LRFD Crane Girder Design Procedure and Aids

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ABSTRACT

The design of crane girders and supporting columns has traditionally followed allowable stress design (ASD) philosophy. With the growing acceptance of load and resistance factor design (LRFD) it has become important to review the ASD design procedures and to establish the corresponding design procedures in an LRFD format. In addition, new design charts and tables will make the design of these industrial building elements much simpler and less time consuming. This paper discusses the steps for LRFD design procedures, reviews the critical limit states, and presents design tables and charts useful for wide flange and channel combination sections.

INTRODUCTION

There are available many texts and design aids that address the design of industrial buildings with cranes. An excellent guide is the publication by Fisher (1993). The format of these aids for the practicing engineer is typically in ASD format. As practicing structural engineers have adopted LRFD philosophy into day to day practice, it has become increasingly important to develop suitable design procedures and aids. Due to the variables involved in the design of wide flange and channel combination sections under bi-axial bending and torsion, new design tables and design aids will prove especially valuable.

CRANE GIRDER DESIGN

Crane girders are distinguished by long unbraced lengths and combined bending about the x and y axis as well as torsion. For typical loading and spans, a wide flange section with a channel cap normally provides an efficient cross section for the design. Historically, the assumption has been made that the channel and the wide flange top flange resist the horizontal loads and the combination section resists the vertical load. This simplifies the analysis of the actual condition and eliminates the need for an analysis of torsional effects on the combination section.

This assumption, while historically successful, should be used with a clear understanding of the actual loading conditions and the nature of the compensating effects. As shown in Figure 1(a), the actual horizontal loads are applied at the top of the rail, which causes a torsional moment about the combination section shear center. Assuming that the horizontal force acts at the web of the channel ignores the torsional moment, M_T as shown in Figure 1(b). In order to eliminate torsional effects to the combination section, the horizontal force must be applied at the shear center of the combination section, typically just below the top flange (see Figure 1(c)). However, the required bending moment resistance of the channel and top flange about the y-axis if the torsional moment, M_T, is ignored is approximately equal to the required resistance of the section if the simplified method of Figure 1(d) is used to include the torsional effects (Salmon and Johnson, 1996). This is due to the relatively close position of the shear center to the top flange of the combination section.

Adopting the results of the above discussion for torsional effects, the crane girder analysis and design is considerably simplified due to the elimination of torsional considerations. The LRFD design procedure then follows in steps 1 through 8 below:

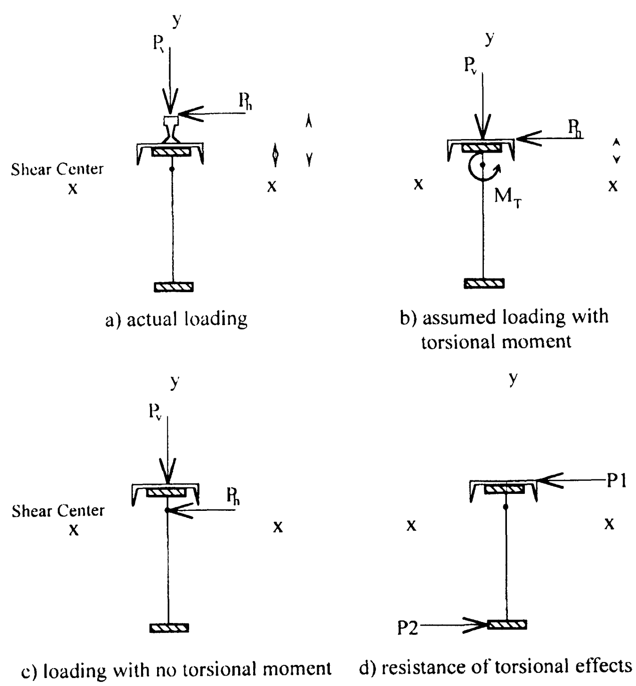

Fig. 1. Application of crane bridge wheel forces to crane girder.

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1. Determine vertical and lateral deflection limits. Vertical deflection is typically limited to $L/600$ for light and medium cranes and $L/1{,}000$ for heavy cranes. Horizontal deflection is typically limited to $L/400$ for all cranes.

2. Calculate the minimum I_x and I_y required to meet the deflection limits discussed above. I_x is based on the entire combination section while the I_y is based on the moment of inertia of the channel and the wide flange top flange only.

