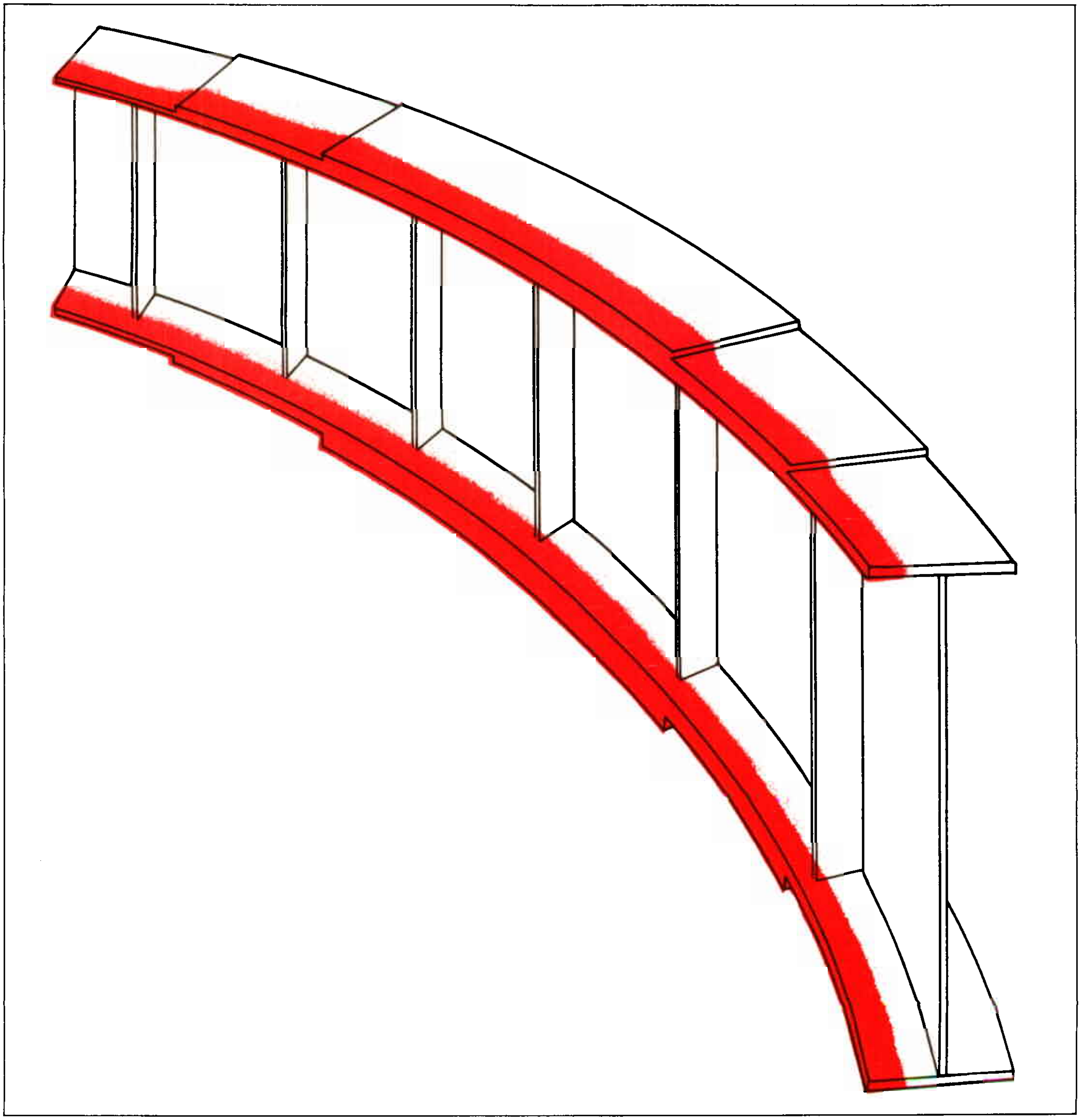
Fabrication Aids For Continuously Heat-Curved Girders



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Fabrication Aids For Continuously Heat-Curved Girders

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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 AASHO 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 temperatures 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 Continuously Heat-Curved Girders. A companion book deals with Girders Curved with V-Heats.

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

An analytical computer program was previously developed[1)]* for determining the radius of curvature that results when an I-shaped girder is continuously heated along one edge of both flanges while in the vertical position, Figure 1 (A). In that analysis, which involved iterative calculations to determine the thermal stresses during heating and cooling, the sum of the moments and the sum of the forces on the girder cross section were maintained at zero since the girder was assumed to be free of external loads and restraints. For the present study the computer program was modified so that the moment on a cross section of the girder was maintained at a predetermined value during heating and cooling, and then released to zero. Also, the program is based on a theoretical profile of the temperatures across the girder flanges for each step. Since the girder is continuously heated, all cross sections are subjected to the same heating conditions.

Thus, the program can be used to simulate the condition whereby the girder is heated and cooled in a horizontal position, Figure 1 (B), and then moved to a vertical position to check the final curvature. When in the horizontal position, the girder bends about the weak axis and causes significant dead-load bending stresses that must be considered in the analysis. The modified program computes the curvature for any given girder cross section and given value of the dead-load bending stress at the edge of the flange. Thus, for the condition where the dead-load stress varies along the length of the girder, several computer runs were required to obtain the curvature at various cross sections.

Selection of Variables

Preliminary runs were made with the computer program to determine which variables were significant and should be considered in developing data for the charts. An analysis of these data showed that (1) the ratio of web area to flange area has a negligible effect on curvature, (2) with the mathematical model used for the computer program, the ratio of radius of curvature to flange width, R/b, is a constant for any given set of heating conditions, and (3) the initial residual stress (due to fabrication of the straight girder), the dead-load bending stress, and the material yield point all have a significant effect on the curvature, at least over part of the temperature range of interest. The preliminary runs also showed that when a relatively narrow width of the flange was heated, the calculated curvature varied greatly with the magnitude of the initial residual stresses, but that the calculated curvature was generally too small to be of practical significance.

The variables considered for the final runs are summarized in Table I. As indicated, the heating conditions included heating the through thickness girder flange along edge strips of 2 widths (1/6 and 1/4 of the flange width) to 5 values of maximum temperature (700 F to 1150 F). Two distributions of initial residual stresses are assumed, corresponding to average values of those in (1) girders with gas-cut flanges[2)] and (2) girders with universal mill (U.M.) flanges[5)] 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.

Several values of the dead-load bending stress are assumed for each yield point. The values range from zero to the maximum stress permitted[4)], 20 ksi for A36 steel and 27 ksi for A588 steel. As will be subsequently discussed, the data calculated for this range of values can be used to determine the required temperature and heating widths for a girder curved in the horizontal position so that the dead-load bending stress varies along its length; the data calculated for zero bending stress can be used for a girder curved in the vertical position.

Heat-Curving Charts

The results of the investigation are summarized in Figures 2 through 9, which show curves relating the radius-to-flange-width ratio, R/b, to the heat-curving temperature. Separate figures are given for each yield point (36 or 50 ksi), type of flange (gas-cut or U.M.), and width of heating (Type 2 or 3). In each figure, a family of 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. The temperatures on the charts refer to an average temperature over the width of

*See References.

girder heated; however, it is assumed that the girder will be heated so as to obtain an approximately uniform temperature over that width and through the thickness of the flanges. The use of the curves is illustrated by the examples given in Figures 10, 11, and 12 as discussed below.

Application of Charts

Girder With Contant-Size Flanges

An application of the charts for an A36 steel girder with constant-size flanges is shown in Figure 10. 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. A girder with a varying flange size is treated in a subsequent example.

The girder must first be checked to make sure that the required radius is not less than the minimum radius that AASHO 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:

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

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, 310 feet, is greater than the minimum, 306 feet; therefore the girder may be heat-curved.

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. Therefore, the distance between supports used during heat curving should 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 10. 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 heating schedule for a Type 3 heat can be obtained from Figure 5. The intersection of the horizontal line for R/b = 155 with the curves for nominal bending stress gives the following temperatures:

Stress, ksi	Temperature, F
20	900
15	950
5	1050

The stress used is the approximate average value in the length of girder considered; the temperatures are rounded to the nearest 50°F, since temperature-indicating crayons are commonly available in such increments. The alternative schedule for a Type 2 heat is obtained from Figure 4 in a similar manner; however, the temperature for the end portion with an average stress of less than 5 ksi would exceed 1150 F – the maximum allowed by AASHO.[4] Therefore, as indicated in Figure 10, the Type 3 heat (1050 F) would be used for that portion.

The girder could have been curved in the vertical position with a Type 3 heat at 1150 F. This temperature is given by the intersection of R/b = 155 with the curve for zero nominal bending stress in Figure 5.

