

# Optimal Design of W-Shape Members Subjected to Combined Forces

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## ABSTRACT

Design of members subjected to combined forces is an iterative process in which the designer selects a trial section and checks the selection for compliance with the appropriate provisions of AISC *Specification for Structural Steel Buildings* Chapter H. This process is repeated until a desired section is identified. The introduction of AISC *Steel Construction Manual* Table 6-1 has made the calculations involved in checking different trial sections considerably easier and faster. However, there is still no comprehensive resource for the designer to select an initial trial section for various scenarios of members subjected to combined forces which leads to an optimal final selection quickly. This paper presents a method and aids for more rational and efficient selection of trial sections for W-shapes subject to combined compression and bending about one or two principal axes, tension and bending about one or two principal axes, or biaxial bending. Unlike some previous methods, there are no limitations on the values of unbraced and effective lengths (e.g., requiring that  $L_b = L_{cy}$ ). The design aids are developed for all W-shapes in Grade 50 steel using both LRFD and ASD methods. The method presented converges quickly, reducing the need for multiple repeated calculations before a final W-shape is selected. Example problems are also included.

**Keywords:** steel design, structural steel, combined forces, compression and bending, beam-column, tension and bending, biaxial bending, structural optimization.

## INTRODUCTION

Section H1 of the AISC *Specification for Structural Steel Buildings* (2022), hereafter referred to as the AISC *Specification*, requires compliance with AISC *Specification* Equation H1-1a or H1-1b for design of doubly and singly symmetric members subject to flexure and axial force. Note that the term *force* refers to both axial load as well as bending moment.

When  $\frac{P_r}{P_c} \geq 0.20$

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

(AISC *Spec.* Eq. H1-1a)

When  $\frac{P_r}{P_c} < 0.20$

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

(AISC *Spec.* Eq. H1-1b)

where

$P_r$  = required axial strength, determined in accordance with AISC *Specification* Chapter C using LRFD or ASD load combinations, kips

=  $P_u$  (LRFD) and  $P_a$  (ASD), must include second-order effects for compression and bending

$P_c$  = available axial strength determined in accordance with AISC *Specification* Chapter D for tension and Chapter E for compression, kips

=  $\phi P_n$  (LRFD) and  $P_n/\Omega$  (ASD)

$M_r$  = required flexural strength, determined in accordance with AISC *Specification* Chapter C using LRFD or ASD load combinations, kip-in.

=  $M_u$  (LRFD) and  $M_a$  (ASD), must include second-order effects for compression and bending

$M_c$  = available flexural strength determined in accordance with AISC *Specification* Chapter F, kip-in.

=  $\phi_b M_n$  (LRFD) and  $M_n/\Omega_b$  (ASD)

AISC *Specification* Equations H1-1a and H1-1b apply to members subjected to either compression and bending (beam-columns) or tension and bending as well as members subjected to biaxial bending.

Second-order effects do not adversely affect the strength of members subject to combined tension and bending. However, second-order effects need to be considered in the design of members subject to compression and bending using pertinent provisions of the AISC *Specification* after identifying a trial section.

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For biaxial bending ( $P_r = 0$ ,  $P_r/P_c = 0 < 0.20$ ), only the portion of the AISC *Specification* Equation H1-1b with moment terms applies; namely,

$$\frac{M_{rx}}{M_{cx}} + \frac{M_{ry}}{M_{cy}} \leq 1.0 \quad (1)$$

For members subject to tension and bending, AISC *Specification* Section H4 offers provisions for tensile rupture of the tension flange with holes subjected to tension. This section in turn references AISC *Specification* Section F13.1, “Strength Reductions for Members with Holes in the Tension Flange.” The reader may refer to Swanson (2016) for an in-depth overview of this subject.

Given the scope of this article, which is the optimum selection of trial sections for members subject to combined forces, there will not be any further elaboration of the calculation of  $M_{rx}$ ,  $M_{ry}$ ,  $M_{cx}$ , and  $M_{cy}$  in the remainder of this article.

## REVIEW OF PREVIOUS WORK

Over the last few decades, multiple researchers have offered procedures and design aids for facilitating selection of a trial section and/or checking the selection for compliance with pertinent provisions of the AISC *Specification*.

A very early method for selecting a beam-column trial section was presented by Rubinsky (1968). The author offered two methods, which he referred to as the  $PM_X$  and MP methods, for selecting a trial section.

The  $PM_X$  method converted the axial load and the bending moment about the  $y$ -axis into equivalent bending moments about the  $x$ -axis. The values of the converted axial load and bending moment about the  $y$ -axis were added to obtain a total equivalent moment about the  $x$ -axis. At that point, the problem was reduced to selection of a trial beam section with bending about the  $x$ -axis only. This method was most appropriate when significant bending about the  $x$ -axis existed.

The second Rubinsky method, the MP method, converted the bending moments about the  $x$ -axis and  $y$ -axis into equivalent axial loads. In a similar manner to the  $PM_X$  method, values of the converted bending moment about the  $x$ - and  $y$ -axes were added to the original axial load to obtain an overall equivalent axial load. This method reduced the problem to the selection of a column shape as a trial section.

Later, Burgett (1973) offered a similar method that used tabulated coefficients  $m$  and  $U$  to convert the bending moments about the  $x$ - and  $y$ -axes to equivalent axial loads  $M_x m$  and  $M_y mU$ . Then a trial section was selected from the column design tables of Part 4 of the AISC *Steel Construction Manual* (2023), hereafter referred to as the AISC *Manual*, that could carry a hypothetical effective load,  $P_{eff}$ , equal to the original axial load,  $P_o$ , plus the equivalent axial loads for bending about the  $x$ - and  $y$ -axes.

$$P_{eff} = P_o + M_x m + M_y mU \quad (2)$$

This trial section would be checked for compliance with provisions of the AISC *Specification* Chapter H using the original combined forces. This process would be repeated until a satisfactory section is obtained.

Uang et al. (1990) observed that when using the LRFD method, the Burgett method resulted in “significantly understressed” or overdesigned members. The authors offered new equations and tabulated values for  $m$  and  $U$  for use with the LRFD method. In the development of their equations and values for  $m$  and  $U$ , the authors stated, “...the unbraced length  $L_b$  of the compression flange is conservatively assumed equal to the effective length of the column.” In other words,  $L_b = L_{cx} = L_{cy}$ . This assumption deserves a discussion.

$L_x$  and  $L_y$  are the laterally unbraced lengths of the member for flexural buckling about the  $x$ - and  $y$ -axes under column action. To brace the member for this condition, it is necessary to prevent lateral displacement of the member in the appropriate direction and prevent flexural buckling where the member is braced. Effective lengths  $L_{cx}$  and  $L_{cy}$  are the products of the appropriate  $K$  and  $L$ ; that is,  $L_{cx} = K_x L_x$  and  $L_{cy} = K_y L_y$ .

On the other hand,  $L_b$  is the laterally unbraced length of the member in flexure. To brace a member to resist lateral torsional buckling, it is necessary to either restrain the member from twist or prevent lateral displacement and thus prevent bending about the  $y$ -axis at the point where bracing occurs. Therefore, bracing a member to prevent flexural buckling about the  $y$ -axis at a particular point will automatically brace the member for lateral torsional buckling at the same location; namely, always  $L_b = L_y$ .

If  $K_y > 1.0$ , such as a beam-column in an unbraced frame, then  $L_b < L_{cy} = K_y L_y$ , and the assumption  $L_b = L_{cy}$  in selecting a shape based on  $L_{cy}$  will indeed be conservative. However, if  $K_y < 1.0$ , then  $L_b > L_{cy} = K_y L_y$ , and the assumption  $L_b = L_{cy}$  will be unconservative. If  $K_y = 1.0$ , then  $L_b = L_{cy} = K_y L_y$ . There is no such relationship between  $L_b$  and  $L_x$  (or  $L_{cx}$ ).

In summary, there is more to the relationship between  $L_b$  and  $L_c$  (specifically  $L_{cy}$ ), and a blanket statement assuming  $L_b$  and  $L_c$  are equal is a conservative assumption that may not always hold.

The Burgett (1973) method and its variations presented by Uang et al. (1990) have been used the longest and remain the most popular method.

In 2000, a new approach and aids for design of steel beam-columns using the LRFD load combinations was presented (Aminmansour, 2000). The method converted AISC *Specification* Equations H1-1a and H1-1b to the following.

When  $bP_u \geq 0.20$

$$bP_u + mM_{ux} + nM_{uy} \leq 1.0 \quad (3)$$

When  $bP_u < 0.20$

$$0.5bP_u + (9/8)(mM_{ux} + nM_{uy}) \leq 1.0 \quad (4)$$

where

$$b = \frac{1}{\phi_c P_n} \quad (5)$$

$$m = \frac{8}{9\phi_b M_{nx}} \quad (6)$$

$$n = \frac{8}{9\phi_b M_{ny}} \quad (7)$$

Tables were generated with values of  $b$ ,  $m$ , and  $n$  for all W-shapes with  $F_y = 50$  ksi.

Tabulated values of  $b$ ,  $m$ , and  $n$  are all exact, taking into consideration all applicable limit states for compression and flexure about the  $x$ - and  $y$ -axes. Criteria such as width-to-thickness ratios of cross-sectional elements,  $L_b$  versus  $L_p$  and  $L_r$  were already accounted for. Further,  $L_c$  and  $L_b$  need not be equal. The tables developed covered a wide range of  $L_c$  and  $L_b$  values.

The method and aids presented in Aminmansour (2000) allow the designer to use sections of any nominal depth as beam-columns rather than being limited to column sections only. Further, there was no need for repeated computations of strength properties. As another benefit of the method, the designer could judge the effectiveness of the section under consideration by observing the values of  $b$ ,  $m$ , and  $n$ . Further, tabulated values of  $b$ ,  $m$ , and  $n$  and Equations 5, 6, and 7 could be used to obtain other information such as  $\phi_c P_n$ ,  $\phi_b M_{nx}$ ,  $\phi_b M_{ny}$ ,  $\phi_b M_{px}$ , and  $\phi_b M_{py}$  for a range of  $L_c$  and  $L_b$  for all W-shapes. The paper also presented aids for selecting initial trial sections. An expanded version of the same method and design aids for selecting trial sections was published later (Aminmansour, 2004).

