Horizontally Curved Steel Girders—Fabrication and Design

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THE USE of horizontally curved steel girders in bridge construction is relatively new. In 1961 there were probably not more than half a dozen bridges built with curved girders. In the American Bridge Div. of U. S. Steel Corporation, total inquiries for bridges using curved girders had only amounted to approximately 1,500 tons by the end of 1965. However, in 1966 alone inquiries amounted to more than 1,600 tons.

Why this relatively sudden interest in curved girder bridges? Some of the reasons are:

1. Increasing demand for highway interchanges in urban areas. These must often be built within tight geometric restrictions.
2. The use of straight girders as chords of short radius curves require simple spans with relatively close supports and numerous expansion joints and bearing devices. Curved girders permit longer spans that may be continuous, with a minimum of expansion joints and bearing details (Fig. 1).
3. Esthetic considerations have led to a preference for curved girders. Straight chord girders for curved bridges on short radii were often unattractive.
4. Curved girders promote a uniformity of concrete deck work through simplicity in arrangement, details and construction (Fig. 2).

FABRICATION METHODS

There are two general methods for the fabrication of horizontally curved girders for bridges. The first, until recent years the generally accepted method called for by most job specifications, is to cut the basic flange components to the stipulated curve and to fabricate to that curve. The second is to fabricate the girder straight in the conventional manner, and then to curve it to the stipulated curve by the proper application of heat to the edges of the flanges.

The second method, which is relatively new, is the more economical of the two methods. Because of economics, its use is increasing. The question might be asked, "If it is the more economical method, why is it not universally used?"

The method does have a limitation, which is based on the upper limits of strain to be allowed during the heat curving operation. To date, acceptance of the method has been prescribed on a job-to-job basis, without the benefit of guidelines established by a nationally accepted specification. The establishment of such guidelines would undoubtedly further promote the use of the heat curving method.

An examination of the detailed operations involved in both fabrication methods will be helpful in making a comparative analysis.

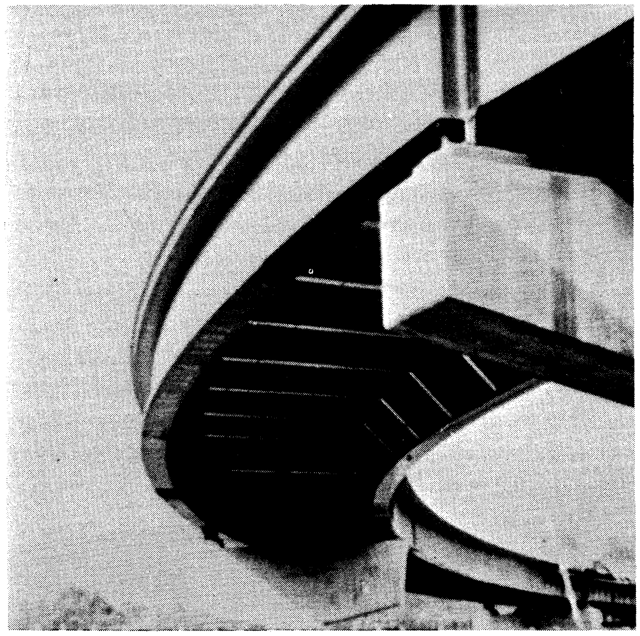

Figure 1

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Method 1—Cutting to Curve—Cutting the basic flange components to the stipulated curve and fabricating to this curve involves the following procedures:

