One Engineer's Opinion

JAMES M. FISHER

The AISC publication *Light and Heavy Industrial Buildings*[1] is currently being distributed to attendees of the ongoing AISC lecture series "Light and Heavy Industrial Buildings" and will be made available for general distribution after the completion of the lecture series. The purpose of this article is to clarify and elaborate on the material contained in Ref. 1 with respect to the determination of slenderness ratios of crane columns. The need for this discussion has been pointed out to the author by the many engineers who have already attended the lecture series.

Since many of the readers of this article have not yet attended the lecture series and thus have not received Ref. 1, the material discussed here will be presented in an independent manner.

SLENDERNESS RATIOS OF CRANE COLUMNS

Shown in Fig. 1 are two typical crane columns. To properly design such columns, stress and stability criteria must be satisfied. The AISC Specification[2] and AISE Technical Report No. 13[3] contain the basic interaction equations which should be used to check such criteria. In both references, the slenderness ratios of the column must be determined in order to calculate an allowable axial stress for the column. Bracketed and stepped crane columns present added complexity in the calculation of effective lengths, when compared to building columns. These added complexities are due to the fact that crane columns have a varying axial load along their length and, in addition, may have varying cross-sectional properties as well.

The recommended procedure to determine slenderness ratios for these columns is to examine both the upper shaft and the lower shaft of the column.[1,3] The determination of slenderness ratios for the upper and lower portions of the column about the weak axis is typically more straightforward, as lateral bracing is generally provided at the crane girder elevation. Since this is a common location for a brace, this problem will not be discussed here. The difficulty, therefore, arises in determining the slenderness ratio about the strong axis. The slenderness ratio of the upper shaft is dependent on the axial load and stiffness of the lower shaft relative to the axial load and stiffness of the upper shaft. The same is true for the lower shaft.

The proper determination of K_x for the upper *or* lower shaft depends on:

1. End fixity conditions of the column
2. Ratio of the axial loads on the column
3. Ratio of the moments of inertia of the upper shaft to lower shaft
4. Ratio of the length of the upper and lower shafts

Most simplified office procedures used to calculate the slenderness ratio of crane columns ignore the interaction of these variables, thereby either overestimating or underestimating the strength of the column in question. The *only* proper way to calculate the slenderness ratio is to include all of the above effects. In 1972 Anderson and Woodward[4] presented a complete flow diagram for the determination of slenderness ratios in stepped columns. The

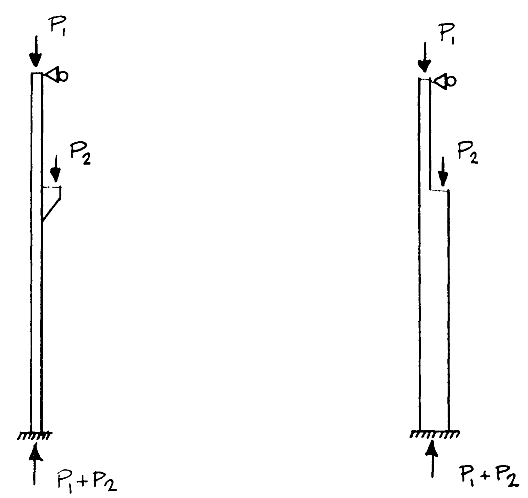

Figure 1

James M. Fisher is Vice President, Computerized Structural Design, Inc., Milwaukee, Wisconsin.

procedure is exact and can be programmed on hand-held calculators or on mini-computers, with little difficulty. Charts and graphs can be prepared from such a program; however, since there are so many combinations of load, lengths, and geometry, such charts can become very lengthy and cumbersome. Today, many design offices own a mini-computer or a hand-held programmable calculator. The author recommends the use of the Anderson-Woodward program as the most reliable and most efficient method of calculating crane column slenderness ratios. (Note: the total time to implement the Anderson-Woodward program in the author's office was twelve hours on an H.P. 9845 mini-computer.)

The charts contained in Ref. 3 give reliable K_x values for heavy mill building stepped columns; however, the disadvantages of these charts as compared to the computer program are:

1. The AISE charts are pertinent to only the lower shaft of stepped columns. Charts are not provided for K_x values for the upper shaft.
2. For most medium size crane buildings, P_1/P_2 is greater than 0.25 and charts are not provided for $P_1/P_2 > 0.25$.
3. The charts are based on columns with no lateral sway. The computer program will provide K_x values for columns free to sway.

The procedure used in Ref. 1 consisted of using the same slenderness ratio for both the upper and lower shafts. This slenderness ratio was determined using the entire length of the column in conjunction with r_x of the lower shaft. While the use of this procedure will generally result in conservative slenderness ratios, in certain cases which cannot be predicted with generalization, the ratio obtained might be unconservative as compared to the exact solution. Since the procedure outlined in Ref. 4 is straightforward and exact, it is recommended that it be substituted for the procedure used in Ref. 1 for the determination of slenderness ratios.

