Placing Curves Overhead

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A simplified analysis of horizontally curved girder bridge erection.

THE ERECTION OF HORIZONTALLY CURVED I-GIRDER bridges may involve significant instability issues, more so than traditional straight bridges, thereby requiring detailed analysis to ensure stability. Twisting may cause warping of the girder cross-section as well as making a partially erected set of girders unstable. As one approach, these issues can be avoided with proper girder lifting procedures during erection, special attention to deck placement sequencing, and appropriate placement of temporary shoring towers at key locations to minimize instabilities.

This article provides a streamlined approach for establishing an idealized erection analysis, which includes methods for determining an adequate erection and deck placement sequence using a finite element analysis program (i.e. STAAD.Pro, or SAP2000). Temporary shoring tower systems will be discussed, which are often a necessity during erection, as their locations and elevations are crucial in minimizing instabilities and controlling the finished geometry.

The erection of horizontally curved I-girder bridges (refer to Fig. 1) is considerably more complex than the erection of straight girder bridges. Unlike a straight steel bridge, a horizontally curved I-girder bridge possesses twisting tendencies due to torsion. The curved shape of the members creates unbalanced self-weight loading, resulting in significant warping and distortional stresses, which are amplified by cross frames transferring load from adjacent girders. Due to this lateral load transfer, members such as cross frames become primary load carrying members in curved bridges. This differs from straight bridges where secondary members are used primarily for stability. The methods used in the erection of curved bridges must address the unique vertical and horizontal displacements caused by these out-of-plane load effects.

The number of curved bridges has increased significantly in recent years. One of the primary reasons for this increase is that curved bridges offer an economical means of satisfying the current demand placed on highway structures within an already congested national transportation infrastructure. Curved bridges are able to meet design requirements and geometric restrictions, providing additional freedoms with proposed alignments (refer to Fig. 2). The curved bridges typically allow for fewer spans and piers, which results in construction cost savings.

There have been great advancements in recent years in the development of user-friendly computer programs for the design of curved I-girders. However, many of these programs do not deal with problems that are encountered during lifting, erection, and placement of temporary shoring tower systems. The streamlined approach presented in this article has been used to model the erection of several curved girder bridges.

Fig 1. Typical Curve Girder During Erection

Fig 2. Curved Girder Bridge Infrastructure

Finite Element Analysis Model

First, select a finite element analysis program to create an idealized linear model of the horizontally curved I-girder bridge. Linear member segments will be used to represent the curvature of the bridge girders. These member segments typically vary from 5 to 15 ft long depending on the structure. Often it is easiest to connect linear member segments at cross-frame locations, which are typically spaced at 10 to 25 ft intervals along the length of the horizontally curved I-girder bridge. A node will have to be placed at the cross-frame locations; therefore, this is also a good point to terminate the girder member segment.

The linear member segments should always terminate at splices or at locations where the girder changes properties, as dimensional changes at these node points allow the assignment of a different finite element beam member. Nodal points of the bridge can be imported into a finite element program from a previously prepared CAD drawing, although it is common for the steel erectors to not have access to these CAD drawings. Therefore, the nodes along the curve of the bridge must be determined from the plan drawings using geometric equations.

It is often more time consuming and more difficult to alter the existing CAD drawing than to create the bridge model from scratch using plan drawings. A simple method to accomplish this task is to develop a spreadsheet with appropriate geometric equations using the tangent offset method (refer to Fig. 3) to determine multiple node points.

