New Method of Design for Combined Tension and Bending

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A new procedure and aids for design of steel members subjected to combined tension and bending have been developed based on the AISC *Specification for Structural Steel Buildings* (AISC, 2005a), hereafter referred to as the AISC Specification, using the load and resistance factor design (LRFD) method. This new design aid is included in the AISC *Steel Construction Manual* (AISC, 2005b), hereafter referred to as the AISC Manual. While the basic concepts utilized in this process apply to prismatic singly or doubly symmetric shapes subjected to flexure and axial tension, W-shapes are the primary focus of the discussion and the design aids presented here. The design aids offer the following advantages:

1. Time-saving. For example, compactness, L_b versus L_p and L_r, is already accounted for.
2. Allows selection of more efficient sections with appropriate t, b_x, and b_y coefficients depending on the relative magnitude of the applied axial force and bending moments.
3. Can choose from a wide range of sections.
4. Designer can easily judge the efficiency of a section by observing its values of t, b_x, and b_y coefficients.
5. Tables provide means for easy calculation of $\phi_t P_n$ for a large number of sections.

GENERAL LRFD SPECIFICATION REQUIREMENTS: t, b_x, AND b_y COEFFICIENTS

Section H1.2 of the AISC Specification states that doubly symmetric members and singly symmetric members constrained to bend about a geometric axis must satisfy Equations H1–1a and H1–1b of the AISC Specification. These formulas are repeated below as Equations 1 and 2, respectively.

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For $\dfrac{P_r}{P_c} \geq 0.2$

$$\frac{P_r}{P_c} + \left(\frac{8}{9}\right)\left(\frac{M_{rx}}{M_{cx}} + \frac{M_{ry}}{M_{cy}}\right) \leq 1.0 \tag{1}$$

For $\dfrac{P_r}{P_c} < 0.2$

$$\frac{P_r}{2P_c} + \left(\frac{M_{rx}}{M_{cx}} + \frac{M_{ry}}{M_{cy}}\right) \leq 1.0 \tag{2}$$

The definitions of the variables in Equations 1 and 2 based on the LRFD method are as follows:

P_r = required tensile strength using appropriate LRFD load combinations, kips (N)

P_c = $\phi_t P_n$ = design tensile strength, kips (N)

M_r = required flexural strength using appropriate LRFD load combinations, kip-in (N-mm)

M_c = $\phi_b M_n$ = design flexural strength, kip-in (N-mm)

As presented by Aminmansour (2000), Equations 1 and 2 may be written as Equations 3 and 4, respectively. These equations have been modified to reflect the new nomenclature used in the 2005 version of the AISC Specification (LRFD method) and the AISC Manual.

For $tP_u \geq 0.20$

$$tP_u + b_x M_{ux} + b_y M_{uy} \leq 1.0 \tag{3}$$

For $tP_u < 0.20$

$$0.5tP_u + \left(\frac{9}{8}\right)\left(b_x M_{ux} + b_y M_{uy}\right) \leq 1.0 \tag{4}$$

where

$$t = \frac{1}{\phi_t P_n} \tag{5}$$

$$b_x = \frac{8}{9\left(\phi_b M_{nx}\right)} \tag{6}$$

$$b_y = \frac{8}{9\left(\phi_b M_{ny}\right)} \tag{7}$$

It is observed from Equations 5 through 7 that coefficients t, b_x, and b_y depend on member design tensile strengths, design flexural strength about the x-axis, and design flexural strength about the y-axis, respectively. Coefficients b_x and b_y apply equally to members under tension and bending or compression and bending. Therefore, values of b_x and b_y given in Table 6–1 of the AISC Manual (pp. 6–5 to 6–95) may be used for design of members subjected to either combined tension and bending or compression and bending.

The reader is reminded that the numbers in the far left column of Table 6–1 of the AISC Manual indicate KL values for looking up the p coefficient for column action as well as L_b values for looking up the b_x coefficient for beam action. Values of the b_y coefficient for each section are based on section and material properties only and do not depend on any length. They are given at the bottom of Table 6–1 of the AISC Manual along with other useful information.

For members subjected to tension and bending, the t coefficient given in Equation 5 is a function of $\phi_t P_n$, the design tensile strength of the member. There are two design strengths for tension members, $\phi_t P_{ny}$ and $\phi_t P_{nr}$, determined based on the limit states of yielding and rupturing, respectively. Therefore, each section will have two t values: one based on $\phi_t P_{ny}$ and one based on $\phi_t P_{nr}$. They will be referred to here as t_y and t_r and are defined below.

$$t_y = \frac{1}{\phi_t P_{ny}} = \frac{1}{0.9 A_g F_y} \tag{8}$$

$$t_r = \frac{1}{\phi_t P_{nr}} = \frac{1}{0.75 A_e F_u} \tag{9}$$

Theoretically, in order to investigate the adequacy of a given section subjected to combined tension and bending, one must use both t_y and t_r as t in Equation 3 or 4. Alternatively, one may simply use the larger of t_y and t_r as t in those equations.