3. Compute the factored loads supported by the crane girder. AISC LRFD Specification load combinations A4-1 through A4-6 include dead load, live load, snow load and other environmental loads. In addition, the Specification requires that "For structures carrying live loads which induce impact, the assumed nominal live load shall be increased to provide for this impact in combination A4-2 and A4-3." Considering the entire gravity load of the crane as a live load may be overly conservative since the crane bridge weight and the trolley weight can be accurately established. The larger load factor of 1.6 reflects the uncertainty generally associated with the live load, however it may be justified to consider the bridge weight as dead load, resulting in a load factor of 1.2. This is in keeping with the intent of the LRFD reliability based format and the uncertainties of the loads involved. The entire crane gravity load and the lifted load should, however, be increased by the appropriate impact factor.

4. Calculate the maximum factored bending moments (M_{ux} and M_{uy}) and shears (V_{ux} and V_{uy}). The wheel loads must be strategically placed so as to create the largest load effect. While it is customary to combine the largest load effects of each load component, it should be kept in mind that these effects do not necessarily occur at the same location on the crane girder.

5. A trial section can now be selected. Because the section is subjected to bi-axial bending, the selection of a trial section is more difficult. Also, in the case of a combination section consisting of a wide flange and a channel, no design tables and graphs are available in the manual. Presented here is the development of a simple and accurate method to obtain the first trial section when a combination section is to be selected. Rearranging Equation (H1-1b) of the AISC LRFD Specification in Equation 1 results in Equation 2:

$$\frac{M_{ux}}{\phi_{bx} M_{nx}} + \frac{M_{uy}}{\phi_{by} M_{ny}} \le 1.0 \qquad (1)$$

$$Z_{x\,required} = \frac{M_{ux}}{\phi_b F_y}\left(1 + \frac{ZR}{MR}\right) \qquad (2)$$

where

M_{ux} and M_{uy} = factored moment about the x and y axis respectively

Table 1. *ZR* Values for Typical Combination Sections				
Section	**C10×15.3**	**C12×20.7**	**C15×33.9**	**MC18×42.7**
W12–W14	2–2.5	1.5–1.8	—	—
W16–W18	—	2.3–3.1	1.4–2.0	—
W21–W24	—	3.9–4.7	2.6–3.5	—
W27	—	—	3.8–4.0	—
W30	—	—	4.6–4.8	3.7–4.0
W33	—	—	5.2–5.4	4.3–4.6
W36	—	—	5.9–6.0	5.0–5.1

ϕM_{nx} and ϕM_{ny} = design moments for the x and y axis respectively

$$ZR = \frac{Z_x}{Z_y}$$

(see Table 1) and

$$MR = \frac{M_{ux}}{M_{uy}},$$

which can be calculated from the analysis results in step 4 above. In terms of the nominal moment capacity, Equation 2 becomes:

$$M_{nx\,required} \approx M_{ux}\left(1 + \frac{ZR}{MR}\right) \qquad (3)$$

Now the first trial section can be selected by using the graphs of Figure 2. The procedure for the use of these charts is identical to the Beam Design Moment graphs already provided in the AISC LRFD Manual in Chapter 4 for wide flange sections. Following the initial selection, the section is verified by Equation (H1-1a) or (H1-1b) of the Specification.

The stiffness of the trial section should also meet the requirements for deflection calculated in step 2 above.

6. Check the section by AISC LRFD Chapter H, Equation (H1-1a) or (H1-1b) for bending and Chapter F for shear. Normally Equation (H1-1b) will control since the axial forces in the crane girder will be small. This equation is intended for doubly and singly symmetric members in flexure and tension or compression. The commonly used wide flange and channel combination section is a singly symmetrical section and therefore Chapter H is applicable. As discussed above, M_{nx} and M_{ny} are based on the equations of Chapter F of the Specification, however M_{ny} is calculated as the y axis strength of the wide flange top flange and the

channel for combination sections. Therefore, M_{ny} is given in Equation 5:

$$\frac{M_{ux}}{\phi_{bx}M_{nx}} + \frac{M_{uy}}{\phi_{by}M_{ny}} \leq 1.0 \tag{4}$$

$$M_{ny} = (Z_{top\,flg + channel})F_y = (Z_{top\,flg} + Z_{x\,channel})F_y$$

$$= \left(\frac{t_w b_f^2}{4} + Z_{x\,channel}\right)F_y \tag{5}$$

Verification of the shear capacity of the section follows Chapter F of the Specification. In a combination section the channel web is assumed to resist the factored horizontal shear and the wide flange web resists the vertical factored shear.

