

Fabrication Aids For Girders Curved with V-Heats

Prepared by

Roger L. Brockenbrough
Associate Research Consultant
U.S. Steel Corporation
Research Laboratory

Introduction

In 1968, a program was initiated by United States Steel Corporation to obtain national acceptance of heat curving of bridge girders. The program included both analytical and experimental investigations on the effect of heat curving on residual stresses, strains, and curvatures, and the preparation of a criteria for heat curving. The ensuing criteria, together with a commentary, were presented to the American Association of State Highway Officials, Committee on Bridges and Structures in 1969 and were subsequently adopted as "Interim Specification", 1970.

As a result of the AASHTO Interim Specification and the inherent economies of heat-curving, this process is being used more frequently by fabricators for producing horizontally curved girders for highway bridges. However, the process has remained essentially an art. That is, within the limits of the specification, each fabricator has relied on his past experience and judgment to select flange areas to be heated, heating temper-

tures and the manner of support for each member. The most practical and economical processes used by most fabricators are either the continuous or intermittent application of heat for curving girders.

To provide steel fabricators with assistance in making proper decisions on both methods, U. S. Steel has developed fabrication aids in the form of charts that relate temperature, radius of curvature, girder geometry and support conditions. This book presents fabrication aids for Girders Curved with V-Heats. A companion book deals with Continuously Heat-Curved Girders.

The proper use of these fabrication aids can assist the fabricator by indicating heat-curving conditions that will result in a curvature close to the specified curvature. However, because of the many uncontrolled variables involved it may be necessary to apply a final corrective heating to bring the girder to the exact curvature desired.

Scope

For this study, sets of temperature profiles were developed on four cross sections within the heated V shape area; these cross sections were evenly spaced along the base dimension of the V as indicated in Figure 1 (B). The temperatures are assumed to be constant through the flange thickness. Profiles for each of the four cross sections are shown in Figure 2 in terms of the dimensionless temperature coefficient, K_H , which relates the temperature at each location and time to the maximum temperature in the heated area of the flange at the end of the heating cycle. The program calculates the temperature, T , at any time and location from the relationship.

$$T = K_H T_Q + T_{AA} \quad (1)$$

where T_Q is the maximum temperature increment and T_{AA} is the ambient temperature. (For this study, $T_Q = 1030$ F, $T_{AA} = 70$ F, and the maximum value of T was 1100 F for $K_H = 1.00$).

Consequently, the program used for this analysis computes the curvature at four cross sections (points A, B, C, and D in Figure 1 (B)) in the heated area. The curvature at each cross section was calculated separately and assumed to be constant over a segment of length bounded by adjacent segments. The curvatures of the segments were summed and divided by the base width of the heated V to get an average curvature, $1/R_V$, for the V.

With the mathematical model used, R_V/b is constant for any given set of heating conditions (b is the flange width). Furthermore, the average radius of curvature, R , of a girder heated as of the heated V's shown in Figure 1 (A) must be proportional to the spacing, of the heated V's since the portion of the beam between the heated V's remains straight. Consequently, the ratio of radius to flange width for any girder is

$$\frac{R}{b} = \frac{R_V}{b} \left(\frac{S'}{s} \right) \quad (2)$$

where S' is the center-to-center spacing of the V's and s is the base dimension of the V. Values of R_V can be determined for given heating conditions for a girder of width, b , and the results portrayed as linear relationships between R/b and S'/s .

Assumed Heating Conditions

In general, the actual temperature profiles vary with the plate size heated, the equipment used, and the operator. The profiles shown in Figure 2 are considered representative for a plate that is heated simultaneously from both sides in the manner described in the Specification⁴⁾* to bring the V to an approximately uniform temperature in approximately 3 to 4 minutes. Since the heat flows out of the V across the girder flange while the heat is applied, the severity (steepness) of the temperature profiles at maximum temperature increases as the time required to heat the V decreases. The curvature obtained increases as the severity of the profiles increases. Thus, it is important to heat each V rapidly. The profiles shown in Figure 2 were extrapolated from the theoretical profiles previously used¹⁾ by assuming that the heat flow in a direction normal to the sides of the V was similar to that normal to the edge of the heated rectangular strip.

Parameters

Table I shows the parameters considered in the present investigation. The ratios of dimensions of the heated area to the flange width are held constant; the V has a base dimension of $b/3$ and an altitude of $5b/8$ as shown in Figure 1 (B). These dimensions generally fall within those permitted, but reference should be made to the Specification⁴⁾ for specific applications.

The maximum temperature considered is 1100 F, which is slightly less than that permitted for heat curving⁴⁾ (1150 F) but is used as a working value by several states. It was not necessary to consider a range of temperatures, because the girder curvature can be changed by varying the spacing of the V-heats.

The remaining parameters summarized in Table I are variables and are similar to those considered for continuously heat-curved girders.⁵⁾ As indicated, two distributions of initial residual stresses are assumed, corresponding to average values of those in (1) girders with gas-cut flanges and (2) girders with universal mill (U.M.) flanges or hot-rolled shapes. The initial residual stresses are assumed to be the same for both of the yield points considered — 36 and 50 ksi. The values

*See References.

of the dead-load bending stress range from zero to the maximum stress permitted⁴⁾ – 20 ksi for A36 steel and 27 ksi for A588 steel. The range of stresses must be used because, when curved in the horizontal position, the stress varies along the length of the girder. It has previously been demonstrated in practice that the girder flanges will not buckle during the heating process if the dead-load bending stress is limited to the usual allowable design stress.

Fabrication Trials

Preliminary results of the mathematical analysis were used to select the spacing of V-heats for production girders in several fabrication shops. These trials showed that the girder curvature could be closely predicted if the theoretical results were modified by an appropriate empirical factor. The following heat-curving charts were prepared to include this experimental modification.

Heat-Curving Charts

The results of the investigation are summarized in Figures 3 through 6, which show curves relating the ratio of radius to flange width, R/b , to the spacing ratio, S'/s . Separate figures are given for each yield point (36 or 50 ksi) and type of flange (gas-cut or U.M.). In each figure, a family of linear curves portrays the results for the several values of bending stress considered. These curves can be used to select the heating conditions for most girders or beams, as illustrated by the examples given in Figures 7, 8, and 9 and discussed below. In all examples, the girder is assumed to be curved in the horizontal position. In general, a girder would not be heat curved in the vertical position (dead load bending stress of 0) with V-heats, because the curvatures obtained are too small. Because the dead load bending stress varies along the beam, the spacing of the V's must be varied continuously to produce a uniform curvature. For practical purposes, however, the spacing may be kept constant over a segment of the beam.

Application of Charts

Girder With Constant-Size Flanges

An application of the charts for an A36 steel girder with constant-size flanges is shown in

Figure 7. Although it is not typical to have a constant-size flange for the full length of the girder, a constant-flange girder provides a convenient illustration of the use of the charts. Girders with varying flange sizes are treated in subsequent examples.