With the appropriate information available, values of t_y and t_r may be calculated and tabulated for different sections. Table 1 (tables begin on page 285) lists numerical values of t_y and t_r for W-sections in Grades 36 and 50 steels. It should be noted that values of t_r listed in this table are determined based on an estimated effective net area of $0.75A_g$. Therefore, actual values of t_r must be calculated and used for each section. This practice is consistent with the procedures outlined in Part 5 of the AISC Manual for design of tension members.

As noted earlier, numerical values of coefficients b_x and b_y given in Table 6–1 of the AISC Manual apply to both combined tension and bending as well as compression and bending. The following observations are noted in using tabulated values of b_x and b_y:

1. Values of the coefficient b_x are based on L_b, the laterally unbraced length for bending about the strong axis.

2. Values of b_x listed already account for L_b versus L_p and L_r for the sections listed.

3. Compact/noncompactness for bending about the x- and y-axes has already been accounted for in developing values of b_x and b_y.

4. Since lateral torsional buckling is not an applicable limit state for bending W-sections about their weak axis, b_y values listed in the tables are unique to each section (and steel type) and do not depend on any length.

5. Values of coefficients t, b_x, and b_y listed in Table 1 of this paper as well as Table 6–1 of the AISC Manual are magnified by 1,000 to avoid excessive decimals in the tables. Tabulated values must be multiplied by 10^{-3} before use.

ANALYSIS OF MEMBERS SUBJECT TO TENSION AND BENDING

A steel member subject to tension and bending is adequate per the AISC Specification if it satisfies Equation 3 or 4, whichever is applicable. It is noted that for members subject to tension and bending, the coefficient t in these equations represents the larger of t_y and t_r given in Table 1 of this paper as well as in Part 6 of the AISC Manual. Values of b_x and b_y may be obtained from Table 6–1 of the AISC Manual. In using Equations 3 and 4 for members subject to tension and bending, M_{ux} and M_{uy} may be considered as the calculated factored moments, and the potential benefits from second order effects may be neglected.

Procedures for Analysis of Members Subject to Tension and Bending

The following procedure is for analysis of members subject to combined tension and bending:

1. Obtain the value of t_y from Table 1 of this paper or Table 6–1 of the AISC Manual. Calculate the exact value of t_r. Use the larger of t_y and t_r as t in Equations 3 or 4.

2. Obtain the values of the b_x and b_y coefficients from Table 6–1 of the AISC Manual.

3. Solve Equation 3 or 4, whichever appropriate, to check compliance with the AISC Specification.

EXAMPLE 1

Given

Use a W10×26 of ASTM A 992 steel; assume tension yielding controls.

1. P_u = 65 kips, M_{ux} = 0, M_{uy} = 20 kip-ft
2. P_u = 160 kips, M_{ux} = 65 kip-ft, M_{uy} = 0, L_b = 4.0 ft, C_b = 1.0.

Find

Using LRFD, determine if the section meets the AISC Specification requirements for combined tension and bending for each case.

Solution

Obtain the following information for a W10×26 of Grade 50 steel.

From Table 1 of this paper (or Table 6–1 of the AISC Manual),

$t_y = 2.92 \times 10^{-3}$ kips^{-1}; t_r is not needed since tension yielding controls.

Use $t = t_y = 2.92 \times 10^{-3}$ kips^{-1}

From Table 6–1 of the AISC Manual,

$b_x = 7.57 \times 10^{-3}$ (kip-ft)$^{-1}$ at L_b = 4.0 ft,

and $b_y = 31.6\times10^{-3}$ (kip-ft)$^{-1}$.

Case A

$tP_u = (2.92 \times 10^{-3}$ kips$^{-1})(65$ kips)

$= 0.190 < 0.20$ ➔ use Equation 4

$$0.5tP_u + \left(\frac{9}{8}\right)\left(b_x M_{ux} + b_y M_{uy}\right)$$

$$= 0.5(0.190) + \left(\frac{9}{8}\right)\left\{0 + \left[31.6\times10^{-3}\,(\text{kip-ft})^{-1}\right](20\text{ kip-ft})\right\}$$

$$= 0.095 + 0 + 0.711 = 0.806 < 1.00$$

Therefore, W10×26, ASTM A 992 is adequate for the given conditions.

Case B

$tP_u = (2.92\times10^{-3}$ kips$^{-1})(160$ kips)

$= 0.467 > 0.20$ ➔ use Equation 3.

$$tP_u + b_x M_{ux} + b_y M_{uy} =$$

$$0.467 + \left[7.57\times10^{-3}\,(\text{kip-ft})^{-1}\right](65\text{ kip-ft}) + 0 =$$

$$0.467 + 0.492 + 0 = 0.959 < 1.00$$

Therefore, W10×26, ASTM A 992 is adequate for the given conditions.

Since the beam is braced, C_b does not apply.