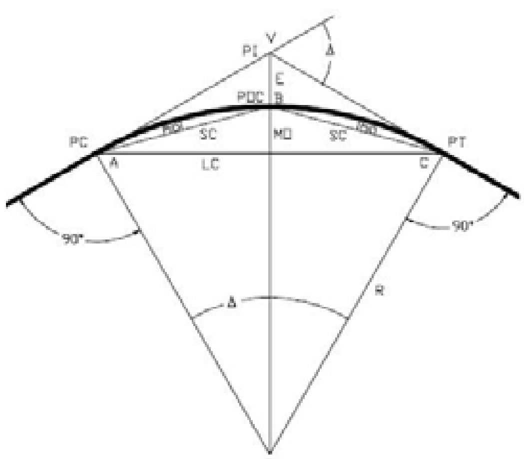

Fig 3. Tangent Offset Method Example

The curved girder element nodes must be broken into x, y, and z coordinates to be imported into the finite element program. It is very important to model the bridge in three-dimensions to account for additional lateral stresses occurring at the piers due to elevation change both along the length of the bridge and transversely across the girders. Examining the structure in only two dimensions is a commonly used shortcut that has created problems in terms of girder overstress and bearing damage. The final list of node numbers and their corresponding coordinates can simply be imported into the finite element program (refer to Figs. 4 and 5). These spreadsheets can save many hours of work and the nodes or beams can be easily revised in the list. Once the node points and beam elements have been imported into the finite element program, the bridge girders and cross-frames have been modeled three dimensionally.

Fig 4. Spreadsheet of Girder Node Locations

NODE	X	Y	Z
1	0.000	0.000	669.812
2	0.000	14.000	669.304
3	12.197	0.039	669.231
4	12.108	14.039	668.682
5	24.393	0.156	668.659
6	24.215	14.155	668.041
7	36.589	0.350	668.103
8	36.321	14.348	667.471
9	48.783	0.623	667.541
10	48.426	14.618	666.908
11	60.975	0.973	666.992
12	60.528	14.966	666.363
13	73.165	1.401	666.433
14	72.629	15.391	665.811
15	85.351	1.907	665.894
16	84.726	15.893	665.276

Fig 5. Spreadsheet of Girder Members and Node Association

BEAM	START	END
1	1	6
2	6	11
3	11	16
4	16	21
5	21	26
6	26	31
7	31	36
8	36	41
9	41	46
10	46	51
11	51	56
12	56	61
13	61	66
14	66	71
15	71	76
16	76	81

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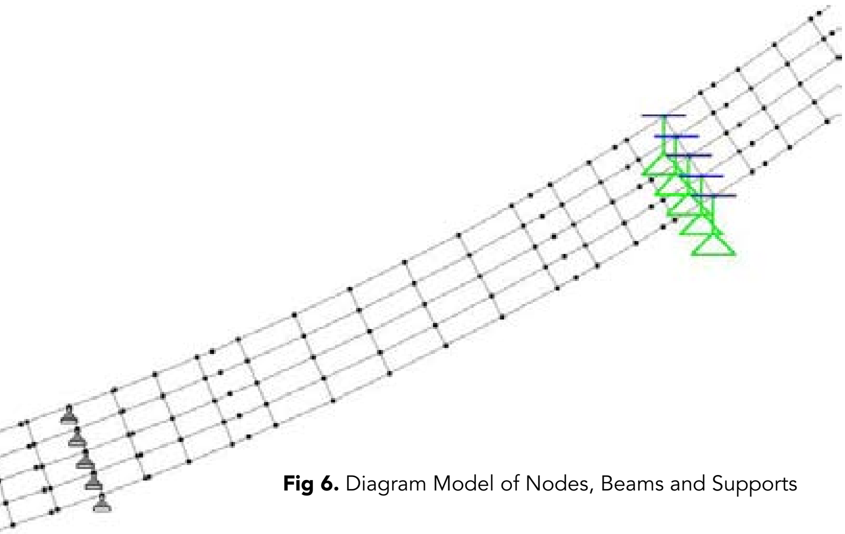