Keil (2000) developed a graphical method using interaction diagrams that could be used for checking a trial section for compliance with the AISC *Specification*. This method is developed for  $L_b = L_c = 12$  ft,  $C_b = 1.0$ , and members under consideration must be subject to axial compression and bending about  $x$ -axis only. Conversion factors use linear transformation to convert compressive and flexural strength for values of  $L_b$  and  $L_c$  other than 12 ft. The method applies to W-shapes typically used as columns ranging from W6 to W14.

Aminmansour (2006) presented a new method and aids for design of structural steel sections subject to tension and bending. The method and aids for tension and bending were very similar to those of compression and bending described previously (Aminmansour, 2000). Equations and design aids developed by Aminmansour (2000, 2006) and were adopted by AISC and included in the third edition of AISC *Manual Part Six* (2001). This was the first time the AISC

*Manual* had a part dedicated to design of members subject to combined forces.

Hosur and Augustine (2007) built on the work done previously by Keil (2000) offering a method for incorporating  $C_b > 1.0$  in the approach developed earlier by Keil. The authors use design aids developed by Aminmansour (2004) for selection of an efficient section.

In 2009, a method for incorporating  $C_b$  for design of members subject to compression and bending, tension and bending, or biaxial bending using AISC *Manual* Table 6-1 was developed (Aminmansour, 2009) and included in the 14th Edition of the AISC *Manual* (AISC, 2011).

Sa'adat and Banan (2014) developed a graphical design aid for selecting the lightest W-shape subject to combined forces. The charts developed along with conversion equations and interpolation allow the designer to select the lightest trial W-shape for a range of  $L_b$ ,  $L_c$ ,  $M_{cx}$ , and  $M_{cy}$ .

Reynolds and Uang (2019) offered a modified version of the equivalent axial load method, originally developed by Burgett (1973) and later refined by Uang et al. (1990), using the following equations.

When  $P_r/P_c \geq 0.20$

$$P_{eq} = P_r + mM_{rx} + muM_{ry} \leq P_c \quad (8)$$

When  $P_r/P_c < 0.20$

$$P_{eq} = \frac{P_r}{2} + \frac{9}{8}mM_{rx} + \frac{9}{8}muM_{ry} \leq P_c \quad (9)$$

The authors provide tabulated average values of  $m$  and  $u$  for wide-flange nominal depths W8 to W36 based on values of  $L_c$  ranging from 8 ft and higher, at 2 ft increments. Tables for modified values of  $m$  and  $u$  include one set for  $C_b = 1.0$  and another set of values for what the authors call high moment gradient cases. The authors also offer an innovative equation for selecting a nominal depth for the member based on the applied forces. This method requires  $L_b = KL = L_c$ . As noted earlier about similar methods, this assumption is indeed conservative if  $L_b \leq KL = L_c$ , otherwise the results will be unconservative. Table 5 presented later in this article summarizes the different methods and their characteristics.

The 15th Edition of the AISC *Manual* (AISC, 2017) includes Table 6-1, also referred to as the "super table," that offers direct available strengths in compression, tension, shear, and flexure about  $x$ - and  $y$ -axes. Tabulated values are exact and consider all applicable limit states with the exception of using  $A_e = 0.75A_g$  for the tensile rupture strength, similar to the assumption made in AISC *Manual* Table 5-1.

AISC *Manual* Table 6-1 can be used for design of beams, columns, and tension members, as well as members subject to combined forces. The table may be used for a wide range of  $L_b$  and  $L_c$  values. Aminmansour (2017) describes the features and uses of this AISC *Manual* table.

## DEVELOPMENT OF THE NEW METHOD AND DESIGN AIDS

Design of W-shape members subjected to combined forces is an iterative process in which a trial section is chosen and checked for compliance with AISC *Specification* Equation H1-1a or H1-1b using available strength values from AISC *Manual* Table 6-1. The process of checking trial sections continues until a desired section is found. The objective, however, is to begin with a trial section from AISC *Manual* Table 6-1 that has available strengths close to the final section and check that section for compliance with AISC *Specification* Equation H1-1a or H1-1b. Note that regardless of which one of Equations H1-1a and H1-1b applies, these equations have three components: axial load component (first term), bending about the  $x$ -axis (second term), and bending about the  $y$ -axis (third term).

AISC *Manual* Table 6-1 is very helpful for checking for compliance of a trial section with provisions of the AISC *Specification*. However, arriving at a trial section that is most appropriate for the given combined forces and as close to the final selection as possible remains a challenge. This is due to the interaction between axial force and bending moments about the  $x$ - and  $y$ -axes. There are at least two, potentially three, variables that need to be established in advance of selecting a trial section: the needed available strengths  $P_c$ ,  $M_{cx}$ , and  $M_{cy}$ . A method that would help come up with estimates for values for these variables in order to select a good trial section would be helpful.

The method presented here relies on using approximate (average) values for the available strengths for the two less dominant forces (smaller values) and a more educated estimate for the available strength of the more dominant force in order to get estimate values for  $P_c$ ,  $M_{cx}$ , and  $M_{cy}$ .

At this point in the process, we are strictly looking at numerical values of the forces; namely, values of the required axial force (tension or compression) and bending moment about the  $x$ - and  $y$ -axes. The objective is to select a trial section that gives a value of equal to or less than but as close to 1.0 as possible for the interaction equation. The largest required force will have a bigger impact on the value of the interaction equation. That force is referred to as the most dominant force.

Of the three variables needed to select a trial section, normally  $M_{cy}$  has the least numerical impact on the overall value of the interaction equation. Therefore, using an estimate such as the average value of  $M_{cy}$  for all shapes within the same nominal depth seems reasonable. Recall that  $M_{cy}$  is a cross-sectional property for W-shape flexural members and only depends on whether the section is compact or non-compact. Specifically, lateral torsional buckling does not apply to bending of W-shape flexural members bent about their weak axis, and thus, there is no unbraced length to use.

The available strength  $M_{cy}$  of a W-shape is a single number and depends on whether the section is compact or not.

For the two remaining applied forces—axial force and bending moment about the  $x$ -axis—often one is more dominant or larger than the other. Therefore, using an average value for the available strength for the force that is less dominant also seems reasonable. If the numerical value of the applied axial force (tension or compression) is more dominant or larger than the numerical value of the bending about the  $x$ -axis, the designer can use the average value of  $M_{cx}$  for W-shapes within the same nominal depth over the same unbraced length to obtain an estimate for  $M_{cx}$ . On the other hand, if bending about the  $x$ -axis is more dominant or larger, the designer can use the average value of  $P_c$  for W-shapes of the same nominal depth and for the same effective length to obtain an estimate for  $P_c$ . By limiting the averages to the shapes within the same nominal depth and the same unbraced length as the design problem, we lower the error in our calculations.

An estimated value for the third available strength related to the most dominant or the largest force can be found by inserting the estimates for the other two available strengths found earlier in the interaction equation while setting the value of the interaction equation equal to unity (1.0). The process of calculating an estimate for the available strength for the most dominant force using the interaction equation will lead to a smaller error in the outcome.

The procedure of using average values for two variables to calculate an estimate for the third variable may seem overly simplistic. However, as will be illustrated in the examples that follow, the method works well, leading to an optimum section in two or three tries with each taking very little time when using AISC *Manual* Table 6-1.

Tables 1, 2, 3, and 4 were developed using a spreadsheet to calculate the average available strengths discussed earlier. Tabulated values are listed for W-shapes with ASTM A992/A992M (2022) ( $F_y = 50$  ksi and  $F_u = 65$  ksi) and for all nominal depths. Given that at this point we are interested in average values of available strengths, it was assumed that all W-shapes are non-slender for compression and that all W-shapes are compact for flexure. In addition, only two significant figures were used in the development of the tables. Finally, it is assumed that the designer has established a desired nominal depth for the design at this point. The design aid tables developed are as follows.

Table 1: Average values of  $P_c$  in compression ( $\phi_c P_n$  for LRFD and  $P_n/\Omega_c$  for ASD)

Table 2: Average values of  $M_{cx}$  ( $\phi_b M_{nx}$  for LRFD and  $M_{nx}/\Omega_b$  for ASD)

Table 3: Average values of  $M_{cy}$  ( $\phi_b M_{ny}$  for LRFD and  $M_{ny}/\Omega_b$  for ASD)

Table 4: Average values of  $P_c$  in tension ( $\phi_t P_n$  for LRFD and  $P_n/\Omega_t$  for ASD)

