Architecture 324

Structures II

Steel Beam Analysis

Part 1

- Steel Properties
- Steel Profiles
- Steel Codes: ASD vs. LRFD
- Analysis Method

Nomenclature of steel shapes

Standard section shapes:

W – wide flange

S – American standard beam

C – American standard channel

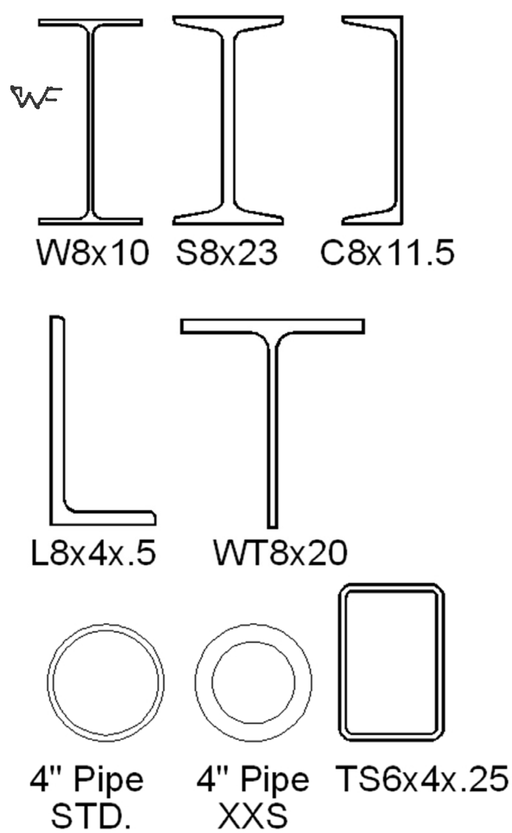
L – angle

WT or **ST** – structural T

STD, **XS** or **XXS** – Pipe

HSS – Hollow Structural Sections
Rectangular, Square, Round

LLBB , **SLBB** - Double Angles



Steel Grades – Rolled Sections

Different sections are made with different grades of steel.

Most structural shapes are:

A36 Carbon Steel Fy = 36ksi

A992 High Strength Fy = 50 ksi

Steel Typ	ASTM Designatio		F_y Min. Yield Stress (ksi)	F_u Tensile Stress[a] (ksi)	Applicable Shape Series: W	M	S	HP	C	MC	L	HSS Rect.	HSS Round	Pipe
Carbon	A36		36	58–80[b]	▒	■	■	▒	■	■	■			
	A53 Gr. B		35	60										■
	A500	Gr. B	42	58									■	
			46	58								■		
		Gr. C	46	62									▒	
			50	62								▒		
	A501	Gr. A	36	58								▒	▒	
		Gr. B	50	70								▒	▒	
	A529[c]	Gr. 50	50	65–100	▒	▒	▒	▒	▒	▒	▒			
		Gr. 55	55	70–100	▒	▒	▒	▒	▒	▒	▒			
High-Strength Low-Alloy	A572	Gr. 42	42	60	▒	▒	▒	▒	▒	▒	▒			
		Gr. 50	50	65[d]	▒	▒	▒	■	▒	▒	▒			
		Gr. 55	55	55	▒	▒	▒	▒	▒	▒	▒			
		Gr. 60[e]	60	60	▒	▒	▒	▒	▒	▒	▒			
		Gr. 65[e]	65	65	▒	▒	▒	▒	▒	▒	▒			
	A618[f]	Gr. I & II	50[g]	70[g]								▒	▒	
		Gr. III	50	50								▒	▒	
	A913	50	50[h]	60[h]	▒	▒	▒	▒	▒	▒	▒			
		60	60	75	▒	▒	▒	▒	▒	▒	▒			
		65	65	80	▒	▒	▒	▒	▒	▒	▒			
		70	70	90	▒	▒	▒	▒	▒	▒	▒			
	A992		50	65[i]	■	▒	▒	▒	▒	▒	▒			
Corrosion Resistant High-Strength Low-Alloy	A242		42[j]	63[j]	▒									
			46[k]	67[k]	▒			▒						
			50[l]	70[l]	▒	▒	▒	▒	▒	▒	▒			
	A588		50	70	▒	▒	▒	▒	▒	▒	▒			
	A847		50	70								▒	▒	

■ = Preferred material specification

▒ = Other applicable material specification, the availability of which should be confirmed prior to specification

☐ = Material specification does not apply

[a] Minimum unless a range is shown.