Girder With Varying Flange Sizes

Figure 11 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 ψ value:

$$b = 22 \text{ in.}$$
$$D = 58 \text{ in.}$$
$$t = 3/8 \text{ in.}$$
$$F_y = 36 \text{ ksi}$$
$$\psi = 82.2/60.4 = 1.36$$

$$F = \frac{14}{\sqrt{F_y}} \frac{b}{\psi} \frac{D}{t} = \frac{14}{6} \frac{22}{1.36} \frac{58}{0.375} = 5838 \text{ in. or } 486 \text{ ft.}$$

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

The required radius, 500 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 by simply summing the moments to either side; the moments divided by the appropriate section modulus give the stresses. Since the stresses were less than 20 ksi, the support distance is adequate. The heating schedules for the gas-cut A36 steel flanges are then obtained from Figures 2 and 3.

The temperatures selected vary from 700 F to 900 F for the Type 3 heat, and from 750 F to 1000 F for the Type 2 heat. If the girder had been curved in the vertical position, a constant temperature of 900 F for a Type 3 heat, or 1000 F for a Type 2 heat, would have been required.

Asymmetrical Girder

An example for a girder with different size top and bottom flanges is shown in Figure 12. The minimum radius is determined at the section with the heaviest flanges:

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

$$R = \frac{14}{\sqrt{F_y}} \frac{b}{\psi} \frac{D}{t} = \frac{14}{\sqrt{50}} \frac{18}{1.24} \frac{42}{0.312} = 3{,}869 \text{ in. or } 322 \text{ ft.}$$

$$R = \frac{7500}{F_y} \frac{b}{\psi} = \frac{7500}{50} \frac{18}{1.24} = 2{,}177 \text{ in. or } 181 \text{ ft.}$$

Since the required radius, 600 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 27 ksi and the support length is satisfactory.

Temperatures for each flange are selected from Figure 6 at R/b = 400 and appropriate stress values. At this value of R/b, about the same temperature is required for the Type 2 and Type 3 heats. Thus, the narrower heating width will be used. The temperatures selected vary from 750 F to 900 F. If the girder had been curved in the vertical position, a constant temperature of about 900 F (Type 2) would have been required for the entire length.

References

1. R. L. Brockenbrough, "Theoretical Stress 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. J Brozzetti, G. A. Alpsten, and L. Tall, "Welding Parameters, Thick Plates, and Column Strength", Fritz Engineering Laboratory Report No. 337.21, Lehigh University, February, 1970.

