Steel Box Girder Bridges—Design Guides & Methods

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IN MEMORIAM

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During the past decade, there has been extensive use of steel box girders for straight and curved highway and transit structures.[13,14] To meet the need for use of such structural elements, design criteria had to be established. Therefore, the purpose of this paper is to present information relative to the design criteria in addition to information on preliminary plate sizes, design aids, and computer-aided design of steel box girder bridges.

INTRODUCTION

Box girders have become a prominent element in the construction of major river crossings, highway interchanges, and transit systems. These types of structural elements are particularly attractive because of their high torsional stiffness, which is required when the bridge is curved.

With the advent of these bridges, appropriate design specifications[1,2,3] design guides[5,6,7] computer solutions[8,9] are required. Here is a summation of this information:

DESIGN SPECIFICATIONS

There are at present a set of standard specifications,[1] which pertain to straight box girders for highway bridges. Guide specifications[2] are also being used for curved box structures, but to date have not been incorporated into the standard code.[1] Further research has also been conducted, which has resulted in a tentative strength or load factor design code for curved bridges.[3] All three of these codes[1,2,3] have been studied and the appropriate criteria for the design of each element of a box (i.e., top flange, bottom flange, web) categorized according to working stress method or strength method as given in Tables 1 and 2. The working stress criteria has recently been incorporated into a design oriented computer program.[9]

In addition to these basic specifications,[1,2,3] a new code[4] has been proposed for consideration, but has yet to be adopted.

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DESIGN GUIDES

Flange Areas—In the design of any complex structure in which the section changes and the forces are not readily computed, it is useful to have data or empirical equations to select plate geometry, which can then be incorporated in a computer program[9] to automate the bridge design. Such information has been developed[5,6,7] and has resulted in the following:

i) Single-span bridge

$$A_T = 10d\left(1 - \frac{84}{L}\right)$$

$$A_B = 13d\left(1 - \frac{92}{L}\right)$$

ii) Two-span bridge

$$A_B^+ = \frac{1}{k}(0.00153L^2 - 0.223L + 13)$$

$$A_B^- = 1.17\, A_B^+ \frac{F_y^-}{F_y^+}$$

$$A_T^+ = 0.64\, A_B^+$$

$$A_T^- = 1.60\, A_B^+ \frac{F_y^-}{F_y^+}$$

Table 1. Working Stress Design Requirements

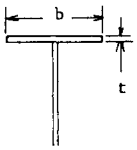
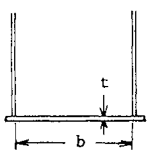
Item	Straight	Curved
Compression Flange (positive moment) 	$\frac{b}{t} \le \frac{3250}{\sqrt{f_b}} \le 24$	$\frac{b}{t} \le \frac{4400}{\sqrt{F_y}}$ and $F_b = 0.55 F_y \left[1 - \frac{\left(\frac{l}{r'}\right)^2 F_y}{4\pi^2 E}\right] \rho_B \rho_w$ where $\rho_B = \frac{1}{1 + \left(\frac{l}{R}\right)\left(\frac{l}{b}\right)}$ and $\rho_w = \rho_{w1}$ or ρ_{w2}, where; $\rho_{w1} = \frac{1}{1 - \left(\frac{f_w}{f_b}\right)\left[1 - \frac{(l/b)}{75}\right]}$ or $\rho_{w2} = \frac{0.95 + \frac{l/b}{[30 + 8000(0.1 - l/R)^2]}}{1 + 0.6\left(\frac{f_w}{f_b}\right)}$ if $\frac{f_w}{f_b}$ (+) use smaller ρ_{w1} or ρ_{w2} $\frac{f_w}{f_b}$ (−) use ρ_{w1}
Compression Flange (negative moment) 	$\frac{b}{t} \le \frac{6140}{\sqrt{F_y}}$ $f_b \le 0.55 F_y$ $\frac{6140}{\sqrt{F_y}} \le \frac{b}{t} \le 60$ or $\frac{13,300}{\sqrt{F_y}}$ $f_b \le 0.55F_y - 0.224F_y\left[1 - \sin\frac{\pi}{2}\left(\frac{13,300 - b/t\sqrt{F_y}}{7160}\right)\right]$ $\frac{13,300}{\sqrt{F_y}} < \frac{b}{t} \le 60$ $f_b \le 57.6 \times 10^6 \left(\frac{t}{b}\right)^2$	$\frac{b}{t} \le \frac{6140}{\sqrt{F_y}} \cdot X$ $F_b = 0.55 F_y \sqrt{1 - 9.2\left[\frac{f_v}{F_y}\right]^2}$ where $X = 1 + 4/3\left(\frac{f_v}{\sqrt{F_y}} - 0.15\right) \ge 1$ $\frac{6140}{\sqrt{F_y}} < \frac{b}{t} \le \frac{13,300}{\sqrt{F_y}}$ or 60 $F_b = \left[0.326F_y + 0.224F_y\left\{\sin\frac{\pi}{2}\left(\frac{13,300 - b\sqrt{F_y}/t}{13,300 - 6140X}\right)\right\}\right]\Delta$ where $\Delta = \sqrt{1 - 9.0\left(\frac{f_v}{F_y}\right)^2}$ if $\frac{b}{t} \ge \frac{13,300}{\sqrt{F_y}}$ F_b is smaller of the following: $F_b = 57.6\left(\frac{t}{b}\right)^2 \cdot 10^6\Delta$ $F_b = 57.6\left(\frac{t}{b}\right)^2 \times 10^6 - \frac{f_v^2}{113.4\left(\frac{t}{b}\right)^2} \times 10^6$

Table 1. *(continued)*

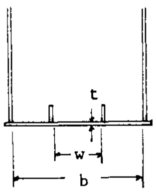
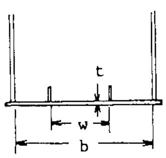
Item	Straight	Curved
Compression Flange (negative moment) With Stiffener  	$\frac{w}{t} \leqq \frac{3070\sqrt{K}}{\sqrt{F_y}}$ $f_b \leqq 0.55F_y$ $\frac{3070\sqrt{K}}{\sqrt{F_y}} < \frac{w}{t} \leqq 60$ or $\frac{6650\sqrt{K}}{\sqrt{F_y}}$ $f_b \leqq 0.55F_y - 0.224F_y\left[1 - \sin\frac{\pi}{2}\,\frac{6650\sqrt{K} - \frac{w}{t}\sqrt{F_y}}{3580\sqrt{K}}\right]$ $\frac{6650\sqrt{K}}{\sqrt{F_y}} < \frac{w}{t} \leqq 60$ $f_b \leqq 14.4 \times 10^6 K\left(\frac{t}{w}\right)^2$ Stiffener requirement with longitudinal Stiffener $I_s \geqq \phi t^3 w$ where $\phi = \begin{cases} 0.07K^3n^4 \text{ for } n > 1 \\ 0.125K^3 \text{ for } n = 1 \end{cases}$	$\frac{w}{t} \leqq \frac{3070\sqrt{K}}{\sqrt{F_y}} \cdot X_1$ $F_b = 0.55F_y\sqrt{1 - 912\left(\frac{f_v}{F_y}\right)^2}$ where $X_1 = 1\ (n > 1)$ $X_1 = 0.93 + \left(1.6 - \frac{K}{K_s}\right)\left(\frac{f_v}{F_y}\right) \geqq 1\ (n = 1)$ $2 \leqq K \leqq 4$ $K_s = \frac{5.34 + 2.84(I_s/wt^3)^{1/3}}{(n+1)^2} \leqq 5.34$
Compression Flange (negative moment) With Stiffener  		$\frac{3070\sqrt{K}}{\sqrt{F_y}}X_1 < \frac{w}{t} \leqq \frac{6650\sqrt{K}}{\sqrt{F_y}}X_2$ or 60 $F_b = \left[0.326F_y + 0.224F_y\left\{\sin\frac{\pi}{2}\,\frac{6650\sqrt{K}X_2 - \frac{w\sqrt{F_y}}{t}}{6650\sqrt{K}X_2 - 3070\sqrt{K}X_1}\right\}\right]\Delta$ Where $\Delta = \sqrt{1 - 9.0\left(\frac{f_v}{F_y}\right)^2}$ $X_2 = 1 - 2.13\left(\frac{f_v}{F_y}\right) + 0.1\left\{\left(\frac{K}{K_s}\right) - 5.34\right\}^2\left(\frac{f_v}{F_y}\right)$ $\frac{6650\sqrt{K}X_2}{\sqrt{F_y}} < \frac{w}{t} \leqq 60$ F_b is smaller value of $F_b = 14.4K\left(\frac{t}{w}\right)^2 \Delta\, 10^6$ or $F_b = 14.4K\left(\frac{t}{w}\right)^2 \times 10^6 - \frac{f_v^2 K}{14.4(K_s)^2\left(\frac{t}{w}\right)^2} \times 10^6$