The girder must first be checked to make sure that the required radius is not less than the minimum radius that AASHTO allows for heat-curved girders.⁴⁾ The minimum radius is the larger of the values calculated from Equations 1 and 2 of the Appendix. The example girder has the following properties:

$$\begin{aligned} b &= 24 \text{ in.} \\ D &= 55 \text{ in.} \\ t &= 5/8 \text{ in.} \\ F_y &= 36 \text{ ksi} \\ \psi &= 130.4/96 = 1.36 \end{aligned}$$

The equations in the Appendix lead to the following calculations:

$$R = \frac{14}{\sqrt{F_y}} \frac{b}{\psi} \frac{D}{t} = \frac{14}{\sqrt{36}} \frac{24}{1.36} \frac{55}{0.625} = 3624 \text{ in. or } 302 \text{ ft.}$$

$$R = \frac{7500}{F_y} \frac{b}{\psi} = \frac{7500}{36} \frac{24}{1.36} = 3676 \text{ in. or } 306 \text{ ft.}$$

The required radius, 2,000 feet, is greater than the minimum, 306 feet; therefore, the girder may be heat-curved.

The distance between supports used during heat curving must be determined so that the dead-load bending stress does not exceed the allowable value (20 ksi for A36 steel and 27 ksi for A588 steel). The equations for this calculation are given in Figure A1 of the Appendix, and their use in the example is shown in Figure 7. The distance between supports is $L_S = 108.0$ ft. The bending moments at various points along the length of the girder are calculated as indicated; the moments are divided by the section modulus of both flanges, S , to obtain the bending stress.

Since the flanges are U.M. plates of A36 steel, the spacing of the V-heats can be obtained from Figure 4. The intersection of the horizontal line for $R/b = 1000$ with the curves for nominal bending stress gives the following spacing ratios:

Stress, ksi	Spacing Ratio, S'/s
20	11.4
15	8.0
5	3.4

The stress used is the approximate average value in the length of girder considered; rounded to the nearest 5 ksi, the spacing ratios are multiplied by the value of s to determine the approximate spacing of the V-heats in each length. As indicated in Figure 7, s is simply $b/3 - 8$ in.

Girder With Varying Flange Sizes

Figure 8 shows an example for a symmetrical A36 steel girder with flanges that vary in thickness. The minimum radius is determined for the center section, which has the small area ratio, ψ :

$$\begin{aligned} b &= 22 \text{ in.} \\ D &= 58 \text{ in.} \\ t &= 3/8 \text{ in.} \\ F_y &= 36 \text{ ksi} \\ \psi &= 82.2/60.5 = 1.36 \end{aligned}$$

$$R = \frac{14}{\sqrt{F_y}} \frac{b}{\psi} \frac{D}{t} = \frac{14}{\sqrt{36}} \frac{22}{1.36} \frac{58}{0.375} = 5838 \text{ in. or 486 ft.}$$

$$R = \frac{7500}{F_y} \frac{b}{\psi} = \frac{7500}{36} \frac{22}{1.36} = 3370 \text{ in. or 281 ft.}$$

The required radius, 1,000 feet, is greater than the minimum 486 feet; therefore the girder may be heat-curved.

The distance between supports is determined in a manner similar to that previously described. However, since the dead load varies along the length of the girder, the equations do not apply exactly. Nevertheless, a trial value of L_S can be calculated from these equations by using the S and W of the center portion of the girder. An exact analysis for the girder with supports spaced at a distance L_S should then be made to ensure that the dead-load stresses do not exceed 20 ksi at any point along the beam. If the dead-load stresses do exceed 20 ksi, the length L_S should be reduced accordingly.

The bending moments are calculated at the points where the flange thickness changes and divided by the appropriate section modulus to give the stresses. Since the stresses were less than 20 ksi, the support distance is adequate. The spacing ratios for the gas-cut A36 steel flanges are then obtained from Figure 3 at the intersection of the horizontal line for $R/b = 545$ and the appropriate stress values, then multiplied by s (7.33 in.) to obtain the required spacing values, S' .

Asymmetrical Girder With Equal Width Flanges

An example for a girder with top and bottom flanges of different thickness but equal width is shown in Figure 9. The minimum radius is determined at the section with the heaviest flanges.

$$\begin{aligned} b &= 18 \text{ in.} \\ D &= 42 \text{ in.} \\ t &= 5/16 \text{ in.} \\ F_y &= 50 \text{ ksi} \\ \psi &= 67.1/54 = 1.24 \end{aligned}$$

$$R = \frac{14}{\sqrt{F_y}} \frac{b}{\psi} \frac{D}{t} = \frac{14}{\sqrt{50}} \frac{18}{1.24} \frac{42}{0.312} = 3869 \text{ in. or 322 ft.}$$

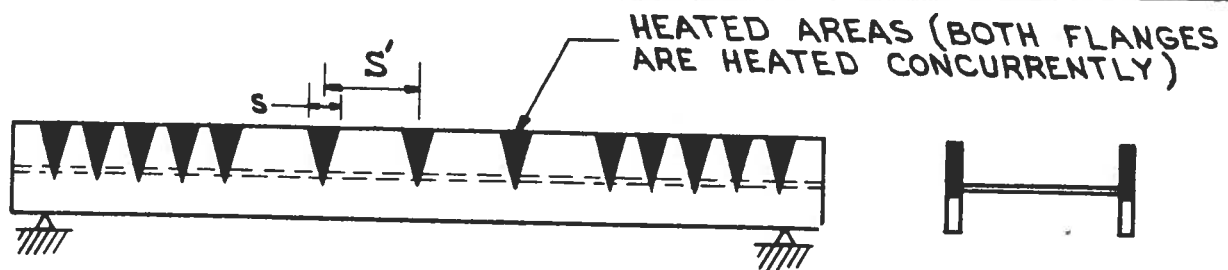
$$R = \frac{7500}{F_y} \frac{b}{\psi} = \frac{7500}{50} \frac{18}{1.24} = 2177 \text{ in. or 181 ft.}$$

Since the required radius, 1,200 feet, is greater than the minimum, 322 feet, the girder may be heat-curved.