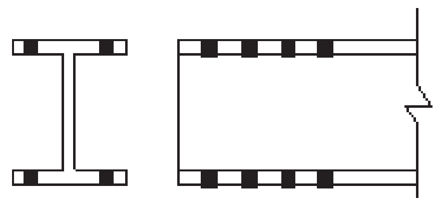
As the reader recalls, the numerical values of tP_u, b_xM_{ux}, and b_yM_{uy} in the interaction Equations 3 and 4 are approximate measures of the relative magnitude of the axial and flexural strengths of the member used.

EXAMPLE 2

Given

Use a W10×49 of ASTM A 992 steel connected as shown with ⅞ in. bolts at 3 in. o.c.

P_u = 100 kips, M_{ux} = 160 kip-ft, M_{uy} = 25 kip-ft, L_b = 12 ft, C_b = 1.0.



Find

Determine if the section meets the AISC Specification for combined tension and bending. Consider member strength only.

Solution

Obtain the following information for a W10×49.

From Table 1–1 of the AISC Manual, A_g = 14.4 in.^{2}, and t_f = 0.560 in.

From Table 1 of this paper (or Table 6–1 of the AISC Manual), $t_y = 1.54 \times 10^{-3}$ kips^{-1}.

From Table 6–1 of the AISC Manual, $b_x = 4.13 \times 10^{-3}$ (kip-ft)$^{-1}$ and $b_y = 8.38 \times 10^{-3}$ (kip-ft)$^{-1}$.

From Table 1–8 of the AISC Manual, $\bar{y} = 0.807$ in. for a WT5×24.5.

A_n = 14.4 in.^{2} – (4 holes)(⅞ in.+ ⅛ in.)(0.560 in.) = 12.2 in.^{2}

Calculate U, the shear lag factor, as defined in Table D3.1, Case 2, of the AISC Specification, using $\bar{x} = \bar{y} = 0.807$.

$U = 1 - \dfrac{\bar{x}}{l} = 1 - \dfrac{0.807\text{ in.}}{9.00\text{ in.}} = 0.910$ (note that the 0.90 upper limit for U is no longer part of the AISC Specification)

$A_e = A_nU$ = (12.2 in.^{2})(0.910) = 11.1 in.^{2}

From Equation 9,

$$t_r = \frac{1}{\phi_t P_{n2}} = \frac{1}{0.75 A_e F_u} = \frac{1}{0.75\left(11.1 \text{ in.}^2\right)\left(65 \text{ ksi}\right)}$$
$$= 1.85 \times 10^{-3} \text{ kip}^{-1}$$

$t_y = 1.54 \times 10^{-3}$ kips^{-1}, $t_r = 1.85 \times 10^{-3}$ kips^{-1}

➔ use $t = t_r = 1.85 \times 10^{-3}$ kips^{-1}.

$tP_u = (1.85 \times 10^{-3} \text{ kips}^{-1})(100 \text{ kips}) = 0.185 < 0.200$

➔ use Equation 4.

Check provisions of Section F13 of the AISC Specification for hole reduction and its potential impact on the b_x coefficient.

$$A_{fn} = \left(t_f\right)\left[b_f - 2\left(⅞ \text{ in.} + ⅛ \text{ in.}\right)\right]$$
$$= (0.560 \text{ in.})[10.0 \text{ in.} - 2(1.00 \text{ in.})] = 4.48 \text{ in.}^2$$
$$A_{fg} = \left(t_f\right)\left(b_f\right) = (0.560 \text{ in.})(10.0 \text{ in.}) = 5.60 \text{ in.}^2$$
$$\frac{F_y}{F_u} = \frac{(50 \text{ ksi})}{(65 \text{ ksi})} = 0.769 < 0.80 \rightarrow Y_t = 1.0$$
$$F_u A_{fn} = (65 \text{ ksi})\left(4.48 \text{ in.}^2\right) = 291 \text{ kips}$$
$$Y_t F_y A_{fg} = (1.0)(50 \text{ ksi})\left(5.60 \text{ in.}^2\right) = 280 \text{ kips}$$

$$F_u A_{fn} = 291 \text{ kips} > Y_t F_y A_{fg} = 280 \text{ kips}$$

Therefore, the limit state of flexural rupture does not apply and the b_x coefficient remains unchanged.

$$0.5tP_u + \left(\frac{9}{8}\right)\left(b_x M_{ux} + b_y M_{uy}\right)$$
$$= (0.5)(0.185) + \left(\frac{9}{8}\right)\left\{\left[4.13 \times 10^{-3} (\text{kip-ft})^{-1}\right](160 \text{ kip-ft})\right.$$
$$\left. + \left[8.38 \times 10^{-3} (\text{kip-ft})^{-1}\right](25 \text{ kip-ft})\right\}$$
$$= 0.093 + 0.743 + 0.236 = 1.07 > 1.00$$

Therefore, W10 × 49, ASTM A 992 is not adequate for the given conditions.