Table 1. *(continued)*

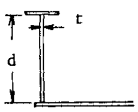
Item	Straight	Curved
With Longitudinal and Transverse Stiffener	Use same formula, but use K_1 instead of K $K_1 = \frac{\left[1+\left(\frac{a}{b}\right)^2\right]^2 + 87.3}{(n+1)^2\left(\frac{a}{b}\right)^2 \lvert 1+0.1(n+1)\rvert}$ $I_s \ge 8t^3 w$ $I_t \ge 0.10(n+1)^3 w^3 \frac{f_s}{E}\frac{A_f}{a}$ where a: spacing of transverse stiffener f_s: maximum longitudinal bending stress A_f: Area of flange including longitudinal stiffener	
Web Without Stiffener  	$\frac{d}{t} \le 150$ $f_v \le \frac{5.625 \times 10^7}{(d/t)^2} \le \frac{F_y}{3}$ $\frac{d}{t} \le \frac{23{,}000.}{\sqrt{F_b}} \le 170$	Same
With Transverse Stiffener	$d_0 \le 1.5d$ $f_v \le \frac{F_y}{3}\left[C + \frac{0.87(1-C)}{\sqrt{1+(d_0/d)^2}}\right]$ $C = \frac{2.2 \times 10^8 \lvert 1+(d/d_0)^2 \rvert}{F_y(d/t)^2} \le 1.0$ d_0 = stiffener spacing	If $d_0/R \le 0.02$ use straight girder criteria If $d_0/R \ge 0.02$ $\frac{d}{t} \le \frac{23{,}000}{F_b}\left\{1.19 - 10\left(\frac{d_0}{R}\right) + 34\left(\frac{d_0}{R}\right)^2\right\} \le 170$ $d_0 \le 1.5d$ $f_v = \frac{F_y}{3}\left[C + \frac{0.87(1-C)}{\sqrt{1+(d_0/d)^2}}\right]$ $C = \frac{2.2 \times 10^8 \lvert 1+(d/d_0)^2 \rvert}{F_y(d/t)^2} \le 1.0$
Web With Transverse Stiffener	Stiffener Criteria $I \ge \frac{d_0 t^3}{10.92} J$ $J = 25\left(\frac{d_0}{d}\right)^2 - 20 \ge 5.0$	Stiffener Criteria $I \ge d_o t^3 J$ $J = \left[25\left(\frac{d_o}{d}\right)^2 - 20\right] X \ge 5.0$ $X = 1.0$ for $\frac{d_0}{d} \le 0.78$ $X = 1.0 + \left(\frac{\left(\frac{d_0}{d} - 0.78\right)}{1775}\right) Z^4; 0.78 \le \frac{d_0}{d} \le 1.0$ $Z = 0.95\frac{d^2}{Rt}$ $\frac{b}{t} \le \frac{2600}{\sqrt{F_y}}$

Table 2. Strength Design Requirements

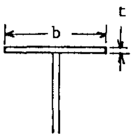
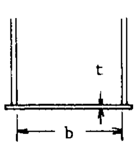
Item	Straight	Curved
Compression Flange (positive moment) 	$\frac{b}{t} \le \frac{3200}{\sqrt{F_y}}$ $f_b = F_y$ if $\frac{3200}{\sqrt{F_y}} \le \frac{b}{t} \le \frac{4400}{\sqrt{F_y}}$ $f_b = F_y(1 - 3\lambda^2)$ $\lambda = \frac{1}{\pi}\frac{l}{b}\sqrt{\frac{F_y}{E}}$	$\frac{b}{t} \le \frac{3200}{\sqrt{F_y}}$ $f_b = F_{bs}\bar{\rho}_B\bar{\rho}_w$ where $\bar{\rho}_B = \frac{1}{1 + \frac{l}{b}\left(1 + \frac{l}{6b}\right)\left(\frac{l}{R} - 0.01\right)^2}$ $\bar{\rho}_w = 0.95 + 18\left[0.1 - \frac{l}{R}\right]^2 + \frac{\frac{f_w}{f_b}\left(0.3 - 0.1\frac{l}{R}\frac{l}{b}\right)}{\bar{\rho}_B F_y/F_{bs}}$ $F_{bs} = Fy(1 - 3\lambda^2)$ $\lambda = \frac{1}{\pi}\left(\frac{l}{b}\right)\sqrt{\frac{F_y}{E}}$ if $\frac{3200}{\sqrt{F_y}} \le \frac{b}{t} \le \frac{4400}{\sqrt{F_y}}$ $f_b \le F_{by}$ where $F_{by} = F_{bs}\rho_B\rho_w$ $\rho_B = \frac{1}{1 + \frac{l}{R}\frac{l}{b}}$ and $\rho_w = \rho_{w1}$ or ρ_{w2}, where; $\rho_{w1} = \frac{1}{1 - \frac{f_w}{f_b}\left(1 - \frac{l}{75b}\right)}$ $\rho_{w2} = \frac{0.95 + \frac{l/b}{30 + 8000(0.1 - l/R)^2}}{1 + 0.6(f_w/f_b)}$ if $\frac{f_w}{f_b}$ (+) use smaller ρ_{w1} or ρ_{w2} $\frac{f_w}{f_b}$ (−) use ρ_{w1}
Compression Flange (negative moment) Without Stiffener 	$\frac{b}{t} \leqq \frac{6140}{\sqrt{F_y}}$ then $F_{cr} = F_y$ $\frac{6140}{\sqrt{F_y}} < \frac{b}{t} \leqq \frac{13{,}300}{\sqrt{F_y}}$ then $F_{cr} = 0.592\, F_y\left(1 + 0.687 \sin\frac{\pi}{2}c\right)$ where $C = \frac{13{,}300 - \frac{b}{t}\sqrt{F_y}}{7160}$ $\frac{b}{t} > \frac{13{,}300}{F_y}$ then $F_{cr} = 105 \times 10^6(t/b)^2$	$f_v \leqq 0.75\frac{F_y}{\sqrt{3}}$ and $\frac{b}{t} \leqq \frac{R_1}{\sqrt{F_y}}$ then $F_b = F_y \cdot \Delta$ $\frac{R_1}{\sqrt{F_y}} < \frac{b}{t} \leqq \frac{R_2}{\sqrt{F_y}}$ or 60 then $F_b = 26.21 \times 10^6 K\left(\frac{t}{b}\right)^2 - \frac{f_v^2 K}{26.21 \times 10^6 K_s\left(\frac{t}{b}\right)^2}$ also if $0.75\frac{F_y}{\sqrt{3}} < f_v \leqq \frac{F_y}{\sqrt{3}}$ $\frac{b}{t} \leqq \frac{R_1}{\sqrt{F_y}}$ $F_b = F_y\Delta$

Table 2. *(continued)*

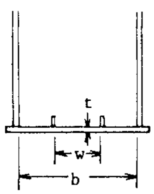
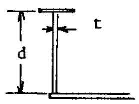
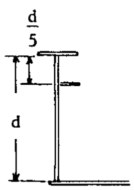
Item	Straight	Curved
		where $R_1 = \dfrac{3070\sqrt{K}}{\sqrt{\dfrac{1}{2}\sqrt{\left(\Delta + \Delta^2 + 4\left(\dfrac{f_v}{F_y}\right)^2\left(\dfrac{K}{K_s}\right)^2\right)}}}$ $R_2 = \dfrac{6650\sqrt{K}}{\sqrt{\dfrac{1}{1.2}\left[\Delta - 0.4 + \sqrt{(\Delta - 0.4)^2 + 4\left(\dfrac{f_v}{F_y}\right)^2\left(\dfrac{K}{K_s}\right)^2}\right]}}$ $\Delta = \sqrt{1 - 3\left(\dfrac{f_v}{F_y}\right)^2}$ $K = 4$ $K_s = 5.34$
Compression Flange (negative moment) With Stiffener  	$\dfrac{w}{t} \leqq \dfrac{3070\sqrt{K}}{\sqrt{F_y}}$ $F_{cr} = F_y$ $\dfrac{3070\sqrt{K}}{\sqrt{F_y}} < \dfrac{w}{t} \leqq \dfrac{6650\sqrt{K}}{\sqrt{F_y}}$ $F_{cr} = 0.592\,F_y\left(1 + 0.687\sin\dfrac{C\pi}{2}\right)$ where $C = \dfrac{6650\sqrt{K} - \dfrac{w}{t}\sqrt{F_y}}{3580\sqrt{K}}$ $\dfrac{w}{t} > \dfrac{6650\sqrt{K}}{\sqrt{F_y}}$ $F_{cr} = 26.2 \times 10^6 K\,(t/w)^2$	$f_v \leq 0.75\dfrac{F_y}{\sqrt{3}}$ and $\dfrac{w}{t} \leq \dfrac{R_1}{\sqrt{F_y}}$ then $F_b = F_y\Delta$ $\dfrac{R_1}{\sqrt{F_y}} \leq \dfrac{w}{t} \leq \dfrac{R_2}{\sqrt{F_y}}$ or 60 then $F_b = F_y\left\{\Delta - 0.4\left\{1 - \sin\dfrac{\pi}{2}\left(\dfrac{R_2 - \dfrac{w\sqrt{F_y}}{t}}{R_2 - R_1}\right)\right\}\right\}$ $R_2 \leq w \leq 60$ $F_b = 26.21 \times 10^6\,K\left(\dfrac{t}{w}\right)^2 \dfrac{-f_v^2 K}{26.1 \times 10^6 K_s\left(\dfrac{t}{w}\right)^2}$ also if $0.75\dfrac{F_y}{\sqrt{3}} \leq f_v \leq \dfrac{F_y}{\sqrt{3}}$ and $\dfrac{w}{t} \leq \dfrac{R_1}{\sqrt{F_y}}$ $F_b = F_y\,\Delta$ R_1, R_2 and Δ are given under compression flange without stiffener section and $2 \leq K \leq 4$ $K_s = \dfrac{5.34 + 2.84\,(I_s/wt^3)^{1/3}}{(n + 1)^2} \leq 5.34$
Compression Flange (negative moment) With Stiffener	Stiffener Criteria $I_s \geq \phi t^3 w$ where $\phi = \begin{bmatrix} 0.07K^3n^4 \text{ for } n = 2,3,4,5 \\ 0.125K^3 \text{ for } n = 1 \end{bmatrix}$ and $\dfrac{b'}{t'} \leqq \dfrac{2{,}600}{\sqrt{F_y}}$ where b': depth of stiffener t': plate thickness of stiffener	Stiffener Criteria $I_s \geq \phi t^3 w$ where: $\phi = 0.07\,K^3 n^4$ for $n > 1$ $\phi = 0.125\,K^3\,n = 1$ $\dfrac{b}{t} \leq \dfrac{2{,}600}{\sqrt{F_y}}$