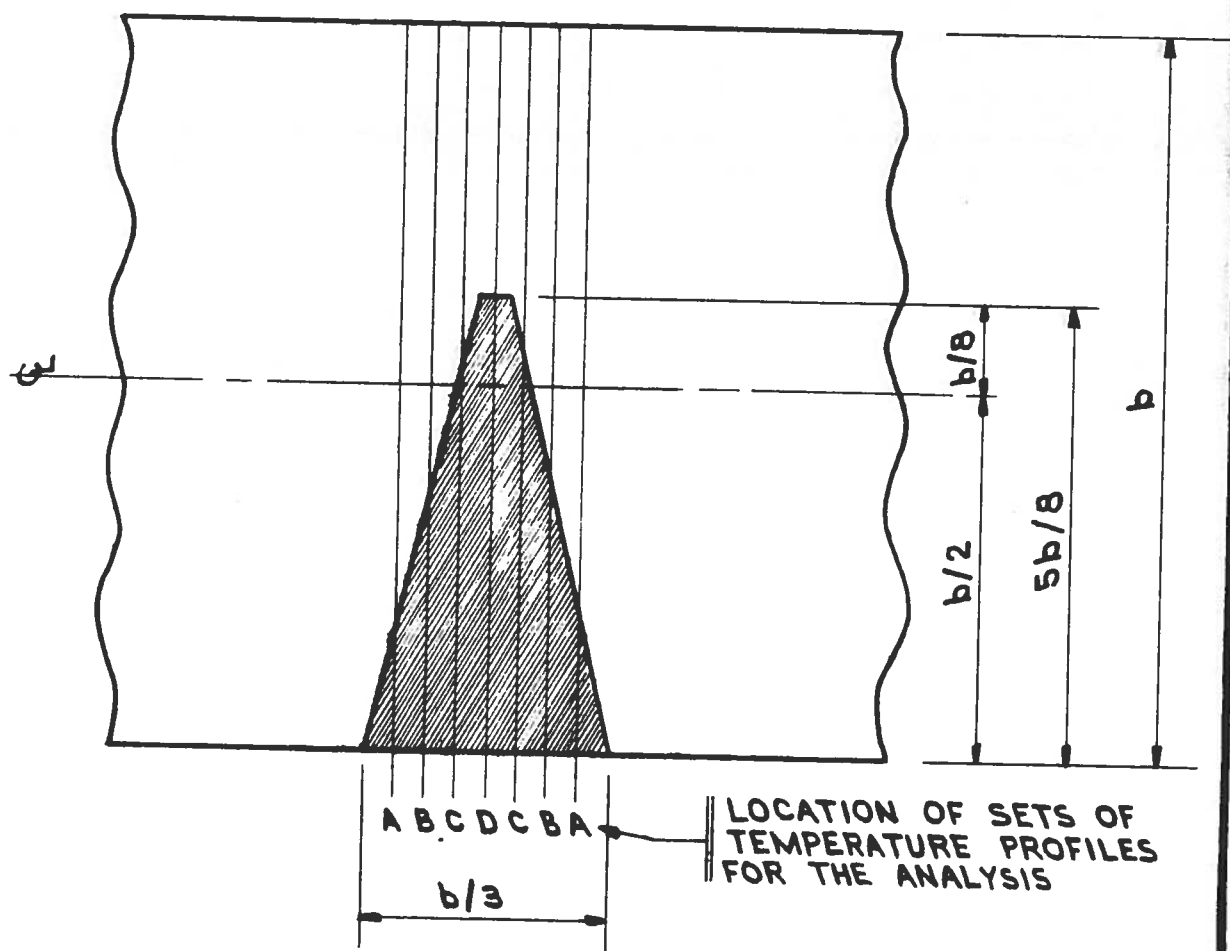
Each flange will be assumed to carry its own weight plus one-half the weight of the web and stiffeners. The distance L_O for each flange exceeds the length of the girder; therefore, the girder will be supported at its ends. Bending moments and stresses are determined for each flange. For the top flange, the values are determined at the 1/4-length points; for the bottom flange, at changes in thickness and at intermediate points. The stresses are less than the allowable 27 ksi for A588 steel and the support length is satisfactory. Spacing ratios for each flange are selected from Figure 5 at the intersection of the horizontal line for $R/b = 800$ and the appropriate stress values, and multiplied by s (6 in.) to obtain the required spacing values, S' .

References

1. R. L. Brockenbrough, "Theoretical Stresses and Strains from Heat Curving," *Journal of the Structural Division, Proceedings ASCE*, 96, No. ST7, July 1970.
2. R. L. Brockenbrough and K. D. Ives, "Experimental Stresses and Strains From Heat Curving," *Journal of the Structural Division, Proceedings ASCE*, 96 No. ST7, July 1970.
3. R. L. Brockenbrough, "Criteria for Heat Curving Steel Beams and Girders," *Journal of the Structural Division, Proceedings ASCE*, 96, No. ST10, October 1970.
4. American Association of State Highway Officials, "Standard Specifications for Highway Bridges," 1969, and "Interim Specification," 1970.
5. U. S. Steel Corporation, "Fabrication Aids for Continuously Heat-Curved Girders."