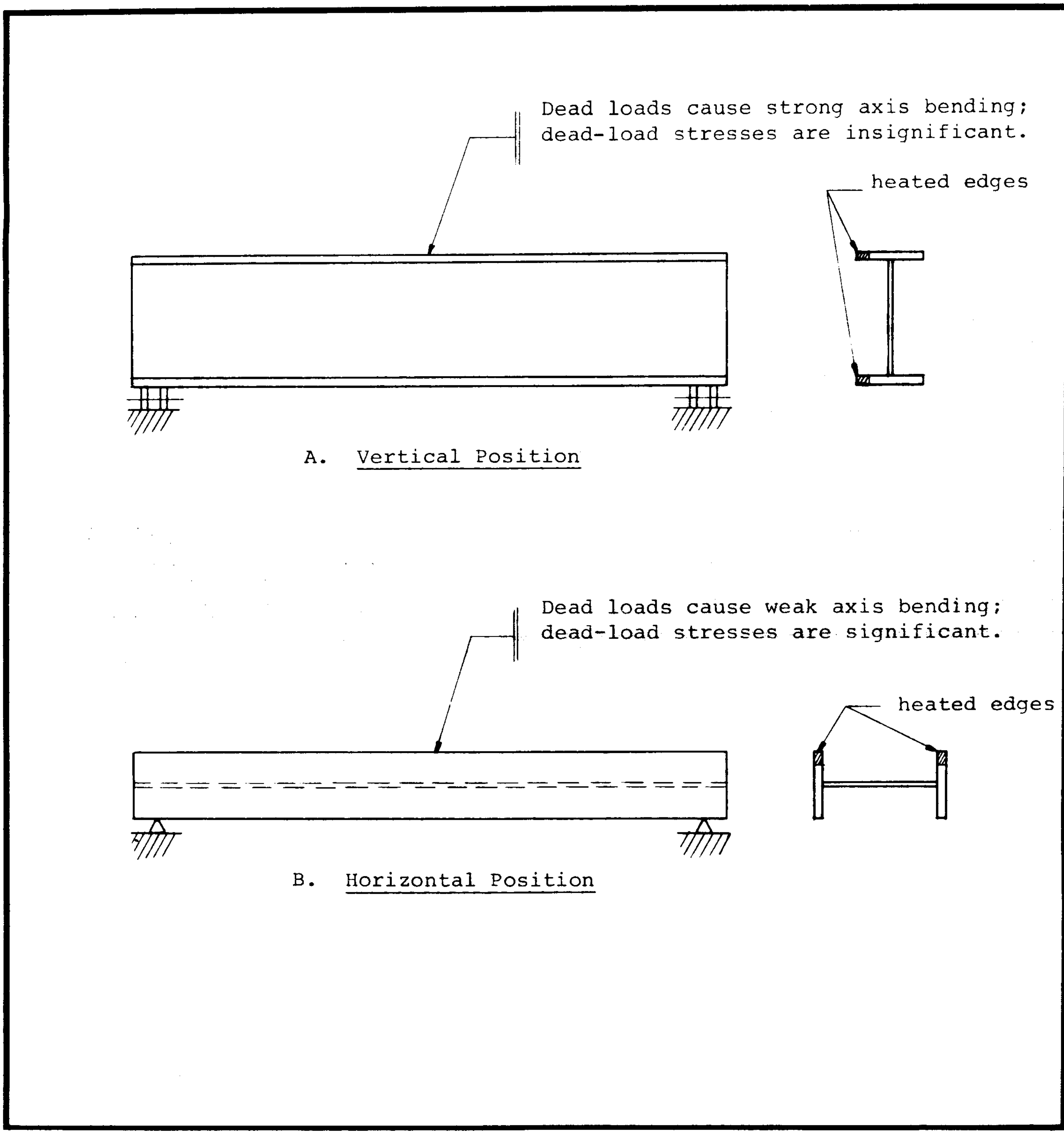


FIG. 1 — POSITIONS FOR HEAT CURVING

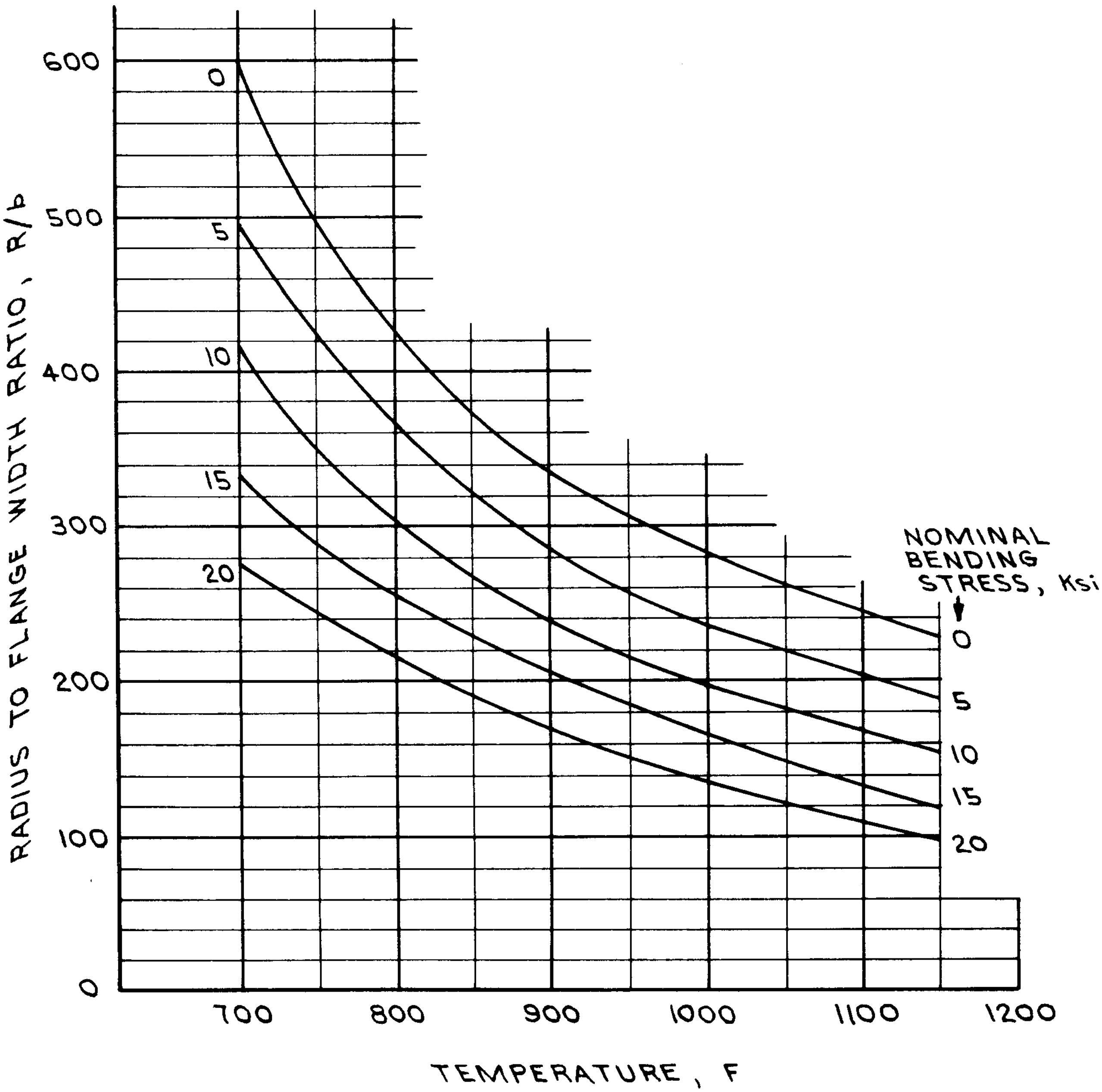


FIG. 2 – CURVATURE FOR A36 STEEL GIRDERS – GAS – CUT FLANGES AND TYPE 2 HEAT

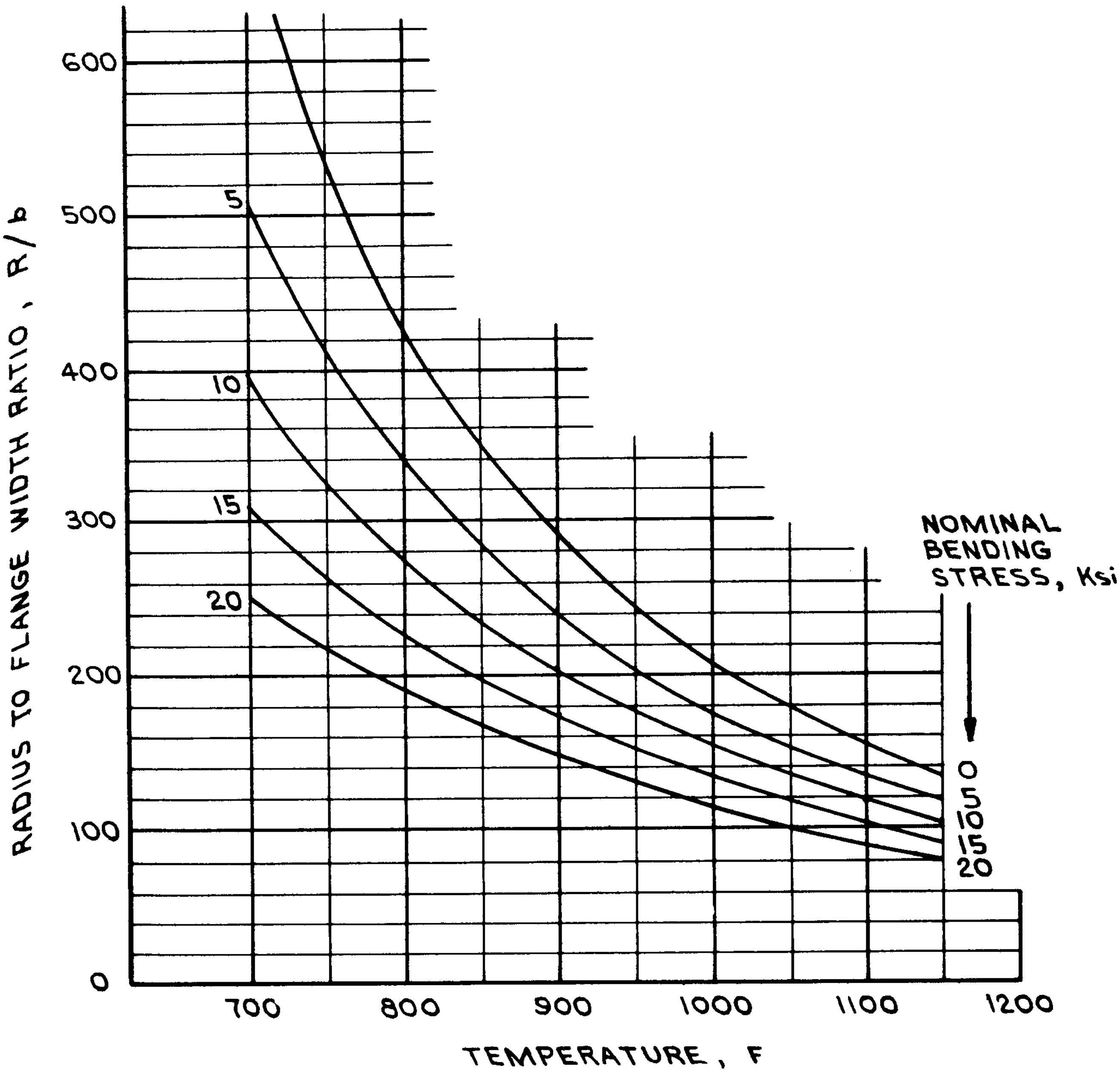


FIG. 3 – CURVATURE FOR A36 STEEL GIRDERS – GAS – CUT FLANGES AND TYPE 3 HEAT