Table 2. *(continued)*

Item	Straight	Curved
Web Without Stiffener  With Transverse Stiffener	$\frac{d}{t} \le 150$ $V_u \le 1.015 \times 10^8 t^3/d$ or $V_u \le 0.58\, F_y dt$ $\frac{d}{t} \le \frac{36{,}500}{\sqrt{F_y}}$ $d_0 \le 1.5\, d$ $V \le V_p\left[C + \frac{0.87(1-C)}{\sqrt{1+(d_0/d)^2}}\right]$ where: $V_p = 0.58\, F_y dt$ $C = 18{,}000\left(\frac{d}{t}\right)\sqrt{\frac{1+(d/d_0)^2}{F_y}} - 0.3 \le 1.0$	$\frac{d}{t} \le 150$ $V_u \le \frac{3.5Et^3}{d}$ or $V_u \le 0.58\, F_y dt$ $\frac{d}{t} \le 150$ $d_0 \le 1.5d$ $V \le 0.58\, F_y dtC$ where: $C = \left\{18{,}000\,(t/d)\sqrt{\frac{1+(d/d_0)^2}{F_y}}\right\} - 0.3 \le 1.0$
Web With Transverse and Longitudinal Stiffener  	$\frac{d}{t} \le \frac{73{,}000}{\sqrt{F_y}}$ $d_0 \le 1.5d$ and longitudinal stiffener is $d/5$ for compression flange. Shear requirements in accordance with transversely stiffened web criteria.	$\frac{36{,}500}{\sqrt{F_y}}\left[1 - 8.6\left(\frac{d_0}{R}\right) + 34\left(\frac{d_0}{R}\right)^2\right]$ $\le \frac{d}{t} \le \frac{73{,}000}{\sqrt{F_y}}\left[1 - 2.9\sqrt{\frac{d_0}{R}} + 2.2\left(\frac{d_0}{R}\right)\right]$ $d_0 \le 1.5d$ and longitudinal stiffener is $d/5$ for compression flange shear requirements in accordance with transversely stiffened web criteria.
Transverse Stiffener Criteria	$b/t \le \frac{2600}{\sqrt{F_y}}$ b = projected width of stiffener and the gross area is $A \ge [0.15Bdt(1-C)(V/V_u) - 18t^2]Y$ *where:* B = 1.0 for stiffener pairs B = 1.8 for single angles B = 2.4 for single plates $C = 18{,}000\,(t/d)\sqrt{\frac{1-(d/d_0)^2}{F_y}} - 0.3 \le 1$ and V_u = as given previously Y = ratio of web plate to stiffener plate yield strengths $I \ge d_0 t^3 J$ $J = 2.5(d/d_0)^2 - 2 \ge 0.5$	Same as straight except $J = [2.5(d/d_0)^2 - 2]\, X \le 0.5$ $X = 1.0$ when $(d_0/d) \le 0.78$ and $X = 1 + \left\{\frac{d_0/d - 0.78}{1775}\right\} Z^4$ when $0.78 < \frac{d_0}{d} \le 1.0$ where $Z = \frac{0.95 d_0^2}{Rt}$
Longitudinal Stiffener Criteria	$\frac{b'}{t'} \le \frac{2600}{\sqrt{F_y}}$ $I = dt^3\left[2.4\left(\frac{d_0}{d}\right)^2 - 0.13\right]$ $r \ge \frac{d_1\sqrt{F_y}}{23{,}000.}$ $S_t \ge \frac{1}{3}\left(\frac{d}{d_0}\right) S_s$ S_t = Section modulers of transverse stiffener S_s = Section modulers of longitudinal stiffener	Same criteria as straight

iii) Three-span bridge

$$\left.\begin{aligned} A_T^+ &= \frac{n}{6.4k}(L_1 - 73) \\ A_B^+ &= \frac{n}{5k}(L_1 - 52) \end{aligned}\right\} \text{Exterior section}$$

$$\left.\begin{aligned} A_T^- &= \frac{n}{2.6k}(L_1 - 100) \\ A_B^- &= \frac{1}{kn}(0.964L_2 - 1.65L_2^2 \times 10^{-3} - 70) \end{aligned}\right\} \text{Support}$$

$$\left.\begin{aligned} A_T^+ &= 0.95A_T^- - 0.011(A_T^-)^2 - 5.4/k \\ A_B^+ &= \frac{n}{10k}(L_2 - 48) \end{aligned}\right\} \text{Interior section}$$

where: $k = \dfrac{N_B F_y d}{w_R \times 600}$

F_y = yield point of material at specified section (ksi)
L, L_1, L_2 = span length (ft)
w_R = roadway width (ft)
N_B = number of boxes
d = girder depth (inches)
$n = L_2/L_1$, L_1 = exterior span, L_2 = interior span
A_T^+, A_T^- = total top flange area (in.^{2}) in positive or negative moment region
A_B^+, A_B^- = total bottom flange area (in.^{2}) in positive or negative moment region

Box Girder Geometry—To select the final cross-sectional dimensions of a box girder bridge, along its length, many designs are required. To facilitate such designs, a study[6] was conducted to optimize the cross sections of single, two- and three-span straight box girder bridges. The specific geometry associated with these bridges are:

1. *Parametric details*
   Span length
   single-span: L = 50 ft, 100 ft, 150 ft
   two-span: $L1$ = 50 ft, 100 ft, 150 ft
   $L2 = N.L1$, N = 1.0, 1.2, 1.4, 1.6
   three-span: $L1$ = 50 ft, 100 ft, 150 ft
   $L2 = N.L1$, N = 1.0, 1.2, 1.4, 1.6
   where $L2$ equals end span for two span or $L2$ equals center span for three span symmetrical bridge.
   Web depth: $d/L \leq 1/25$
   Top flange: $b/t \leq 23$. (positive moment region)
   Bottom flange width: 80 in., 100 in., 120 in.
   Bottom flange stiffener: ST 7.5 × 25. (negative moment region)
   Concrete slab 8.5 in.
   Steel type $A36$, F_y = 36 ksi
   $N = 9$, $3N = 27$, $f'c$ = 4 ksi
   Unit weight: steel 490 pcf, concrete 150 pcf
   General parameters
   parapit: 300 lbs./ft
   wearing surface: 15 lbs./ft^2
   miscellaneous concrete: 112 lbs./ft
   miscellaneous steel: 12%
2. *Procedure*
   The determination of the correct plate geometry the various bridges, involved the following prc dure:
   Fix span length L
   Select web depth $d = 12L/25$
   Select bottom flange width W = 80 in.
   Select web thickness
   Select top flange width $b \leq 23t$
   Determine dead-load moments
   Determine location of cross sectional chan using data given in Tables 3 and 4 and Fig. 1
   Revise sections and computed dead-load, live-l forces and stress.
   Revise per specifications.
   Set bottom flange width W = 100 in., repeat.
3. *Results*
   The procedure outlined above was followed for design of 81 bridges. The results of these designs single, two span and three span bridges are tabul in Tables 5, 6, and 7.