[b] For shapes over 426 lb/ft, only the minimum of 58 ksi applies.

[c] For shapes with a flange thickness less than or equal to 1½ in. only. To improve weldability, a maximum carbon equivalent can be specified (per ASTM Supplementary Requirement S78). If desired, maximum tensile stress of 90 ksi can be specified (per ASTM Supplementary Requirement S79).

[d] If desired, maximum tensile stress of 70 ksi can be specified (per ASTM Supplementary Requirement S91).

[e] For shapes with a flange thickness less than or equal to 2 in. only.

[f] ASTM A618 can also be specified as corrosion-resistant; see ASTM A618.

[g] Minimum applies for walls nominally ¾-in. thick and under. For wall thicknesses over ¾ in., F_y = 46 ksi and F_u = 67 ksi.

[h] If desired, maximum yield stress of 65 ksi and maximum yield-to-tensile strength ratio of 0.85 can be specified (per ASTM Supplementary Requirement S75).

[i] A maximum yield-to-tensile strength ratio of 0.85 and carbon equivalent formula are included as mandatory in ASTM A992.

[j] For shapes with a flange thickness greater than 2 in. only.

[k] For shapes with a flange thickness greater than 1½ in. and less than or equal to 2 in. only.

[l] For shapes with a flange thickness less than or equal to 1½ in. only.

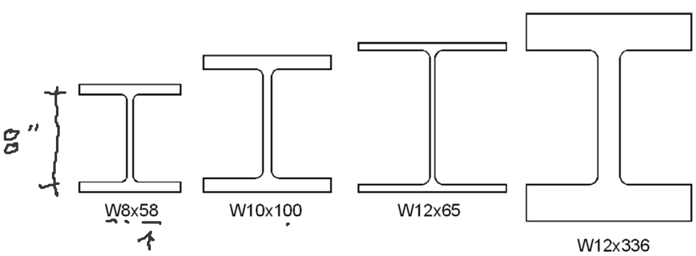
Source: AISC Manual, Table 2-4, p. 2-48, 14th ed, 2011.

Steel W-sections for beams and columns

Columns:

Closer to square

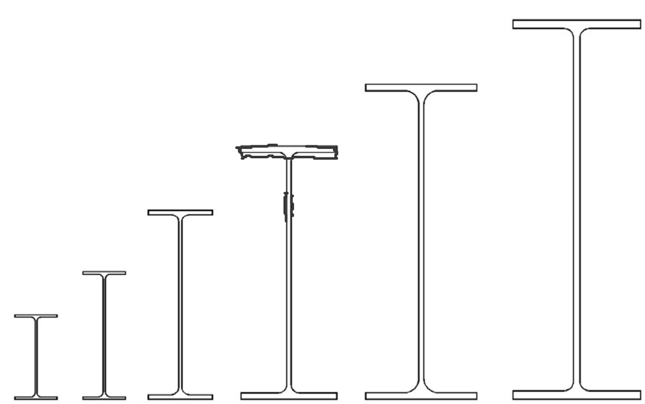
Thicker web & flange



Beams:

Deeper sections

Flange thicker than web



Steel W-sections for beams and columns

Columns:

Closer to square
Thicker web & flange

Beams:

Deeper sections
Flange thicker than web

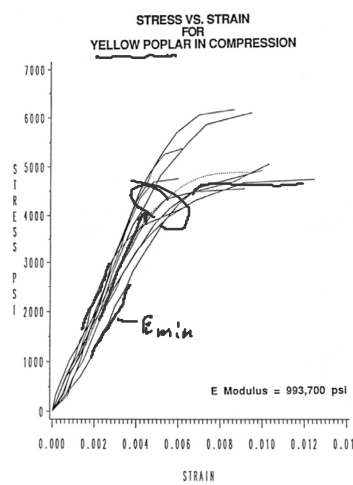
Photo by Gregor Y.