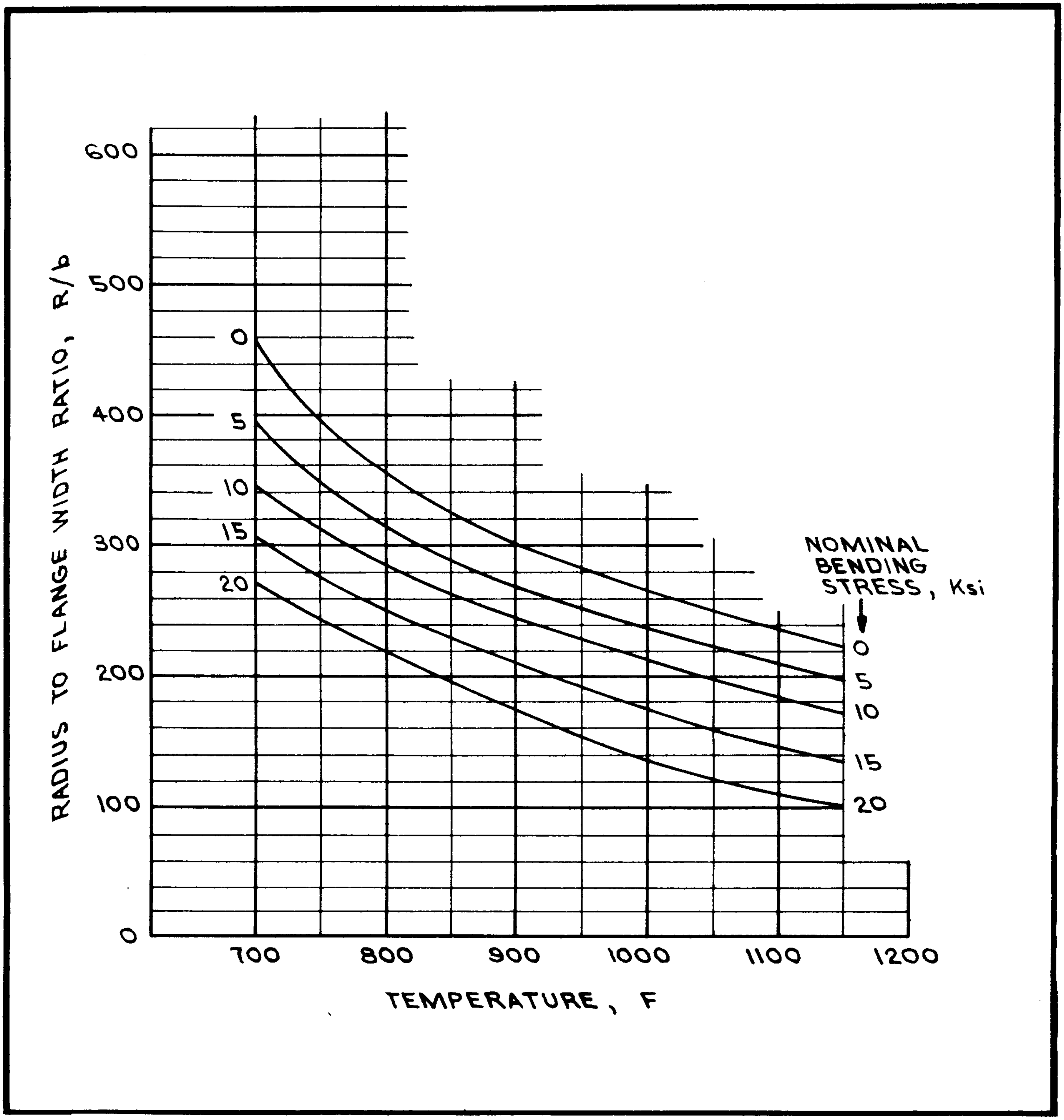


FIG. 4 – CURVATURE FOR A36 STEEL GIRDERS – UM FLANGES AND TYPE 2 HEAT

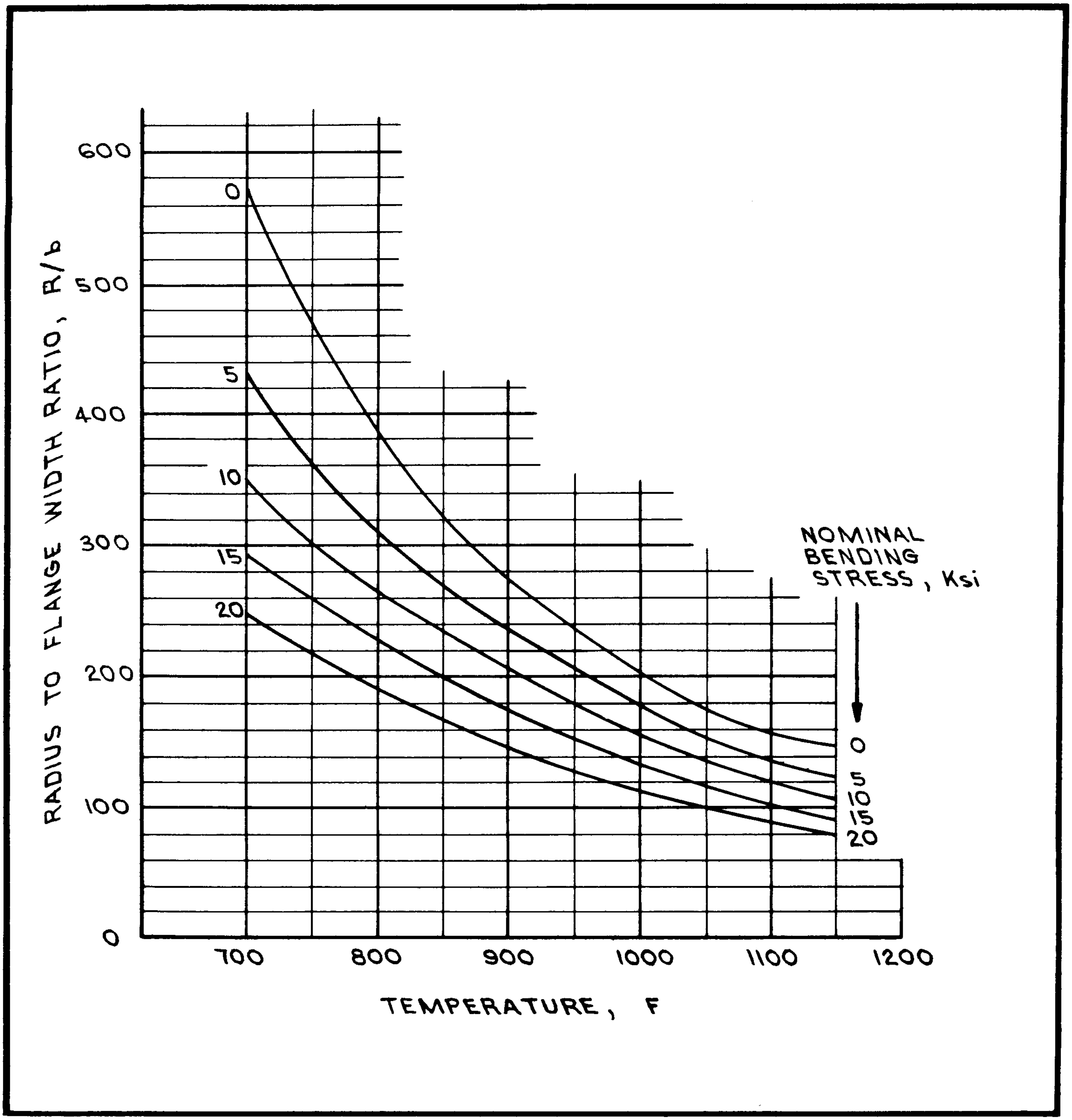


FIG. 5 – CURVATURE FOR A36 STEEL GIRDERS – UM FLANGES AND TYPE 3 HEAT

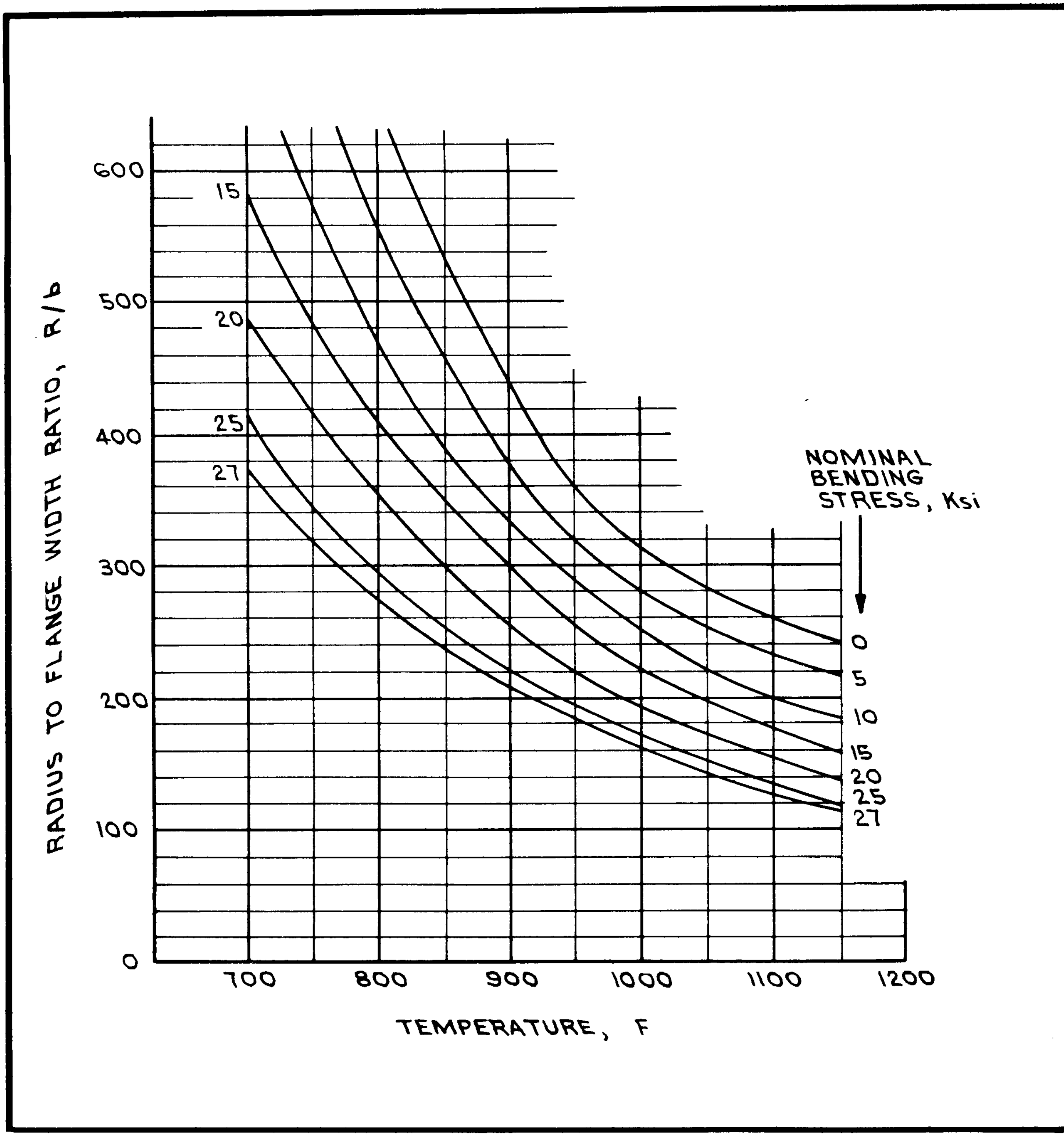