The two examples in Ref. 1 are worked below to illustrate the use of the correct slenderness ratios as determined from the computer solution.

EXAMPLE 1. BRACKETED CRANE COLUMN DESIGN

Given: Assume a Class D building and use AISE provisions. See Fig. 2.

Crane forces:
P_2 = 50 kips, including impact
P_H = 3.4 kips
M = 90 kip-ft

Note: 50 kips is the maximum allowable load on a bracket (AISE Technical Report 13.)

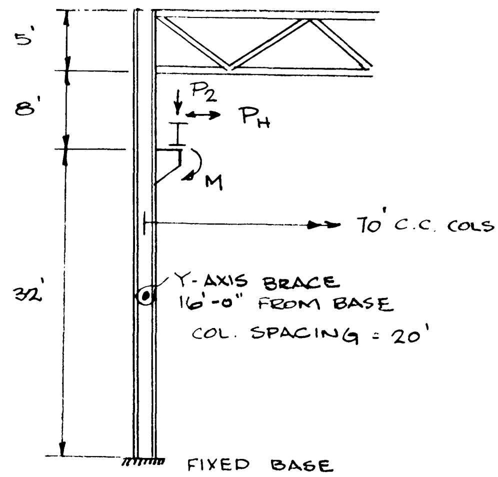

Figure 2

Frame Analysis:
A frame analysis was performed using the AISE loading combinations. The critical moment diagrams were obtained from cases 2 and 3. See Fig. 3.

Case 2 = DL + LL + Crane (lateral & vertical)

Case 3 = (DL + vertical crane + wind) × 0.75

Check the capacity of a W16x77 section (A36):

$I_x = 1110$ in.^{4} $r_x = 7.0$ in. $r_T = 2.77$ in.
$S_x = 134$ in.^{3} $r_y = 2.47$ in.
$A = 22.6$ in.^{2} $d/A_f = 2.11$ in.$^{-1}$

The input and output of the author's program are shown below:

Check of Lower Shaft:

$$f_a = \frac{81}{22.6} = 3.58 \text{ ksi}$$

$$f_b = \frac{125 \times 12}{134} = 11.19 \text{ ksi}$$

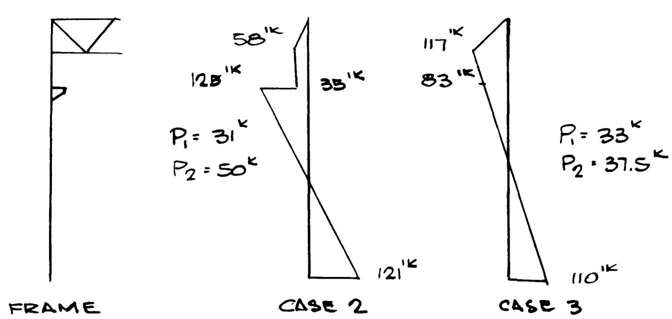

Figure 3

$$\frac{Kl}{r_y} = \frac{(1)\,(16)\,(12)}{2.47} = 77.7 > 70.93 \text{ (from program):}$$

$$F_a = 15.61 \text{ ksi}$$

$$\text{From } \frac{Kl}{r_x} = 70.93\text{:} \quad F'_e = 29.68 \text{ ksi}$$

$$F_b = 22 \text{ ksi:} \quad C_m = 0.85$$

$$\therefore \frac{f_a}{F_a} + \frac{C_m f_b}{\left(1 - \frac{f_a}{F'_e}\right)F_b} = \frac{3.58}{15.61} + \frac{0.85 \times 11.19}{\left(1 - \frac{3.58}{29.68}\right)22}$$

$$= 0.72 < 1.0 \quad \textbf{o.k.}$$

$$\frac{f_a}{0.6F_y} + \frac{f_b}{F_b} = \frac{3.58}{22} + \frac{11.19}{22} = 0.67 < 1.0 \quad \textbf{o.k.}$$

Check of Upper Shaft:

$$\frac{Kl}{r_x} = 114.65 \text{ (from computer output)}$$

$$\frac{Kl}{r_y} = \frac{(1)\,(8 \times 12)}{2.47} = 38.9$$

$$\therefore \text{ Determine } F_a \text{ from } 114.65;\ F_a = 11.04 \text{ ksi}$$

$$F'_e = 11.36 \text{ ksi}$$

$$F_b = 22 \text{ ksi}$$

$$f_a = \frac{33}{22.6} = 1.46 \text{ ksi}$$

$$f_b = \frac{117 \times 12}{134} = 10.48 \text{ ksi}$$

$$\frac{f_a}{F_a} = \frac{1.46}{11.04} = 0.13$$

$$\therefore \frac{f_a}{F_a} + \frac{f_b}{F_b} = 0.13 + \frac{10.48}{22} = 0.61 < 1.0 \quad \textbf{o.k.}$$

