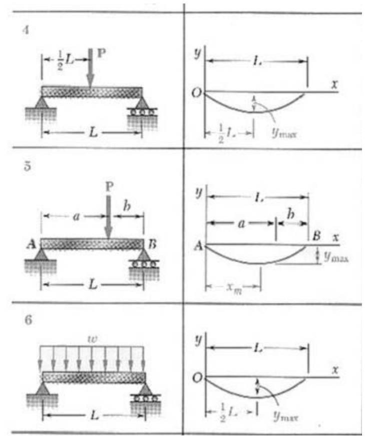
**TABLE 3.1. Coefficients for Rectangular Bars in Torsion**

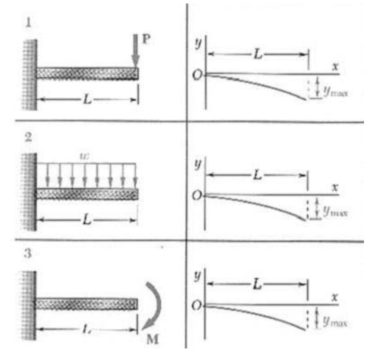
| $a/b$ | $c_1$ | $c_2$ |
|---|---|---|
| 1.0 | 0.208 | 0.1406 |
| 1.2 | 0.219 | 0.1661 |
| 1.5 | 0.231 | 0.1958 |
| 2.0 | 0.246 | 0.229 |
| 2.5 | 0.258 | 0.249 |
| 3.0 | 0.267 | 0.263 |
| 4.0 | 0.282 | 0.281 |
| 5.0 | 0.291 | 0.291 |
| 10.0 | 0.312 | 0.312 |
| ∞ | 0.333 | 0.333 |



# Beam Design (revisited)

9. Evaluate deflections – NO LOAD FACTORS





$$y_{\max}(x) = \Delta_{actual} \le \Delta_{allowable}$$



# Load Tables & Equivalent Load

- uniformly distributed loads
- equivalent "w"

$$M_{\max} = \frac{w_{equivalent} L^2}{8}$$

**LRFD**

STANDARD LOAD TABLE FOR OPEN WEB STEEL JOISTS, K-SERIES
Based on a 50 ksi Maximum Yield Strength - Loads Shown in Pounds per Linear Foot (plf)