FIG. 6 – CURVATURE FOR A588 STEEL GIRDERS – GAS – CUT FLANGES AND TYPE 2 HEAT

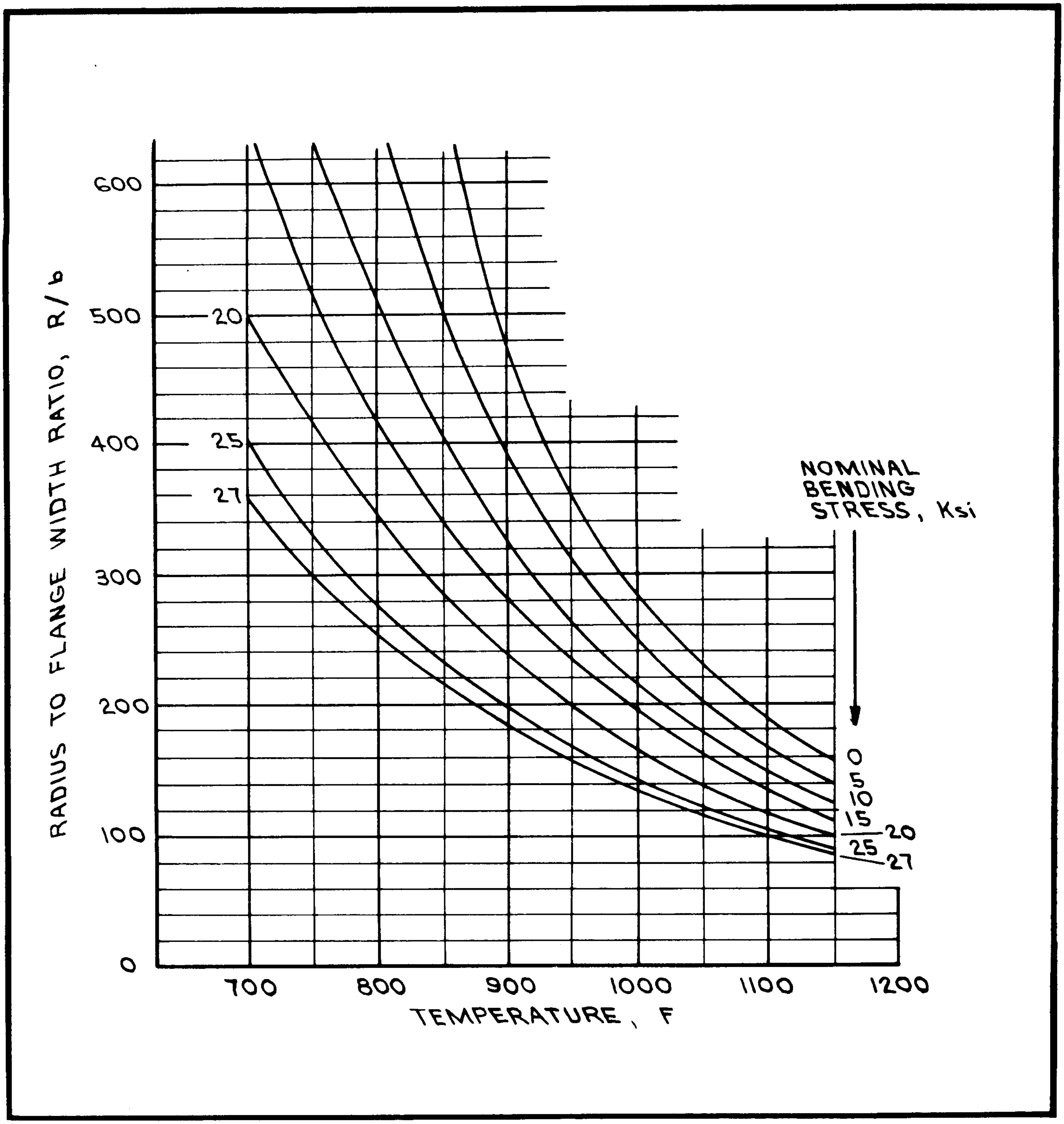


FIG. 7 – CURVATURE FOR A588 STEEL GIRDERS – GAS – CUT FLANGES AND TYPE 3 HEAT

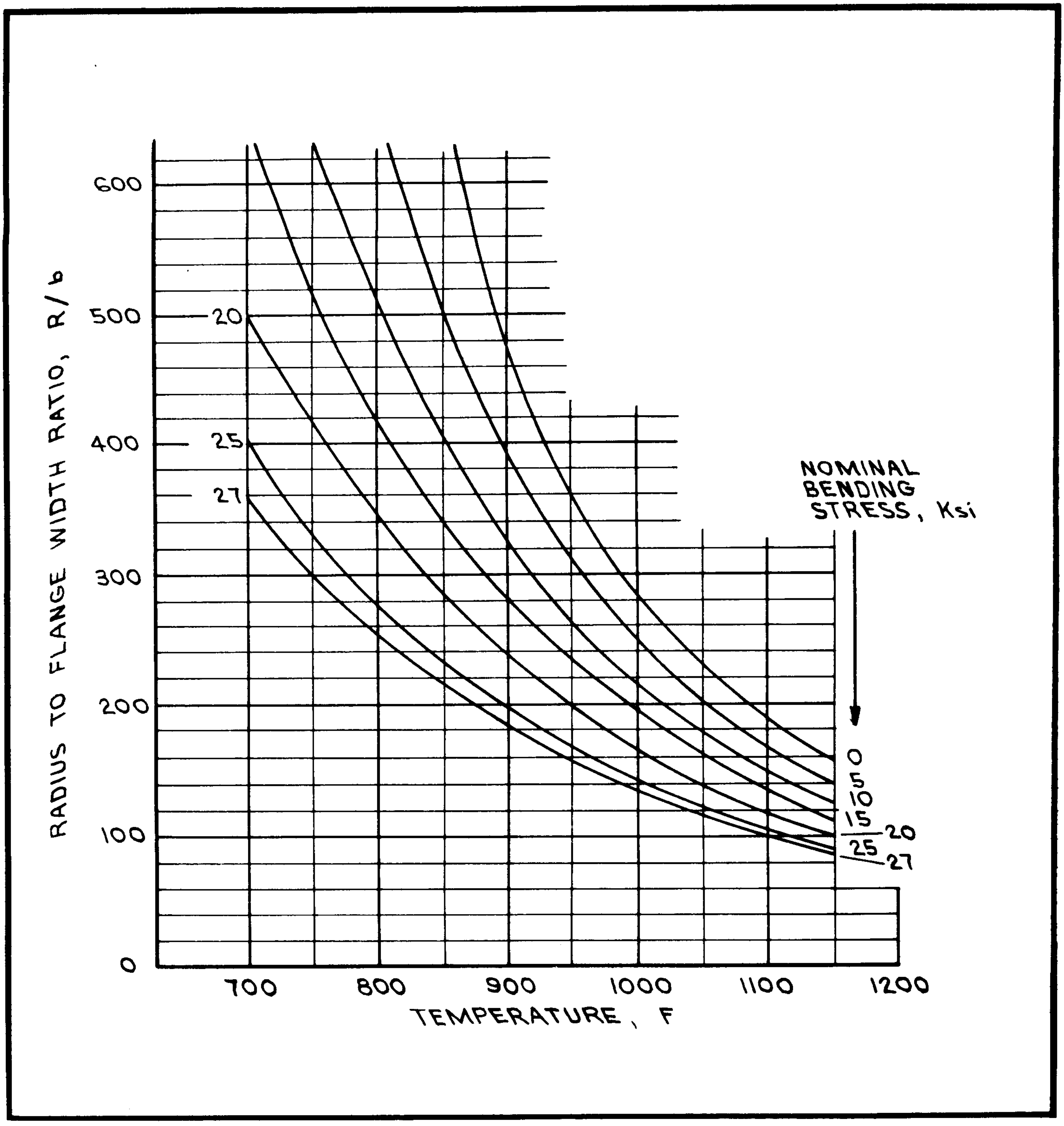


FIG. 7 – CURVATURE FOR A588 STEEL GIRDERS – GAS – CUT FLANGES AND TYPE 3 HEAT

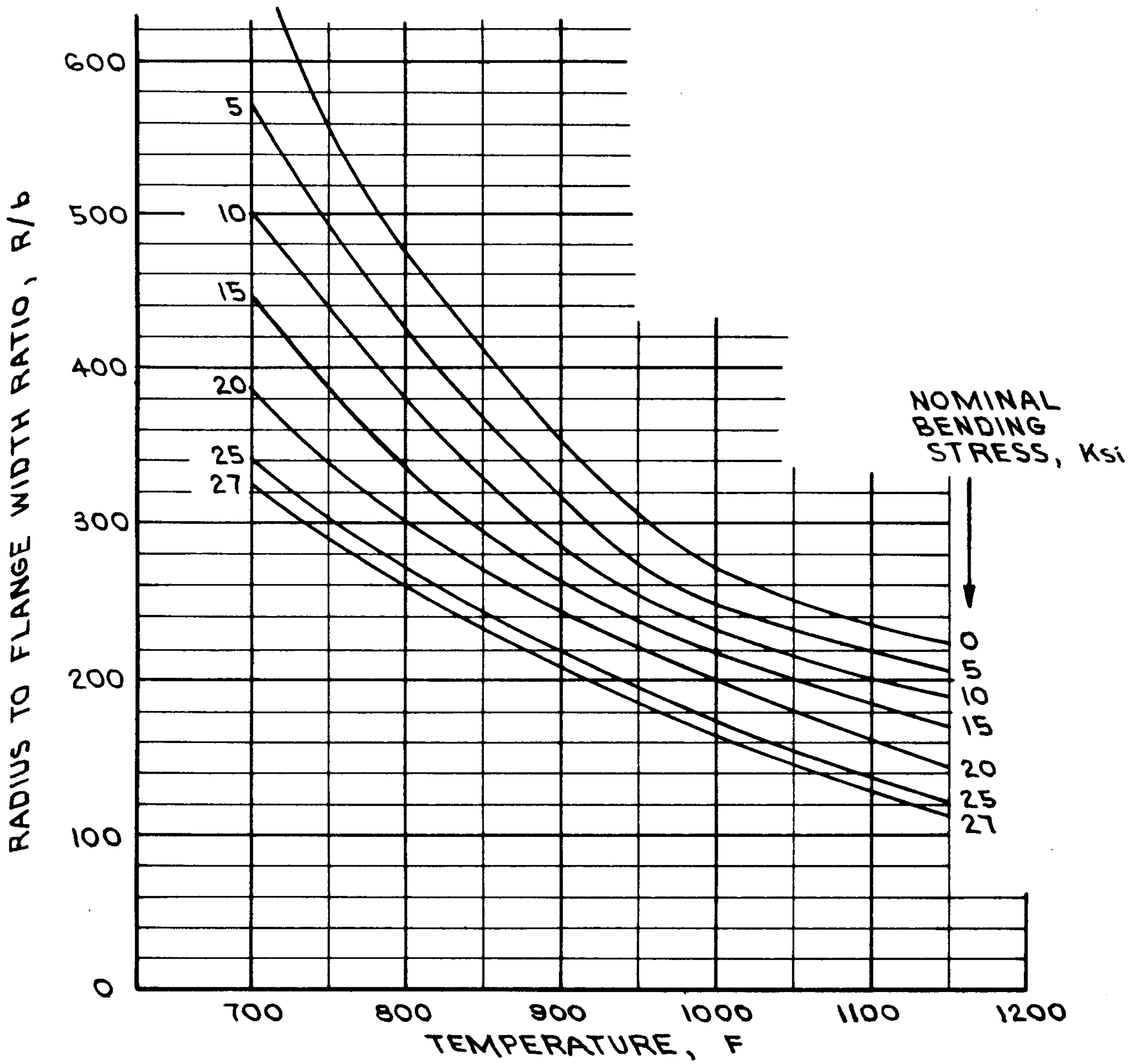