Young's Modulus

Young's Modulus or the Modulus of Elasticity, is obtained by dividing the stress by the strain present in the material. (Thomas Young, 1807)

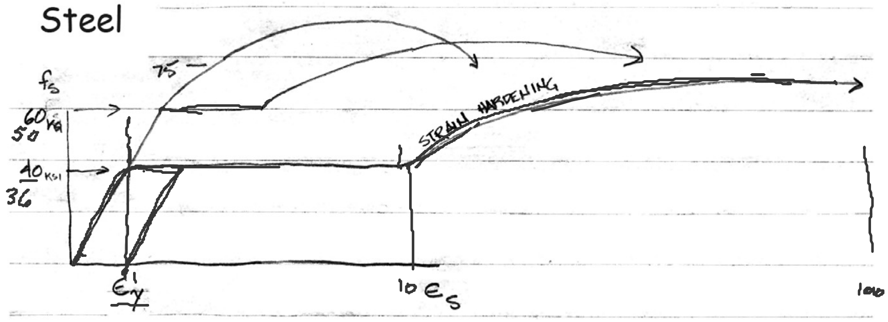
$$E = \frac{P/A}{D/L} = \frac{\sigma}{\varepsilon}$$

It thus represents a measure of the stiffness of the material.



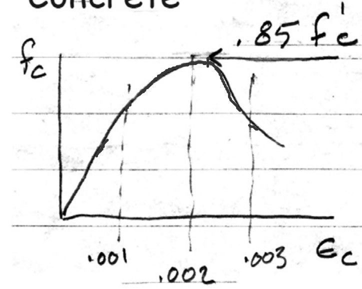
E = 1000 ksi

Steel



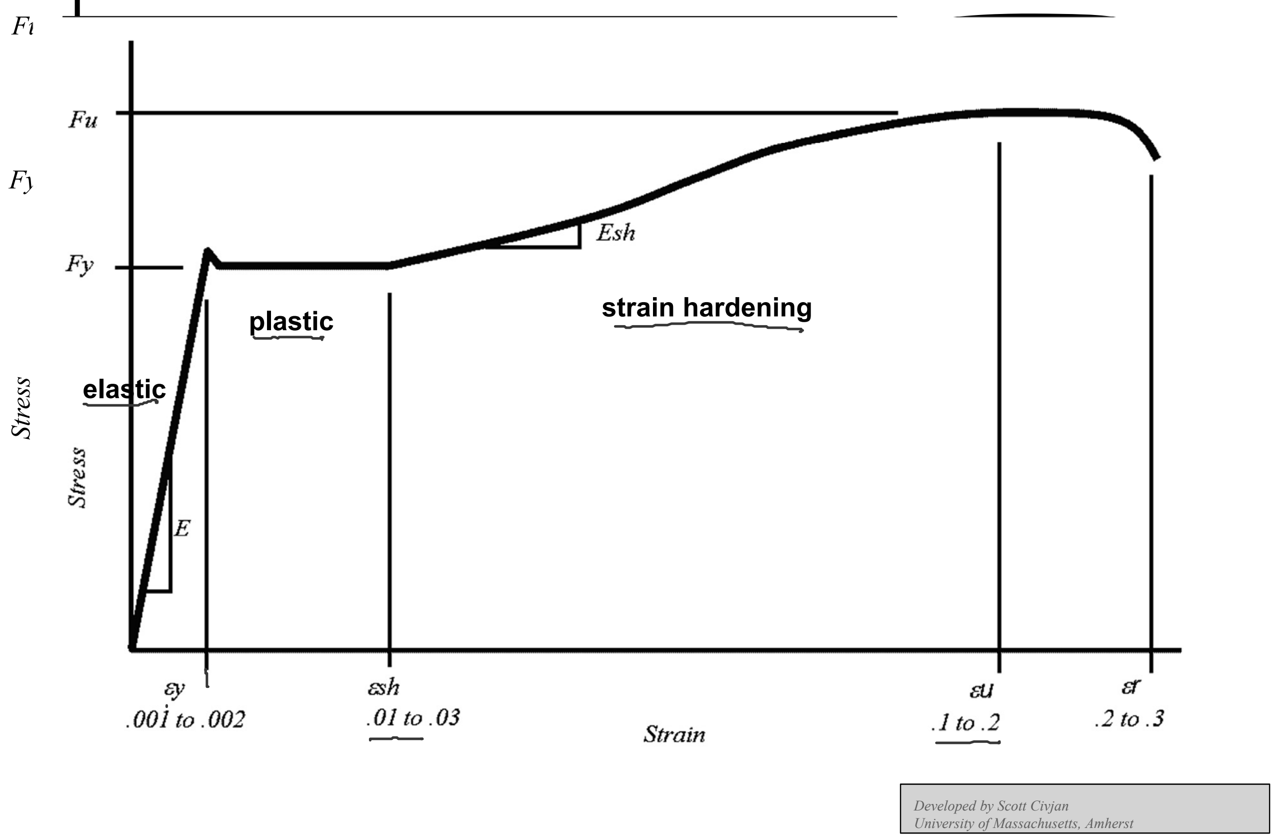
E = 29000 ksi

Concrete

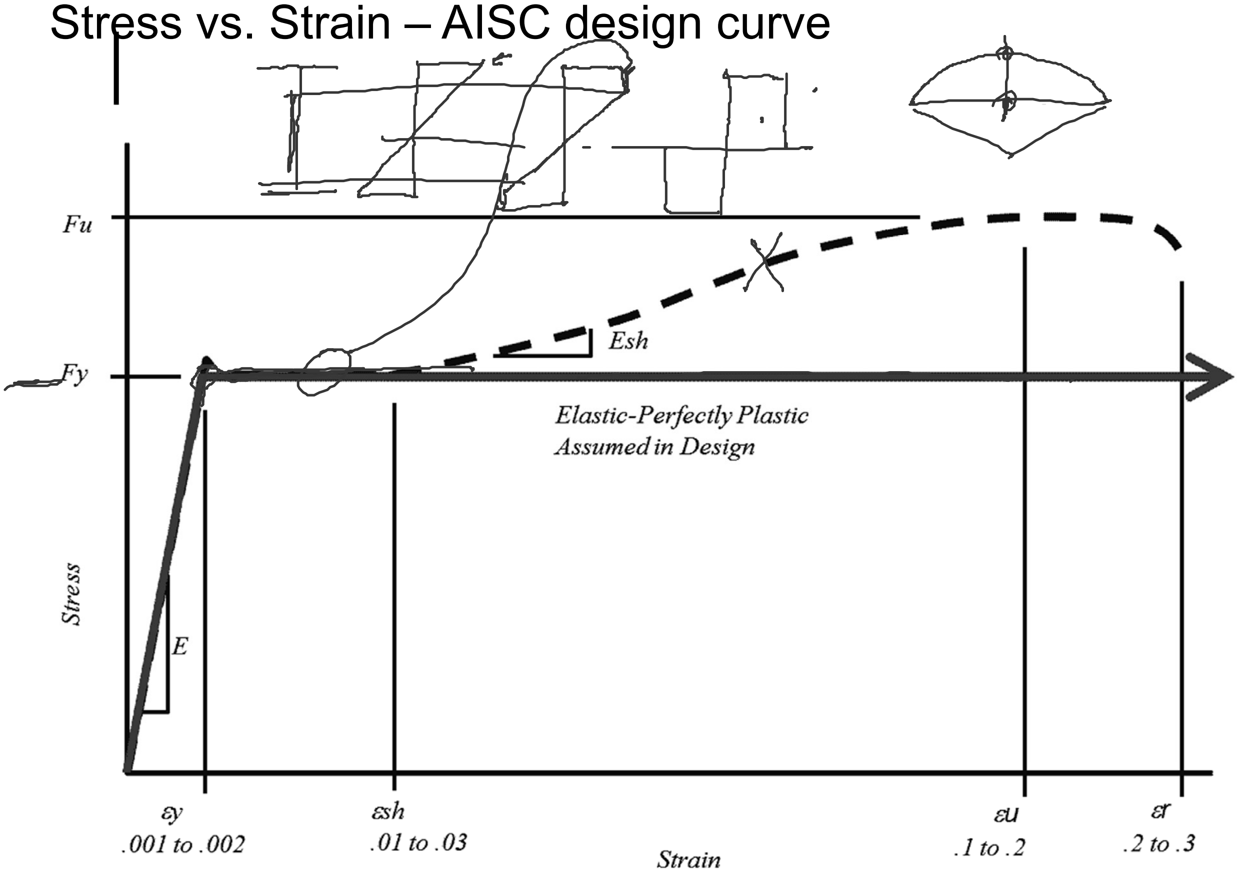


E = 3500 ksi

Stress vs. Strain – mild steel