Use: W16×77

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**STEPPED COLUMN ANALYSIS**

AXIAL LOAD AT TOP OF COLUMN..... 31   KIPS
AXIAL LOAD AT STEP OF COLUMN.... 50   KIPS
LENGTH OF UPPER SEGMENT......... 10.5  FT.
LENGTH OF LOWER SEGMENT......... 32   FT.
AREA OF UPPER SEGMENT........... 22.6  IN^2
AREA OF LOWER SEGMENT........... 22.6  IN^2
INERTIA OF UPPER SEGMENT........ 1110  IN^4
INERTIA OF LOWER SEGMENT........ 1110  IN^4
END FIXITY CODE:................ FIXED-ROLLER
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EFFECTIVE LENGTH FACTOR (K) OF UPPER SEGMENT..  6.38
EFFECTIVE LENGTH KL OF UPPER OF SEGMENT....... 66.96
KL/R UPPER SEGMENT............................114.65
EFFECTIVE LENGTH FACTOR (K) OF LOWER SEGMENT..  1.29
EFFECTIVE LENGTH KL OF LOWER OF SEGMENT....... 41.42
KL/R LOWER SEGMENT............................ 70.93
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Figure 4

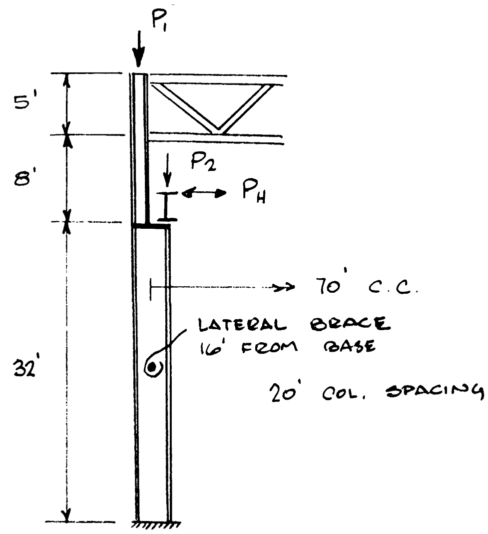

Figure 5

EXAMPLE 2. STEPPED CRANE COLUMN

Given: Assume a Class D building and use AISE provisions. See Fig. 5.

Crane forces:
P_2 = 50 kips, including impact
P_H = 3.4 kips
P_1 = 31 kips

Frame Analysis:

A frame analysis was performed using the AISE loading combinations. The critical moment diagram is shown in Fig. 6.

Check the capacity of a W24×68 lower shaft in combination with a W12×35 upper shaft:

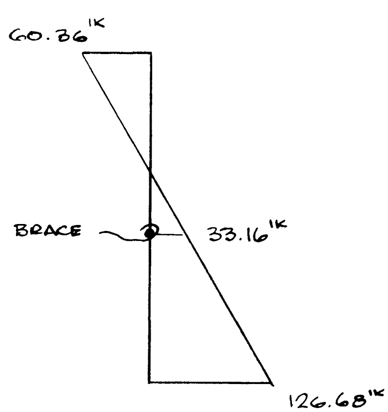

Figure 6

Section Properties:

W12X35:

$I_x = 285;\quad A = 10.3$
$S_x = 45.6;\quad r_x = 5.25$
$r_y = 1.54;\quad r_T = 1.74$

W24X68:

$I_x = 1820;\quad A = 20.1$
$S_x = 154;\quad r_x = 9.55$
$r_y = 1.87;\quad r_T = 2.26$

The input and output of the author's program are shown in Fig. 7:

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**STEPPED COLUMN ANALYSIS**

AXIAL LOAD AT TOP OF COLUMN..... 31   KIPS
AXIAL LOAD AT STEP OF COLUMN.... 50   KIPS
LENGTH OF UPPER SEGMENT......... 10.5  FT.
LENGTH OF LOWER SEGMENT......... 32  FT.
AREA OF UPPER SEGMENT........... 10.3  IN^2
AREA OF LOWER SEGMENT........... 20.1  IN^2
INERTIA OF UPPER SEGMENT........ 285   IN^4
INERTIA OF LOWER SEGMENT........ 1820  IN^4
END FIXITY CODE:................ FIXED-ROLLER
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EFFECTIVE LENGTH FACTOR (K) OF UPPER SEGMENT..  3.48
EFFECTIVE LENGTH KL OF UPPER OF SEGMENT....... 36.51
KL/R UPPER SEGMENT............................ 83.29
EFFECTIVE LENGTH FACTOR (K) OF LOWER SEGMENT..  1.78
EFFECTIVE LENGTH KL OF LOWER OF SEGMENT....... 57.08
KL/R LOWER SEGMENT............................ 71.98
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Figure 7