Bracing Requirements—The required cross diaphr bracing area,[10] as shown in Figs. 2 and 3, can be de mined from the following;

$$A_b \geqq 750 \frac{Sb}{d^2} \frac{t^3}{(d+b)} \text{ (in.}^2\text{)}$$

where

s = Diaphragm spacing (in.)
b = Width of box (in.), at bottom flange
d = Depth of box (in.)
$t = \dfrac{A}{2(d+b)}$ = weighted section thickness (in
A = Total cross sectional plate area (in.^{2}) a diaphragm location
A_b = Required area of cross diaphragm bra (in.^{2})

The bracing spacing requirement is given by the lowing:

$$s \leqq 12L\left(\frac{R}{200L - 7500}\right)^{1/2} \leqq 300 \text{ in.}$$

where
L = Span length (ft)
R = Radius of girder (ft)

Top lateral bracing is utilized in stiffening the box du shipment and erection. Such bracing can also provide

Table 3

Span	No. cross sect.	Web Depth	Web Thickness	Top Flange Width	Top Flange Thickness	Bottom Flange Width	Bottom Flange Thickness	Bottom Stiffener A	Bottom Stiffener Ix	Bottom Stiffener no.	At/Ab
** 50′-80″	1	24.0	0.375	7.0	0.375	80.0	0.375				0.175
	2	24.0	0.375	11.75	0.5875	80.0	0.375				0.460
	3	24.0	0.375	7.0	0.375	80.0	0.375				0.175
50-100	1	24.0	0.375	8.25	0.375	100.0	0.340				0.165
	2	24.0	0.375	13.75	0.625	100.0	0.340				0.510
	3	24.0	0.375	8.25	0.375	100.0	0.340				0.165
50-120	1	24.0	0.375	8.75	0.4375	120.0	0.310				0.170
	2	24.0	0.375	13.75	0.750	120.0	0.310				0.555
	3	24.0	0.375	8.75	0.4375	120.0	0.310				0.170
100-80	1	48.0	0.500	10.50	0.5625	80.0	0.500				0.393
	2	48.0	0.500	18.75	1.000	80.0	0.750				0.625
	3	48.0	0.500	10.50	0.5625	80.0	0.500				0.393
100-100	1	48.0	0.500	11.75	0.750	100.0	0.375				0.470
	2	48.0	0.500	17.75	1.250	100.0	0.6875				0.648
	3	48.0	0.500	11.75	0.750	100.0	0.375				0.470
100-120	1	48.0	0.500	15.50	0.750	120.0	0.375				0.517
	2	48.0	0.500	20.75	1.250	120.0	0.625				0.692
	3	48.0	0.500	15.50	0.750	120.0	0.375				0.517

** $L - b_w$.

eral stiffness to create a pseudo closed box and thus minimize the warping stresses. The required area for such bracing, as shown in Fig. 4, is given by;

$$A_{bl} \geqq 0.036 \text{ (in.}^2\text{)}$$

where

A_{bl} = Required area of lateral bracing (in.^{2})

Natural Frequency—The designer is often required to evaluate the vertical natural frequency f, especially if the structure is subjected to train loadings. Such evaluation, for curved structures, has been determined[11] and has resulted in the following equations:

$$f = \frac{\pi}{2k^2L^2}\left[\left(EI_x + \frac{EI_w}{R^2} - \frac{GK_TL^2}{R^2}\right)\Big/ M\right]^{1/2} \text{ (cps)}$$

Table 4. Location of Section Changes for Negative Moment

Negative Region Moment					
Length (ft)	No. of Cros. sect.	X_1	X_2	X_3	X_4
$L < 49$	3	$0.109L$	$0.239L$		
$49 \leq L < 82$	4	$0.081L$	$0.172L$	$0.282L$	
$82 \leq L < 115$	5	$0.065L$	$0.136L$	$0.215L$	$0.310L$

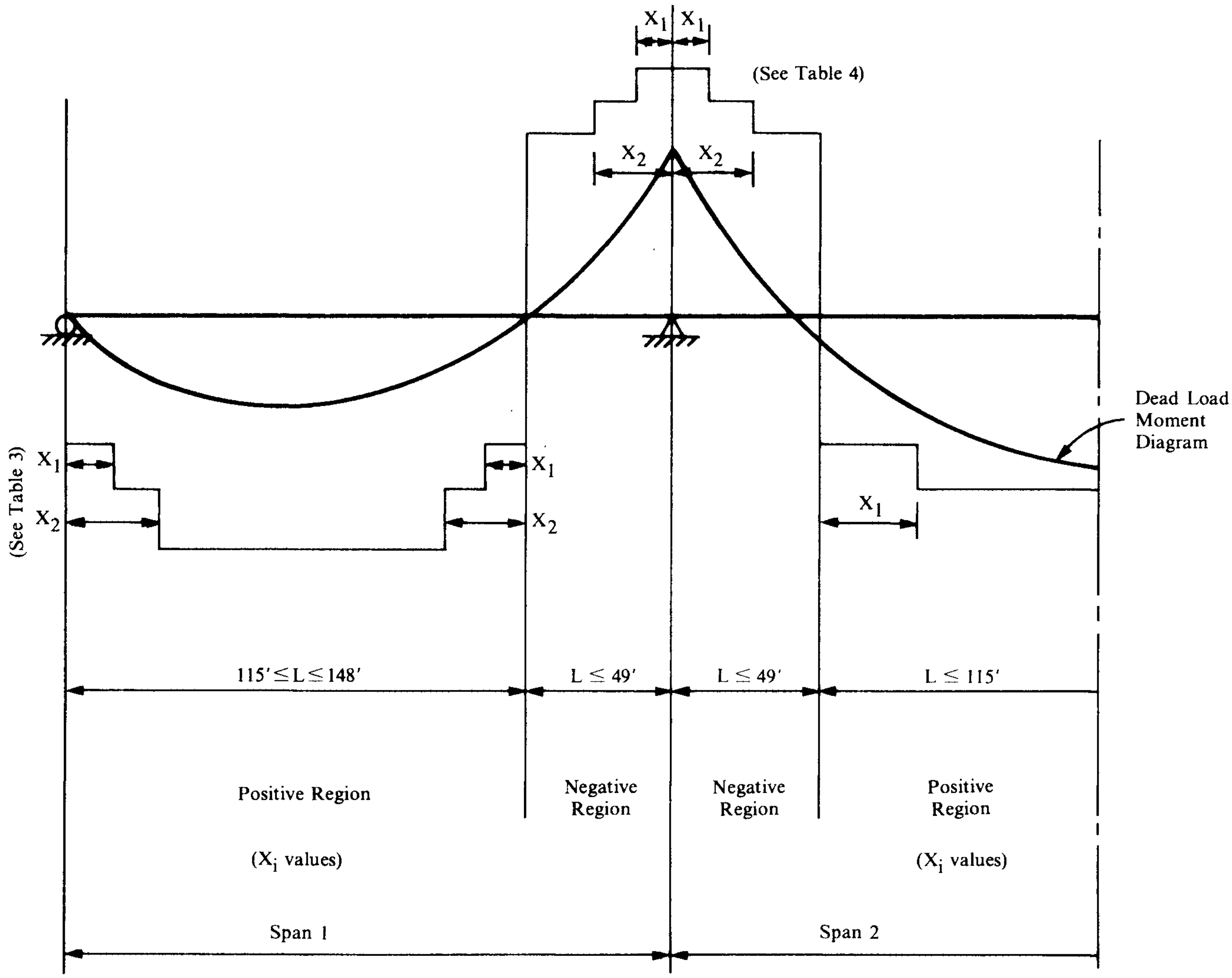


Fig. 1. Example of location of section changes

where:

EI_x = bending stiffness (kip-in.^{2})
EI_w = warping stiffness (kip-in.^{4})
GK_T = torsional stiffness (kip-in.^{2})
R = radius (in.)
M = mass (w/g) (kip-sec^2/in.)
L = exterior span length (in.)
$k = Bn^2 + Cn + D$ (for simple spans, $k = 1$)

and B, C, D are constants defined as:

	B	C	D
Two span	0.242	−0.80	1.55
Three span	0.367	−1.24	1.87

and $n = L_{\text{interior}}/L_{\text{exterior}}$ $1.0 \leq n \leq 1.7$.