It can be verified that W10 × 49 is a compact section in ASTM A 992 steel. Further, for this member, $L_p = 8.97$ ft < $L_b = 12$ ft < $L_r = 31.6$ ft (see Table 3–2 on page 3–18 of the AISC Manual). But, these facts are already accounted for in determining the b_x values listed in Table 6–1 of the AISC Manual.

Note: If $F_u A_{fn} < Y_t F_y A_{fg}$ then the b_x coefficient should be calculated using provisions of Section F13.1b of the AISC Specification and Equation 6.

DESIGN OF MEMBERS SUBJECT TO TENSION AND BENDING

Design of members subject to tension and bending is a trial-and-error process in which a trial section is selected based on the given conditions. The trial section is then checked for compliance with Equation 3 or 4, whichever is appropriate. This process may be carried out until the most appropriate section is found.

In order to select a trial section, one may use initial estimates for coefficients t, b_x, and b_y. Table 2 of this paper gives estimates for the t coefficient for W-sections. Exact values of t_y and estimated values of t_r are given in Table 1 of this paper as well as Table 6–1 of the AISC Manual for W-sections. Values of b_x and b_y coefficients are given in Table 6–1 of the AISC Manual.

Procedures for Design of Members Subject to Tension and Bending

The following procedure is for design of members subject to combined tension and bending. Note that in early stages of design of a member subjected to tension, with or without bending, it is typically not known whether the limit state of yielding or rupture controls the design. However, it is reasonable to initially assume yielding controls to allow use of t_y for the t coefficient. Once a trial section is chosen, this assumption will need to be checked for correctness. The procedure is:

1. Obtain estimates for coefficients t, b_x, and b_y.

   a. If relatively large axial load is present, obtain an estimate for b_x from Table 6–1 of the AISC Manual.

   b. If relatively large bending moment about the x-axis is present, obtain a median t value from Table 2 of this paper.

   c. If there is bending about the weak axis, obtain an estimate for b_y from Table 6–1 of the AISC Manual as well.

2. Solve Equation 3 or 4, whichever is appropriate, to calculate an estimate for the remaining unknown coefficient (t coefficient for case "a" and b_x for case "b" above).

3. Consider Table 1 of this paper or Table 6–1 of the AISC Manual and select a trial section based on the t, b_x, and b_y values obtained above.

4. Check the trial section for compliance with Equation 3 or 4.

5. Continue steps 3 and 4 until a satisfactory section is found.

It is noted that this process converges very quickly. Therefore, the designer is encouraged to not spend much time in obtaining a "better" trial section.

Considerations for Selecting Trial Sections

The following observations are helpful in selecting sections with more appropriate values of t, b_x, and b_y. For better comprehension of the following observations, consider the mathematical relationships expressed in Equations 3 and 4.

1. Sections with smaller coefficients t, b_x, and b_y are more effective and thus more desirable. For instance, a section that has a t value half of that of another section can carry twice the axial load. The same concept applies to b_x and b_y coefficients.

2. When a "relatively large" axial load is present, a section with a smaller t value is more effective overall, though it may have a larger b_x value. Similarly, in the case of a relatively large bending moment about the x-axis, a section with a smaller b_x value may be more desirable, though t may be larger than desired. The goal is to minimize the portion of Equation 3 or 4 with a larger overall value.

3. Assuming no restrictions on the section depth, deeper sections may be more effective when subjected to relatively large bending moment about the x-axis.

EXAMPLE 3

Given

Use a W-section with welded end connection and maximum moments occurring at mid-span.

P_u = 450 kips in tension

M_{ux} = 85 kip-ft

M_{uy} = 25 kip-ft

L_b = 15 ft

C_b = 1.0

Assume tension yielding controls.

Find

Select the lightest W10 of ASTM A 992 steel for the given conditions.

Solution

The axial load seems relatively large. Therefore, use estimates for b_x and b_y.

Use $b_{x(est.)}$ = 5.50 × 10^{-3} (kip-ft)$^{-1}$ and $b_{y(est.)}$ = 13.0 × 10^{-3} (kip-ft)$^{-1}$.

Assume tP_u > 0.20, solve for $t_{est.}$ using Equation 3.

$t_{est.}$(450 kips) + [5.50 × 10^{-3} (kip-ft)$^{-1}$](85 kip-ft) + [13.0 × 10^{-3} (kip-ft)$^{-1}$](25 kip-ft) = 1.00

Therefore, $t_{est.}$ = 0.461 × 10^{-3} kips^{-1}.

From Table 1 of this paper and/or Table 6–1 of the AISC Manual, obtain a trial W10 section keeping in mind the considerations discussed earlier for selecting a trial section. Recall that for combined tension and bending, t represents the larger of t_y and t_r.

Try W10×60 (has a larger t value, but much smaller b_x and b_y values—may still work).

Obtain the following information for a W10×60.

From Table 1 of this paper (or Table 6–1 of the AISC Manual), t_y = 1.26 × 10^{-3} kips^{-1}.