7. Check the concentrated load criteria in Chapter K of the Specification. The purpose of the concentrated load check is to: (1) distribute local concentrated forces to web shear; (2) prevent local yielding or crippling in the web at concentrated loads; and (3) prevent general vertical buckling of the web. A critical criterion is sidesway web buckling. If the compression flange is not restrained against rotation, Equation (K1-7) of the Specification (Equation 6 below):

$$\text{for } \frac{\left(\frac{h}{t_w}\right)}{\left(\frac{l}{b_f}\right)} \leq 1.7,\ R_n = \frac{C_r t_w^3 t_f}{h^2}\left[0.4\left(\frac{\frac{h}{t_w}}{\frac{l}{b_f}}\right)^3\right] \tag{6}$$

8. Check Fatigue criteria by AISC LRFD Appendix K.

CONCLUSION

A simplified LRFD format design procedure is discussed for crane girders. Beam design moment design graphs and tables are presented to allow rapid selection of an accurate trial selection for typical combination section. Included in the Appendix is the FORTRAN program used to generate the tables and graphs. For combinations sections not included in Figure 2 and Table 2, the program can be used to determine the design moment vs. unbraced length. This information and procedure will result in more efficient use of design effort.

REFERENCES

1. Salmon, C. G. and Johnson, J. E., *Steel Structures: Design and Behavior*, 4th Ed., Harper Collins, New York, 1996.
2. American Institute of Steel Construction, *Manual of Steel Construction, Load and Resistance Factor Design*, 2nd Ed., 1994.
3. Fisher, J. M., *Industrial Buildings: Roofs to Column Anchorage*, AISC, Steel Design Guide Series 7, 1993.

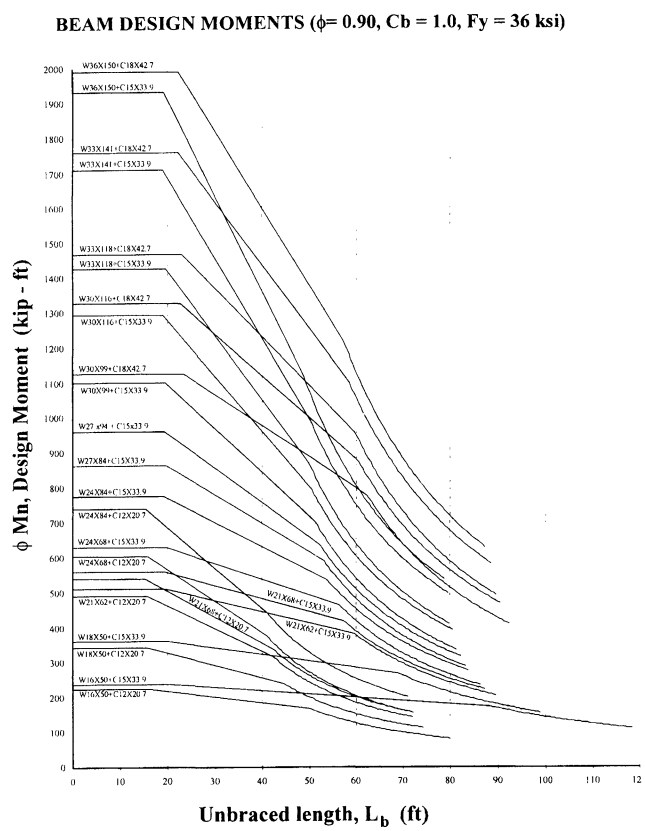

Fig. 2. Beam design moment diagram.