FIG. 8 – CURVATURE FOR A588 STEEL GIRDERS – UM FLANGES AND TYPE 2 HEAT

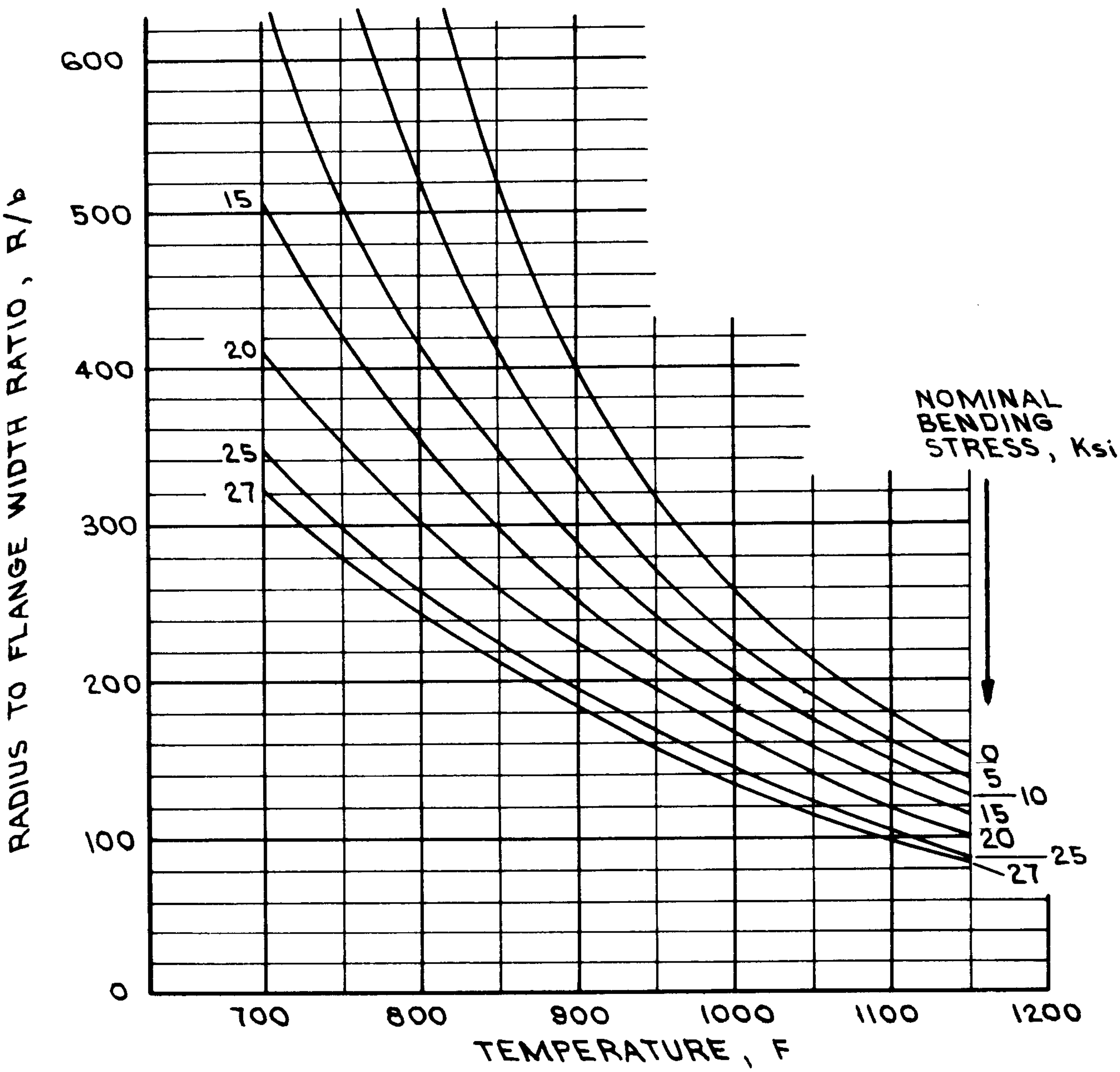


FIG. 9 – CURVATURE FOR A588 STEEL GIRDERS – UM FLANGES AND TYPE 3 HEAT

Given Conditions

Required Radius = 310 ft
Curving Position: Horizontal
Girder as shown below (A36 steel):