A. POSITION FOR V-HEATING



B. DIMENSIONS ASSUMED FOR HEATING PATTERN

FIG. 1 - ARRANGEMENT FOR V-HEATING

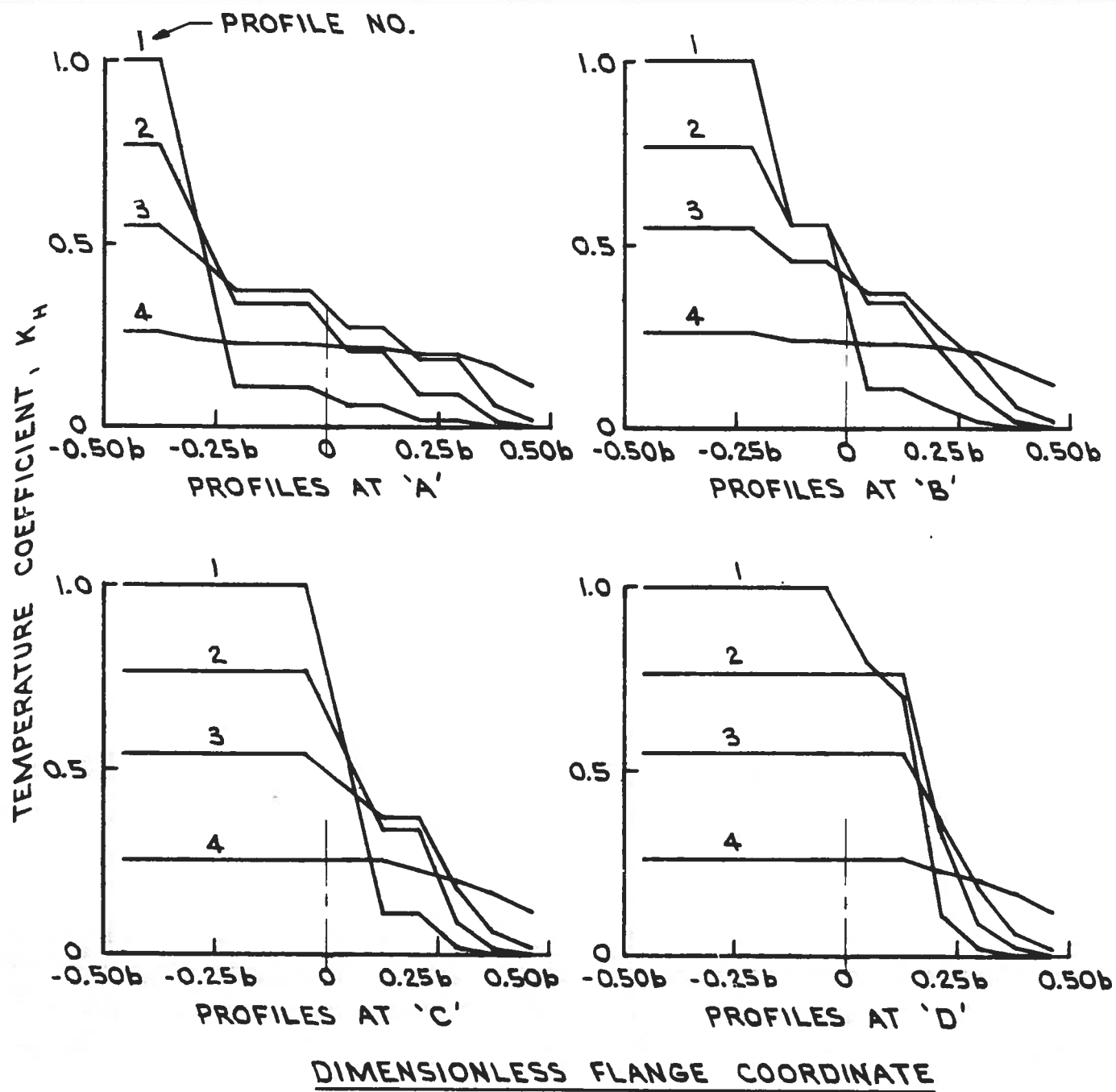


FIG. 2 – INSTANTANEOUS TEMPERATURE DISTRIBUTIONS FOR V-HEATS

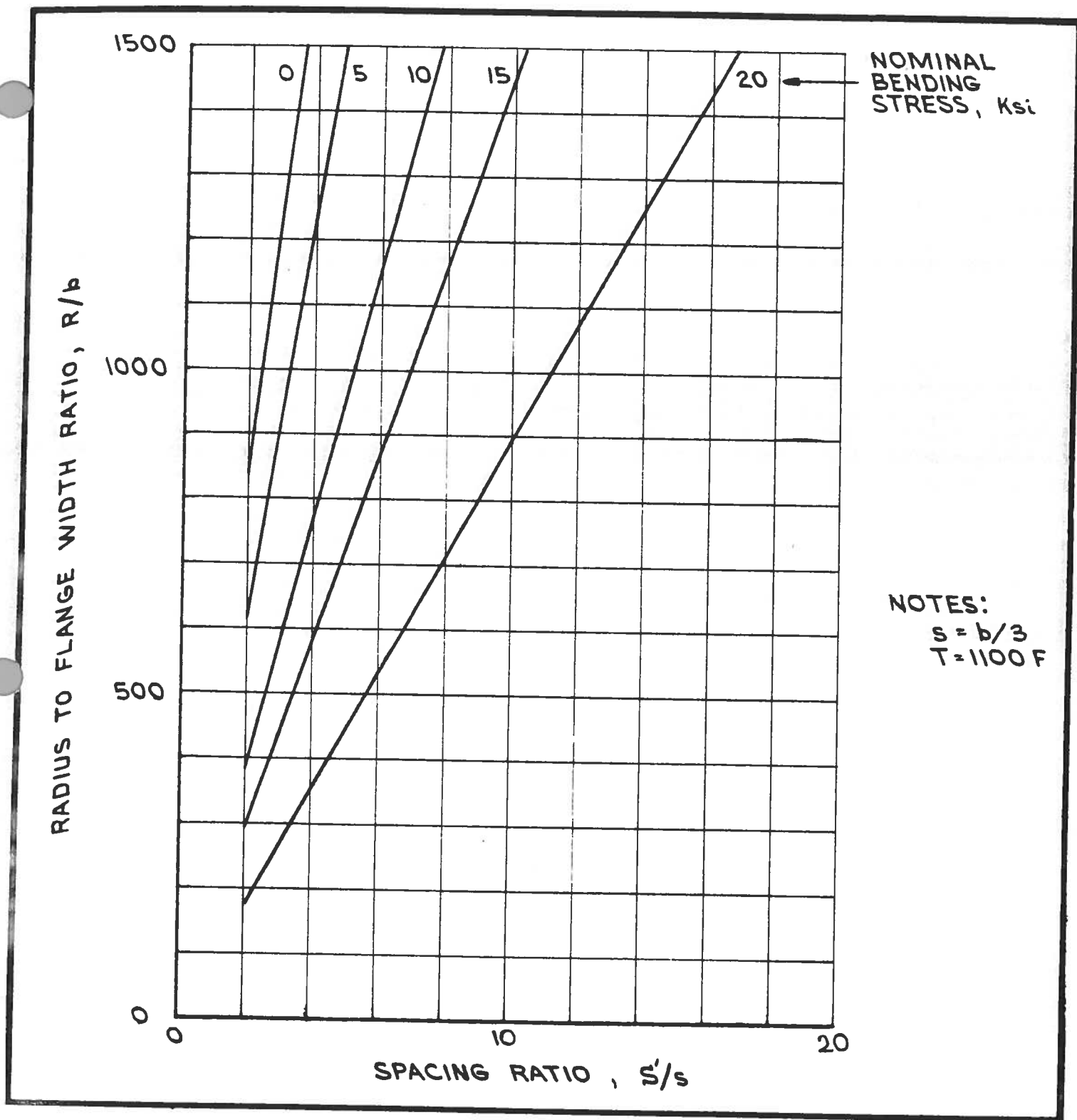


FIG. 3 – CURVATURE FOR A36 STEEL GIRDERS – GAS – CUT FLANGES AND V-HEATS

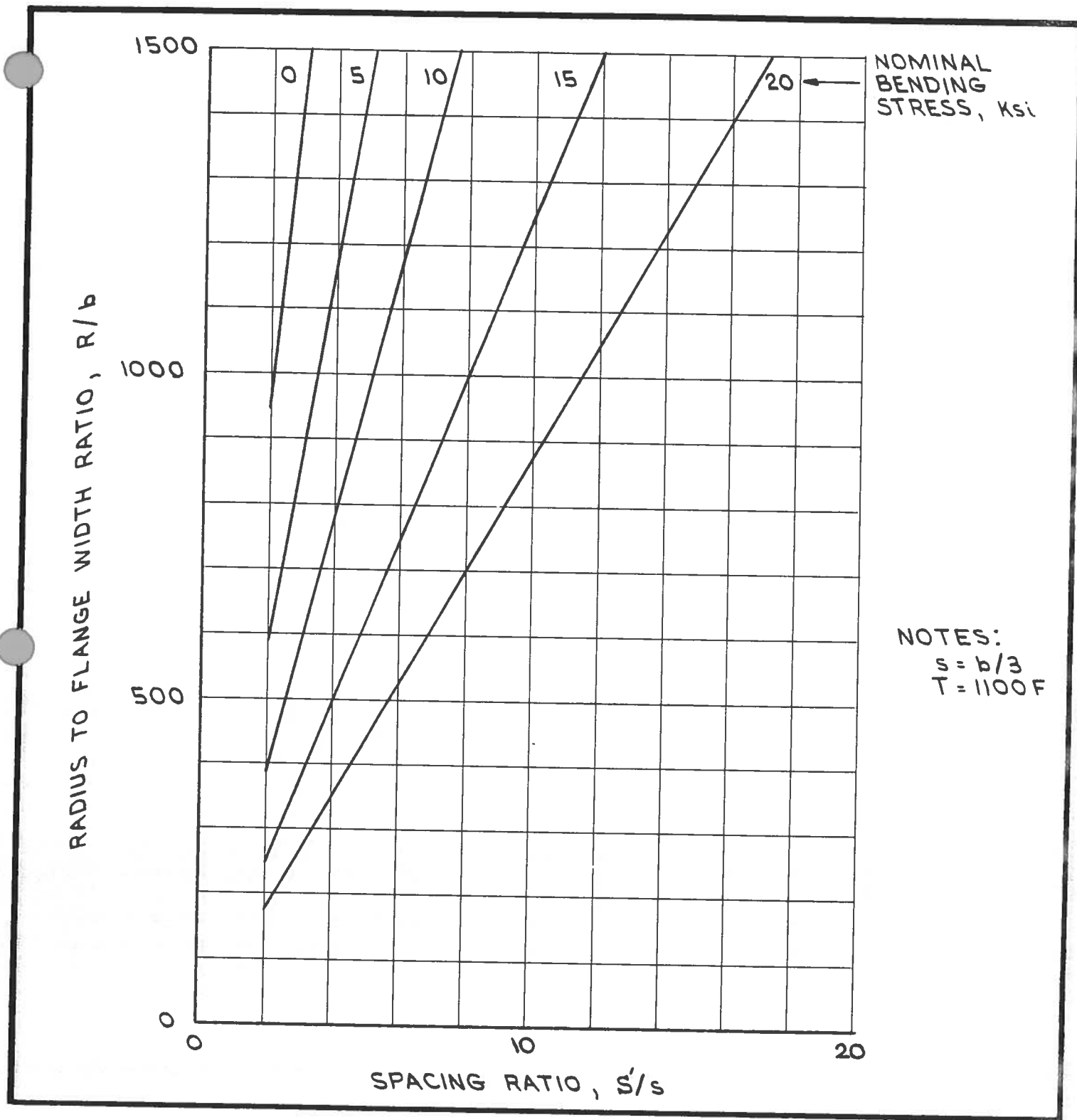


FIG. 4 – CURVATURE FOR A36 STEEL GIRDERS – UM FLANGES AND V-HEATS