1. The flange sections are cut to the proper curve from wider plates. They may be cut from one wide plate or nested for multiple cutting, depending on the radius of curve, the length, width and thickness of flange sections, and the number of plates having the same thickness (see Fig. 3). Careful planning is required for economical cutting of the flange plates, but even with the best of planning a considerable amount of scrap may be generated.
2. The individual flange sections required to make up the flange of a girder shipping section are spliced with full-penetration butt welds.
3. The full length flange is marked for web position.
4. The webs are cut, spliced as necessary, and cut to proper camber, with allowances for the effect of flange welding. Figure 4 shows two flanges, previously cut and spliced, being marked for web position. At the right is the web, spliced and cut to camber, ready for assembly.
5. The holes for flange and web field splices may be located and sub-punched or sub-drilled at this time, or they may be left blank and drilled in the assembled girder later—depending upon the fabricator's equipment or preference.
6. Jigs are required to hold the web plate to the stipulated curve for fit-up operations. Figure 5 illustrates a typical jig. These are normally made special, as required, for a specific project. However, one jig may be utilized to accommodate several web plates of different curvature by altering the jig bearing surfaces. Curved girders with different radii are required for most curved bridge projects. As the quantity of different radius girders increases on a project, it becomes increasingly important that the design of jigs be correlated with production planning for selective sequencing of girder fabrication processes.
7. Chock blocks, which serve as flange fixtures in the girder fitting operation, are tack welded to the flanges along a previously scribed center line (Fig. 6).
8. The flanges are assembled to the web on the fitting jig. The chock blocks are used first to position the flanges to the web and then, by welding the chock blocks to the web, to fix the flanges and web as a curved unit. Clamping fixtures are used to apply pressure between flanges and web during the fitting and welding of the chock blocks to the web. See Fig. 7.
9. The flanges are tack welded to the web, preparatory to final welding.
10. The fit-up assembly is placed into a tilting frame fixture (Fig. 8) and the flange-to-web welds are made by an automatic welding process.

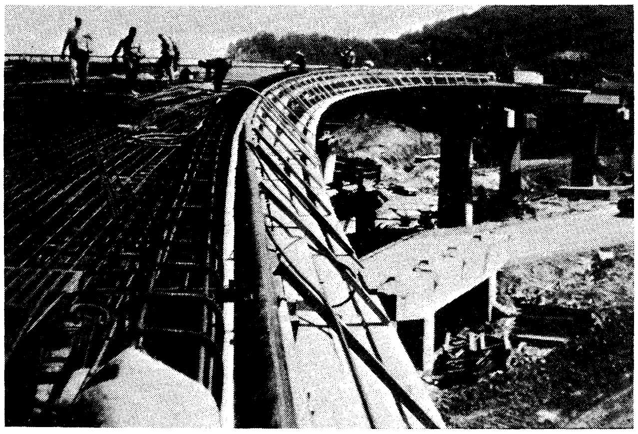
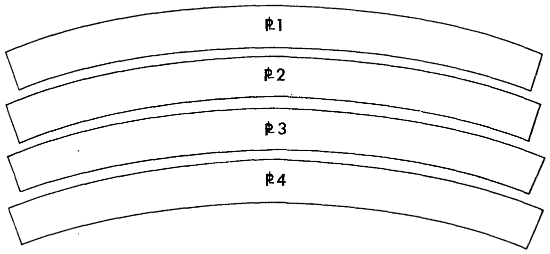
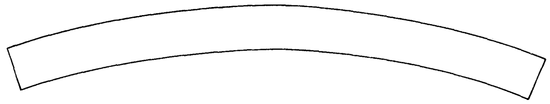