As approximations for the torsional properties, the following expressions may be used;

$$K_T = \frac{2t'(b'd')^2}{(d + b)}$$

$$L_W = \frac{t'b'^2d'^3}{24}\frac{(1 - b'/d')^2}{(1 + b'/d')^2}$$

where

b' = average width of box
d' = average depth of box
t' = average plate thickness

Ultimate Strength—The ultimate strength determination of a curved box girder requires consideration of the interaction between the bending moment and torque. A com-

Table 5. Single-Span Section Dimensions

Span (ft)	No. cross sect.	Web		Top Flange		Bottom Flange		Bottom Stiffener			A_T/A_B
		Depth	Thickness	Width	Thickness	Width	Thickness	A	Ix	no.	
50	1	24.0	0.375	7.0	0.375	80.0	0.375				0.175
	2	24.0	0.375	11.75	0.5875	80.0	0.375				0.460
	3	24.0	0.375	7.0	0.375	80.0	0.375				0.175
50	1	24.0	0.375	8.25	0.375	100.0	0.340				0.165
	2	24.0	0.375	13.75	0.625	100.0	0.340				0.510
	3	24.0	0.375	8.25	0.375	100.0	0.340				0.165
50	1	24.0	0.375	8.75	0.4375	120.0	0.310				0.170
	2	24.0	0.375	13.75	0.750	120.0	0.310				0.555
	3	24.0	0.375	8.75	0.4375	120.0	0.310				0.170
100	1	48.0	0.500	10.50	0.5625	80.0	0.500				0.393
	2	48.0	0.500	18.75	1.000	80.0	0.750				0.625
	3	48.0	0.500	10.50	0.5625	80.0	0.500				0.393
100	1	48.0	0.500	11.75	0.750	100.0	0.375				0.470
	2	48.0	0.500	17.75	1.250	100.0	0.6875				0.648
	3	48.0	0.500	11.75	0.750	100.0	0.375				0.470
100	1	48.0	0.500	15.50	0.750	120.0	0.375				0.517
	2	48.0	0.500	20.75	1.250	120.0	0.625				0.692
	3	48.0	0.500	15.50	0.750	120.0	0.375				0.517
150	1	72.0	0.750	7.00	0.375	80.0	0.375				0.175
	2	72.0	0.750	26.25	1.250	80.0	1.1875				0.69
	3	72.0	0.750	7.00	0.375	80.0	0.375				0.175
150	1	72.0	0.750	7.00	0.375	100.0	0.375				0.14
	2	72.0	0.750	28.75	1.3125	100.0	1.0625				0.71
	3	72.0	0.750	7.00	0.375	100.0	0.375				0.14
150	1	72.0	0.750	7.00	0.375	120.0	0.375				0.117
	2	72.0	0.750	30.50	1.4375	120.0	1.000				0.731
	3	72.0	0.750	7.00	0.375	120.0	0.375				0.117

Table 6. Two-Span Section Dimensions

SPANS (ft)	No. cross sect.	Web		Top Flange		Bottom Flange		Bottom Stiffener			A_T/A_B
		Depth	Thickness	Width	Thickness	Width	Thickness	A	Ix	no.	
**	1	24.0	0.375	7.50	0.375	80.0	0.375				0.187
50-50	2	24.0	0.375	20.25	1.000	80.0	0.500	7.35	40.6	2	1.013
	3	24.0	0.375	7.50	0.375	80.0	0.375				0.187
	1	24.0	0.375	8.375	0.4375	100.0	0.375				0.195
50-50	2	24.0	0.375	21.25	1.125	100.0	0.5625	7.35	40.6	2	0.850
	3	24.0	0.375	8.375	0.4375	100.0	0.375				0.195
	1	24.0	0.375	9.375	0.4375	120.0	0.375				0.182
50-50	2	24.0	0.375	25.50	1.125	120.0	0.5625	7.35	40.6	3	0.850
	3	24.0	0.375	9.375	0.4375	120.0	0.375				0.182
	1	24.0	0.375	6.500	0.375	80.0	0.375				0.163
50-60	2	24.0	0.375	24.00	1.250	80.0	0.6875	7.35	40.6	2	1.090
	3	24.0	0.375	9.750	0.625	80.0	0.375				0.406
	1	24.0	0.375	7.250	0.375	100.0	0.375				0.145
50-60	2	24.0	0.375	29.00	1.250	100.0	0.6875	7.35	40.6	2	1.054
	3	24.0	0.375	11.00	0.625	100.0	0.375				0.366
	1	24.0	0.375	7.750	0.375	120.0	0.375				0.129
50-60	2	24.0	0.375	31.00	1.4375	120.0	0.6875	7.35	40.6	2	1.080
	3	24.0	0.375	12.75	0.625	120.0	0.375				0.354
	1	24.0	0.4375	6.00	0.375	80.0	0.375				0.15
50-70	2	24.0	0.4375	31.00	1.4375	80.0	0.9375	7.35	40.6	3	1.188
	3	24.0	0.4375	14.25	0.6875	80.0	0.500				0.49
	1	24.0	0.4375	6.00	0.375	100.0	0.375				0.12
50-70	2	24.0	0.4375	36.50	1.375	100.0	0.9375	7.35	40.6	3	1.07
	3	24.0	0.4375	16.00	0.8125	100.0	0.500				0.52
	1	24.0	0.4375	6.00	0.375	120.0	0.375				0.10
50-70	2	24.0	0.4375	41.00	1.625	120.0	1.000	7.35	40.6	3	1.11
	3	24.0	0.4375	18.00	0.875	120.0	0.4375				0.60
	1	24.0	0.500	6.00	0.375	80.0	0.375				0.15
50-80	2	24.0	0.500	31.00	1.500	80.0	1.000	7.35	40.6	3	1.162
	3	24.0	0.500	15.75	0.875	80.0	0.625				0.55

Table 6. Two-Span Section Dimensions

SPANS (ft)	No. cross sect.	Web		Top Flange		Bottom Flange		Bottom Stiffener			A_T/A_B
		Depth	Thickness	Width	Thickness	Width	Thickness	A	Ix	no.	
50-80	1	24.0	0.500	6.00	0.375	100.0	0.375				0.12
	2	24.0	0.500	35.50	1.625	100.0	1.000	7.35	40.6	3	1.153
	3	24.0	0.500	18.75	0.875	100.0	0.5625				0.583
50-80	1	24.0	0.500	6.00	0.375	120.0	0.375				0.100
	2	24.0	0.500	42.00	1.8125	120.0	1.125	7.35	40.6	4	1.127
	3	24.0	0.500	19.75	1.000	120.0	0.5625				0.585
100-100	1	48.0	0.5625	8.00	0.4375	80.0	0.375				0.233
	2	48.0	0.5625	30.50	1.3750	80.0	0.9375	7.35	40.6	2	1.118
	3	48.0	0.5625	8.00	0.4375	80.0	0.375				0.233
100-100	1	48.0	0.5625	9.50	0.4375	100.0	0.375				0.222
	2	48.0	0.5625	35.50	1.4375	100.0	0.875	7.35	40.6	2	1.166
	3	48.0	0.5625	9.50	0.4375	100.0	0.375				0.222
100-100	1	48.0	0.5625	10.25	0.500	120.0	0.375				0.227
	2	48.0	0.5625	37.25	1.625	120.0	0.9375	7.35	40.6	2	1.076
	3	48.0	0.5625	10.25	1.625	120.0	0.375				0.227
100-120	1	48.0	0.5625	6.25	0.375	80.0	0.375				0.156
	2	48.0	0.5625	40.5	1.5625	80.0	1.500	7.35	40.6	2	1.054
	3	48.0	0.5625	15.50	0.750	80.0	0.625				0.465
100-120	1	48.0	0.5625	6.50	0.375	100.0	0.375				0.13
	2	48.0	0.5625	42.50	1.875	100.0	1.500	7.35	40.6	2	1.063
	3	48.0	0.5625	16.00	0.8125	100.0	0.500				0.52
100-120	1	48.0	0.5625	7.00	0.375	120.0	0.375				0.116
	2	48.0	0.5625	48.0	2.0625	120.0	1.5625	7.35	40.6	2	1.056
	3	48.0	0.5625	18.25	0.875	120.0	0.500				0.532
100-140	1	48.0	0.625	6.75	0.375	80.0	0.375				0.168
	2	48.0	0.625	39.25	1.875	80.0	1.750	7.35	40.6	2	1.051
	3	48.0	0.625	24.00	1.125	80.0	1.0625				0.635
100-140	1	48.0	0.625	6.75	0.375	100.0	0.375				0.135
	2	48.0	0.625	51.00	2.000	100.0	1.9375	7.35	40.6	2	1.053
	3	48.0	0.625	26.50	1.250	100.0	0.9375				0.706

Table 6. Two-Span Section Dimensions

SPANS (ft)	No. cross sect.	Web		Top Flange		Bottom Flange		Bottom Stiffener			A_T/A_B
		Depth	Thickness	Width	Thickness	Width	Thickness	A	Ix	no.	
100-140	1	48.0	0.625	6.75	0.375	120.0	0.375				0.113
	2	48.0	0.625	57.00	2.437	120.0	2.1875	7.35	40.6	2	1.058
	3	48.0	0.625	28.50	1.375	120.0	0.875				0.75
100-160	1	48.0	0.6875	6.75	0.375	80.0	0.375				0.168
	2	48.0	0.6875	40.5	1.9375	80.0	1.8125	7.35	40.6	2	1.083
	3	48.0	0.6875	27.00	1.375	80.0	1.3125				0.707
100-160	1	48.0	0.6875	6.75	0.375	100.0	0.375				0.135
	2	48.0	0.6875	48.00	2.0625	100.0	1.875	7.35	40.6	2	1.056
	3	48.0	0.6875	28.50	1.500	100.0	1.1875				0.72
100-160	1	48.0	0.6875	6.75	0.375	120.0	0.375				0.1125
	2	48.0	0.6875	51.0	2.4375	120.0	2.000	7.35	40.6	2	1.036
	3	48.0	0.6875	32.25	1.5625	120.0	1.0625				0.79
150-150	1	72.0	0.75	7.25	0.4375	80.0	0.4375				0.181
	2	72.0	0.75	39.0	1.6875	80.0	1.4375	7.35	40.6	2	1.144
	3	72.0	0.75	7.25	0.4375	80.0	0.4375				0.181
150-150	1	72.0	0.75	9.00	0.500	100.0	0.375				0.240
	2	72.0	0.75	41.00	1.875	100.0	1.4375	7.35	40.6	2	1.069
	3	72.0	0.75	9.00	0.500	100.0	0.375				0.240
150-150	1	72.0	0.75	9.50	0.625	120.0	0.375				0.264
	2	72.0	0.75	46.0	2.000	120.0	1.4375	7.35	40.6	2	1.066
	3	72.0	0.75	9.50	0.625	120.0	0.375				0.264
150-180	1	86.0	0.8125	6.00	0.375	80.0	0.375				0.150
	2	86.0	0.8125	40.00	1.75	80.0	1.625	7.35	40.6	2	1.076
	3	86.0	0.8125	13.0	0.625	80.0	0.5625				0.361
150-180	1	86.0	0.8125	6.00	0.375	100.0	0.375				0.12
	2	86.0	0.8125	45.0	1.9375	100.0	1.5625	7.35	40.6	2	1.116
	3	86.0	0.8125	14.0	0.75	100.0	0.500				0.42
150-180	1	86.0	0.8125	6.0	0.375	120.0	0.375				0.100
	2	86.0	0.8125	49.0	2.125	120.0	1.625	7.35	40.6	2	1.068
	3	86.0	0.8125	16.0	0.8125	120.0	0.4375				0.495