From Table 6–1 of the AISC Manual, b_x = 3.46 × 10^{-3} (kip-ft)$^{-1}$ and b_y = 6.77 × 10^{-3} kips^{-1}.

Use $t = t_y$ = 1.26 × 10^{-3} kips^{-1} (tension yielding controls; t_r does not apply).

tP_u = (1.26 × 10^{-3} kips^{-1})(450 kips) = 0.567 > 0.200

➔ use Equation 3.

$$
\begin{aligned}
&tP_u + b_x M_{ux} + b_y M_{uy}\\
&= 0.567 + \left[3.46\times10^{-3}\left(\text{kip-ft}\right)^{-1}\right]\left(85\text{ kip-ft}\right)\\
&\quad + \left[6.77\times10^{-3}\left(\text{kip-ft}\right)^{-1}\right]\left(25\text{ kip-ft}\right)\\
&= 0.567 + 0.294 + 0.169 = 1.03 > 1.00
\end{aligned}
$$

W10×60 is not adequate for the given conditions.

Note: The value of 0.567 for tP_u versus 0.294 and 0.169 for b_xM_{ux} and b_yM_{uy} confirms our initial assumption that the axial load is relatively large in this case.

Try W10×68.

Obtain the following information for a W10×68.

From Table 1 of this paper and/or Table 6–1 of the AISC Manual, t_y = 1.11 × 10^{-3} kips^{-1}, b_x = 2.99 × 10^{-3} (kip-ft)$^{-1}$, and b_y = 5.91 × 10^{-3} kips^{-1}.

Use $t = t_y$ = 1.11 × 10^{-3} kips^{-1}.

tP_u = (1.11 × 10^{-3} kips^{-1})(450 kips) = 0.500 > 0.200

➔ use Equation 3.

$$
\begin{aligned}
&tP_u + b_x M_{ux} + b_y M_{uy}\\
&= 0.500 + \left[2.99\times10^{-3}\left(\text{kip-ft}\right)^{-1}\right]\left(85\text{ kip-ft}\right)\\
&\quad + \left[5.91\times10^{-3}\left(\text{kip-ft}\right)^{-1}\right]\left(25\text{ kip-ft}\right)\\
&= 0.500 + 0.254 + 0.148 = 0.902 < 1.00
\end{aligned}
$$

Therefore, W10×68 is adequate.

Use W10×68, ASTM A 992 steel.

In both cases, compactness and L_b versus L_p and L_r have been accounted for through values of coefficients listed in Table 6–1 of the AISC Manual.

ADDITIONAL BENEFITS OF COEFFICIENTS

Use of coefficients b_x and b_y given in Table 6–1 of the AISC Manual offer additional benefits including easy calculation of $\phi_b M_{nx}$, and $\phi_b M_{ny}$ for beams. See Aminmansour (2000) for more information and examples. Values of t_y and t_r offered in Table 1 of this paper and Table 6–1 of the AISC Manual allow easy calculation of $\phi_t P_n$ for tension members by simply using Equation 8 or 9.

REFERENCES

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Table 1. Values of t_y and t_r for W-Sections ($kips^{-1}$)*