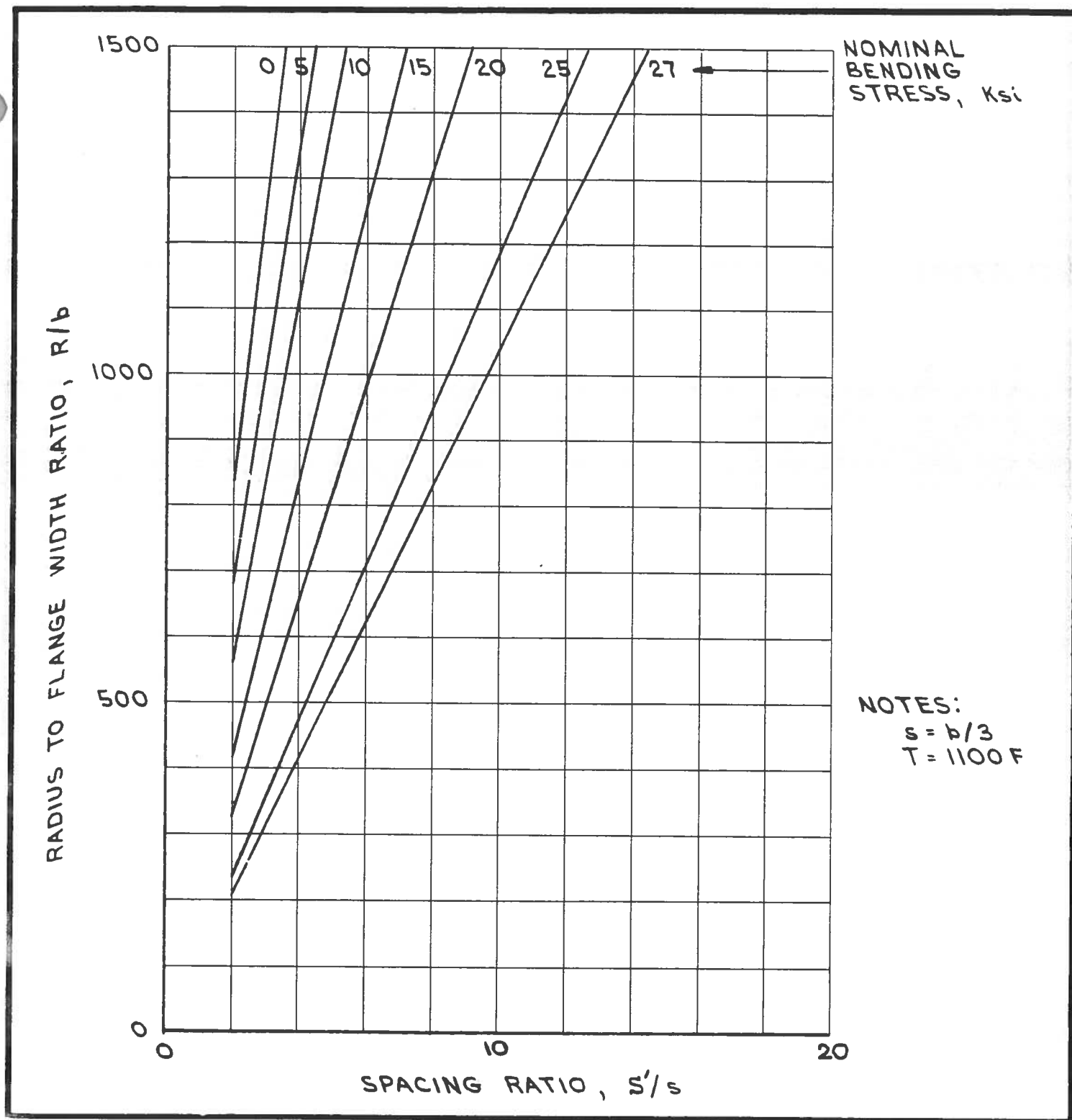


FIG. 5 – CURVATURE FOR A588 STEEL GIRDERS – GAS – CUT FLANGES AND V-HEATS

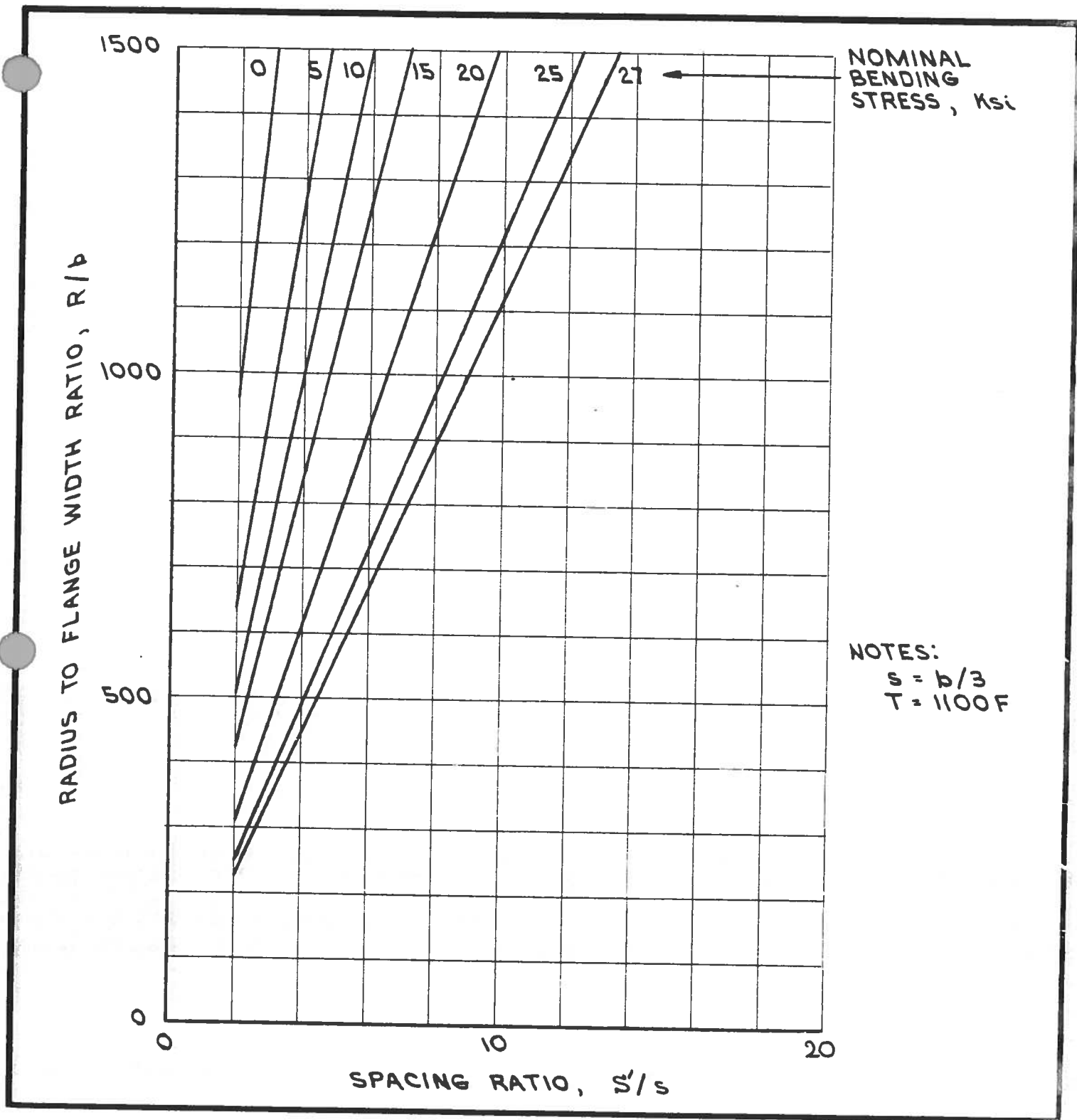
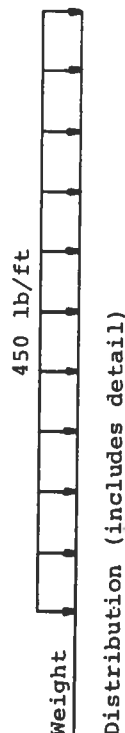
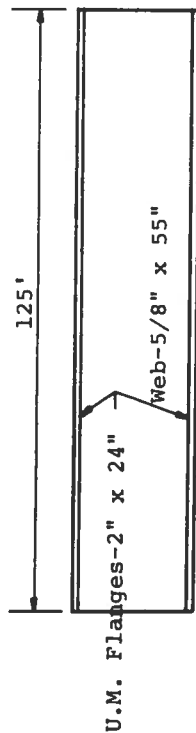


FIG. 6 - CURVATURE FOR A588 STEEL GIRDERS - UM FLANGES AND V-HEATS

Given Conditions

Required Radius = 2000 ft
 Curving Position: Horizontal
 Girder as shown below (A36 steel):