**Table 1**  
**Average Available Compressive Strength ( $P_{c,avg}$ , kips)**  
**W-Shapes**

$F_y = 50$  ksi

|                             | Effective Length, $L_c$ (ft) |              |                |              |                |              |                |              |                |              |                |              |                |              |                |              |
|-----------------------------|------------------------------|--------------|----------------|--------------|----------------|--------------|----------------|--------------|----------------|--------------|----------------|--------------|----------------|--------------|----------------|--------------|
|                             | 0                            |              | 2              |              | 4              |              | 6              |              | 8              |              | 10             |              | 12             |              | 14             |              |
|                             | ASD                          | LRFD         | ASD            | LRFD         | ASD            | LRFD         | ASD            | LRFD         | ASD            | LRFD         | ASD            | LRFD         | ASD            | LRFD         | ASD            | LRFD         |
| Nominal Depth               | $P_n/\Omega_c$               | $\phi_c P_n$ | $P_n/\Omega_c$ | $\phi_c P_n$ | $P_n/\Omega_c$ | $\phi_c P_n$ | $P_n/\Omega_c$ | $\phi_c P_n$ | $P_n/\Omega_c$ | $\phi_c P_n$ | $P_n/\Omega_c$ | $\phi_c P_n$ | $P_n/\Omega_c$ | $\phi_c P_n$ | $P_n/\Omega_c$ | $\phi_c P_n$ |
| W44                         | 2500                         | 3700         | 2500           | 3700         | 2400           | 3700         | 2400           | 3600         | 2300           | 3500         | 2300           | 3400         | 2200           | 3300         | 2100           | 3100         |
| W40 (> 200 lb)              | 3400                         | 5200         | 3400           | 5100         | 3400           | 5100         | 3300           | 5000         | 3300           | 4900         | 3200           | 4800         | 3100           | 4600         | 3000           | 4400         |
| W40 (< 200 lb)              | 2200                         | 3300         | 2200           | 3300         | 2200           | 3300         | 2100           | 3200         | 2000           | 3000         | 1900           | 2900         | 1800           | 2700         | 1600           | 2500         |
| W36 (> 400 lb)              | 5100                         | 7600         | 5000           | 7600         | 5000           | 7500         | 4900           | 7400         | 4900           | 7300         | 4700           | 7100         | 4600           | 6900         | 4400           | 6700         |
| W36 (> 200 lb and < 400 lb) | 2500                         | 3700         | 2500           | 3700         | 2500           | 3700         | 2400           | 3600         | 2400           | 3500         | 2300           | 3400         | 2200           | 3300         | 2100           | 3100         |
| W36 (< 200 lb)              | 1500                         | 2200         | 1500           | 2200         | 1400           | 2100         | 1400           | 2100         | 1300           | 2000         | 1200           | 1900         | 1200           | 1700         | 1100           | 1600         |
| W33                         | 2000                         | 3000         | 2000           | 3000         | 2000           | 3000         | 2000           | 2900         | 1900           | 2900         | 1800           | 2800         | 1800           | 2600         | 1700           | 2500         |
| W30                         | 1800                         | 2700         | 1800           | 2700         | 1800           | 2600         | 1700           | 2600         | 1700           | 2500         | 1600           | 2400         | 1500           | 2300         | 1400           | 2200         |
| W27                         | 2000                         | 2900         | 1900           | 2900         | 1900           | 2900         | 1900           | 2800         | 1800           | 2700         | 1800           | 2600         | 1700           | 2500         | 1600           | 2400         |
| W24                         | 1500                         | 2200         | 1500           | 2200         | 1500           | 2200         | 1400           | 2100         | 1400           | 2000         | 1300           | 1900         | 1200           | 1800         | 1100           | 1700         |
| W21                         | 1100                         | 1600         | 1100           | 1600         | 1000           | 1600         | 1000           | 1500         | 950            | 1400         | 900            | 1400         | 830            | 1300         | 770            | 1200         |
| W18                         | 1200                         | 1700         | 1100           | 1700         | 1100           | 1700         | 1100           | 1600         | 1000           | 1500         | 970            | 1500         | 900            | 1400         | 830            | 1200         |
| W16                         | 500                          | 740          | 490            | 730          | 470            | 710          | 440            | 660          | 410            | 610          | 370            | 550          | 320            | 480          | 280            | 420          |
| W14 (> 300 lb)              | 4300                         | 6400         | 4300           | 6400         | 4300           | 6400         | 4200           | 6300         | 4200           | 6200         | 4100           | 6100         | 4000           | 6000         | 3900           | 5800         |
| W14 (< 300 lb)              | 760                          | 1100         | 750            | 1100         | 740            | 1100         | 720            | 1100         | 690            | 1000         | 660            | 990          | 630            | 940          | 590            | 880          |
| W12 (> 200 lb)              | 1000                         | 1600         | 1000           | 1600         | 1000           | 1500         | 990            | 1500         | 950            | 1400         | 910            | 1400         | 860            | 1300         | 810            | 1200         |
| W12 (< 200 lb)              | 640                          | 970          | 640            | 960          | 620            | 940          | 600            | 900          | 570            | 860          | 540            | 810          | 510            | 760          | 540            | 810          |
| W10                         | 430                          | 640          | 420            | 630          | 410            | 610          | 380            | 570          | 360            | 540          | 330            | 490          | 300            | 450          | 300            | 450          |
| W8                          | 280                          | 420          | 270            | 410          | 260            | 390          | 240            | 360          | 220            | 330          | 190            | 290          | 170            | 250          | 140            | 220          |
| W6                          | 130                          | 200          | 130            | 190          | 120            | 180          | 100            | 150          | 82.0           | 120          | 65             | 97           | 50             | 76           | 39             | 58           |
| W5                          | 150                          | 230          | 150            | 230          | 140            | 210          | 120            | 180          | 100            | 150          | 80             | 120          | 60             | 90           | 44             | 66           |
| W4                          | 120                          | 170          | 110            | 170          | 97             | 150          | 79             | 120          | 59             | 88           | 40             | 60           | 28             | 42           | 20             | 31           |

**Table 1 (continued)**  
**Average Available Compressive Strength ( $P_c$ )<sub>avg</sub>, kips**  
**W-Shapes**

$F_y = 50$  ksi

| Nominal Depth               | Effective Length, $L_c$ (ft) |              |                |              |                |              |                |              |                |              |                |              |                |              |                |              |
|-----------------------------|------------------------------|--------------|----------------|--------------|----------------|--------------|----------------|--------------|----------------|--------------|----------------|--------------|----------------|--------------|----------------|--------------|
|                             | 16                           |              | 18             |              | 20             |              | 22             |              | 24             |              | 26             |              | 28             |              | 30             |              |
|                             | ASD                          | LRFD         | ASD            | LRFD         | ASD            | LRFD         | ASD            | LRFD         | ASD            | LRFD         | ASD            | LRFD         | ASD            | LRFD         | ASD            | LRFD         |
|                             | $P_n/\Omega_c$               | $\phi_c P_n$ | $P_n/\Omega_c$ | $\phi_c P_n$ | $P_n/\Omega_c$ | $\phi_c P_n$ | $P_n/\Omega_c$ | $\phi_c P_n$ | $P_n/\Omega_c$ | $\phi_c P_n$ | $P_n/\Omega_c$ | $\phi_c P_n$ | $P_n/\Omega_c$ | $\phi_c P_n$ | $P_n/\Omega_c$ | $\phi_c P_n$ |
| W44                         | 2000                         | 3000         | 1900           | 2800         | 1700           | 2600         | 1600           | 2400         | 1500           | 2200         | 1400           | 2100         | 1200           | 1900         | 1100           | 1700         |
| W40 (> 200 lb)              | 2800                         | 4200         | 2700           | 4000         | 2500           | 3800         | 2400           | 3500         | 2200           | 3300         | 2000           | 3000         | 1900           | 2800         | 1700           | 2600         |
| W40 (< 200 lb)              | 1500                         | 2200         | 1300           | 2000         | 1200           | 1800         | 1000           | 1600         | 900            | 1300         | 770            | 1200         | 670            | 1000         | 580            | 880          |
| W36 (> 400 lb)              | 4300                         | 6400         | 4100           | 6100         | 3900           | 5800         | 3700           | 5500         | 3500           | 5200         | 3300           | 4900         | 3000           | 4600         | 2800           | 4200         |
| W36 (> 200 lb and < 400 lb) | 2000                         | 3000         | 1900           | 2800         | 1800           | 2600         | 1600           | 2400         | 1500           | 2300         | 1400           | 2100         | 1300           | 1900         | 1200           | 1700         |
| W36 (< 200 lb)              | 950                          | 1400         | 850            | 1300         | 750            | 1100         | 650            | 970          | 550            | 830          | 470            | 710          | 410            | 610          | 350            | 530          |
| W33                         | 1600                         | 2400         | 1500           | 2200         | 1400           | 2100         | 1300           | 1900         | 1200           | 1700         | 1100           | 1600         | 970            | 1500         | 880            | 1300         |
| W30                         | 1300                         | 2000         | 1300           | 1900         | 1200           | 1700         | 1100           | 1600         | 970            | 1500         | 880            | 1300         | 800            | 1200         | 720            | 1100         |
| W27                         | 1500                         | 2200         | 1400           | 2100         | 1300           | 1900         | 1200           | 1800         | 1100           | 1600         | 970            | 1500         | 880            | 1300         | 790            | 1200         |
| W24                         | 1100                         | 1600         | 970            | 1500         | 890            | 1300         | 800            | 1200         | 790            | 1200         | 710            | 1100         | 630            | 950          | 560            | 830          |
| W21                         | 700                          | 1100         | 630            | 950          | 570            | 860          | 560            | 840          | 530            | 790          | 470            | 700          | 430            | 650          | 420            | 630          |
| W18                         | 760                          | 1100         | 680            | 1000         | 610            | 920          | 620            | 930          | 550            | 820          | 480            | 720          | 450            | 680          | 460            | 690          |
| W16                         | 240                          | 360          | 210            | 310          | 210            | 320          | 180            | 270          | 160            | 230          | 140            | 220          | 200            | 300          | 180            | 260          |
| W14 (> 300 lb)              | 3800                         | 5600         | 3600           | 5400         | 3500           | 5200         | 3300           | 5000         | 3200           | 4700         | 3000           | 4500         | 2800           | 4200         | 2700           | 4000         |
| W14 (< 300 lb)              | 550                          | 830          | 540            | 810          | 530            | 790          | 490            | 730          | 450            | 680          | 490            | 730          | 450            | 670          | 410            | 610          |
| W12 (> 200 lb)              | 750                          | 1100         | 740            | 1100         | 720            | 1100         | 660            | 1000         | 610            | 910          | 690            | 1000         | 630            | 940          | 560            | 850          |
| W12 (< 200 lb)              | 530                          | 790          | 480            | 730          | 440            | 660          | 400            | 600          | 360            | 540          | 380            | 560          | 330            | 500          | 290            | 440          |
| W10                         | 310                          | 460          | 270            | 410          | 240            | 360          | 210            | 310          | 220            | 330          | 190            | 290          | 160            | 250          | 140            | 220          |
| W8                          | 160                          | 230          | 130            | 200          | 110            | 160          | 110            | 160          | 89.0           | 130          | 76             | 110          | 79             | 120          | 68             | 100          |
| W6                          | 45                           | 67           | 42             | 64           | 34             | 52           | 28             | 43           | 24             | 36           |                |              |                |              |                |              |
| W5                          | 34                           | 51           | 27             | 40           | 22             | 33           |                |              |                |              |                |              |                |              |                |              |
| W4                          | 16                           | 23           |                |              |                |              |                |              |                |              |                |              |                |              |                |              |