Section	F_y = 36 ksi		F_y = 50 ksi		Section	F_y = 36 ksi		F_y = 50 ksi	
	t_y x10^3	t_r x10^3	t_y x10^3	t_r x10^3		t_y x10^3	t_r x10^3	t_y x10^3	t_r x10^3
W44x335	0.313	0.311	0.226	0.278	W36x256	0.409	0.407	0.295	0.363
W44x290	0.361	0.359	0.260	0.320	W36x232	0.453	0.450	0.326	0.402
W44x262	0.401	0.399	0.289	0.356	W36x210	0.499	0.496	0.360	0.443
W44x230	0.456	0.453	0.328	0.404	W36x194	0.541	0.538	0.390	0.480
W40x593	0.177	0.176	0.128	0.157	W36x182	0.576	0.572	0.415	0.510
W40x503	0.209	0.207	0.150	0.185	W36x170	0.616	0.612	0.444	0.546
W40x431	0.243	0.241	0.175	0.215	W36x160	0.657	0.652	0.473	0.582
W40x397	0.264	0.262	0.190	0.234	W36x150	0.698	0.693	0.503	0.619
W40x372	0.283	0.281	0.204	0.251	W36x135	0.777	0.772	0.560	0.689
W40x362	0.288	0.286	0.208	0.256	W33x387	0.271	0.269	0.195	0.240
W40x324	0.324	0.322	0.233	0.287	W33x354	0.297	0.295	0.214	0.263
W40x297	0.353	0.351	0.254	0.313	W33x318	0.330	0.327	0.237	0.292
W40x277	0.379	0.377	0.273	0.336	W33x291	0.360	0.358	0.259	0.319
W40x249	0.421	0.418	0.303	0.373	W33x263	0.398	0.396	0.287	0.353
W40x215	0.487	0.483	0.351	0.431	W33x241	0.435	0.432	0.313	0.385
W40x199	0.528	0.524	0.380	0.468	W33x221	0.473	0.470	0.341	0.419
W40x392	0.268	0.267	0.193	0.238	W33x201	0.521	0.518	0.375	0.462
W40x331	0.317	0.314	0.228	0.281	W33x169	0.624	0.619	0.449	0.553
W40x327	0.322	0.319	0.231	0.285	W33x152	0.689	0.684	0.496	0.611
W40x294	0.358	0.355	0.257	0.317	W33x141	0.742	0.737	0.534	0.657
W40x278	0.376	0.374	0.271	0.334	W33x130	0.806	0.800	0.580	0.714
W40x264	0.398	0.395	0.286	0.352	W33x118	0.889	0.883	0.640	0.788
W40x235	0.447	0.444	0.322	0.396	W30x391	0.268	0.267	0.193	0.238
W40x211	0.498	0.494	0.358	0.441	W30x357	0.294	0.292	0.212	0.260
W40x183	0.579	0.575	0.417	0.513	W30x326	0.322	0.320	0.232	0.285
W40x167	0.627	0.623	0.452	0.556	W30x292	0.359	0.357	0.259	0.318
W40x149	0.705	0.700	0.507	0.624	W30x261	0.401	0.399	0.289	0.356
W36x800	0.131	0.130	0.094	0.116	W30x235	0.446	0.443	0.321	0.395
W36x652	0.161	0.160	0.116	0.142	W30x211	0.496	0.493	0.357	0.440
W36x529	0.198	0.196	0.142	0.175	W30x191	0.548	0.544	0.395	0.486
W36x487	0.216	0.214	0.155	0.191	W30x173	0.605	0.601	0.436	0.536
W36x441	0.237	0.236	0.171	0.210	W30x148	0.710	0.705	0.511	0.629
W36x395	0.266	0.264	0.192	0.236	W30x132	0.793	0.788	0.571	0.703
W36x361	0.291	0.289	0.210	0.258	W30x124	0.846	0.840	0.609	0.749
W36x330	0.318	0.316	0.229	0.282	W30x116	0.902	0.896	0.650	0.800
W36x302	0.348	0.345	0.250	0.308	W30x108	0.974	0.967	0.701	0.863
W36x282	0.372	0.370	0.268	0.330	W30x99	1.06	1.05	0.764	0.940
W36x262	0.401	0.398	0.289	0.355	W30x90	1.17	1.16	0.842	1.036
W36x247	0.426	0.423	0.307	0.377	W27x539	0.194	0.193	0.140	0.172
W36x231	0.453	0.450	0.326	0.402	W27x368	0.286	0.284	0.206	0.253