Determination of Heating and Support Conditions

$$S = 2 \times 2 \times 24 \times 24/6 = 384 \text{ in.}^3$$

$$L_o = \sqrt{8FS/W} = \sqrt{8 \times 20 \times 384 / .450 \times 12} = 106.7 \text{ ft}$$

$$L_s = L_o + (L - L_o)^2 / 2L = 106.7 + 18.3 \times 18.3 / 250 = 108.0 \text{ ft}$$

$$R/b = 2000 \times 12 / 24 = 1000$$

$$s = b/3 = 24/3 = 8 \text{ in. (base width of v)}$$

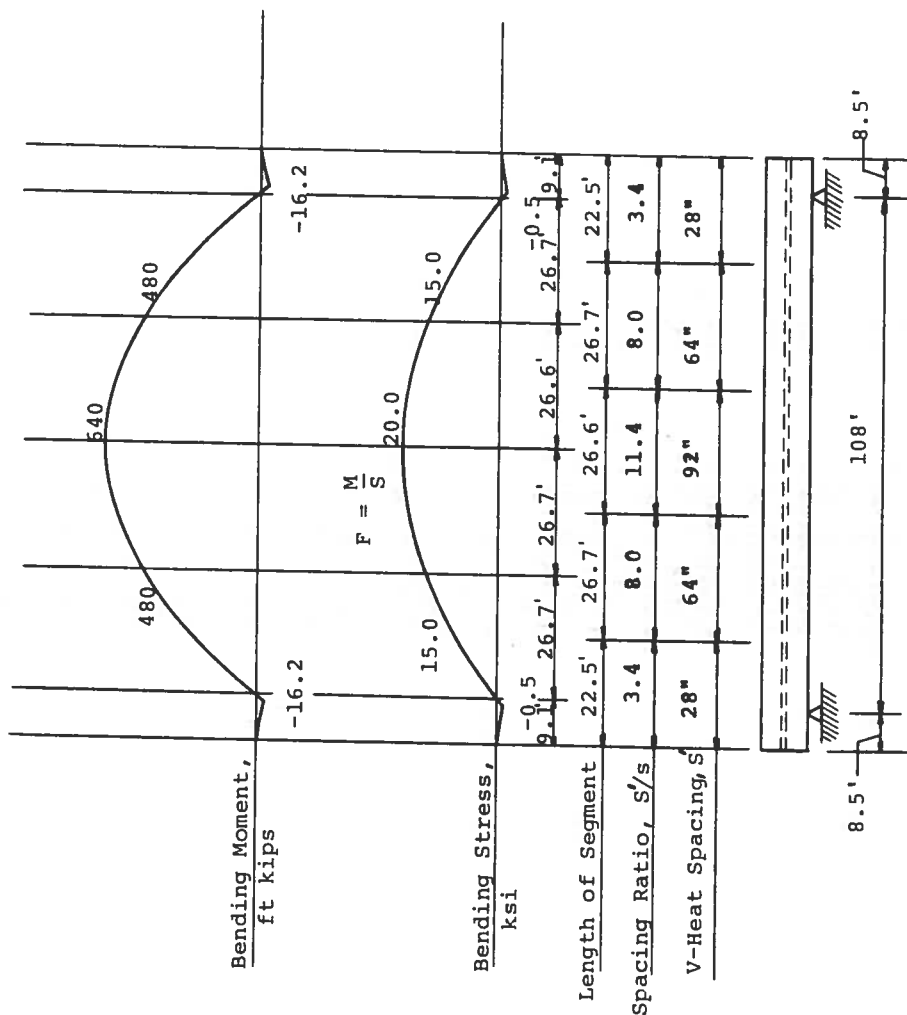
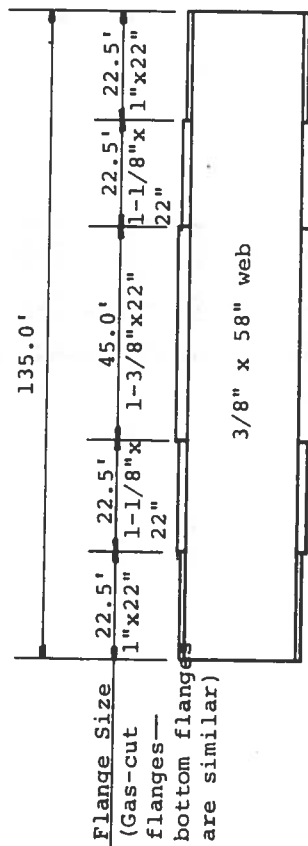