APPENDIX

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C ********************************************************************************
C
C FORTRAN PROGRAM TO GENERATE MOMENT CAPACITY VS UNBRACED
C LENGTH FOR WIDE FLANGE SECTIONS WITH CHANNEL CAPS
C
C DEFINITION OF VARIABLES:
C           NSEC = NUMBER OF SECTIONS TO BE ANALYZED
C           ACH = AREA OF THE CHANNEL
C           XIXCH = STRONG AXIS MOMENT OF INERTIA FOR THE CHANNEL
C           XJC = TORSIONAL CONSTANT FOR THE CHANNEL
C           BFW = FLANGE WIDTH OF THE WIDE FLANGE SECTION
C           TFW = FLANGE THICKNESS OF THE WIDE FLANGE SECTION
C           XHW = "h" DIMENSION OF THE WIDE FLANGE SECTION
C           XJW = TORSIONAL CONSTANT FOR THE WIDE FLANGE SECTION
C           FY = YIELD STRESS OF THE SECTIONS
C           SXT = SECTION MODULUS OF THE W AND C SECTION AT THE BOTTOM
C           SXC = SECTION MODULUS OF THE W AND C SECTION AT THE TOP
C           ZXCW = PLASTIC SECTION MODULUS OF THE W AND C SECTION
C           XIYCW = WEAK AXIS MOMENT OF INERTIA OF THE W AND C SECTION
C
C ********************************************************************************
C
        CHARACTER*20 INPUT
        CHARACTER*22 OUTPUT
        CHARACTER*52 TITLE
        WRITE(*,*) 'ENTER YOUR INPUT FILE NAME'
        READ(*,515) INPUT
        WRITE(*,*) 'ENTER YOUR OUTPUT FILE NAME'
        READ(*,515) OUTPUT
        WRITE(*,*) 'ENTER THE YIELD STRESS'
        READ(*,*) FYFL
510     FORMAT(20A)
515     FORMAT(20A)
        OPEN(5,FILE=INPUT)
        OPEN(6,FILE=OUTPUT)
        READ(5,*) NSEC
        DO 200 I=1,NSEC
        READ(5,510) SECTION
        WRITE(6,610) SECTION
        XLB=10
        READ(5,*) ACH,XIXCH,XJC,BFW,TFW,XHW,XJW,FY,SXT,SXC,ZXCW,XIYCW
C CALCULATE LP (XLP)
        XIYFLG=(TFW*((BFW)**3))/12
        XIYC=XIXCH+XIYFLG
        RYC=(XIYC/(BFW*TFW+ACH))**0.5
        XLP=(300*RYC)/((FYFL)**0.5)
C CALCULATE J, Mr, Mt:
        XJCW=XJC+XJW
        XMR=(FYFL-16.5)*SXC
        XMT=FYFL*SXT
        IF(XMR.GT.XMT) XMR=XMT
```