*t_r values estimated assuming $A_e = 0.75A_g$

Table 1 (cont.). Values of t_y and t_r for W-Sections (kips^{-1})*

Section	F_y = 36 ksi		F_y = 50 ksi		Section	F_y = 36 ksi		F_y = 50 ksi	
	t_y x10^3	t_r x10^3	t_y x10^3	t_r x10^3		t_y x10^3	t_r x10^3	t_y x10^3	t_r x10^3
W27x336	0.312	0.310	0.225	0.277	W21X132	0.795	0.790	0.573	0.705
W27x307	0.341	0.339	0.246	0.303	W21X122	0.860	0.854	0.619	0.762
W27x281	0.372	0.370	0.268	0.330	W21X111	0.944	0.937	0.680	0.836
W27x258	0.406	0.403	0.292	0.360	W21X101	1.04	1.03	0.746	0.918
W27x235	0.445	0.442	0.320	0.394	W21X93	1.13	1.12	0.814	1.002
W27x217	0.482	0.479	0.347	0.427	W21X83	1.27	1.26	0.914	1.126
W27x194	0.540	0.536	0.389	0.478	W21X73	1.44	1.43	1.03	1.272
W27x178	0.588	0.584	0.423	0.521	W21X68	1.54	1.53	1.11	1.368
W27x161	0.648	0.644	0.467	0.575	W21X62	1.69	1.67	1.21	1.495
W27x146	0.716	0.711	0.516	0.635	W21X55	1.91	1.89	1.37	1.688
W27x129	0.817	0.811	0.588	0.724	W21X48	2.19	2.17	1.58	1.940
W27x114	0.921	0.915	0.663	0.816	W21X57	1.85	1.84	1.33	1.638
W27x102	1.03	1.02	0.741	0.912	W21X50	2.10	2.09	1.51	1.861
W27x94	1.11	1.11	0.802	0.987	W21X44	2.37	2.36	1.71	2.104
W27x84	1.245	1.236	0.896	1.103	W18x311	0.337	0.335	0.243	0.299
W24x370	0.283	0.281	0.204	0.251	W18x283	0.371	0.368	0.267	0.328
W24x335	0.314	0.311	0.226	0.278	W18x258	0.407	0.404	0.293	0.360
W24x306	0.344	0.341	0.247	0.305	W18x234	0.449	0.446	0.323	0.398
W24x279	0.376	0.374	0.271	0.334	W18x211	0.497	0.494	0.358	0.440
W24x250	0.420	0.417	0.302	0.372	W18x192	0.547	0.543	0.394	0.485
W24x229	0.459	0.456	0.331	0.407	W18x175	0.602	0.597	0.433	0.533
W24x207	0.508	0.505	0.366	0.451	W18x158	0.667	0.662	0.480	0.591
W24x192	0.548	0.544	0.395	0.486	W18x143	0.733	0.728	0.528	0.650
W24x176	0.597	0.593	0.430	0.529	W18x130	0.808	0.802	0.582	0.716
W24x162	0.647	0.643	0.466	0.573	W18x119	0.879	0.873	0.633	0.779
W24x146	0.718	0.713	0.517	0.636	W18x106	0.992	0.986	0.715	0.879
W24x131	0.802	0.796	0.577	0.710	W18x97	1.08	1.08	0.780	0.960
W24x117	0.897	0.891	0.646	0.795	W18x86	1.22	1.21	0.878	1.08
W24x104	1.01	1.00	0.726	0.894	W18x76	1.38	1.37	0.997	1.23
W24x103	1.02	1.01	0.733	0.903	W18x71	1.48	1.47	1.07	1.31
W24x94	1.11	1.11	0.802	0.987	W18x65	1.62	1.60	1.16	1.43
W24x84	1.25	1.24	0.900	1.11	W18x60	1.75	1.74	1.26	1.55
W24x76	1.38	1.37	0.992	1.22	W18x55	1.91	1.89	1.37	1.69
W24x68	1.54	1.52	1.11	1.36	W18x50	2.10	2.09	1.51	1.86
W24x62	1.70	1.68	1.22	1.50	W18x46	2.29	2.27	1.65	2.03
W24x55	1.91	1.89	1.37	1.69	W18x40	2.62	2.60	1.88	2.32
W21x201	0.521	0.518	0.375	0.462	W18x35	3.00	2.98	2.16	2.66
W21x182	0.576	0.572	0.415	0.510	W16x100	1.05	1.04	0.753	0.93
W21x166	0.632	0.628	0.455	0.560	W16x89	1.18	1.17	0.848	1.04
W21x147	0.714	0.710	0.514	0.633	W16x77	1.37	1.36	0.983	1.21

*t_r values estimated assuming $A_e = 0.75A_g$

Table 1 (cont.). Values of t_y and t_r for W-Sections (kips^{-1})*

Section	F_y = 36 ksi		F_y = 50 ksi		Section	F_y = 36 ksi		F_y = 50 ksi	
	t_y x10^3	t_r x10^3	t_y x10^3	t_r x10^3		t_y x10^3	t_r x10^3	t_y x10^3	t_r x10^3
W16x67	1.57	1.56	1.13	1.39	W14x34	3.09	3.07	2.22	2.74
W16x57	1.84	1.82	1.32	1.63	W14x30	3.49	3.46	2.51	3.09
W16x50	2.10	2.09	1.51	1.86	W14x26	4.01	3.99	2.89	3.56
W16x45	2.32	2.30	1.67	2.06	W14x22	4.76	4.72	3.42	4.21
W16x40	2.62	2.60	1.88	2.32	W12x336	0.312	0.310	0.225	0.277
W16x36	2.91	2.89	2.10	2.58	W12x305	0.344	0.342	0.248	0.305
W16x31	3.38	3.36	2.43	3.00	W12x279	0.377	0.374	0.271	0.334
W16x26	4.02	3.99	2.89	3.56	W12x252	0.417	0.414	0.300	0.370
W14x730	0.144	0.143	0.103	0.127	W12x230	0.456	0.453	0.328	0.404
W14x665	0.157	0.156	0.113	0.140	W12x210	0.499	0.496	0.360	0.443
W14x605	0.173	0.172	0.125	0.154	W12x190	0.553	0.549	0.398	0.490
W14x550	0.191	0.189	0.137	0.169	W12x170	0.617	0.613	0.444	0.547
W14x500	0.210	0.209	0.151	0.186	W12x152	0.690	0.686	0.497	0.612
W14x455	0.230	0.229	0.166	0.204	W12x136	0.774	0.768	0.557	0.685
W14x426	0.247	0.245	0.178	0.219	W12x120	0.874	0.868	0.630	0.775
W14x398	0.264	0.262	0.190	0.234	W12x106	0.989	0.982	0.712	0.877
W14x370	0.283	0.281	0.204	0.251	W12x96	1.09	1.09	0.788	0.970
W14x342	0.306	0.303	0.220	0.271	W12x87	1.21	1.20	0.868	1.07
W14x311	0.338	0.335	0.243	0.299	W12x79	1.33	1.32	0.958	1.18
W14x283	0.371	0.368	0.267	0.328	W12x72	1.46	1.45	1.05	1.30
W14x257	0.408	0.405	0.294	0.362	W12x65	1.62	1.60	1.16	1.43
W14x233	0.451	0.447	0.324	0.399	W12x58	1.82	1.80	1.31	1.61
W14x211	0.498	0.494	0.358	0.441	W12x53	1.98	1.96	1.42	1.75
W14x193	0.543	0.540	0.391	0.482	W12x50	2.11	2.10	1.52	1.87
W14x176	0.596	0.592	0.429	0.528	W12x45	2.36	2.34	1.70	2.09
W14x159	0.661	0.656	0.476	0.586	W12x40	2.64	2.62	1.90	2.34
W14x145	0.723	0.718	0.520	0.641	W12x35	3.00	2.98	2.16	2.66
W14x132	0.795	0.790	0.573	0.705	W12x30	3.51	3.49	2.53	3.11
W14x120	0.874	0.868	0.630	0.775	W12x26	4.03	4.01	2.90	3.58
W14x109	0.965	0.958	0.694	0.855	W12x22	4.76	4.73	3.43	4.22
W14x99	1.06	1.05	0.764	0.940	W12x19	5.54	5.50	3.99	4.91
W14x90	1.16	1.16	0.839	1.03	W12x16	6.55	6.51	4.72	5.81
W14x82	1.29	1.28	0.926	1.14	W12x14	7.42	7.37	5.34	6.57
W14x74	1.42	1.41	1.02	1.25	W10x112	0.938	0.932	0.675	0.831
W14x68	1.54	1.53	1.11	1.37	W10x100	1.05	1.04	0.756	0.930
W14x61	1.72	1.71	1.24	1.53	W10x88	1.19	1.18	0.858	1.06
W14x53	1.98	1.96	1.42	1.75	W10x77	1.37	1.36	0.983	1.21
W14x48	2.19	2.17	1.58	1.94	W10x68	1.54	1.53	1.11	1.37
W14x43	2.45	2.43	1.76	2.17	W10x60	1.75	1.74	1.26	1.55
W14x38	2.76	2.74	1.98	2.44	W10x54	1.95	1.94	1.41	1.73