FIG. 7 – EXAMPLE FOR A36 STEEL GIRDER WITH CONSTANT SIZE FLANGES

Given Conditions

Required Radius = 1000 ft
 Curving Position: Horizontal
 Girder as shown below (A36 steel):



Determination of Heating and Support Conditions

$S = 2 \times 1.375 \times 22 \times 22/6 = 222 \text{ in.}^3$ (1-3/8" flanges)

$S = 182 \text{ in.}^3$ (1-1/8" flanges)

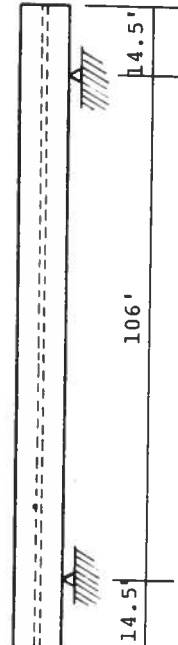
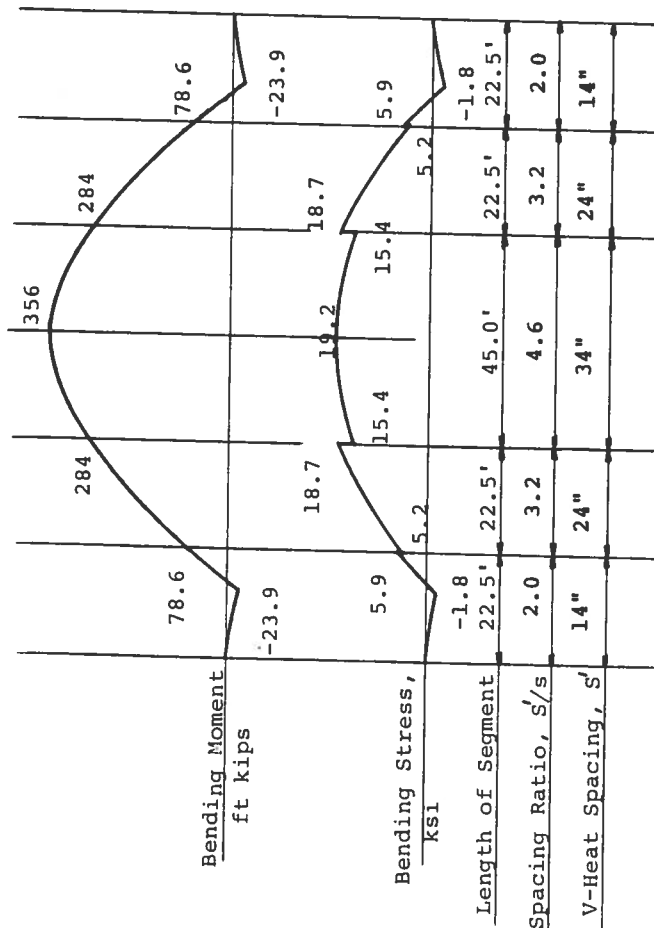
$S = 161 \text{ in.}^3$ (1" flanges)

$L_o = \sqrt{8FS/W} = \sqrt{8 \times 20 \times 222 / .283 \times 12} = 102 \text{ ft}$

$L_g = L_o + (L - L_o)^2 / 2L = 102 + 33 \times 33 / 270 = 106 \text{ ft}$

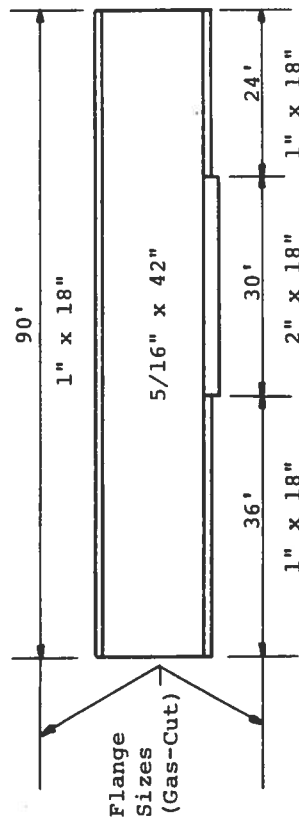
$R/b = 1000 \times 12 / 22 = 545$

$s = b/3 = 22/3 = 7.33 \text{ in.}$ (base width of V)

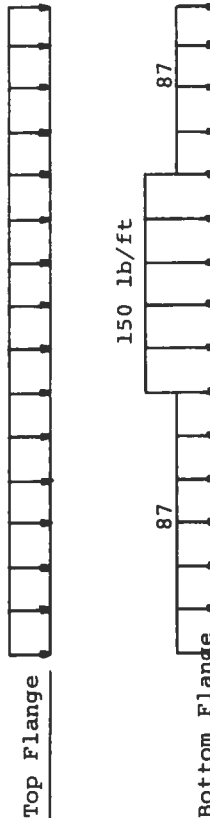


Given Conditions

Required Radius = 1200 ft
Curving Position: Horizontal
Girder as shown below (A588 steel):



Weight Distributions:



Determination of Heating and Support Conditions

$$S = 1 \times 18 \times 18^3 / 6 = 54 \text{ in.}^3 \text{ (1" flanges)}$$

$$L_o = \sqrt{8FS/W} = \sqrt{8 \times 27 \times 54 / .087 \times 12}$$

$$L_o = 106' \text{ (top flange)} \quad L_o = \sqrt{8 \times 27 \times 108 / .150 \times 12}$$

$$S = 108 \text{ in.}^3 \text{ (2" flange)} \quad L_o = 114' \text{ (bottom flange)}$$

Therefore, the 90' girder may be supported at its ends.