**Table 2**  
**Average Available Flexural Strength about x-Axis ( $M_{cx}$ )<sub>avg</sub>, kip-ft**  
**W-Shapes**

$F_y = 50$  ksi

| Nominal Depth               | Unbraced Length, $L_b$ (ft) |                 |                   |                 |                   |                 |                   |                 |                   |                 |                   |                 |                   |                 |                   |                 |
|-----------------------------|-----------------------------|-----------------|-------------------|-----------------|-------------------|-----------------|-------------------|-----------------|-------------------|-----------------|-------------------|-----------------|-------------------|-----------------|-------------------|-----------------|
|                             | 0                           |                 | 2                 |                 | 4                 |                 | 6                 |                 | 8                 |                 | 10                |                 | 12                |                 | 14                |                 |
|                             | ASD                         | LRFD            | ASD               | LRFD            | ASD               | LRFD            | ASD               | LRFD            | ASD               | LRFD            | ASD               | LRFD            | ASD               | LRFD            | ASD               | LRFD            |
|                             | $M_{nx}/\Omega_b$           | $\phi_b M_{nx}$ | $M_{nx}/\Omega_b$ | $\phi_b M_{nx}$ | $M_{nx}/\Omega_b$ | $\phi_b M_{nx}$ | $M_{nx}/\Omega_b$ | $\phi_b M_{nx}$ | $M_{nx}/\Omega_b$ | $\phi_b M_{nx}$ | $M_{nx}/\Omega_b$ | $\phi_b M_{nx}$ | $M_{nx}/\Omega_b$ | $\phi_b M_{nx}$ | $M_{nx}/\Omega_b$ | $\phi_b M_{nx}$ |
| W44                         | 3400                        | 5100            | 3400              | 5100            | 3400              | 5100            | 3400              | 5100            | 3400              | 5100            | 3400              | 5100            | 3400              | 5100            | 3300              | 4900            |
| W40 (> 200 lb)              | 4500                        | 6700            | 4500              | 6700            | 4500              | 6700            | 4500              | 6700            | 4500              | 6700            | 4500              | 6700            | 4500              | 6700            | 4400              | 6600            |
| W40 (< 200 lb)              | 2700                        | 4100            | 2700              | 4100            | 2700              | 4100            | 2700              | 4100            | 2700              | 4100            | 2700              | 4100            | 2700              | 4100            | 2500              | 3700            |
| W36 (> 400 lb)              | 6400                        | 9600            | 6400              | 9600            | 6400              | 9600            | 6400              | 9600            | 6400              | 9600            | 6400              | 9600            | 6400              | 9600            | 6400              | 9600            |
| W36 (> 200 lb and < 400 lb) | 3000                        | 4500            | 3000              | 4500            | 3000              | 4500            | 3000              | 4500            | 3000              | 4500            | 3000              | 4500            | 3000              | 4500            | 2900              | 4300            |
| W36 (< 200 lb)              | 1600                        | 2400            | 1600              | 2400            | 1600              | 2400            | 1600              | 2400            | 1600              | 2400            | 1600              | 2400            | 1600              | 2400            | 1500              | 2200            |
| W33                         | 2200                        | 3400            | 2200              | 3400            | 2200              | 3400            | 2200              | 3400            | 2200              | 3400            | 2200              | 3400            | 2200              | 3400            | 2200              | 3200            |
| W30                         | 1800                        | 2700            | 1800              | 2700            | 1800              | 2700            | 1800              | 2700            | 1800              | 2700            | 1800              | 2700            | 1800              | 2700            | 1800              | 2600            |
| W27                         | 1800                        | 2700            | 1800              | 2700            | 1800              | 2700            | 1800              | 2700            | 1800              | 2700            | 1800              | 2700            | 1800              | 2700            | 1800              | 2600            |
| W24                         | 1200                        | 1800            | 1200              | 1800            | 1200              | 1800            | 1200              | 1800            | 1200              | 1800            | 1200              | 1800            | 1200              | 1800            | 1200              | 1700            |
| W21                         | 770                         | 1200            | 770               | 1200            | 770               | 1200            | 770               | 1200            | 770               | 1200            | 770               | 1200            | 770               | 1200            | 700               | 1000            |
| W18                         | 740                         | 1100            | 740               | 1100            | 740               | 1100            | 740               | 1100            | 740               | 1100            | 740               | 1100            | 740               | 1100            | 680               | 1000            |
| W16                         | 270                         | 400             | 270               | 400             | 270               | 400             | 270               | 400             | 270               | 400             | 270               | 400             | 270               | 400             | 210               | 320             |
| W14 (> 300 lb)              | 2600                        | 3900            | 2600              | 3900            | 2600              | 3900            | 2600              | 3900            | 2600              | 3900            | 2600              | 3900            | 2600              | 3900            | 2600              | 3900            |
| W14 (< 300 lb)              | 370                         | 560             | 370               | 560             | 370               | 560             | 370               | 560             | 370               | 560             | 370               | 560             | 370               | 560             | 350               | 530             |
| W12 (> 200 lb)              | 510                         | 760             | 510               | 760             | 510               | 760             | 510               | 760             | 510               | 760             | 510               | 760             | 510               | 760             | 480               | 720             |
| W12 (< 200 lb)              | 280                         | 420             | 280               | 420             | 280               | 420             | 280               | 420             | 280               | 420             | 280               | 420             | 280               | 420             | 260               | 390             |
| W10                         | 150                         | 230             | 150               | 230             | 150               | 230             | 150               | 230             | 150               | 230             | 150               | 230             | 150               | 230             | 130               | 200             |
| W8                          | 78                          | 120             | 78                | 120             | 78                | 120             | 78                | 120             | 78                | 120             | 78                | 120             | 78                | 120             | 64                | 96              |
| W6                          | 27                          | 41              | 27                | 41              | 27                | 41              | 27                | 41              | 27                | 41              | 27                | 41              | 27                | 41              | 20                | 30              |
| W5                          | 27                          | 40              | 27                | 40              | 27                | 40              | 27                | 40              | 27                | 40              | 27                | 40              | 27                | 40              | 22                | 33              |
| W4                          | 16                          | 24              | 16                | 24              | 16                | 24              | 16                | 24              | 16                | 24              | 16                | 24              | 16                | 24              | 12                | 17              |

**Table 2 (continued)**  
**Average Available Flexural Strength about x-Axis ( $M_{cx}$ )<sub>avg</sub>, kip-ft**  
**W-Shapes**

$F_y = 50$  ksi

|                             | Unbraced Length, $L_b$ (ft) |                 |                   |                 |                   |                 |                   |                 |                   |                 |                   |                 |                   |                 |                   |                 |
|-----------------------------|-----------------------------|-----------------|-------------------|-----------------|-------------------|-----------------|-------------------|-----------------|-------------------|-----------------|-------------------|-----------------|-------------------|-----------------|-------------------|-----------------|
|                             | 16                          |                 | 18                |                 | 20                |                 | 22                |                 | 24                |                 | 26                |                 | 28                |                 | 30                |                 |
|                             | ASD                         | LRFD            | ASD               | LRFD            | ASD               | LRFD            | ASD               | LRFD            | ASD               | LRFD            | ASD               | LRFD            | ASD               | LRFD            | ASD               | LRFD            |
| Nominal Depth               | $M_{nx}/\Omega_b$           | $\phi_b M_{nx}$ | $M_{nx}/\Omega_b$ | $\phi_b M_{nx}$ | $M_{nx}/\Omega_b$ | $\phi_b M_{nx}$ | $M_{nx}/\Omega_b$ | $\phi_b M_{nx}$ | $M_{nx}/\Omega_b$ | $\phi_b M_{nx}$ | $M_{nx}/\Omega_b$ | $\phi_b M_{nx}$ | $M_{nx}/\Omega_b$ | $\phi_b M_{nx}$ | $M_{nx}/\Omega_b$ | $\phi_b M_{nx}$ |
| W44                         | 3200                        | 4800            | 3100              | 4600            | 3000              | 4400            | 2900              | 4300            | 2800              | 4100            | 2600              | 4000            | 2500              | 3800            | 2400              | 3600            |
| W40 (> 200 lb)              | 4300                        | 6400            | 4200              | 6300            | 4100              | 6100            | 4000              | 6000            | 3900              | 5800            | 3800              | 5700            | 3700              | 5500            | 3600              | 5400            |
| W40 (< 200 lb)              | 2400                        | 3500            | 2300              | 3400            | 2200              | 3200            | 2100              | 3100            | 2000              | 2900            | 1900              | 2800            | 1700              | 2600            | 1600              | 2400            |
| W36 (> 400 lb)              | 6300                        | 9500            | 6200              | 9300            | 6100              | 9200            | 6100              | 9100            | 6000              | 8900            | 5900              | 8800            | 5800              | 8700            | 5700              | 8600            |
| W36 (> 200 lb and < 400 lb) | 2800                        | 4200            | 2700              | 4100            | 2600              | 4000            | 2600              | 3800            | 2500              | 3700            | 2400              | 3600            | 2300              | 3500            | 2200              | 3300            |
| W36 (< 200 lb)              | 1400                        | 2000            | 1300              | 1900            | 1200              | 1800            | 1100              | 1700            | 1100              | 1600            | 970               | 1500            | 880               | 1300            | 780               | 1200            |
| W33                         | 2100                        | 3100            | 2000              | 3000            | 2000              | 2900            | 1900              | 2800            | 1800              | 2700            | 1700              | 2600            | 1700              | 2500            | 1600              | 2400            |
| W30                         | 1700                        | 2500            | 1600              | 2400            | 1600              | 2300            | 1500              | 2200            | 1400              | 2100            | 1400              | 2100            | 1300              | 2000            | 1300              | 1900            |
| W27                         | 1700                        | 2500            | 1700              | 2500            | 1600              | 2400            | 1600              | 2300            | 1500              | 2300            | 1500              | 2200            | 1400              | 2100            | 1400              | 2100            |
| W24                         | 1100                        | 1700            | 1100              | 1600            | 1000              | 1600            | 1000              | 1500            | 970               | 1500            | 940               | 1400            | 910               | 1400            | 880               | 1300            |
| W21                         | 670                         | 1000            | 640               | 960             | 620               | 930             | 590               | 890             | 570               | 850             | 550               | 820             | 530               | 790             | 510               | 760             |
| W18                         | 660                         | 990             | 640               | 960             | 620               | 930             | 600               | 900             | 590               | 880             | 570               | 850             | 550               | 830             | 540               | 800             |
| W16                         | 200                         | 300             | 180               | 270             | 170               | 250             | 160               | 240             | 150               | 220             | 140               | 210             | 130               | 190             | 120               | 180             |
| W14 (> 300 lb)              | 2600                        | 3900            | 2600              | 3800            | 2500              | 3800            | 2500              | 3800            | 2500              | 3800            | 2500              | 3800            | 2500              | 3700            | 2500              | 3700            |
| W14 (< 300 lb)              | 340                         | 510             | 330               | 500             | 320               | 480             | 310               | 470             | 300               | 460             | 290               | 440             | 290               | 430             | 280               | 420             |
| W12 (> 200 lb)              | 470                         | 700             | 460               | 690             | 450               | 680             | 440               | 660             | 440               | 650             | 430               | 640             | 420               | 630             | 410               | 620             |
| W12 (< 200 lb)              | 250                         | 380             | 240               | 370             | 240               | 360             | 230               | 350             | 220               | 340             | 220               | 330             | 210               | 320             | 210               | 310             |
| W10                         | 130                         | 190             | 120               | 180             | 120               | 180             | 110               | 170             | 110               | 160             | 110               | 160             | 100               | 150             | 98                | 150             |
| W8                          | 61                          | 91              | 58                | 87              | 55                | 83              | 53                | 79              | 50                | 75              | 48                | 72              | 46                | 68              | 44                | 65              |
| W6                          | 16                          | 25              | 15                | 22              | 14                | 20              | 12                | 19              | 11                | 17              | 10                | 16              | 10                | 14              | 8.9               | 13              |
| W5                          | 20                          | 30              | 18                | 28              | 17                | 26              | 16                | 24              | 15                | 22              | 14                | 20              | 13                | 19              | 12                | 17              |
| W4                          | 11                          | 16              | 10                | 15              | 9.2               | 14              | 8.3               | 13              | 7.6               | 11              | 7.0               | 11              | 6.5               | 10              | 6.1               | 9.1             |