Table 6. Two-Span Section Dimensions

SPANS (ft)	No. cross sect.	Web		Top Flange		Bottom Flange		Bottom Stiffener			A_T/A_B
		Depth	Thickness	Width	Thickness	Width	Thickness	A	Ix	no.	
	1	100.0	0.9375	6.00	0.375	80.0	0.375				0.150
150-210	2	100.0	0.9375	40.25	2.000	80.0	1.875	7.35	40.6	2	1.073
	3	100.0	0.9375	19.00	0.875	80.0	0.75				0.554
	1	100.0	0.9375	6.00	0.375	100.0	0.375				0.12
150-210	2	100.0	0.9375	49.00	2.0625	100.0	1.9375	7.35	40.6	2	1.043
	3	100.0	0.9375	20.5	0.9375	100.0	0.6875				0.560
	1	100.0	0.9375	6.00	0.375	120.0	0.375				0.100
150-210	2	100.0	0.9375	54.00	2.3125	120.0	2.0625	7.35	40.6	2	1.009
	3	100.0	0.9375	22.00	1.0625	120.0	0.625				0.623
	1	115.0	1.0625	6.00	0.375	80.0	0.375				0.15
150-240	2	115.0	1.0625	45.00	1.9375	80.0	2.0625	7.35	40.6	2	1.046
	3	115.0	1.0625	26.00	1.1250	80.0	1.0625				0.688
	1	115.0	1.0625	6.00	0.375	100.0	0.375				0.12
150-240	2	115.0	1.0625	50.00	2.4375	100.0	2.3125	7.35	40.6	2	1.054
	3	115.0	1.0625	28.0	1.25	100.0	0.9375				0.7466
	1	115.0	1.0625	6.00	0.375	120.0	0.375				0.100
150-240	2	115.0	1.0625	58.00	2.75	120.0	2.625	7.35	40.6	2	1.012
	3	115.0	1.0625	30.0	1.375	120.0	0.9375				0.733

** $L1$-$L2$.

prehensive laboratory study,[12] in which composite and noncomposite negative and positive sections were tested, has resulted in the following interaction equation:

$$\left(\frac{M}{M_p}\right)^{3/2} + \left(\frac{T}{T_p}\right)^{3/2} \leq 1.0$$

where:

M_p = plastic bending strength
M = design bending moment
T_p = plastic torsional strength
T = design torsional moment

Subsequent examination of typical box girders and their moment capacities, as controlled by the current AASHTO specifications[1] and as given in Table 2, has also permitted development of a series of design charts[17] which permit rapid evaluation of these moments.

Computerized Design—The general response of single or continuous curved box girder bridges can be predicted by the solution of a series of coupled differential equations, when written in difference form as given in Fig. 5.

These equations have been subsequently incorporated into a computer program,[9] which automates the design/analysis of prismatic or nonprismatic straight or curved box girders as governed by the AASHTO criteria.[1,2]

The box girder may be either composite or noncomposite construction and can have integral transverse diaphragms spaced along the box and contain top lateral bracing. The

Table 7. Three-Span Box Dimensions

SPANS (ft)	No. cross sect.	Web		Top Flange		Bottom Flange		Bottom Stiffener			A_T/A_B
		Depth	Thickness	Width	Thickness	Width	Thickness	A	Ix	no.	
**	1	24.0	0.375	8.25	0.4375	80.0	0.375				0.241
50-50-50	2	24.0	0.375	19.00	0.8125	80.0	0.4375	7.35	40.6	4	0.882
	3	24.0	0.375	6.00	0.375	80.0	0.375				0.15
	1	24.0	0.375	9.75	0.4375	100.0	0.375				0.227
50-50-50	2	24.0	0.375	20.25	0.875	100.0	0.4375	7.35	40.6	3	0.81
	3	24.0	0.375	6.00	0.375	100.0	0.375				0.12
	1	24.0	0.375	10.25	0.500	120.0	0.375				0.227
50-50-50	2	24.0	0.375	22.25	0.9375	120.0	0.500	7.35	40.6	3	0.695
	3	24.0	0.375	6.00	0.375	120.0	0.375				0.100
	1	24.0	0.375	7.00	0.375	80.0	0.375				0.175
50-60-50	2	24.0	0.375	22.25	1.000	80.0	0.375	7.35	40.6	3	1.483
	3	24.0	0.375	6.75	0.375	80.0	0.375				0.1687
	1	24.0	0.375	7.75	0.375	100.0	0.375				0.155
50-60-50	2	24.0	0.375	24.00	1.0625	100.0	0.4375	7.35	40.6	3	1.165
	3	24.0	0.375	7.25	0.375	100.0	0.375				0.145
	1	24.0	0.375	7.75	0.375	120.0	0.375				0.129
50-60-50	2	24.0	0.375	24.50	1.0625	120.0	0.500	7.35	40.6	3	0.8677
	3	24.0	0.375	7.00	0.375	120.0	0.375				0.1167
	1	24.0	0.375	7.00	0.375	80.0	0.375				0.175
50-70-50	2	24.0	0.375	24.0	1.125	80.0	0.5625	7.35	40.6	2	1.200
	3	24.0	0.375	8.50	0.375	80.0	0.375				0.212
	1	24.0	0.375	8.00	0.375	100.0	0.375				0.16
50-70-50	2	24.0	0.375	26.25	1.1875	100.0	0.5625	7.35	40.6	2	1.108
	3	24.0	0.375	9.00	0.4375	100.0	0.375				0.21
	1	24.0	0.375	8.50	0.4375	120.0	0.375				0.165
50-70-50	2	24.0	0.375	28.5	1.3125	120.0	0.6875	7.35	40.6	2	0.906
	3	24.0	0.375	10.00	0.500	120.0	0.375				0.222
	1	24.0	0.4375	6.00	0.375	80.0	0.375				0.15
50-80-50	2	24.0	0.4375	28.00	1.3125	80.0	0.8125	7.35	40.6	2	1.13
	3	24.0	0.4375	9.50	0.4375	80.0	0.375				0.277

Table 7. Three-Span Box Dimensions

SPANS (ft)	No. cross sect.	Web		Top Flange		Bottom Flange		Bottom Stiffener			A_T/A_B
		Depth	Thickness	Width	Thickness	Width	Thickness	A	Ix	no.	
50-80-50	1	24.0	0.4375	6.00	0.375	100.0	0.375				0.12
	2	24.0	0.4375	31.00	1.375	100.0	0.750	7.35	40.6	2	1.136
	3	24.0	0.4375	11.50	0.500	100.0	0.375				0.306
50-80-50	1	24.0	0.4375	6.00	0.375	120.0	0.375				0.100
	2	24.0	0.4375	33.00	1.500	120.0	0.750	7.35	40.6	2	1.10
	3	24.0	0.4375	11.50	0.5625	120.0	0.375				0.287
100-100-100	1	48.0	0.5625	12.75	0.5625	80.0	0.4375				0.410
	2	48.0	0.5625	25.50	1.125	80.0	0.5625	7.35	40.6	2	1.275
	3	48.0	0.5625	6.00	0.375	80.0	0.375				0.15
100-100-100	1	48.0	0.5625	14.00	0.625	100.0	0.4375				0.40
	2	48.0	0.5625	28.50	1.1875	100.0	0.5625	7.35	40.6	2	1.203
	3	48.0	0.5625	6.00	0.375	100.0	0.375				0.12
100-100-100	1	48.0	0.5625	15.50	0.6875	120.0	0.375				0.4376
	2	48.0	0.5625	31.00	1.3125	120.0	0.6875	7.35	40.6	2	0.986
	3	48.0	0.5625	6.00	0.375	120.0	0.375				0.100
100-120-100	1	48.0	0.5625	8.00	0.4375	80.0	0.375				0.238
	2	48.0	0.5625	30.00	1.4375	80.0	0.9375	7.35	40.6	2	1.15
	3	48.0	0.5625	7.00	0.375	80.0	0.375				0.175
100-120-100	1	48.0	0.5625	9.50	0.4375	100.0	0.375				0.222
	2	48.0	0.5625	33.50	1.500	100.0	0.875	7.35	40.6	2	1.148
	3	48.0	0.5625	7.50	0.375	100.0	0.375				0.15
100-120-100	1	48.0	0.5625	10.25	0.500	120.0	0.375				0.228
	2	48.0	0.5625	37.00	1.625	120.0	0.875	7.35	40.6	2	1.145
	3	48.0	0.5625	8.50	0.375	120.0	0.375				0.142
100-140-100	1	48.0	0.5625	7.50	0.4375	80.0	0.375				0.219
	2	48.0	0.5625	34.0	1.6250	80.0	1.250	7.35	40.6	2	1.105
	3	48.0	0.5625	11.00	0.5625	80.0	0.4375				0.353
100-140-100	1	48.0	0.5625	8.75	0.4375	100.0	0.375				0.204
	2	48.0	0.5625	40.00	1.6875	100.0	1.250	7.35	40.6	2	1.08
	3	48.0	0.5625	12.50	0.625	100.0	0.4375				0.357