$$R/b = 1200 \times 12 / 18 = 800 \quad s = b/3 = 18/3 = 6 \text{ in.}$$

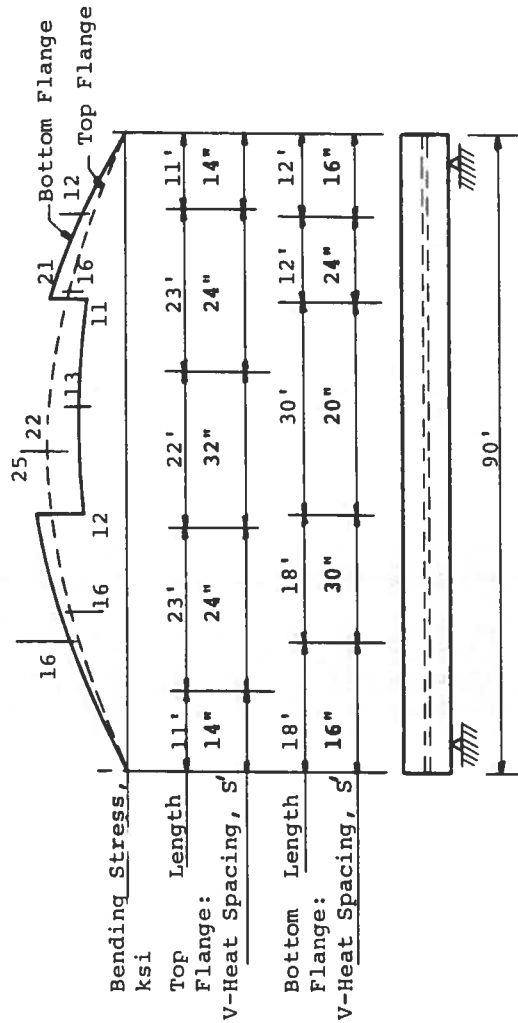
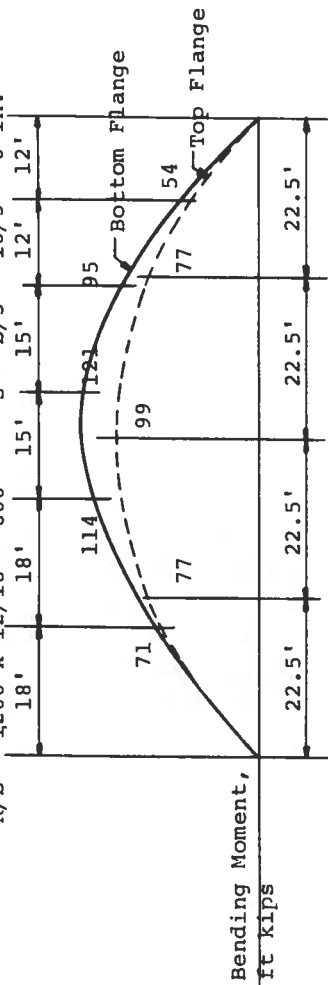
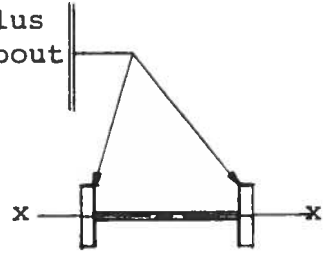
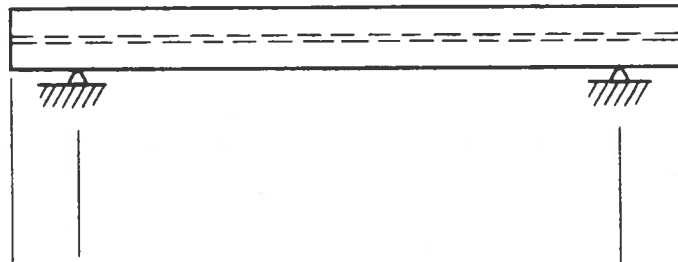


FIG. 9 - EXAMPLE FOR ASYMMETRICAL A588 STEEL GIRDER

S is section modulus
of both flanges about
x-x axis.



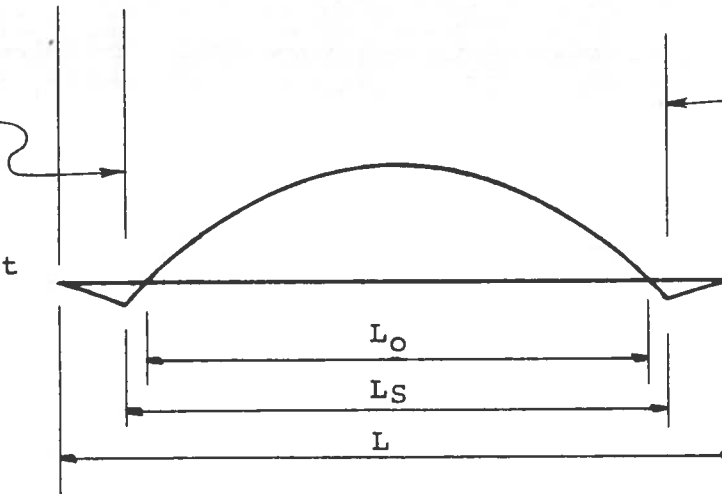
Girder:



Uniform Loading:



Support



Support

Bending Moment
Diagram:

Equations: Midspan Moment is $M = WL_o^2/8$
Bending Stress is $F = M/S$
Therefore, maximum distance between points of zero moment is

$$L_o = \sqrt{8FS/W}$$

where F is the maximum allowable stress ($0.55 F_y$).
The distance between points of support can now be
found and is:

$$L_s = L_o + (L - L_o)^2/2L$$

(Note: If L_o is greater than L, then the girder may be supported at its ends.)

FIG. A1 – EQUATIONS FOR SUPPORT LENGTH

Appendix

Equations for Minimum Radius

Heat curving is permitted when the required radius, R, equals or exceeds both of the following values:

$$* R = \frac{14}{\sqrt{F_y}} \frac{b}{\Psi} \frac{D}{t} \quad (1)$$

$$* R = \frac{7500}{F_y} \frac{b}{\Psi} \quad (2)$$

* In no case shall the radius be less than 150 feet

In these expressions, F_y is the specified minimum yield point of the web in ksi, Ψ is the ratio of the total cross-sectional area to the area of both flanges, b is the widest flange width, D is the distance between flanges, and t is the web thickness (R , b , D , and t are expressed in inches).

*In addition, the radius must be at least 1,000 feet when the flange thickness exceeds 3 inches or the flange width exceeds 30 inches.

* In accordance with Art. 1.7.116 of the 1970 Interim Specification of the AASHTO Committee on Bridges and Structures.

Table I

Parameters Considered

Constants

Dimensions of Heated Area:

Base of V-b/3
Altitude of V-5b/8

Maximum Temperature: 1100 F

Variables

Initial Residual Stresses (ksi):

Gas-Cut Flanges

Rolled (U.M.) Flanges
or Rolled Shapes

Yield Point (ksi):

36-(A36 steel)
50-(A588, A572-50, A441 steel)

Dead-Load Bending Stress (ksi):

A36 steel-0, 5.0, 10.0, 15.0, 20.0
A588 steel-0, 5.0, 10.0, 15.0, 20.0, 25.0, 27.0