| <b>Table 3</b><br><b>Average Available Flexural Strength about y-Axis (<math>M_{cy}</math>)<sub>avg</sub>, kip-ft</b><br><b>W-Shapes</b> |                   |                 |
|--|-------------------|-----------------|
| Shape  | ASD               | LRFD            |
|  | $M_{ny}/\Omega_b$ | $\phi_b M_{ny}$ |
| W44  | 490               | 730             |
| W40 (> 200 lb)   | 750               | 1100            |
| W40 (< 200 lb)   | 330               | 490             |
| W36 (> 400 lb)   | 1300              | 1900            |
| W36 (> 200 lb and < 400 lb)  | 520               | 780             |
| W36 (< 200 lb)   | 200               | 300             |
| W33  | 400               | 610             |
| W30  | 340               | 520             |
| W27  | 380               | 570             |
| W24  | 270               | 400             |
| W21  | 170               | 260             |
| W18  | 190               | 280             |
| W16  | 60                | 90              |
| W14 (> 300 lb)   | 1300              | 1900            |
| W14 (< 300 lb)   | 160               | 240             |
| W12 (> 200 lb)   | 210               | 320             |
| W12 (< 200 lb)   | 120               | 180             |
| W10  | 62                | 93              |
| W8   | 32                | 48              |
| W6   | 10                | 16              |
| W5   | 13                | 19              |
| W4   | 7.3               | 11              |

| Table 4<br>Average Available Tensile Strength ( $P_c$ ) <sub>avg</sub> , kips<br>W-Shapes |                   |                 |
|---|-------------------|-----------------|
| Shape   | ASD               | LRFD            |
|   | $P_{ny}/\Omega_t$ | $\phi_t P_{ny}$ |
| W44   | 2200              | 3400            |
| W40 (> 200 lb)  | 3100              | 4700            |
| W40 (< 200 lb)  | 2000              | 3000            |
| W36 (> 400 lb)  | 4600              | 6900            |
| W36 (> 200 lb and < 400 lb)   | 2300              | 3400            |
| W36 (< 200 lb)  | 1300              | 2000            |
| W33   | 1800              | 2800            |
| W30   | 1600              | 2400            |
| W27   | 1800              | 2600            |
| W24   | 1400              | 2000            |
| W21   | 970               | 1500            |
| W18   | 1000              | 1600            |
| W16   | 450               | 670             |
| W14 (> 300 lb)  | 3900              | 5800            |
| W14 (< 300 lb)  | 690               | 1000            |
| W12 (> 200 lb)  | 940               | 1400            |
| W12 (< 200 lb)  | 580               | 880             |
| W10   | 390               | 580             |
| W8  | 250               | 380             |
| W6  | 120               | 180             |
| W5  | 140               | 210             |
| W4  | 100               | 150             |

**PROCEDURE FOR USING THE PROPOSED METHOD AND TABLES**

AISC *Specification* Equations H1-1a and H1-1b apply to members subject to tension and bending as well as subject to compression and bending. Only the values of the first term in the equation are affected if the axial load is tension or compression.

Ideally, the value of the applicable AISC *Specification* interaction Equation H1-1a or H1-1b will be unity as shown here.

When  $\frac{P_r}{P_c} \geq 0.20$

$$\frac{P_r}{P_c} + \frac{8}{9} \left( \frac{M_{rx}}{M_{cx}} + \frac{M_{ry}}{M_{cy}} \right) = 1.0 \quad (10)$$

When  $\frac{P_r}{P_c} < 0.20$

$$\frac{P_r}{2P_c} + \left( \frac{M_{rx}}{M_{cx}} + \frac{M_{ry}}{M_{cy}} \right) = 1.0 \quad (11)$$

For biaxial bending ( $P_r = 0$ ,  $P_r/P_c = 0 < 0.20$ ), the equivalent for AISC *Specification* Equation H1-1b becomes the following.

$$\frac{M_{rx}}{M_{cx}} + \frac{M_{ry}}{M_{cy}} = 1.0 \quad (12)$$

These equations will be used in the following procedure for design.

If it is not obvious which of Equation 10 or 11 applies, it is reasonable to begin with Equation 10 because this equation is applicable in many common situations. When checking each trial section, the appropriate equation will be used as illustrated in the following examples. The new design procedure may be summarized as follows.

1. Combined axial load (tension or compression) and bending when the numerical value of the required axial strength,  $P_r$ , is larger than the value of the required flexural strength about the  $x$ -axis,  $M_{rx}$ ; namely,  $|P_r| > |M_{rx}|$ .
  - a. Look up the average available flexural strength  $(M_{cx})_{avg}$  from Table 2 based on  $L_b$ .
  - b. If bending about  $y$ -axis is present, look up the average available flexural strength about  $y$ -axis  $(M_{cy})_{avg}$  from Table 3.
  - c. Use results of steps a and b and Equation 10 or 11 to solve for an estimate for the available axial strength  $(\phi_c P_n \text{ or } P_n / \Omega_c)_{est}$ .
  - d. Choose a trial section from AISC *Manual* Table 6-1 using the results of steps a, b, and c while paying closer attention to sections with higher available axial strengths.

- e. Check section using AISC *Specification* Equation H1-1a or H1-1b.

The flowcharts of Figures 1 and 2 illustrate this procedure.

2. Combined axial load (tension or compression) and bending when the numerical value of the required flexural strength about the  $x$ -axis,  $M_{rx}$ , is larger than the value of the required axial strength,  $P_r$ ; namely,  $|M_{rx}| > |P_r|$ .
  - a. Look up the average available axial strength  $(P_c)_{avg}$  from Table 1 for compression based on  $L_c$  or  $(P_c)_{avg}$  from Table 4 for tension.
  - b. If bending about  $y$ -axis is present, look up the average available flexural strength about  $y$ -axis  $(M_{cy})_{avg}$  from Table 3.
  - c. Use results of steps a and b and Equation 10 or 11 to solve for an estimate for the desired available flexural strength  $(\phi_b M_{nx} \text{ or } M_{nx} / \Omega_b)_{est}$ .
  - d. Choose a trial section from AISC *Manual* Table 6-1 using results of steps a, b, and c while paying closer attention to sections with higher available flexural strengths about  $x$ -axis.
  - e. Check section using AISC *Specification* Equation H1-1a or H1-1b.

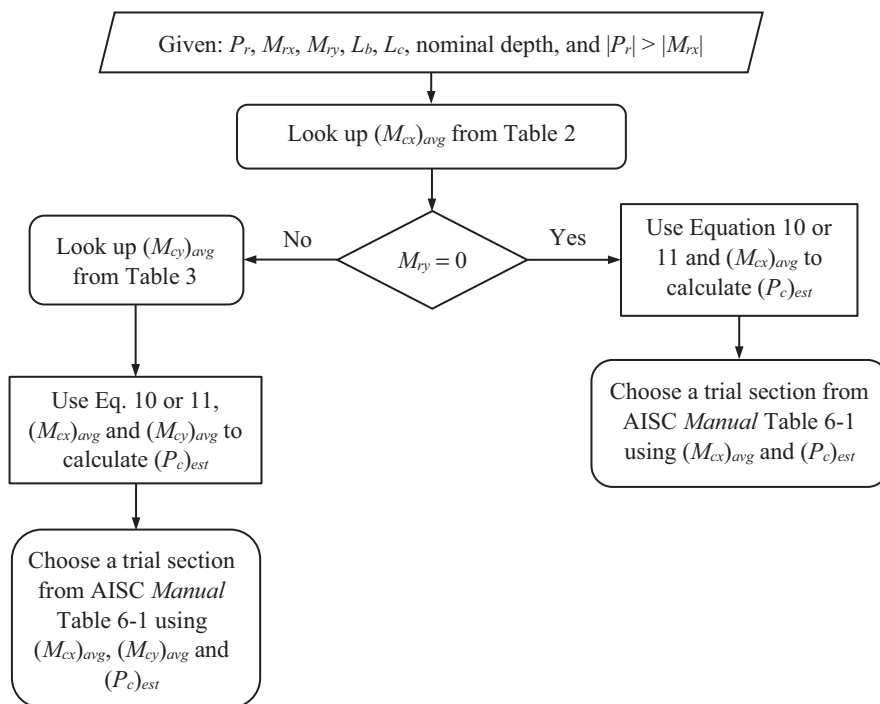


Fig. 1. Flowchart for choosing a trial section for combined compression and bending with large axial load.

The flowcharts of Figures 3 and 4 illustrate this procedure.