Figure 2



Multiple Flange Plates Cut From An Ordered Plate



Single Flange Plates Cut From An Ordered Plate

Figure 3

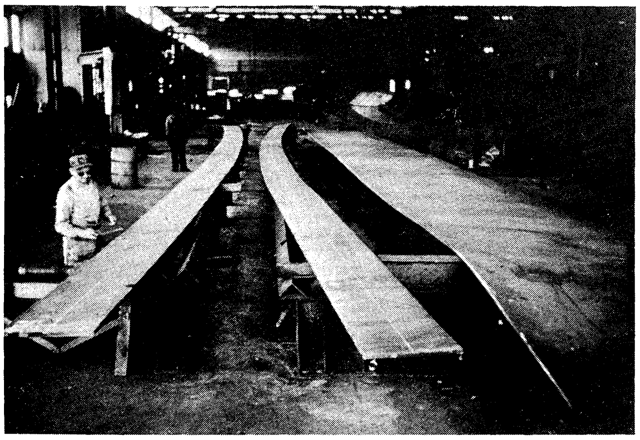
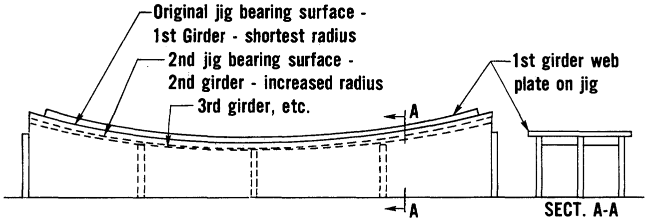
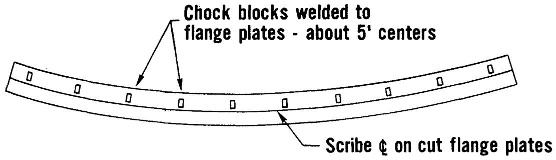


Figure 4



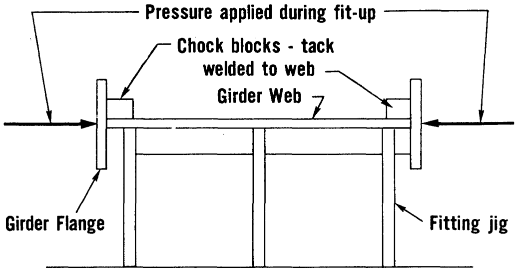
Fitting Jig

Figure 5



Flange Plates - Preparation For Fit-Up

Figure 6



Curved Girder - Fitting Operation

Figure 7

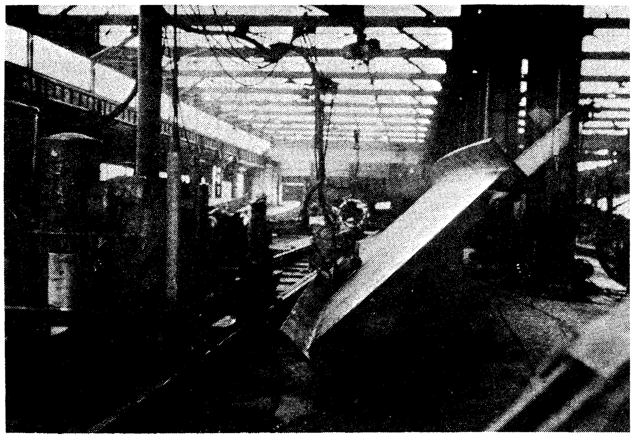


Figure 8

11. The stiffener and connection material are welded to the girder.

12. The curvature of the girder is rechecked, since the heat of welding can alter the planned curvature. If this occurs, it must be corrected by press bending or by heating the edges of the flanges as necessary. Generally the heat method is used. A few years ago, very few job specifications recognized that correction might be necessary, and made no reference to the subject. However recent trends in specifications from state highway departments have stipulated that corrections may be made by the heat method.

13. The girder sections are assembled end-to-end for assembly reaming—usually two or three sections at a time, as required by the job specifications.

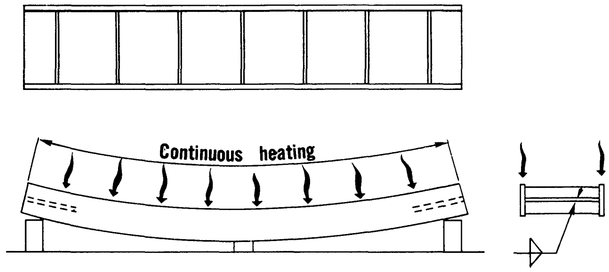
14. The girders are disassembled, cleaned, painted, and shipped to the erection site.