Fig 6. Diagram Model of Nodes, Beams and Supports

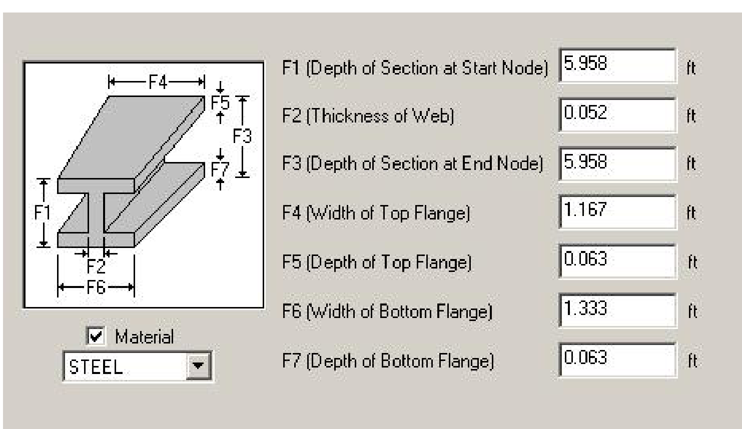

Fig 7. Plate Girder Input Interface

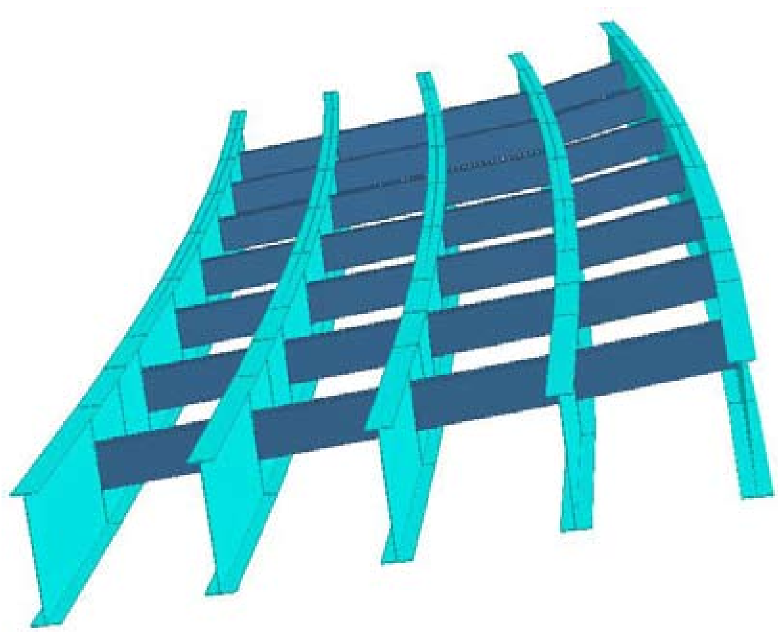

Fig 8. 3D Rendering of Curved Girders with Idealized Cross Bracing

The supports are entered into the model at their proper locations along the length of the bridge. The supports should be restrained or released depending on the intended behavior during erection (refer to Fig. 6). The curved shape and considerable elevation change between piers and bearings often can lead to large lateral and longitudinal forces and related displacements along the girders during erection and deck concrete placement. These forces and deflections must be restrained at bearing locations or additional supports, such as shoring towers or tie-downs, must be added. Therefore, it is important to model the supports properly based on the bearing type, configuration, elevations, and intended design behavior.

Plate girders, due to their unique dimensions, are not found in the standard catalog of I-shaped members in finite element programs. Therefore, the dimensions of the girders must be entered manually in order to define the member properties (refer to Fig. 7).

The cross-frames typically consist of a frame of several members, which must be inserted into the model as a single cross-braced element. The depth of the girders is represented in the model with a single layer of nodes; therefore, it is extremely difficult to input a three-dimensional frame between the girders. The stiffness of the frame system can be determined and a single beam of equal stiffness can be placed in the model to represent the cross bracing (refer to Fig. 8). The easiest way to perform this substitution is to model the frame separately with a dummy load at one end. The stiffness of the frame can be determined from this model and an equivalent beam can be selected to represent the frame system. This quick and easy solution yields accurate results because the deflections and stresses determined by the finite element analysis are based on the stiffness of the members. It is important to note that the self weight of the frame is different than that of the idealized beam. Therefore, the self weight of these members must be entered manually into the finite element program to accurately represent the actual weight of the cross braces.

At this point, the modeled bridge members are ready for loading. The self weights of the girders and cross-frames are entered manually to account for the difference in cross brace weights. A spreadsheet to determine the weight and structural properties of each girder is a helpful, useful tool during member capacity analysis (refer to Fig. 9 on opposite page). It can be seen in Figure 9 that the girder weight has been increased by 5% to account for stiffeners and connection weights.