### 3. Biaxial Bending (no axial force)

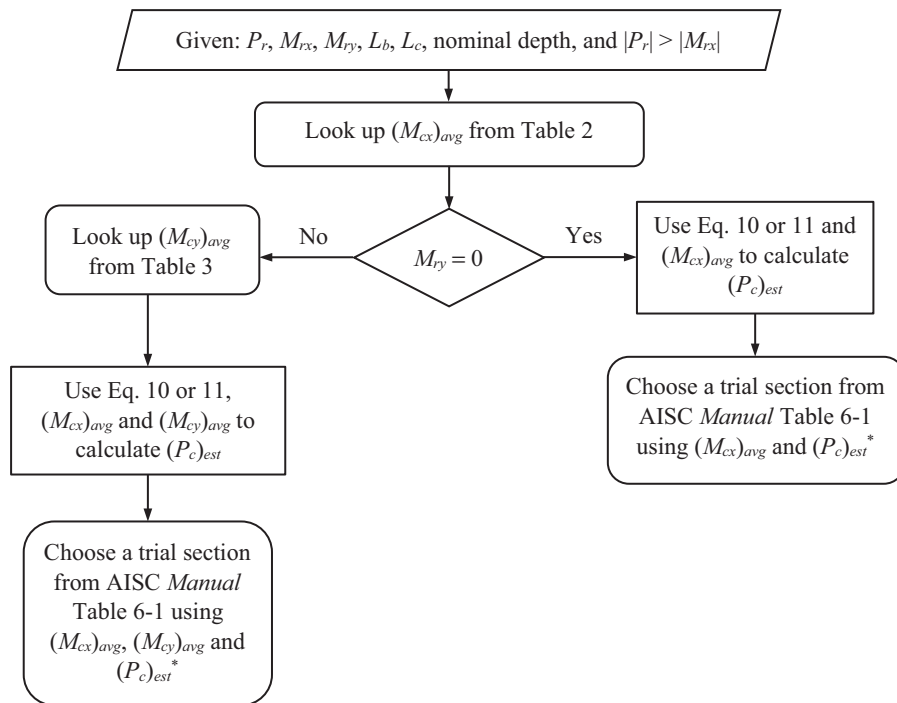
- Look up the average available flexural strength for bending about the  $y$ -axis  $(M_{cy})_{avg}$  from Table 3.
- Use result of step a and Equation 12 to solve for an estimate for the available flexural strength  $(M_{cx})_{est}$ .
- Select a trial section from AISC *Manual* Table 6-1 using results of steps a and b while paying closer attention to sections with higher available flexural strength about the  $x$ -axis.
- Check section using AISC *Specification* Equation H1-1b.

The flowchart of Figure 5 illustrates this procedure.

### Additional Notes on Use of the Proposed Method and Tables

The following notes are offered for using the proposed method and tables.

- The proposed procedure converges quickly to the desired section. Ordinarily, the desired section is attained by checking one or two trial sections. At times, three trial sections may need to be checked. It is rare that four trial sections would need to be checked to attain the desired section.
- If the values of  $P_r$  and  $M_{rx}$  are close, use either procedure 1 or 2.
- To choose a trial section, it is reasonable to interpolate between values of  $L_c$  and  $L_b$  when using Tables 1 and 2 (see Example 3).
- Some average available strengths for a certain nominal depth in Tables 1 to 4 are broken down based on weight per foot of the member. If a wrong weight range is assumed, the process still works and converges rapidly (see Example 4).
- Values of average available tensile strength in Table 4 can be used without knowing whether yielding or rupture strength governs design at this point. Exact available



\* Consider tensile yielding and tensile rupture available strengths when checking the trial section.

Fig. 2. Flowchart for choosing a trial section for combined tension and bending with large axial load.

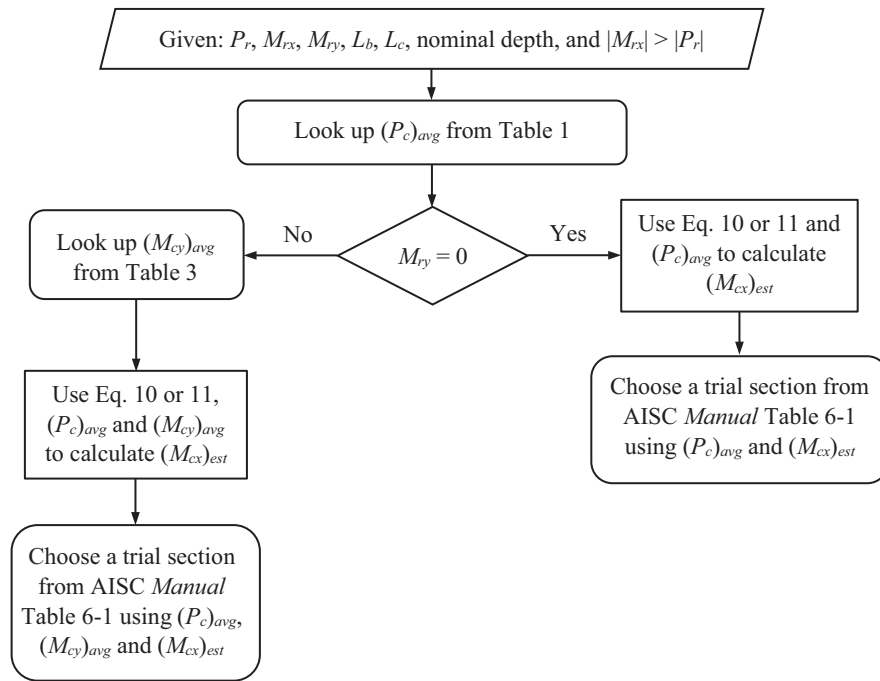
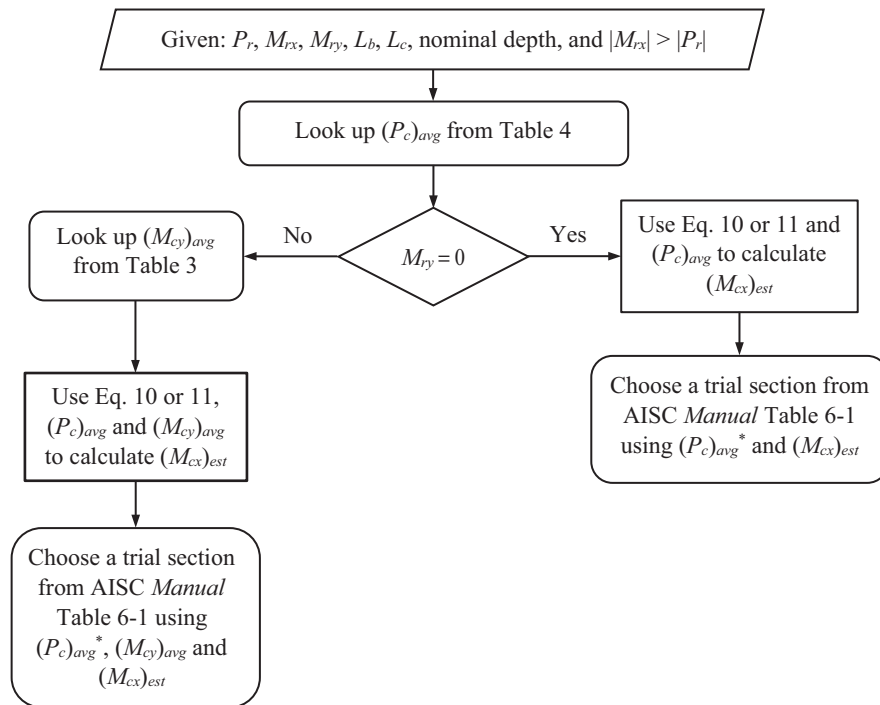


Fig. 3. Flowchart for choosing a trial section for combined compression and bending with large bending moment about the x-axis.



\* Consider tensile yielding and tensile rupture available strengths when checking the trial section.

Fig. 4. Flowchart for choosing a trial section for combined tension and bending with large bending moment about the x-axis.

strengths for tensile yielding are listed in AISC *Manual* Table 6-1. Available tensile rupture strengths must be calculated based on member connections when checking for compliance with AISC *Specification* provisions regardless of method used to obtain a trial section (see Example 3).

6. When considering a trial section from AISC *Manual* Table 6-1, if each of the available strengths are larger than the average and estimated values, the section will lead to an interaction equation value of less than 1.0 and the shape under consideration is an appropriate trial section for the given conditions. Similarly, if each of the available strengths are smaller than the average and estimated values, the section will lead to an interaction value of greater than 1.0, and the section under consideration is not adequate (see Example 1).
7. At times, a W-shape under consideration from AISC *Manual* Table 6-1 as a trial section will have one available strength larger and one or two smaller than the average and estimated values. The designer may still consider such a trial section since the math for the interaction equation may still result in a value less than or equal to 1.0 (see Example 1).
8. Trial sections must be checked for compliance with AISC *Specification* Equation H1-1a or H1-1b, whichever is appropriate, along with its available strengths. If in choosing a trial section it was assumed that AISC *Specification* Equation H1-1a governs, but indeed AISC *Specification* Equation H1-1b governs, Equation H1-1b must be checked to determine the adequacy of the section (see Example 2).

9. If the required flexural strength about the y-axis,  $M_{ry}$ , is larger than  $M_{rx}$  and  $P_r$ , steps 1(a) and 2(a) in the procedure can be adjusted accordingly. Choose a trial section using  $(P_c)_{avg}$  and  $(M_{cx})_{avg}$ , then use AISC *Specification* Equation 10 or 11 to solve for an estimate for the desired available flexural strength  $(M_{cy})_{est}$ . Select a trial section from AISC *Manual* Table 6-1 based on  $(P_c)_{avg}$ ,  $(M_{cx})_{avg}$  and  $(M_{cy})_{est}$ .

### Examples Using the Proposed Method and Design Aids

The focus of this article is on choosing an optimum trial section, not complete design. The following remarks are independent of how the designer chooses a trial section and are not limited to the method and aids proposed here.

Second-order effects must be considered in the design of members subjected to compression and bending (beam-columns). During the process of selecting a trial section, the designer may decide to neglect second-order effects initially. Alternatively, the designer can use estimates for moment amplifications  $B_1$  and  $B_2$  (if applicable) to include some level of second-order effects at this stage. In the end, every trial section must be checked for compliance with all the pertinent provisions of the AISC *Specification*, including second-order effects.