Method 2—Heat Curving Method—The procedure for curving plate girders by the heat method is as follows:

1. The girders are fabricated straight, in the conventional manner, including the placing of end and intermediate stiffeners, except that stiffeners are welded to the web only. Welds between stiffeners and flanges are made after the curving process.

2. The girder is curved by the use of heat. Two positioning methods have been used for this operation. Figure 9 illustrates the curving operation with the girder in a horizontal position, i.e., with the web horizontal. The top edges of both flanges may be heated simultaneously and continuously. The heat must not exceed 1150°F. The shrinkage of the heated flange during the cooling process induces curvature. The heating and cooling process is repeated as necessary to bring the girder to the predetermined curvature. Final curvature is measured only after complete cooling and with the girder repositioned to a vertical position.

Figure 10 shows the girder being curved from a vertical position. The edges of both top and bottom flanges, which will be the inside edges of the finished curve, are heated simultaneously to a heat not exceeding 1150°F. The edges may be spot heated on 2- to 3-ft



Heat Curving Girders - Horizontal Positioning

Figure 9

centers, or may be heated continuously. When spot heating, the heated zone at each spot is pie-shaped, with the point of the heated zone close to the web. Generally, this type of heating is used for long radius curves, because better control can be exercised in the more delicate curving operation of long curves. Curving girders in the vertical position eliminates the influence of dead load deflection. It also eliminates the need for repositioning the girder for a final check of the curvature.

In the future, heat curving of girders will undoubtedly utilize both horizontal and vertical positioning, depending on the girder size and configuration.

3. After curving the girders by the heat method, stiffeners may be welded to the flange, if required.

It should be noted that the heat curving method is suitable only for rolled carbon and low alloy steel. It should not be used for quenched and tempered steel such as ASTM A514.

With the heat curving method, shrinkage takes place on one side of the flanges, due to the heating and subsequent cooling, while stretching takes place on the other side of the flanges. Thus, residual compressive strains are present on one side and residual tensile strains on the other. As there is a limit of 1150°F placed on the heating, well below the transformation temperature of steel, there is no detrimental metallurgical change in the steel due to heating. The question of acceptance of the method, or the limits under which it will be acceptable, should be based primarily on the acceptable limits of strain induced in the flanges. Until standard specifications are developed, these limits must be determined on a job-to-job basis.

It is interesting to note that some states have set up their own rules governing the method of fabrication of curved girders. For instance, at least one state has set up the following rules:

> "Built up girders on a curvature of 600-ft radius or greater may be curved by cutting the flanges to the required radius or by the process of heat shrinking. Built up girders curved by heat shrinking after they are assembled shall not have the intermediate stiffeners and connection plates welded to the compression flange until the curving process has been completed. Built up girders on a curvature of less than 600-ft radius shall be curved by cutting the flanges to the required radius."

Such local rules may be a step in the right direction. However, they may also (like this one) be so simplified that they can be too restrictive. For example, the rule just quoted is based strictly on radius, without regard to flange width. Figure 11 shows strain curves for 24-in., 18-in. and 12-in. flanges. Note that the strain for a 24-in. flange at 600-ft radius is comparable to that for an 18-in. flange at 450-ft radius or a 12-in. flange at 300-ft radius. Therefore, a cut-off rule based on a radius only must be uneconomical.

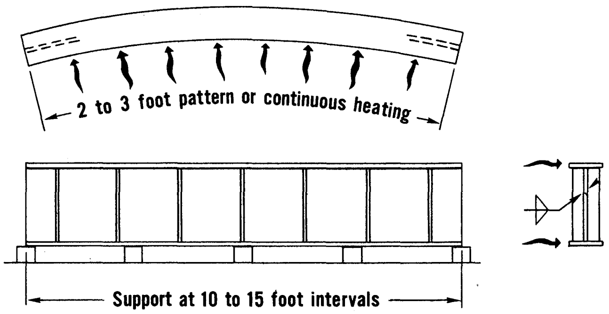
There is a great need for nationally accepted guidelines with limits as nonrestrictive as possible, but still technically sound. A quality product with the best economic advantage should be the common goal.