Table 7. Three-Span Box Dimensions

SPANS (ft)	No. cross sect.	Web		Top Flange		Bottom Flange		Bottom Stiffener			A_T/A_B
		Depth	Thickness	Width	Thickness	Width	Thickness	A	Ix	no.	
100-140-100	1	48.0	0.5625	9.50	0.4375	120.0	0.375				0.185
	2	48.0	0.5625	44.50	1.875	120.0	1.3125	7.35	40.6	2	1.059
	3	48.0	0.5625	15.00	0.6875	120.0	0.375				0.458
100-160-100	1	48.0	0.625	6.00	0.375	80.0	0.375				0.15
	2	48.0	0.625	39.00	1.750	80.0	1.5625	7.35	40.6	2	1.092
	3	48.0	0.625	18.00	0.8125	80.0	0.750				0.332
100-160-100	1	48.0	0.625	6.00	0.375	100.0	0.375				0.12
	2	48.0	0.625	43.00	1.875	100.0	1.500	7.35	40.6	2	1.075
	3	48.0	0.625	18.00	0.875	100.0	0.625				0.504
100-160-100	1	48.0	0.625	6.00	0.375	120.0	0.375				0.100
	2	48.0	0.625	46.00	2.0625	120.0	1.500	7.35	40.6	2	1.054
	3	48.0	0.625	20.00	0.875	120.0	0.5625				0.519
150-150-150	1	72.0	0.750	17.25	0.750	80.0	0.6875				0.47
	2	72.0	0.750	31.50	1.375	80.0	0.9375	7.35	40.6	2	1.154
	3	72.0	0.750	6.00	0.375	80.0	0.375				0.15
150-150-150	1	72.0	0.750	18.75	0.8125	100.0	0.5625				0.542
	2	72.0	0.750	34.50	1.500	100.0	0.875	7.35	40.6	2	1.183
	3	72.0	0.750	6.00	0.375	100.0	0.375				0.12
150-150-150	1	72.0	0.750	20.00	0.9375	120.0	0.5625				0.555
	2	72.0	0.750	37.50	1.625	120.0	0.875	7.35	40.6	2	1.161
	3	72.0	0.750	6.00	0.375	120.0	0.375				0.100
150-180-150	1	72.0	0.750	10.00	0.4375	80.0	0.4375				0.25
	2	72.0	0.750	37.50	1.750	80.0	1.500	7.35	40.6	2	1.093
	3	72.0	0.750	7.00	0.375	80.0	0.375				0.15
150-180-150	1	72.0	0.750	11.00	0.5625	100.0	0.375				0.33
	2	72.0	0.750	43.00	1.8125	100.0	1.4375	7.35	40.6	2	1.084
	3	72.0	0.750	7.75	0.375	100.0	0.375				0.155
150-180-150	1	72.0	0.750	14.00	0.625	120.0	0.375				0.388
	2	72.0	0.750	46.00	2.00	120.0	1.4375	7.35	40.6	2	1.066
	3	72.0	0.750	8.50	0.375	120.0	0.375				0.142

Table 7. Three-Span Box Dimensions

SPANS (ft)	No. cross sect.	Web		Top Flange		Bottom Flange		Bottom Stiffener			
		Depth	Thickness	Width	Thickness	Width	Thickness	A	Ix	no.	A_T/A_B
150-210-150	1	72.0	0.750	8.50	0.375	80.0	0.4375				0.182
	2	72.0	0.750	45.00	2.000	80.0	2.125	7.35	40.6	2	1.059
	3	72.0	0.750	17.00	0.750	80.0	0.6875				0.464
150-210-150	1	72.0	0.750	9.50	0.4375	100.0	0.375				0.222
	2	72.0	0.750	51.50	2.1875	100.0	2.125	7.35	40.6	2	1.06
	3	72.0	0.750	18.00	0.8750	100.0	0.625				0.504
150-210-150	1	72.0	0.750	9.00	0.4375	120.0	0.375				0.175
	2	72.0	0.750	58.00	2.500	120.0	2.250	7.35	40.6	2	1.086
	3	72.0	0.750	21.50	0.9375	120.0	0.5625				0.597
150-240-150	1	72.0	0.8125	7.00	0.375	80.0	0.375				0.175
	2	72.0	0.8125	52.00	2.250	80.0	2.750	7.35	40.6	2	1.063
	3	72.0	0.8125	23.50	1.125	80.0	1.0625				0.622
150-240-150	1	72.0	0.8125	7.00	0.375	100.0	0.375				0.140
	2	72.0	0.8125	57.50	2.500	100.0	2.6875	7.35	40.6	2	1.069
	3	72.0	0.8125	24.50	1.125	100.0	0.875				0.63
150-240-150	1	72.0	0.8125	7.00	0.375	120.0	0.375				0.117
	2	72.0	0.8125	62.00	2.750	120.0	2.625	7.35	40.6	2	1.082
	3	72.0	0.8125	26.0	1.125	120.0	0.750				0.65

** $L1$-$L2$-$L3$.

basic configuration of a typical box and the type of cross diaphragms is shown in Figs. 2, 3 and 4.

The computer output contains influence line ordinates, stresses on top and bottom flanges at locations along the span due to dead load, superimposed dead load, and live load plus impact. The stress resultants include the effects of bending, warping and distortion, utilizing the automatically computed section properties.

Stress envelopes are given for fatigue design. Specifications (AASHTO) are used to establish allowable stresses, web and flange stiffening requirements and shear connector spacing, as given in Tables 1 and 2.

Resulting girder deflections and rotations, due to sequential concrete placements, can also be determined for specified length of pours. Composite/noncomposite actions may be assured after the concrete hardens.

The entire output sequence is as follows:

Basic Data

- Job description
- Girder geometry
- Structural details
- Concrete properties
- Loading properties
- Section details: span length, plate sizes, section properties, stiffener and bracing details, dead loads
- Pouring sequence geometry

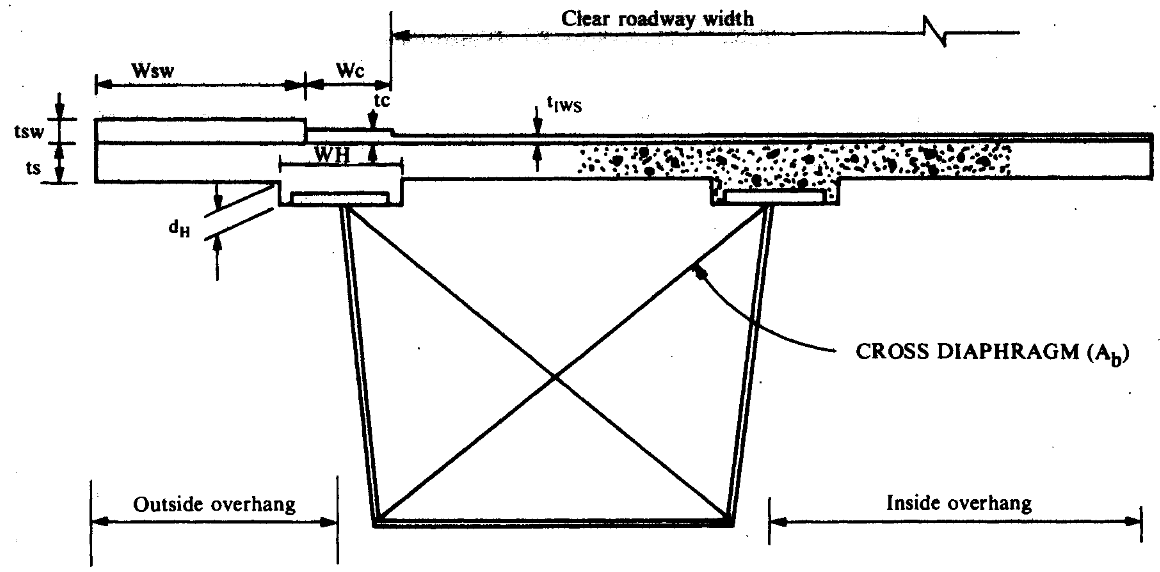


Fig. 2. Structural details

Stresses

- Dead-load normal stress
- Superimposed dead-load normal stress
- Live-load normal stress (positive and negative moment)