Girder Lift and Erection Analysis

Problems can occur during lifting of the curved girders when the proper lifting procedure is not determined through analysis. Lifting and setting presents less difficulty for straight I-girders because the center of gravity is located along the web of the member. The center of gravity of a curved I-girder is offset from the web of the member, to the inside of the curve. The lifting of curved girders at discrete points induces distortion and warping stresses. The resulting stresses during erection may exceed

Girder #1 – South Abutment to Splice #1

Properties X-X

	t	b_f or h_w	A	y	Ay	Ay^2	I
Top Flange	1	15	15.00	43.50	652.50	28,383.75	1.25
Web	0.5	40.625	20.31	22.69	460.84	10,455.30	2,793.6
Bottom Flange	2.375	18	42.75	1.19	50.77	60.28	20.09
			78.06		1,164.11	38,899.34	2,814.97

Y_b	14.91	I_x	24,354.61	S_{bx}	1,633.17
Y_t	29.09	d	44	S_{tx}	837.29

Properties Y-Y

	t	b_f or h_w	A	x	Ax	Ax^2	I
Top Flange	1	15	15.00	9.00	135.00	1,215.00	281.25
Web	0.5	40.625	20.31	9.00	182.81	1,645.31	0.4
Bottom Flange	2.375	18	42.75	9.00	384.75	3,462.75	1,154.25
			78.06		702.56	6,323.06	1,435.92

X	9.00	I_y	1,435.92	S_{by}	159.55

Weight	265.6
W (+5% misc)	279

Fig 9. Spreadsheet of Plate Girder Properties

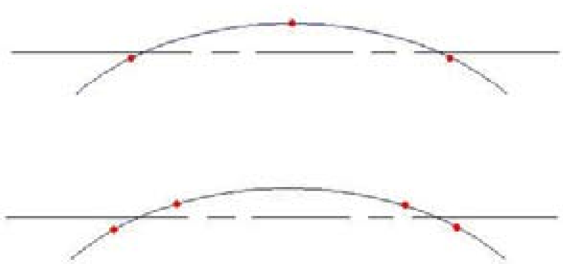

Fig 10. 3 Point and 4 Point Curved Girder Lifting Setups

the permanent beam stresses which were considered in the original design of the system.

Once the self weights of all the girders and cross frames are entered into the finite element program, the girder lift analysis can be undertaken. It is easiest to delete all members from the model, except the individual girder(s) that are analyzed during lifting, and save the configuration as a separate model file. The support locations in the model, which represent the pick points, can then be altered until acceptable stresses are found in the member.

In Fig. 10, the red dots represent typical pick points on a 3-point or 4-point girder lift. Stability is a significant concern during curved girder lifting. The pick points must be positioned to prevent rolling and tipping of the girder during the lift. In many instances for larger girders, a second crane is required to lift the girder to establish a stable configuration.

Typically, the first individually erected girder will not be stable if set in place on the bearings by itself. Therefore, it is common for the first two girders to be braced together and lifted as an assembly. Otherwise, additional cranes and/or shoring systems are required to hold the first girder in place while a second and perhaps a third adjacent girder are lifted and connected with cross frames (refer to Fig. 11 and 12). As previously mentioned, it is convenient to set up a spreadsheet or a math computing program, such as MathCAD, in order to quickly determine stresses in each member while adjusting the lifting points in the computer model. Fig. 13 (on the following page) is an example of a MathCAD file used to verify the adequacy of the bending stress in a curved girder. The maximum moment and unbraced length can easily be altered as different trial

Fig 11. Connection of Adjacent Curved Girder Cross Bracing

Fig 12. Typical Girder Lifts

South Abutment to Splice 1 Girder Lift;

$t_{tf} := 1in$ $\quad b_{tf} := 14in$ $\quad S_{bx} := 1916in^3$ $\quad k := 1000lb$ $\quad ksi := \frac{k}{in^2}$

$t_{bf} := 1.25in$ $\quad b_{bf} := 16in$ $\quad S_{tx} := 1672in^3$ $\quad F_y := 50ksi$