ADVANTAGES OF HEAT CURVING

Following are some of the economic factors which favor the heat curving method:

1. *Material savings*—Cutting of flange plates to curvature generates scrap in amounts considerably dependent on the degree of curvature.

2. *Savings from multiple welding and stripping of flange plates*—The flange plates of most girder sections consist of an assemblage of plates of varying thickness. Usually, in a bridge project, there will be several like flanges. The most economical way to prepare these flanges is to order multiple width flange plates of the required thickness, join the sections with automatic welding equipment, and then strip them longitudinally into individual flanges. However, it is not practical to use this procedure with curved flange segments, so these must be cut and joined individually.



Heat-Curving Girders - Vertical Positioning

Figure 10

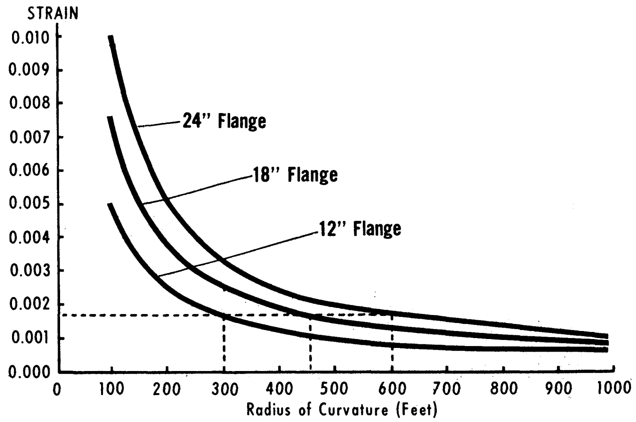


Figure 11

3. *Savings in jigs and fixtures*—The heat curving method eliminates the need for costly special jigs and fixtures required in the "cutting to curve" method.

4. *General fabrication savings*—To fabricate welded girders at the lowest possible cost, most fabricators utilize special equipment and techniques. These were designed for fabricating straight girders, and are not readily adaptable for girders to be fabricated with curved components. This affects most major operations, such as flange cutting, flange welding, flange-to-web fitting, and flange-to-web welding.

DESIGN CONSIDERATIONS

The following discussion considers all components of a steel curved girder bridge, and is not limited to girder elements only.

Fabrication—One of the major considerations to the designer is the method of fabrication, already discussed. The method to be used—curved components or heat curving—should be stipulated in the project specification.

Lateral Bracing—Another design consideration is the use of lateral bracing—not from a theoretical standpoint, but as a fabrication and/or erection aid (see Fig. 12). There are two conditions that may be troublesome to the field erector unless some lateral bracing is supplied:

1. Due to handling, rehandling and shipping, a single curved girder at the construction site may have a curvature slightly different than when fabricated.

2. A single curved plate girder resting on two piers is unstable unless the center of the girder is shored up.

If the curved girder bridge is provided with one set of lateral bracing between one pair of curved girders, as shown in Fig. 13, these troublesome conditions may be eliminated. The erector can assemble the two girders on the ground, joining them with the lateral bracing and diaphragms. The lateral bracing acts as a device for pulling the girders back into their fabricated alignment. The assembled unit can be placed on the piers without need for shoring, as it will be stable. The other curved girders of the span may be added one by one. Their connection to diaphragms, while being held in the raised position, will pull them into the fabricated curvature and make them stable without need for temporary shoring.

By keeping the lateral bracing at the top flange level, the esthetics of the "open framing" system is maintained.