Check of Lower Shaft:

$$f_a = \frac{81}{20.1} = 4.03 \text{ ksi}$$

$$f_b = \frac{126.68 \times 12}{154} = 9.87 \text{ ksi}$$

$$\frac{Kl}{r_y} = \frac{0.8 \times 16 \times 12}{1.87} = 82 > 71.98 \text{ (from program):}$$

$$F_a = 15.13 \text{ ksi}$$

$$\text{From } \frac{Kl}{r_x} = 71.98{:}\quad F'_e = 28.83 \text{ ksi}$$

Determine F_b of lower shaft (See Fig. 8):

$$C_b = 1.75 + 1.05\left(-\frac{33.16}{126.68}\right) + 0.3\left(-\frac{33.16}{126.68}\right)^2$$

$$= 1.5$$

$$\frac{l}{r_t} = \frac{16 \times 12}{2.26} = 84.96$$

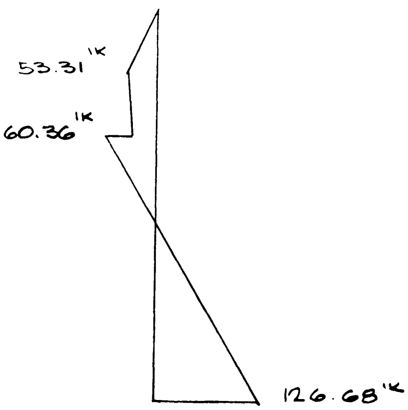

Figure 8

From AISC Formula (1.5 − 6*a*):

$$F_b = \left[\frac{2}{3} - \frac{F_y(l/r_T)^2}{1530 \times 10^3 C_b}\right] F_y$$

$$= 24 - \frac{(84.96)^2}{1181 \times 1.5} = 19.93 \text{ ksi}$$

$$C_m = 0.95 \text{ (as per AISE)}$$

$$\frac{f_a}{F_a} + \frac{C_m f_b}{\left(1 - \frac{f_a}{F'_e}\right) F_b} = \frac{4.03}{15.13} + \frac{0.95 \times 9.87}{\left(1 - \frac{4.03}{28.83}\right) 19.93}$$

$$= 0.82 \quad \textbf{o.k.}$$

$$\frac{f_a}{0.6F_y} + \frac{f_b}{F_b} = \frac{4.03}{22} + \frac{9.87}{19.93} = 0.8 < 1.0 \quad \textbf{o.k.}$$

Check Upper Shaft:

$$f_a = \frac{31}{10.3} = 3.01 \text{ ksi}$$

$$f_b = \frac{53.31 \times 12}{45.6} = 14.03 \text{ ksi}$$

$$\frac{Kl}{r_x} = 83.29 \text{ (from program)}$$

$$\frac{Kl}{r_y} = \frac{10.5 \times 12}{1.54} = 81.82$$

$$\therefore F_a = 18.35$$

$$\frac{f_a}{F_a} = \frac{3.01}{18.35} = 0.16$$

$$F'_e = 21.53 \text{ ksi}$$

$$F_b = 22 \text{ ksi}$$

$C_m = 0.95$

$$\therefore \frac{f_a}{F_a} + \frac{C_m f_b}{\left[1 - \left(\frac{f_a}{F'_e}\right)\right] F_b} = \frac{3.01}{18.35} + \frac{0.95 \times 14.03}{\left[1 - \left(\frac{3.01}{21.53}\right)\right] 22}$$

$$= 0.86 < 1.0 \quad \textbf{o.k.}$$

$$\frac{f_a}{0.6F_y} + \frac{f_b}{F_b} = \frac{3.01}{22} + \frac{14.03}{22} = 0.78 < 1.0 \quad \textbf{o.k.}$$

Use: W12×35 and W24×68.

REFERENCES

1. *Fisher, James M. and Donald R. Buettner* Light and Heavy Industrial Buildings *American Institute of Steel Construction, Chicago, Ill., 1979.*
2. Specification for the Design, Fabrication and Erection of Structural Steel for Buildings *November 1978, American Institute of Steel Construction, Chicago, Ill.*
3. Guide For The Design And Construction of Mill Buildings *AISE Technical Report No. 13, August 1, 1979, Association of Iron and Steel Engineers, Pittsburgh, Pa.*
4. *Anderson, John P. and James H. Woodward* Calculation of Effective Lengths and Effective Slenderness Ratios of Stepped Columns *AISC Engineering Journal,* Vol. 9, No. 4, Oct. 1972.