Stress vs. Strain – AISC design curve



Stress Analysis – Two Methods

Allowable Stress Design (ASD)

- use design loads (no F.S. on loads)
- reduce stress by a Factor of Safety F.S.

$$f_{actual} = \frac{P}{A}$$

$$f_{actual} \leq F_{allowable}$$

$$F_{allowable} = F.S. \cdot f_{yield}$$

Load & Resistance Factored Design (LRFD)

- Use loads with safety factor γ
- Use factor on ultimate strength ϕ

$$P_{load} = \gamma \cdot P_{applied\_load}$$

$$P_{load} \leq P_{resisting}$$

$$P_{resisting} = \phi \cdot P_{material\_strength}$$

LRFD Analysis

Load & Resistance Factored Design (LRFD)

- Use loads with safety factor γ
- Use forces with strength factor ϕ

LOAD

STRENGTH

$$P_{load} = \gamma \cdot P_{applied}$$

$$P_{load} \leq P_{resisting}$$

$$P_{resisting} = \phi \cdot P_{material}$$

Design Strength $P_u \leq \phi\, P_n$ Required (Nominal) Strength

2.3 LOAD COMBINATIONS FOR STRENGTH DESIGN

γ

1. $1.4D$
2. $1.2D + 1.6L + 0.5(L_r \text{ or } S \text{ or } R)$
3. $1.2D + 1.6(L_r \text{ or } S \text{ or } R) + (L \text{ or } 0.5W)$
4. $1.2D + 1.0W + L + 0.5(L_r \text{ or } S \text{ or } R)$
5. $0.9D + 1.0W$