Under some conditions more lateral bracing may be advisable. In Fig. 14, alternate pairs of girders are provided with top lateral bracing, and each braced pair is fabricated and shipped as a unit. The author believes the best control toward maintaining the planned curvature can be attained in this way. It certainly simplifies the field erection process.

Expansion—Curved girder bridges may vary from long spans of long radii to short spans with very short radii. These may be simple spans or continuous for several spans, and they may be narrow (of two girder construction) or very wide (of multiple girder construction). These variables, along with the curved nature of construction, make it necessary that a designer carefully analyze the location, positioning and construction of fixed and expansion bearing devices. Figure 15 depicts the action of expansion under uniform temperature change. Using a continuous two-curved-girder two-span as an

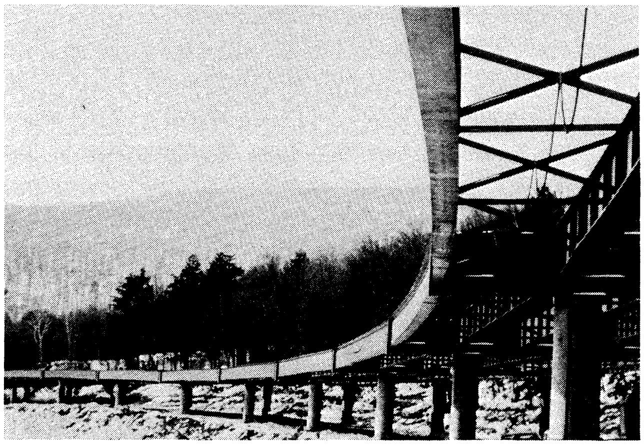


Figure 12

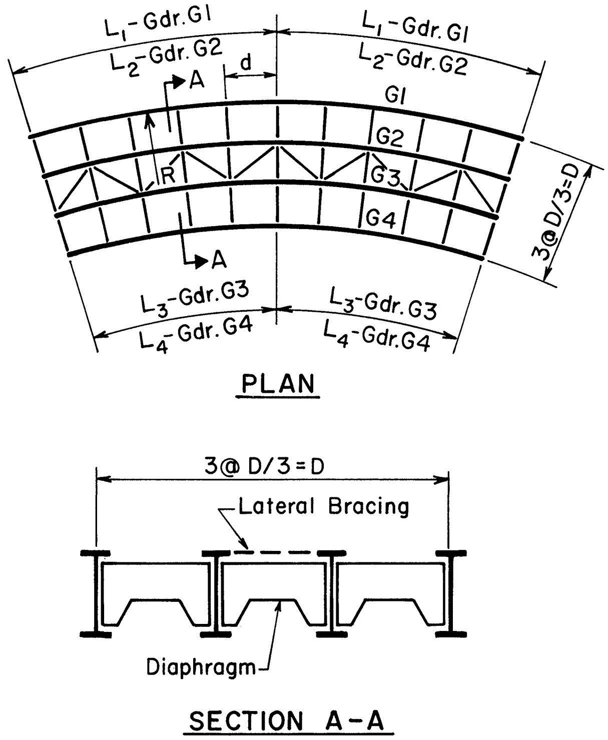


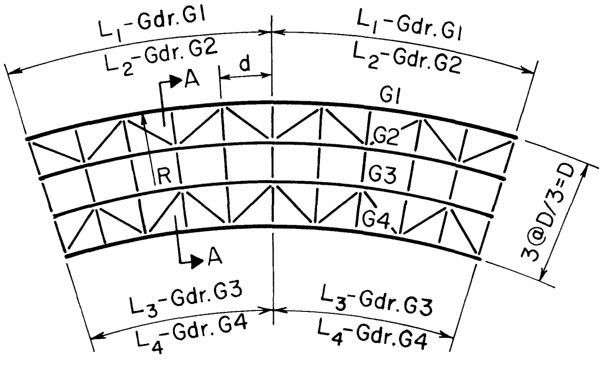
Figure 13

example, the top sketch illustrates free expansion with the bearings at the end pier being the fixed bearing; the bottom sketch depicts free expansion with the bearings at the center pier being the fixed bearing.