In considering second-order effects, cross-sectional properties of each trial section must be used in calculating  $P_r$ ,  $M_{rx}$ , and  $M_{ry}$ . The values of  $P_r$ ,  $M_{rx}$ , and  $M_{ry}$  are dependent on the trial section's cross-sectional properties and may be different for one trial section versus another. For example,  $P$ - $\delta$  effect depends on  $I_x$ , which varies from one section to another. However, while choosing a trial section, it may be

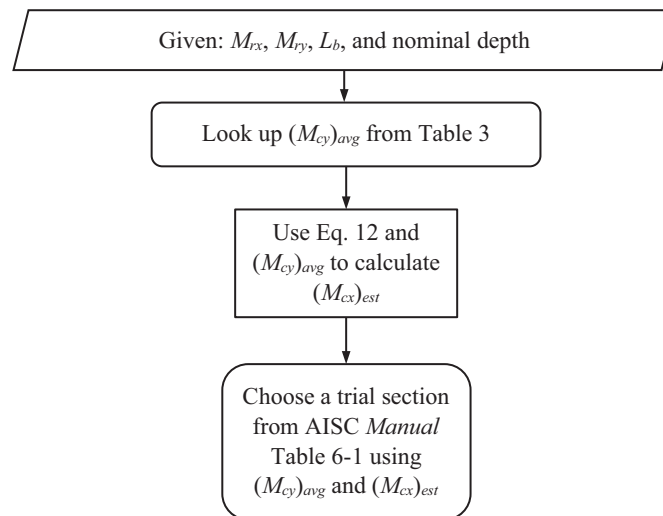


Fig. 5. Flowchart for choosing a trial section for biaxial bending.

reasonable to assume these values do not change between trial sections that are close in size.

The scope of this article does not include second-order effects. Therefore, in the examples that follow, the assumption is made that second-order effects do not change the

value of the required strengths  $P_r$ ,  $M_{rx}$ , and  $M_{ry}$  for different trial sections.

Example problems that follow are done using the LRFD method. Solutions using the ASD method would be similar except for looking up ASD values from Tables 1 through 4 as well as the ASD versions of Equations 10, 11, and 12.

### EXAMPLE 1

#### Given:

Determine the lightest ASTM A992/A992M W14 section for a beam-column with the following conditions:

$$L_b = 10 \text{ ft}, L_c = 14 \text{ ft}$$

$$P_u = 600 \text{ kips}, M_{ux} = 170 \text{ kip-ft}, M_{uy} = 40 \text{ kip-ft}$$

#### Solution:

The numerical value of  $P_u$  is larger than that of  $M_{ux}$ . Look up the average values for  $M_{cx}$  and  $M_{cy}$  ( $\phi_b M_{nx}$  and  $\phi_b M_{ny}$ ) from Tables 2 and 3, respectively, as follows. Assume member weight is  $\leq 200$  lb/ft. For  $L_b = 10$  ft,  $(M_{cx})_{avg} = (\phi_b M_{nx})_{avg} = 550$  kip-ft, and  $(M_{cy})_{avg} = (\phi_b M_{ny})_{avg} = 240$  kip-ft.

Use Equation 10 to calculate an estimate for  $\phi_c P_n$

$$\frac{P_r}{P_c} + \frac{8}{9} \left( \frac{M_{rx}}{M_{cx}} + \frac{M_{ry}}{M_{cy}} \right) = 1.0 \quad (10)$$

$$\frac{600 \text{ kips}}{(\phi_c P_n)_{est}} + \frac{8}{9} \left( \frac{170 \text{ kip-ft}}{550 \text{ kip-ft}} + \frac{40 \text{ kip-ft}}{240 \text{ kip-ft}} \right) = 1.0$$

Therefore,  $(\phi_c P_n)_{est} = 1,040$  kips.

From AISC *Manual* Table 6-1, choose a W14 trial section with the following approximate values:

$$\phi_c P_n = 1,040 \text{ kips } (L_c = 14 \text{ ft}), \phi_b M_{nx} = 550 \text{ kip-ft } (L_b = 10 \text{ ft}), \text{ and } \phi_b M_{ny} = 240 \text{ kip-ft}$$

Try a W14×90 with  $\phi_c P_n = 1,030$  kips ( $L_c = 14$  ft),  $\phi_b M_{nx} = 574$  kip-ft ( $L_b = 10$  ft), and  $\phi_b M_{ny} = 273$  kip-ft.

Note that this section has a lower  $\phi_c P_n$  but higher  $\phi_b M_{nx}$  and  $\phi_b M_{ny}$  than the target values.

Check the W14×90 for compliance with AISC *Specification* Equation H1-1a or H1-1b.

$$\begin{aligned} \frac{P_u}{\phi_c P_n} &= \frac{600 \text{ kips}}{1,030 \text{ kips}} \\ &= 0.583 > 0.20 \end{aligned}$$

Therefore, use AISC *Specification* Equation H1-1a.

$$\begin{aligned} \frac{P_u}{\phi_c P_n} + \frac{8}{9} \left( \frac{M_{ux}}{\phi_b M_{nx}} + \frac{M_{uy}}{\phi_b M_{ny}} \right) &\leq 1.0 \\ 0.583 + \frac{8}{9} \left( \frac{170 \text{ kip-ft}}{574 \text{ kip-ft}} + \frac{40 \text{ kip-ft}}{273 \text{ kip-ft}} \right) &= 0.976 < 1.0 \quad \mathbf{o.k.} \end{aligned}$$

The W14×90 is an appropriate trial section.

For a lighter section, try a W14×82 with  $\phi_c P_n = 772$  kips ( $L_c = 14$  ft),  $\phi_b M_{nx} = 511$  kip-ft ( $L_b = 10$  ft), and  $\phi_b M_{ny} = 168$  kip-ft.

By inspection, a W14×82 is not adequate because all the available strength values are less than what made the interaction equation equal to unity ( $\phi_c P_n = 772$  kips < 1,040 kips,  $\phi_b M_{nx} = 511$  kip-ft < 550 kip-ft, and  $\phi_b M_{ny} = 168$  kip-ft < 240 kip-ft).

Choose a W14×90 (ASTM A992/A992M) as the trial section.

### EXAMPLE 2

#### Given:

Determine the lightest ASTM A992/A992M W18 section for a beam-column with the following conditions:

$$L_c = L_b = 14 \text{ ft}$$

$$P_u = 170 \text{ kips}, M_{ux} = 600 \text{ kip-ft}, M_{uy} = 40 \text{ kip-ft}$$

#### Solution:

The numerical value of  $M_{ux}$  is larger than that of  $P_u$ . Look up average values for  $P_c$  and  $M_{cy}$  ( $\phi_c P_n$ , and  $\phi_b M_{ny}$ ) from Tables 1 and 3, respectively, as follows:

$$\text{For } L_c = 14 \text{ ft}, (P_c)_{avg} = (\phi_c P_n)_{avg} = 1,200 \text{ kips}, \text{ and } (M_{cy})_{avg} = (\phi_b M_{ny})_{avg} = 280 \text{ kip-ft}$$

Use Equation 10 to calculate an estimate for  $(\phi_b M_{nx})_{est}$ .

$$\frac{P_r}{P_c} + \frac{8}{9} \left( \frac{M_{rx}}{M_{cx}} + \frac{M_{ry}}{M_{cy}} \right) = 1.0 \tag{10}$$

$$\frac{170 \text{ kips}}{1,200 \text{ kips}} + \frac{8}{9} \left[ \frac{600 \text{ kips}}{(\phi_b M_{nx})_{est}} + \frac{40 \text{ kip-ft}}{280 \text{ kip-ft}} \right] = 1.0$$

$$\text{Therefore, } (\phi_b M_{nx})_{est} = 729 \text{ kip-ft.}$$

From AISC *Manual* Table 6-1, choose a trial W18 section with the following approximate values:

$$\phi_c P_n = 1,200 \text{ kips } (L_c = 14 \text{ ft}), \phi_b M_{nx} = 729 \text{ kip-ft } (L_b = 14 \text{ ft}), \text{ and } \phi_b M_{ny} = 280 \text{ kip-ft}$$

Try a W18×119 with  $\phi_c P_n = 1,190$  kips ( $L_c = 14$  ft),  $\phi_b M_{nx} = 914$  kip-ft ( $L_b = 14$  ft), and  $\phi_b M_{ny} = 259$  kip-ft.

$$\frac{P_u}{\phi_c P_n} = \frac{170 \text{ kips}}{1,190 \text{ kips}} = 0.143 < 0.20$$

Use AISC *Specification* Equation H1-1b. Note that originally it was assumed that Equation H1-1a governed.

$$\frac{P_u}{2(\phi_c P_n)} + \left( \frac{M_{ux}}{\phi_b M_{nx}} + \frac{M_{uy}}{\phi_b M_{ny}} \right) \leq 1.0$$

$$\frac{0.143}{2} + \left( \frac{600 \text{ kip-ft}}{914 \text{ kip-ft}} + \frac{40.0 \text{ kip-ft}}{259 \text{ kip-ft}} \right) = 0.882 < 1.0 \quad \mathbf{o.k.}$$

For a lighter section, try a W18×106 with  $\phi_c P_n = 1,050$  kips ( $L_c = 14$  ft),  $\phi_b M_{nx} = 795$  kip-ft ( $L_b = 14$  ft), and  $\phi_b M_{ny} = 227$  kip-ft.

Check the W18×106 for compliance with AISC *Specification* Equation H1-1a or H1-1b.

$$\frac{P_u}{\phi_c P_n} = \frac{170 \text{ kips}}{1,050 \text{ kips}} = 0.162 < 0.20$$

Therefore, use AISC *Specification* Equation H1-1b. Note that originally it was assumed that AISC *Specification* Equation H1-1a controlled.

$$\frac{P_u}{2(\phi_c P_n)} + \left( \frac{M_{ux}}{\phi_b M_{nx}} + \frac{M_{uy}}{\phi_b M_{ny}} \right) \leq 1.0$$

$$\frac{0.162}{2} + \left( \frac{600 \text{ kip-ft}}{795 \text{ kip-ft}} + \frac{40.0 \text{ kip-ft}}{227 \text{ kip-ft}} \right) = 1.01 > 1.0 \quad \mathbf{n.g.}$$

Choose a W18×119 (ASTM A992/A992M) as the trial section.

### EXAMPLE 3

#### Given:

Determine the lightest ASTM A992/A992M W10 section connected as shown in Figure 6.

$$L_b = 15 \text{ ft}$$

$$d_b = \frac{7}{8} \text{ in. bolts at } 3 \text{ in. o.c.}$$

$$P_u = 300 \text{ kips in tension, } M_{ux} = 85 \text{ kip-ft, } M_{uy} = 25 \text{ kip-ft}$$

#### Solution:

The numerical value of  $P_u$  is larger than that of  $M_{ux}$ . Look up the average values for  $M_{cx}$  and  $M_{cy}$  ( $\phi_b M_{nx}$ , and  $\phi_b M_{ny}$ ) from Tables 2 and 3, respectively, as follows. Note that it is reasonable at this point to interpolate between values of  $L_b$  in Table 2 and 3.