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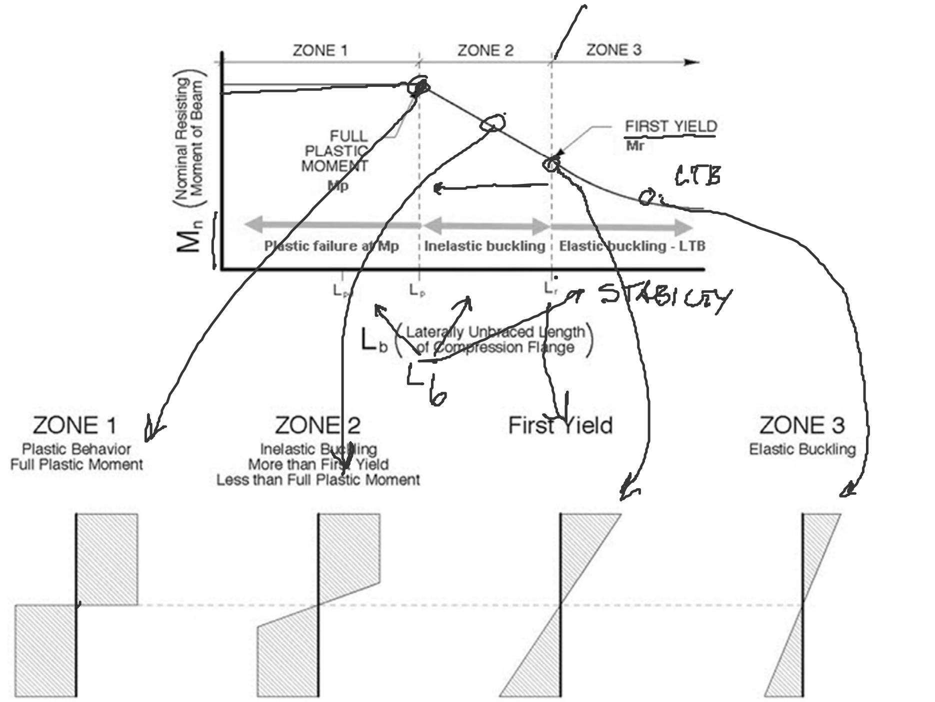
Beam Strength vs Unbraced Length



$M_n = M_p = F_y Z \leq 1.5 M_y$ — $M_u = \O_b M_n$

$M_n = C_b\left(M_p - (M_p - M_r)\left(\frac{L_b - L_p}{L_r - L_p}\right)\right) < M_p$ — $M_u = \O_b M_n$

$M_r = 0.7 F_y S_x$ — $M_u \leq \O_b M_r$

$M_{cr} = C_b \frac{\pi}{L_b} \sqrt{E I_y G J + \left(\frac{\pi E}{L_b}\right)^2 I_y C_w}$ — $M_u \leq \O_b M_{cr}$

(for doubly symmetric sections)

$\phi_b = 0.90$

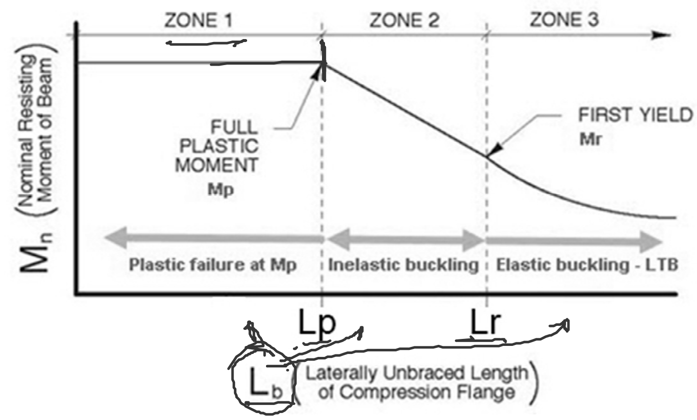
Steel Beams by LRFD

Yield Stress Values

- A36 Carbon Steel Fy = 36 ksi
- A992 High Strength Fy = 50 ksi

Elastic Analysis for Bending

- **Plastic Behavior (zone 1)**
  Mn = Mp = Fy Z < 1.5 My
  - Braced against LTB (Lb < Lp)
- **Inelastic Buckling "Decreased" (zone 2)**
  Mn = Cb(Mp-(Mp-Mr)[(Lb-Lp)/(Lr-Lp)] ≤ Mp
  - Lp < Lb < Lr
- **Elastic Buckling "Decreased Further" (zone 3)**
  Mcr = Cb * π/Lb √(E*Iy*G*J + (π*E/Lb)^2 * IyCw)
  - Lb > Lr