*t_r values estimated assuming $A_e = 0.75A_g$

Table 1 (cont.). Values of t_y and t_r for W-Sections (kips^{-1})*

Section	F_y = 36 ksi		F_y = 50 ksi		Section	F_y = 36 ksi		F_y = 50 ksi	
	t_y x10^3	t_r x10^3	t_y x10^3	t_r x10^3		t_y x10^3	t_r x10^3	t_y x10^3	t_r x10^3
W10x49	2.14	2.13	1.54	1.90	W8x28	3.75	3.72	2.70	3.32
W10x45	2.32	2.30	1.67	2.06	W8x24	4.36	4.33	3.14	3.86
W10x39	2.68	2.67	1.93	2.38	W8x21	5.01	4.98	3.61	4.44
W10x33	3.18	3.16	2.29	2.82	W8x18	5.87	5.83	4.22	5.20
W10x30	3.49	3.47	2.51	3.09	W8x15	6.95	6.90	5.01	6.16
W10x26	4.06	4.03	2.92	3.59	W8x13	8.04	7.98	5.79	7.12
W10x22	4.76	4.72	3.42	4.21	W8x10	10.4	10.4	7.51	9.24
W10x19	5.49	5.45	3.95	4.87	W6x25	4.20	4.18	3.03	3.73
W10x17	6.19	6.14	4.45	5.48	W6x20	5.26	5.22	3.79	4.66
W10x15	7.00	6.95	5.04	6.20	W6x15	6.97	6.92	5.02	6.17
W10x12	8.72	8.66	6.28	7.73	W6x16	6.51	6.47	4.69	5.77
W8x67	1.57	1.56	1.13	1.39	W6x12	8.69	8.63	6.26	7.70
W8x58	1.80	1.79	1.30	1.60	W6x9	11.5	11.4	8.29	10.2
W8x48	2.19	2.17	1.58	1.94	W6x8.5	12.2	12.2	8.82	10.9
W8x40	2.64	2.62	1.90	2.34	W5x19	5.55	5.51	4.00	4.92
W8x35	3.00	2.98	2.16	2.66	W5x16	6.55	6.51	4.72	5.81
W8x31	3.38	3.36	2.44	3.00	W4x13	8.06	8.00	5.80	7.14

*t_r values estimated assuming $A_e = 0.75A_g$

Table 2. Initial *t*-Estimates (kips^{-1}) for Combined Tension and Bending

Section	F_y = 36 ksi	F_y = 50 ksi	Section	F_y = 36 ksi	F_y = 50 ksi
W44	0.38	0.31	W16	1.87	1.51
W40	0.38	0.31	W14	0.82	0.66
W36	0.42	0.34	W12	1.29	1.04
W33	0.52	0.42	W10	2.71	2.21
W30	0.63	0.51	W8	3.07	2.47
W27	0.61	0.49	W6	5.70	4.59
W24	0.84	0.68	W5	6.03	4.86
W21	1.30	1.05	W4	8.03	6.47
W18	1.47	1.19			