```
C CALCULATE Lr (XLR):
10      XLB=XLB+0.1
        B1=2.25*(2*(XIYC/XIYCW)-1)*(XHW/XLB)*((XIYCW/XJW)**0.5)
        B2=25*(1-(XIYC/XIYCW))*(XIYC/XJCW)*((XHW/XLB)**2)
        XMCR=(57000/XLB)*((XIYCW*XJCW)**0.5)*(B1+((1+B2+(B1**2))**0.5))
        ERROR=ABS(XMCR-XMR)
        IF (ERROR.LE.10) GO TO 30
        GO TO 10
30      XLR=XLB
C CALCULATE THE MOMENT CAPACITY
        XMPFT=(ZXCW*FYFL/12)
        XLPFT=XLP/12
        XLRFT=XLR/12
        XMRFT=XMR/12
        BF=((XMPFT-XMRFT)/(XLRFT-XLPFT))*0.90
        FIXMRFT=XMRFT*0.90
        FIXMPFT=XMPFT*0.90
        ZERO=0.0
        WRITE(6,630) ZERO,FIXMPFT
        WRITE(6,630) XLPFT,FIXMPFT
        RITE(6,630) XLRFT,FIXMRFT
        DO 80 J=6,360,6
        XXLB=XLR+J
60      B1=2.25*(2*(XIYC/XIYCW)-1)*(XHW/XXLB)*((XIYCW/XJW)**0.5)
        B2=25*(1-(XIYC/XIYCW))*(XIYC/XJCW)*((XHW/XXLB)**2)
        FIMN=0.9*((57000/XXLB)*((XIYCW*XJCW)**0.5)*
        *(B1+((1+B2+(B1**2))**0.5)))/12
70      CONTINUE
        XXLBFT=XXLB/12
        WRITE(6,630) XXLBFT,FIMN
80      CONTINUE
200     CONTINUE
610     FORMAT(20A)
615     FORMAT(F5.1,2X,F5.1,2X,F5.1,2X,F6.1,2X,F6.1)
630     FORMAT(F6.1,2X,F6.1)
        STOP
        END
```

Table 2.
Load Factor Design Selection Table for Typical Combination Sections

For Shapes Used as Beams
$\phi_b = 0.90$

F_y = 36 ksi							F_y = 50 ksi				
BF kips	L_r ft	L_p ft	$\phi_b M_r$ ft-kips	$\phi_b M_p$ ft-kips	Z_x in.^{3}	Shape	BF kips	L_r ft	L_p ft	$\phi_b M_r$ ft-kips	$\phi_b M_p$ ft-kips
1.0	43.6	13.8	98.0	126.9	47.0	W12×26 + C10×15.3	1.7	35.5	11.7	136.1	176.2
0.7	63.4	16.7	99.4	131.8	48.8	W12×26 + C12×20.7	1.2	51.5	14.2	138.0	183.0
1.5	40.0	13.8	123.7	163.3	60.5	W14×30 + C10×15.3	2.6	32.7	11.7	172.9	226.9
1.0	56.9	16.7	126.4	168.2	62.3	W14×30 + C12×20.7	1.8	46.6	14.1	175.5	233.6
1.7	50.0	16.4	169.6	225.7	83.6	W16×36 + C12×20.7	2.9	41.0	13.9	235.5	313.5
1.0	88.4	20.9	174.4	239.2	88.6	W16×36 + C15×33.9	1.7	72.1	17.8	242.2	332.2
3.6	44.4	15.8	242.8	345.6	128.0	W18×50 + C12×20.7	5.4	34.5	13.4	365.3	480.0
1.9	68.9	20.2	270.0	361.8	134.0	W18×50 + C15×33.9	3.3	56.1	17.2	375.0	502.5
6.5	42.1	15.7	318.8	491.4	182.0	W21×62 + C12×20.7	9.1	31.4	13.3	517.5	682.5
3.3	59.6	19.9	383.4	513.0	190.0	W21×62 + C15×33.9	5.6	48.8	16.9	532.5	712.5
7.5	42.2	15.4	339.3	540.0	200.0	W21×68 + C12×20.7	10.3	30.5	13.1	570.0	750.0
3.8	57.2	19.6	419.7	561.6	208.0	W21×68 + C15×33.9	6.5	46.5	16.7	585.0	780.0
9.1	41.0	15.9	377.3	604.8	224.0	W24×68 + C12×20.7	12.4	30.4	13.5	630.0	840.0
4.5	56.3	20.0	467.1	631.8	234.0	W24×68 + C15×33.9	7.8	46.5	17.0	648.7	877.5
11.6	41.0	15.3	443.1	742.5	275.0	W24×84 + C12×20.7	16.6	29.3	13.0	761.3	1,031.3
6.9	53.8	19.3	538.2	777.6	288.0	W24×84 + C15×33.9	10.5	41.7	16.4	813.8	1,080.0
8.2	53.2	19.8	590.8	864.0	320.0	W27×84 + C15×33.9	12.4	42.0	16.8	888.8	1,200.0
9.9	52.2	19.4	637.6	963.9	357.0	W27×94 + C15×33.9	14.3	39.8	16.5	1,005.0	1,338.8
12.6	51.4	19.7	702.0	1,101.6	408.0	W30×99 + C15×33.9	18.0	39.2	16.7	1,125.0	1,530.0
8.9	62.4	23.4	779.5	1,128.6	418.0	W30×99 + C18×42.7	14.1	50.2	19.8	1,140.0	1,567.5
15.9	50.5	19.1	795.6	1,296.0	480.0	W30×116 + C15×33.9	21.9	36.8	16.2	1,350.0	1,800.0
11.9	60.5	22.6	876.0	1,328.4	492.0	W30×116 + C18×42.7	17.5	46.4	19.2	1,368.8	1,845.0
18.4	49.9	19.6	871.6	1,428.3	529.0	W33×118 + C15×33.9	24.9	36.8	16.6	1,481.3	1,983.8
13.9	59.7	23.1	959.4	1,468.8	544.0	W33×118 + C18×42.7	20.2	46.3	19.6	1,500.0	2,040.0
22.9	49.7	19.0	1,007.7	1,711.8	634.0	W33×141 + C15×33.9	32.7	35.9	16.1	1,731.1	2,377.5
18.2	58.6	22.3	1,098.3	1,760.4	652.0	W33×141 + C18×42.7	25.1	43.1	18.9	1,837.5	2,445.0
27.5	48.8	19.2	1,118.8	1,933.2	716.0	W36×150 + C15×33.9	39.8	35.5	16.3	1,922.1	2,685.0
22.1	57.4	22.4	1,216.8	1,992.6	738.0	W36×150 + C18×42.7	30.1	42.0	19.0	2,073.8	2,767.5