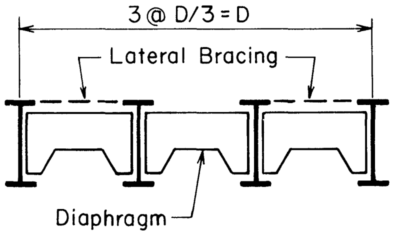
There are some important points to note in Fig. 15, which should be considered in the planning and design of curved girder bridges and their bearings:

1. The theoretical direction of movement of any girder expansion bearing is along the chord line of that girder between the fixed bearing and the expansion bearing under consideration.

2. If the span is allowed to move along the theoretical lines of movement, a slight misalignment of roadway will exist between the expansion end of the span and the abutment.



PLAN



SECTION A-A

Figure 14

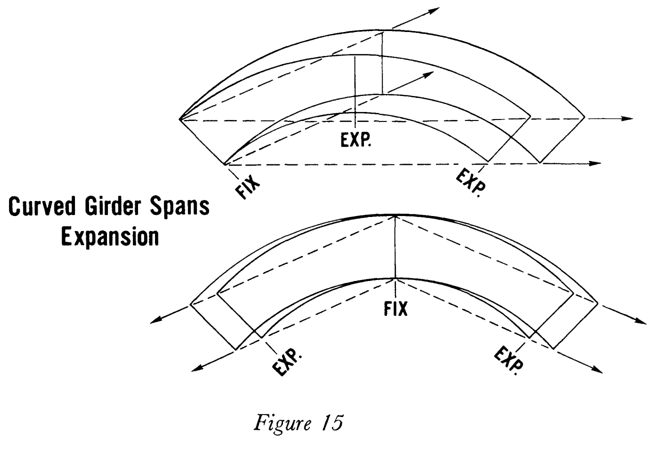


Figure 15

3. In continuous spans, the amount of misalignment between the expansion ends of the span and the abutment may be minimized by locating the fixed bearings at the interior piers. However, this may not be economical, as in additional expansion dam will be required for each continuous span unit, and pier costs may be increased due to an interior pier becoming a fixed pier rather than an expansion pier.

The previous discussion has dealt with movements caused by temperature changes. What about movements due to application of load?

The girders will rotate at the bearing points and have slight changes in length, center-to-center of bearings, due to the application of load. The axis of the hinges at the bearing points should theoretically be perpendicular to the tangent of the curve at the hinge point, i.e., radially. The slight change in length will, for all practical purposes, be along the tangent of the curve at the hinge point.

Therefore, in curved girder expansion devices, the theoretical planes of movement (longitudinal movement caused by temperature and longitudinal movement and rotation caused by applied loads) are angular to one another, rather than being in the same plane as in a straight girder bridge. The amount of movement and the degree of angular relationship between the planes of motion must definitely be a consideration in the design of curved girder bridges.

The following guidelines should be appropriate in the design of expansion bearing devices:

1. Investigate the movements and their relationship to one another.
2. Provide for rotation due to applied loads by placing the hinge radially—the movement of the girder thereby being in a plane tangent to the curve at the bearing point.
3. Investigate the ability of a conventional type shoe acting in the plane of the hinge movement—tangent to the curve—to satisfy the transverse movements required due to temperature.
4. If a conventional shoe cannot be utilized because of the transverse movements, design a special bearing device that will satisfy the compound movements.

These guidelines are based on the supposition that misalignment between the span and the abutments can be tolerated. If not, the bearing devices must act in a plane tangent to the curve at the end bearing, and the effect of restricted movement must be considered in the design of the span and the bearings.

As knowledge is further developed on the design and fabrication of curved girders, they will become more and more commonplace as highway bridge structures which fit particular locations as economically and esthetically as possible.