Determination of Heating and Support Conditions

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

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

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

$R/b = 310 \times 12/24 = 155$

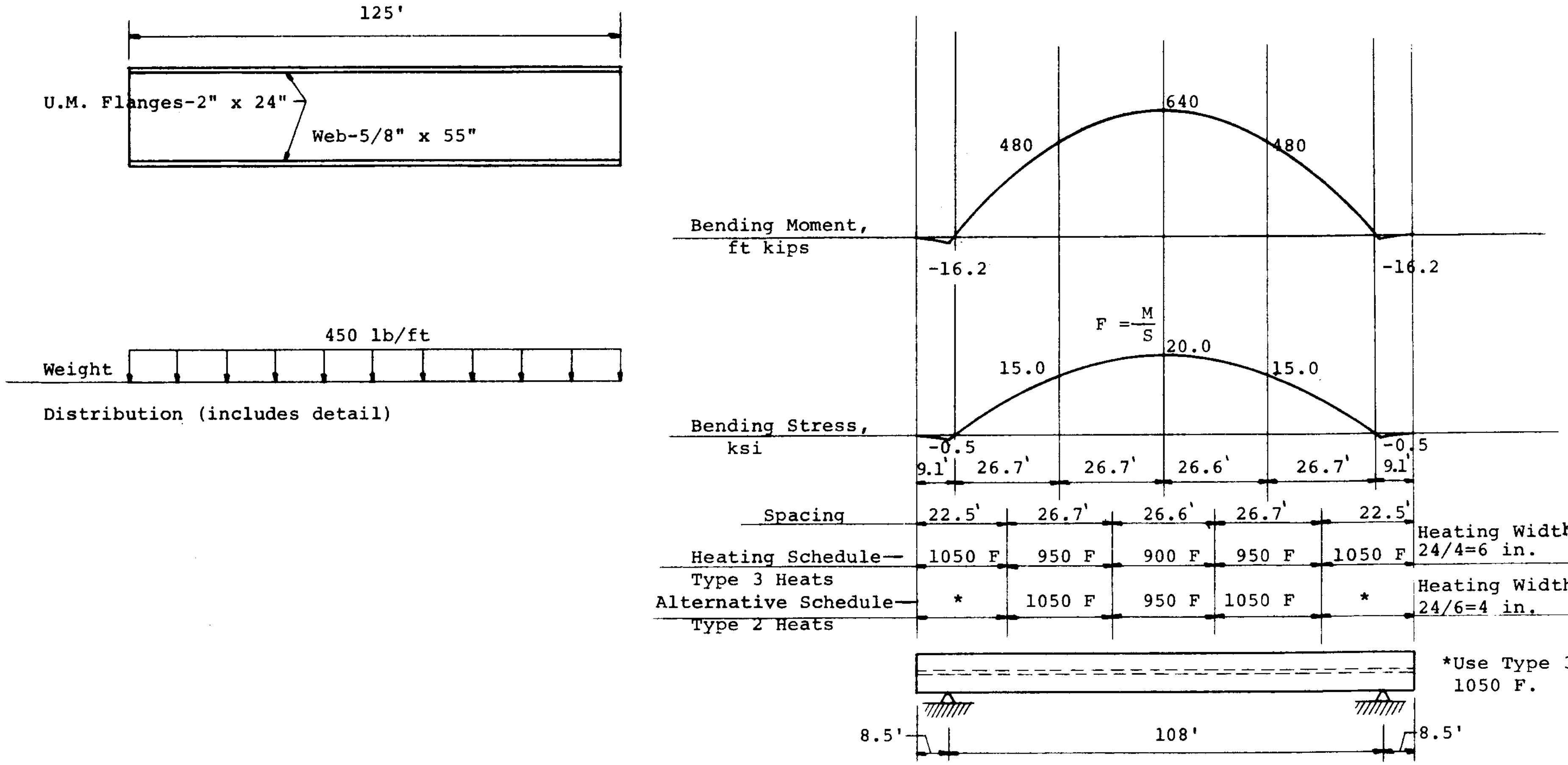
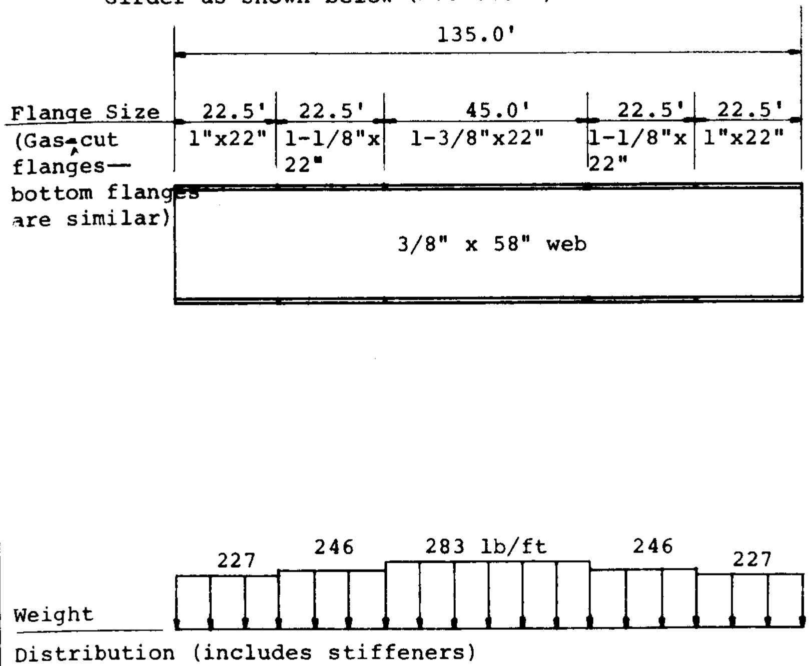


FIG. 10 – EXAMPLE FOR A36 STEEL GIRDER WITH CONSTANT SIZE FLANGES

Given Conditions

Required Radius = 505 ft
Curving Position: Horizontal
Girder as shown below (A36 steel):



Determination of Heating and Support Conditions

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

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

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

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

$L_S = L_o + (L-L_o)^2/2L = 102 + 33 \times 33/270 = 106$ ft

$R/b = 505 \times 12/22 = 275$

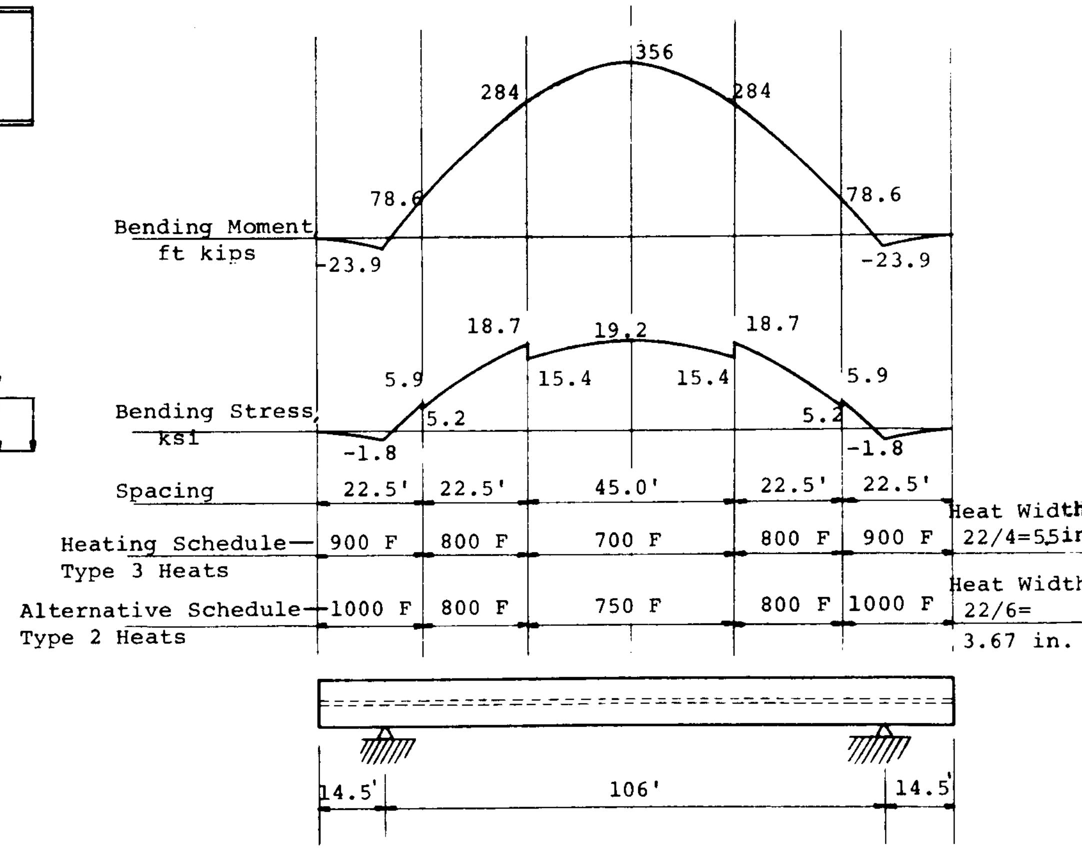
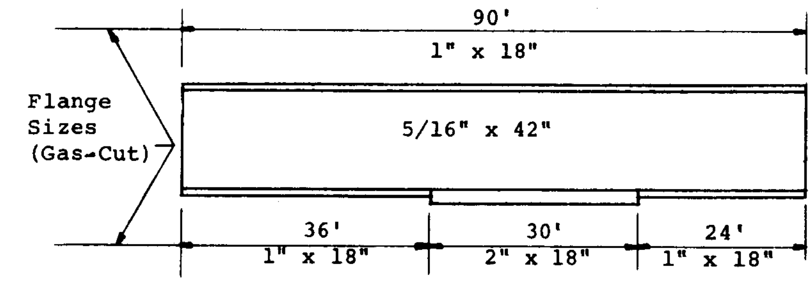
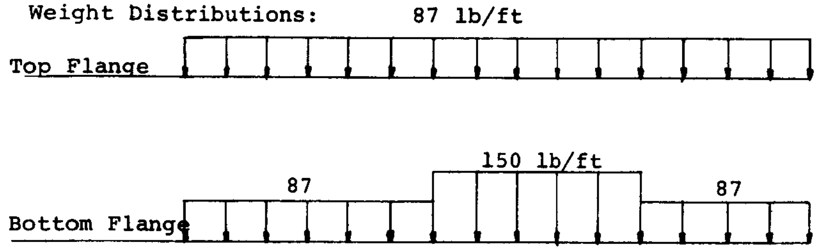