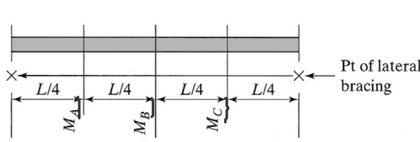


$L_p = 1.76\, r_y \sqrt{E/F_y}$

Mp = Fy Zx

Mr = 0.7 Fy Sx

Cb is LTB modification factor



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

Steel Beams by LRFD

Yield Stress Values

A36 Carbon Steel Fy = 36 ksi
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Analysis for Bending

- Plastic Behavior (zone 1)
  Mn = Mp = Fy Z < 1.5 My
  - Braced against LTB (Lb < Lp)
- Inelastic Buckling "Decreased" (zone 2)
  Mn = Cb(Mp-(Mp-Mr)[(Lb-Lp)/(Lr-Lp)] < Mp
  - Lp < Lb < Lr
- Elastic Buckling "Decreased Further" (zone 3)
  $M_{cr} = C_b \cdot \pi/L_b \sqrt{(E \cdot I_y \cdot G \cdot J + (\pi \cdot E/L_b)^2 \cdot I_y C_w)}$
  - Lb > Lr

Z_x **Table 3-2 (continued)**
W-Shapes
Selection by Z_x
F_y = 50 ksi

Shape	Z_x	M_{px}/Ω_b	$\phi_b M_{px}$	M_{rx}/Ω_b	$\phi_b M_{rx}$	BF/Ω_b	$\phi_b BF$	L_p	L_r	I_x	V_{nx}/Ω_v	$\phi_v V_{nx}$
		kip-ft	kip-ft	kip-ft	kip-ft	kips	kips				kips	kips
	in.^{3}	ASD	LRFD	ASD	LRFD	ASD	LRFD	ft	ft	in.^{4}	ASD	LRFD
W21×44	**95.4**	**238**	358	**143**	214	**11.1**	16.8	**4.45**	**13.0**	**843**	**145**	217
W16×50	92.0	230	345	141	213	7.69	11.4	5.62	17.2	659	124	186
W18×46	90.7	226	340	138	207	9.63	14.6	4.56	13.7	712	130	195
W14×53	87.1	217	327	136	204	5.22	7.93	6.78	22.3	541	103	154
W12×58	86.4	216	324	136	205	3.82	5.69	8.87	29.8	475	87.8	132
W10×68	85.3	213	320	132	199	2.58	3.85	9.15	40.6	394	97.8	147
W16×45	82.3	205	309	127	191	7.12	10.8	5.55	16.5	586	111	167
W18×40	**78.4**	**196**	294	**119**	180	**8.94**	13.2	**4.49**	**13.1**	**612**	**113**	169
W14×48	78.4	196	294	123	184	5.09	7.67	6.75	21.1	484	93.8	141
W12×53	77.9	194	292	123	185	3.65	5.50	8.76	28.2	425	83.5	125
W10×60	74.6	186	280	116	175	2.54	3.82	9.08	36.6	341	85.7	129
W16×40	**73.0**	**182**	274	**113**	170	**6.67**	10.0	**5.55**	**15.9**	**518**	**97.6**	146
W12×50	71.9	179	270	112	169	3.97	5.98	6.92	23.8	391	90.3	135
W8×67	70.1	175	263	105	159	1.75	2.59	7.49	47.6	272	103	154
W14×43	69.6	174	261	109	164	4.88	7.28	6.68	20.0	428	83.6	125
W10×54	66.6	166	250	105	158	2.48	3.75	9.04	33.6	303	74.7	112
W18×35	**66.5**	**166**	249	**101**	151	**8.14**	12.3	**4.31**	**12.3**	**510**	**106**	159
W12×45	64.2	160	241	101	151	3.80	5.80	6.89	22.4	348	81.1	122
W16×36	64.0	160	240	98.7	148	6.24	9.36	5.37	15.2	448	93.8	141
W14×38	61.5	153	231	95.4	143	5.37	8.20	5.47	16.2	385	87.4	131
W10×49	60.4	151	227	95.4	143	2.46	3.71	8.97	31.6	272	68.0	102
W8×58	59.8	149	224	90.8	137	1.70	2.55	7.42	41.6	228	89.3	134
W12×40	57.0	142	214	89.9	135	3.66	5.54	6.85	21.1	307	70.2	105
W10×45	54.9	137	206	85.8	129	2.59	3.89	7.10	26.9	248	70.7	106
W14×34	**54.6**	**136**	205	**84.9**	128	**5.01**	7.55	**5.40**	**15.6**	**340**	**79.8**	120
W16×31	**54.0**	**135**	203	**82.4**	124	**6.86**	10.3	**4.13**	**11.8**	**375**	**87.5**	131
W12×35	51.2	128	192	79.6	120	4.34	6.45	5.44	16.6	285	75.0	113
W8×48	49.0	122	184	75.4	113	1.67	2.55	7.35	35.2	184	68.0	102
W14×30	**47.3**	**118**	177	**73.4**	110	**4.63**	6.95	**5.26**	**14.9**	**291**	**74.5**	112
W10×39	46.8	117	176	73.5	111	2.53	3.78	6.99	24.2	209	62.5	93.7
W16×26[v]	**44.2**	**110**	166	**67.1**	101	**5.93**	8.98	**3.96**	**11.2**	**301**	**70.5**	106
W12×30	43.1	108	162	67.4	101	3.97	5.96	5.37	15.6	238	64.0	95.9