At  $L_b = 14 \text{ ft}$ ,  $(M_{cx})_{avg} = (\phi_b M_{nx})_{avg} = 200 \text{ kip-ft}$ , and at  $L_b = 16 \text{ ft}$ ,  $(M_{cx})_{avg} = (\phi_b M_{nx})_{avg} = 190 \text{ kip-ft}$ .

Therefore, at  $L_b = 15 \text{ ft}$ ,  $(M_{cx})_{avg} = (\phi_b M_{nx})_{avg} = 195 \text{ kip-ft}$  (by interpolation). Also,  $(M_{cy})_{avg} = (\phi_b M_{ny})_{avg} = 93.0 \text{ kip-ft}$  from Table 3.

Use Equation 10 to calculate an estimate for  $\phi_t P_n$ .

$$\frac{P_r}{P_c} + \frac{8}{9} \left( \frac{M_{rx}}{M_{cx}} + \frac{M_{ry}}{M_{cy}} \right) = 1.0 \quad (10)$$

$$\frac{300 \text{ kips}}{(\phi_t P_n)_{est}} + \frac{8}{9} \left( \frac{85.0 \text{ kip-ft}}{195 \text{ kip-ft}} + \frac{25.0 \text{ kip-ft}}{93.0 \text{ kip-ft}} \right) = 1.0$$

Therefore,  $(\phi_t P_n)_{est} = 803 \text{ kips}$ .

From AISC *Manual* Table 6-1, choose a W10 trial section with the following approximate values:

$$\phi_t P_n = 803 \text{ kips, } \phi_b M_{nx} = 195 \text{ kip-ft } (L_b = 15 \text{ ft}), \text{ and } \phi_b M_{ny} = 93.0 \text{ kip-ft}$$

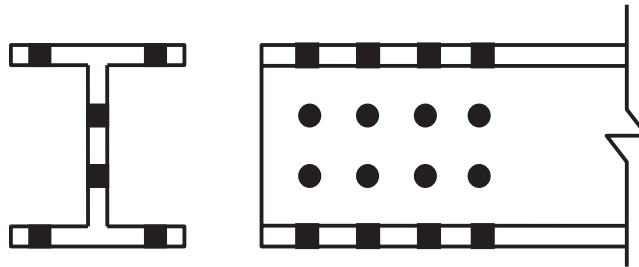


Fig. 6. Example 3 connection.

Consider a W10×60 with  $\phi_t P_{ny} = 797$  kips (tensile yielding),  $\phi_b M_{nx} = 257$  kips ( $L_b = 15$  ft), and  $\phi_b M_{ny} = 131$  kip-ft. Also, from AISC *Manual* Table 1-1,  $A_g = 17.7$  in.<sup>2</sup>,  $t_w = 0.420$  in., and  $t_f = 0.680$  in.

The available tensile rupture strength must be calculated based on the member connection.

$$A_n = 17.7 \text{ in.}^2 - (4 \text{ flange holes})(7/8 \text{ in.} + 1/8 \text{ in.})(0.680 \text{ in.}) - (2 \text{ web holes})(7/8 \text{ in.} + 1/8 \text{ in.})(0.420 \text{ in.}) \\ = 14.1 \text{ in.}^2$$

$$U = 1.0 \text{ (AISC Specification Table D3.1, Case 1), therefore, } A_e = A_n = 14.1 \text{ in.}^2$$

Available tensile rupture strength:

$$\phi_t P_{nr} = 0.75 F_u A_e \\ = (0.75)(65 \text{ ksi})(14.1 \text{ in.}^2) \\ = 687 \text{ kips}$$

Available tensile yielding strength:

From AISC *Manual* Table 6-1,  $\phi_t P_{nv} = 797$  kips

$$\phi_t P_{nv} = 797 \text{ kips} > \phi_t P_{nr} = 687 \text{ kips}$$

Therefore, use  $\phi_t P_n = 687$  kips

Check the W10×60 for compliance with AISC *Specification* Equation H1-1a or H1-1b.

$$\frac{P_u}{\phi_t P_n} = \frac{300 \text{ kips}}{687 \text{ kips}} \\ = 0.437 > 0.20$$

Therefore, use AISC *Specification* Equation H1-1a.

$$\frac{P_u}{\phi_t P_n} + \frac{8}{9} \left( \frac{M_{ux}}{\phi_b M_{nx}} + \frac{M_{uy}}{\phi_b M_{ny}} \right) \leq 1.0 \\ 0.437 + \frac{8}{9} \left( \frac{85.0 \text{ kip-ft}}{257 \text{ kip-ft}} + \frac{25.0 \text{ kip-ft}}{131 \text{ kip-ft}} \right) = 0.90 < 1.0 \quad \text{o.k.}$$

The W10×60 (ASTM A992/A992M) is an appropriate trial section. For the lightest section try a W10×54. The remainder of the solution is similar to trying the W10×60. Note that to complete the design, provisions of AISC *Specification* Sections H4 and F13.1 must be checked as well.

#### EXAMPLE 4

##### Given:

Determine the lightest ASTM A992/A992M W12 section in biaxial bending with the following conditions:

$$L_b = 14 \text{ ft}$$

$$M_{ux} = 600 \text{ kip-ft, } M_{uy} = 110 \text{ kip-ft}$$

##### Solution:

Look up the average value for  $M_{cy}$  ( $\phi_b M_{ny}$ ) from Table 3 as follows. Given the relatively large  $M_{uy}$ , assume that this section may be heavier than 200 lb/ft at this point.

$$(M_{cy})_{avg} = (\phi_b M_{ny})_{avg} = 320 \text{ kip-ft}$$

Use Equation 12 to calculate an estimate for  $(\phi_b M_{nx})_{est}$ .

$$\frac{M_{rx}}{M_{cx}} + \frac{M_{ry}}{M_{cy}} = 1.0 \quad (12)$$

$$\frac{600 \text{ kip-ft}}{(\phi_b M_{nx})_{est}} + \frac{110 \text{ kip-ft}}{320 \text{ kip-ft}} = 1.0$$

Therefore,  $(\phi_b M_{nx})_{est} = 914 \text{ kip-ft}$ .

From AISC *Manual* Table 6-1, choose a trial W12 section with the following approximate values:

$$\phi_b M_{nx} = 914 \text{ kip-ft } (L_b = 14 \text{ ft}), \text{ and } \phi_b M_{ny} = 320 \text{ kip-ft}$$

Try a W12×152 with  $\phi_b M_{nx} = 895 \text{ kip-ft}$  ( $L_b = 14 \text{ ft}$ ), and  $\phi_b M_{ny} = 416 \text{ kip-ft}$ . Note that this section is not heavier than 200 lb/ft as assumed earlier, but that is fine because exact strength values will be used for these calculations.

Use Equation 12 to check compliance with AISC *Specification* provisions. Note that Equation 12 is a modified version of AISC *Specification* Equation H1-1b with  $P_r = 0$  and, thus,  $\frac{P_r}{P_c} = 0 < 0.20$ .

$$\begin{aligned} \frac{M_{ux}}{\phi_b M_{nx}} + \frac{M_{uy}}{\phi_b M_{ny}} &= \frac{600 \text{ kip-ft}}{895 \text{ kip-ft}} + \frac{110 \text{ kip-ft}}{416 \text{ kip-ft}} \\ &= 0.935 < 1.0 \quad \mathbf{o.k.} \end{aligned}$$

For a lighter section, try a W12×136 with  $\phi_b M_{nx} = 785 \text{ kip-ft}$  ( $L_b = 14 \text{ ft}$ ), and  $\phi_b M_{ny} = 368 \text{ kip-ft}$  from AISC *Manual* Table 6-1.

Use Equation 12 to check compliance with AISC *Specification* provisions.

$$\begin{aligned} \frac{M_{ux}}{\phi_b M_{nx}} + \frac{M_{uy}}{\phi_b M_{ny}} &= \frac{600 \text{ kip-ft}}{785 \text{ kip-ft}} + \frac{110 \text{ kip-ft}}{368 \text{ kip-ft}} \\ &= 1.06 > 1.0 \quad \mathbf{n.g.} \end{aligned}$$

Choose a W12×152 (ASTM A992/A992M) as the trial section.

## COMPARISON OF DIFFERENT METHODS

Table 5 lists the characteristics of the different methods discussed for comparison purposes.

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**Table 5. Comparison of Different Methods for Design of Members Subject to Combined Forces**

| Method <sup>1</sup>        | Constraints <sup>2</sup>    |                                   |                          | Flexibilities <sup>3</sup> |         |         |       |             |
|----------------------------|-----------------------------|-----------------------------------|--------------------------|----------------------------|---------|---------|-------|-------------|
|                            | Method Limitations          | Column Sections Only <sup>4</sup> | $L_b = L_c$ <sup>5</sup> | Axial Load                 |         | Bending |       |             |
|                            |                             |                                   |                          | Comp.                      | Tension | $M_x$   | $M_y$ | $M_x + M_y$ |
| Burgett (1973)             | Uses $P_{eff}$ <sup>6</sup> | x                                 | x                        | x                          |         | x       | x     | x           |
| Uang et al. (1990)         | Uses $P_{eff}$ <sup>6</sup> | x                                 | x                        | x                          |         | x       | x     | x           |
| Aminmansour (2000)         |                             |                                   |                          | x                          |         | x       | x     | x           |
| Keil (2000)                |                             | x                                 | $x^7$                    | x                          |         | x       |       |             |
| Aminmansour (2006)         |                             |                                   |                          |                            | x       | x       | x     | x           |
| Hosur and Augustine (2007) |                             | x                                 | $x^7$                    | x                          |         | x       |       |             |
| Sa'adat and Banam (2014)   |                             |                                   |                          | x                          | x       | x       |       |             |
| Reynolds and Uang (2019)   | Uses $P_{eq}$ <sup>6</sup>  |                                   | x                        | x                          |         | x       | x     | x           |
| Proposed Method            |                             |                                   |                          | x                          | x       | x       | x     | x           |

<sup>1</sup> See References list.  
<sup>2</sup> Fewer entries per method is better.  
<sup>3</sup> More entries per method is better.  
<sup>4</sup> Selection limited to sections ordinarily used as columns.  
<sup>5</sup> Method assumes  $L_b = L_c$ , otherwise outcome may be unconservative in some instances.  
<sup>6</sup> Method requires conversion of bending moments to an equivalent axial load.  
<sup>7</sup> Modifications available for other lengths.

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