FIG. 11 – EXAMPLE FOR A36 STEEL GIRDER WITH VARYING FLANGE SIZES

Given Conditions

Required Radius = 600 ft
Curving Position: Horizontal
Girder as shown below (A588 steel):





Determination of Heating and Support Conditions

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

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

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

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

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

$R/b = 600 \times 12/18 = 400$

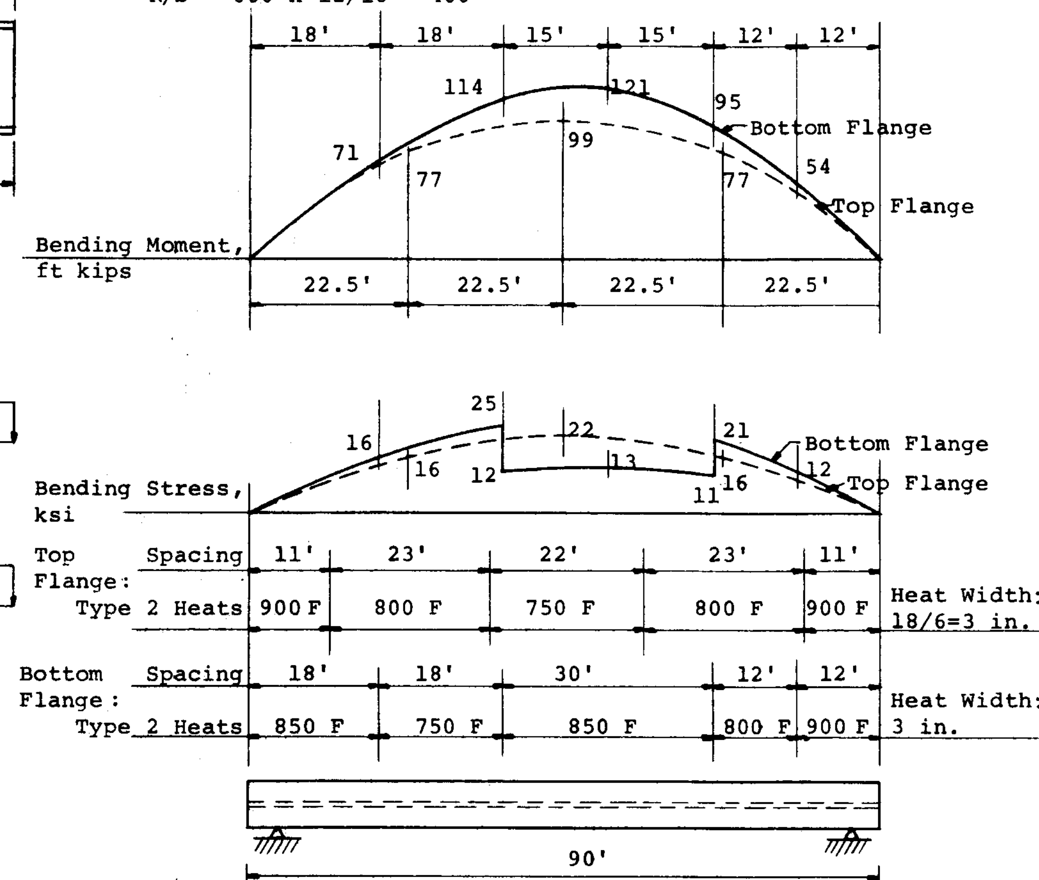
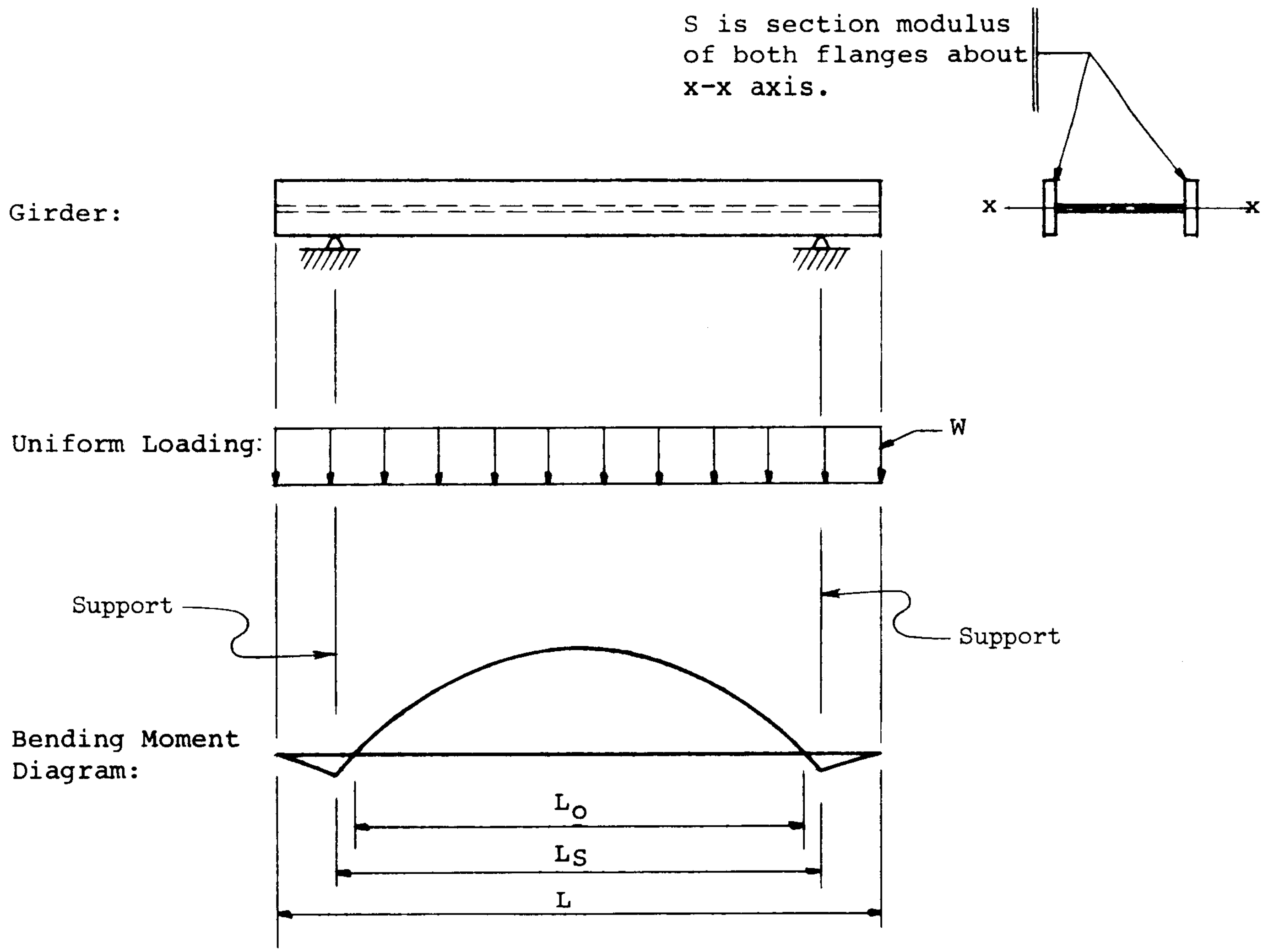


FIG. 12 – EXAMPLE FOR ASYMMETRICAL A588 STEEL GIRDER



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:

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

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

* 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 Spec. of the AASHO Committee on Bridges & Structures.

Table I

Variables Considered

Flange Width Heated:

1/6 of total width (Type 2 Heat)
1/4 of total width (Type 3 Heat)

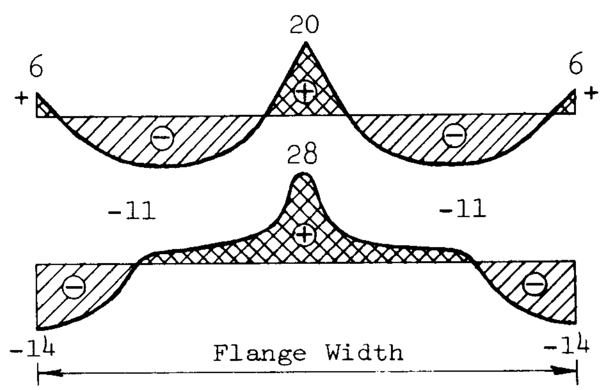
Maximum Temperatures:

700 F, 800 F, 900 F, 1000 F, 1150 F

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