ASD	LRFD
$\Omega_b = 1.67$ $\Omega_v = 1.50$	$\phi_b = 0.90$ $\phi_v = 1.00$

[v] Shape does not meet the h/t_w limit for shear in AISC *Specification* Section G2.1(a) with F_y = 50 ksi; therefore, $\phi_v = 0.90$ and $\Omega_v = 1.67$.

American Institute of Steel Construction

AISC 15th ed.

Design for Shear

Shear stress in steel sections is approximated by averaging the stress in the web:

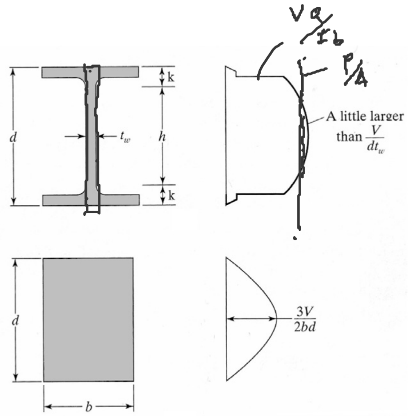
$F_v = V / A_w$

$A_w = d \cdot t_w$

To adjust the stress a reduction factor of 0.6 is applied to F_y

$F_v = 0.6\ F_y$

so, $V_n = 0.6\ F_y\ A_w$ **(Zone 1)**



The equations for the 3 stress zones:
(ϕ in all cases = 1.0)

Zone 1:
WEB YIELDING (Most beam sections fall into this category)

if $\frac{h}{t_w} \leq 2.45\sqrt{E/F_y} = 59$ (for 50 ksi steel)

then: $V_n = 0.6\ F_y\ A_w$

Zone 2:
INELASTIC WEB BUCKLING

if $2.45\sqrt{E/F_y} < \frac{h}{t_w} \leq 3.07\sqrt{E/F_y} = 74$ (for 50 ksi steel)

then: $V_n = 0.6\ F_y\ A_w\ (2.45\sqrt{E/F}\ ) / \frac{h}{t_w}$

Zone 3:
ELASTIC WEB BUCKLING

if $3.07\sqrt{E/F_y} < \frac{h}{t_w} \leq 260$

then: $V_n = A_w \left[\frac{4.25\ E}{\left(\frac{h}{t_w}\right)^2}\right]$

Design for Shear

Steel