Forces

- Moment envelope
- Deflection envelope
- Shear envelope
- Vertical reaction envelope
- Torsion reaction envelope
- Torsion envelope
- Bimoment envelope
- Normal stress envelope
- Stress range envelope
- d/t, b/t requirements, web stress
- Theoretical web stiffener requirement
- Total stresses
- Shear connector spacing requirements
- Fatigue criteria
- Pouring sequence deflections
- Natural frequency
- Pouring sequence rotations

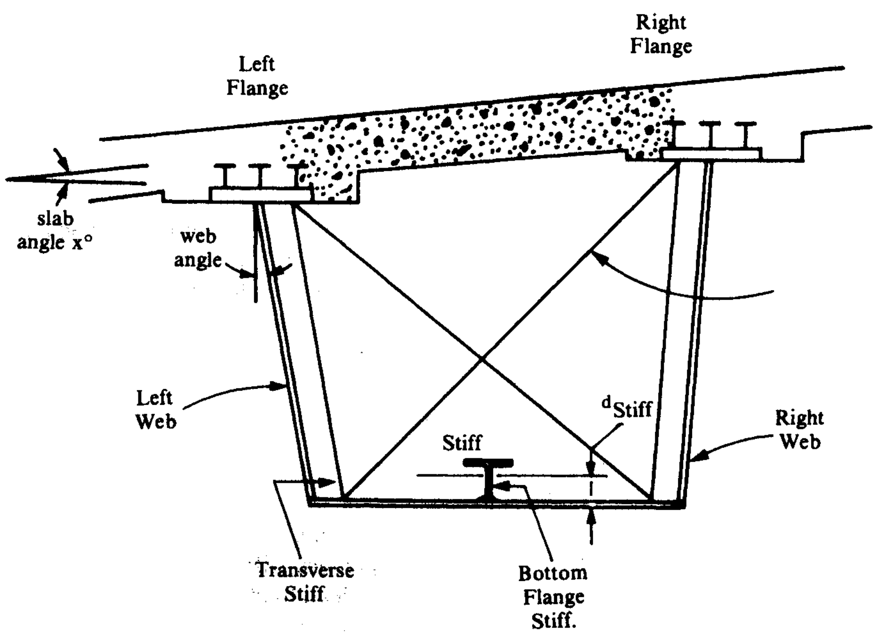
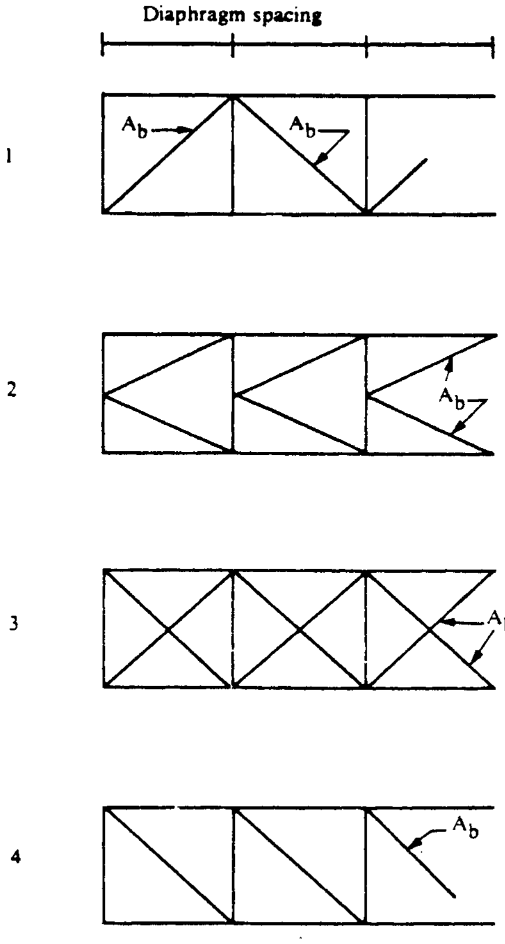


Fig. 3. Cross section



A_b = Bracing member area.

Fig. 4. Bracing types (top lateral)

Field-Test Comparison to Theoretical Results—The static and dynamic response of a full scale bridge structure, when subjected to a known truck loading, was examined during the Fall 1973.[16] The bridge consisted of twin steel boxes (4.5 ft × 8.8 ft) in composite action with a 9½-in. concrete slab. That part of the bridge under test was a three-span continuous with span lengths 100 ft, 130 ft, and 120 ft and centerline radius of 1,317 ft. The bridge was designed as a two-lane structure. The deformations and strains throughout the structure were measured during the application of the test vehicle. The resulting static load data were then examined and the results compared to the data obtained by the previously described analytical technique.[8,9]

In summary, the resulting induced stresses, at various locations along the structure, are described in Table 8. The sections are located as follows:

Section A 0.4 (exterior span)
Section B $1.0L_1$ (first interior support)
Section C $0.5L_2$ (midspan of interior span)

Examination of the data given in Table 8 indicates reasonable correlation between theory and experiment and the importance of the top lateral bracing during the dead-load response.

The resulting girder deflections at Section A and Section C are given in Table 9. The data shown in this table show comparisons between theory and tests, indicating reasonable correlation especially for live load effects. The discrepancy in the dead-load results is due to the sequential placement of the concrete and time dependent composite actions.

$$
\begin{array}{c}
n \\ \phi
\end{array}
\left[
\begin{array}{c|c|c|c|c}
\frac{EI_w}{R} & 4\left(\frac{EI_w}{R}\right) + \frac{h^2(EI_x + CK_t)}{R} & -\left[6\frac{EI_w}{R} + \frac{2h^2(EI_w + CK_t)}{R}\right] & 4\left(\frac{EI_w}{R}\right) + \frac{h^2(EI_x + CK_t)}{R} & -\frac{EI_w}{R} \\
-EI_w & 4EI_w + h^2CK_t & -\left[6EI_w + 2h^2CK_t + \frac{h^4EI_x}{R^2}\right] & 4EI_w + h^2CK_t & -EI_w \\
\hline
n-2 & n-1 & n & n+1 & n+2
\end{array}
\right] = -m_z h^2
$$

$$
\begin{array}{c}
n \\ \phi
\end{array}
\left[
\begin{array}{c|c|c|c|c}
-\left(\frac{EI_w}{R} + EI_x\right) & 4\left(\frac{EI_w}{R^2} + EI_x\right) + \frac{h^2CK_t}{R^2} & -\left[6\left(\frac{EI_w}{R^2} + EI_x\right) + \frac{2h^26K_t}{R^2}\right] & 4\left(\frac{EI_w}{R^2} + EI_x\right) + \frac{h^26K_t}{R^2} & -\left(\frac{EI_w}{R^2} + EI_x\right) \\
-\frac{EI_w}{R} & 4\left(\frac{EI_w}{R}\right) + \frac{h^2(EI_x + CK_t)}{R} & -\left[6\left(\frac{EI_w}{R}\right)\frac{2h^2(EI_x + CK_t)}{R}\right] & 4\left(\frac{EI_w}{R}\right) + \frac{h^2(EI_x + 6K_t)}{R} & -\frac{EI_w}{R}
\end{array}
\right] = -q_y h^2
$$

Fig. 5. Curved girder finite difference equation

Table 8. Prototype Bridge Test-Stresses

Cross Sections	Loading	Test (ksi)	Theory (ksi)	
			With bracing	Without bracing
A	DL	7.70	6.25	9.02
	LL + I	2.32	2.65	2.65
	Total	10.02	8.90	11.67
B	DL	−5.14	−4.96	−6.66
	LL + I	− .76	−1.05	−1.05
	Total	−5.90	−6.01	−7.71
C	DL	6.12	3.26	4.27
	LL + I	1.83	2.07	2.07
	Total	7.95	5.33	6.34

Table 9. Prototype Bridge Test-Vertical Deflections

Cross Section	Loading	Test (in.)	Theory	
			With bracing	Without bracing
A	DL	1.19	0.88	0.93
	LL + I	0.20	0.23	0.23
	Total	1.39	1.11	1.16
C	DL	0.50	0.51	0.47
	LL + I	0.26	0.27	0.27
	Total	0.76	0.78	0.74

In general, results indicate the curved girder finite difference theory provides an excellent technique for box girder design.

CONCLUSIONS

This paper presents the results of various research which has permitted a better understanding of steel box girder bridges and the development of design criteria. Through use of these design data, more efficient and rapid design of such structures can be achieved, and a better service to the public provided.

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