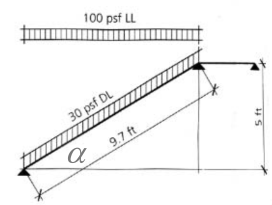
| Joist Designation | 8K1 | 10K1 | 12K1 | 12K3 | 12K5 | 14K1 | 14K3 | 14K4 | 14K6 | 16K2 | 16K3 | 16K4 | 16K5 | 16K6 | 16K7 | 16K9 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Depth (in.) | 8 | 10 | 12 | 12 | 12 | 14 | 14 | 14 | 14 | 16 | 16 | 16 | 16 | 16 | 16 | 16 |
| Approx. Wt (lbs./ft.) | 5.1 | 5.0 | 5.0 | 5.7 | 7.1 | 5.2 | 6.0 | 6.7 | 7.7 | 5.5 | 6.3 | 7.0 | 7.5 | 8.1 | 8.6 | 10.0 |
| Span (ft.) ▼ | | | | | | | | | | | | | | | | |
| 8 | 825 / 550 | | | | | | | | | | | | | | | |
| 9 | 825 / 550 | | | | | | | | | | | | | | | |
| 10 | 825 / 480 | 825 / 550 | | | | | | | | | | | | | | |
| 11 | 798 / 377 | 825 / 542 | | | | | | | | | | | | | | |
| 12 | 666 / 288 | 825 / 455 | 825 / 550 | 825 / 550 | 825 / 550 | | | | | | | | | | | |
| 13 | 565 / 225 | 718 / 363 | 825 / 510 | 825 / 510 | 825 / 510 | | | | | | | | | | | |
| 14 | 486 / 179 | 618 / 289 | 750 / 425 | 825 / 463 | 825 / 463 | 825 / 550 | 825 / 550 | 825 / 550 | 825 / 550 | | | | | | | |
| 15 | 421 / 145 | 537 / 234 | 651 / 344 | 814 / 428 | 825 / 434 | 766 / 475 | 825 / 507 | 825 / 507 | 825 / 507 | | | | | | | |
| 16 | 369 / 119 | 469 / 192 | 570 / 282 | 714 / 351 | 825 / 396 | 672 / 390 | 825 / 467 | 825 / 467 | 825 / 467 | 825 / 550 | 825 / 550 | 825 / 550 | 825 / 550 | 825 / 550 | 825 / 550 | 825 / 550 |
| 17 | | 415 / 159 | 504 / 234 | 630 / 291 | 825 / 366 | 592 / 324 | 742 / 404 | 825 / 443 | 825 / 443 | 768 / 488 | 825 / 526 | 825 / 526 | 825 / 526 | 825 / 526 | 825 / 526 | 825 / 526 |
| 18 | | 369 / 134 | 448 / 197 | 561 / 245 | 760 / 317 | 528 / 272 | 661 / 339 | 795 / 397 | 825 / 408 | 684 / 409 | 762 / 456 | 825 / 490 | 825 / 490 | 825 / 490 | 825 / 490 | 825 / 490 |
| 19 | | 331 / 113 | 402 / 167 | 502 / 207 | 681 / 269 | 472 / 230 | 592 / 287 | 712 / 336 | 825 / 383 | 612 / 347 | 682 / 386 | 820 / 452 | 825 / 455 | 825 / 455 | 825 / 455 | 825 / 455 |
| 20 | | 298 / 97 | 361 / 142 | 453 / 177 | 613 / 230 | 426 / 197 | 534 / 246 | 642 / 287 | 787 / 347 | 552 / 297 | 615 / 330 | 739 / 386 | 825 / 426 | 825 / 426 | 825 / 426 | 825 / 426 |
| 21 | | | 327 / 123 | 409 / 153 | 555 / 198 | 385 / 170 | 483 / 212 | 582 / 248 | 712 / 299 | 499 / 255 | 556 / 285 | 670 / 333 | 754 / 373 | 822 / 405 | 825 / 406 | 825 / 406 |
| 22 | | | 298 / 106 | 373 / 132 | 505 / 172 | 351 / 147 | 439 / 184 | 529 / 215 | 648 / 259 | 454 / 222 | 505 / 247 | 609 / 289 | 687 / 323 | 747 / 351 | 825 / 385 | 825 / 385 |
| 23 | | | 271 / 93 | 340 / 116 | 462 / 150 | 321 / 128 | 402 / 160 | 483 / 188 | 592 / 226 | 415 / 194 | 462 / 216 | 556 / 252 | 627 / 282 | 682 / 307 | 760 / 339 | 825 / 363 |

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:

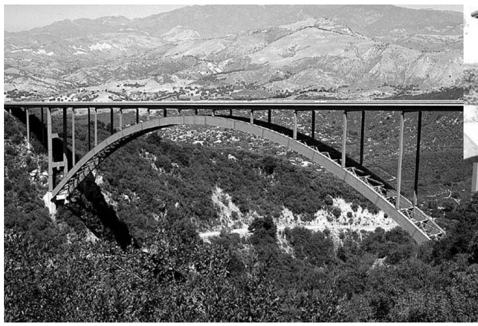
$$w_{\perp} = w \cdot \cos\alpha$$

- equivalent distributed load:

$$w_{adj.} = \frac{w}{\cos\alpha}$$

# Steel Arches and Frames

- *solid sections or open web*




http:// nisee.berkeley.edu/godden



# Steel Shell and Cable Structures



# Approximate Depths