$t_w := 0.6875in$ $\quad h := 72in$ $\quad d := 74.25in$

Unbraced Length: $\quad l := 45ft$

Maximum Moments: $\quad M_{max} := 350k \cdot ft$ $\quad$ Conservative Moment (see Att D)

Check Compression Flange

Partially Supported Girders - AASHTO Table 10.32.1A

$$F_{bt} = \frac{50000 \cdot C_b}{S_{xc}} \cdot \left(\frac{I_{yc}}{l}\right) \cdot \sqrt{0.772 \cdot \left(\frac{J_1}{I_{yc}}\right) + 9.87 \cdot \left(\frac{d}{l}\right)^2}$$

Where $\quad F_{bt} \le 0.55F_y = 27.5ksi$ $\quad C_b := 1.0$

$S_{xc} := S_{bx}$ $\quad S_{xc} = 1916\,in^3$ $\quad I_{yc} := \frac{1}{12} \cdot t_{bf} \cdot b_{bf}^3$ $\quad I_{yc} = 426.7\,in^4$

$$J_1 := \frac{b_{tf} \cdot t_{tf}^3 + b_{bf} \cdot t_{bf}^3 + h \cdot t_w^3}{3}$$ $\quad J_1 = 22.9\,in^4$

$$F_{b1} := \frac{50000 \cdot C_b}{S_{xc}} \cdot \left(\frac{I_{yc}}{l}\right) \cdot \sqrt{0.772 \cdot \left(\frac{J_1}{I_{yc}}\right) + 9.87 \cdot \left(\frac{d}{l}\right)^2} \cdot ksi$$ $\quad F_{b1} = 9.8\,ksi$ $\quad F_{b2} := 27.5ksi$

$F_b := \min(F_{b1}, F_{b2})$ $\quad F_b = 9.85\,ksi$

$f_b := \frac{M_{max}}{S_{bx}}$ $\quad f_b = 2.2\,ksi$

FbCHECK := if($F_b > f_b$,"OK" ,"NG") $\quad$ FbCHECK = "OK"

Fig 13. Girder Stress Adequacy Analysis in MathCAD

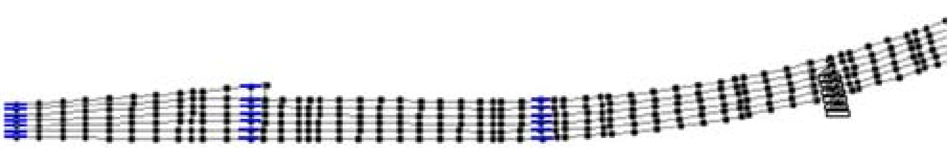

Fig 14. Diagram Model of Straight to Curved Bridge

runs of the lifting setup are analyzed in the finite element program model.

The sequencing of the curved girder erection is another important factor in maintaining stability and a concern not typically associated with erecting straight girders. As previously stated, this analysis can be easily completed by beginning with the original, fully erected bridge and deleting given members to simulate each step of the erection sequence, otherwise known as "reverse erection." In some cases the number of shoring towers, extra cranes and tie-downs can be reduced by analyzing different erection sequencing possibilities. Also, the risk of accidents due to instability during erection can be greatly reduced with a complete step-by-step analysis.

One example of this benefit involves a bridge that begins with a section of straight girders for two spans and then curves for the remaining three spans (refer to Fig. 14). The contractor assumed it would be much easier and safer to erect the straight sections first. Analysis showed that large twisting forces would be generated within the straight sections as the curved sections were erected and became cantilevered over the pier. That configuration would have required shoring tower systems under all six girders of the bridge for support until the adjacent span was fully erected. A quick check of an erection sequence in the opposite direction found that erecting the curved section first provided adequate lateral stability and eliminated the need for shoring towers. One or two days of analysis saved the contractor considerable costs in shoring tower materials, fabrication and erection, and removal.

Idealization of supports is particularly important during erection analysis. Understanding the behavior of the structure during the various erection sequence steps depends on properly modeling the restraint properties of the bearings. During erection, the bearings are typically not fully loaded, preventing the friction capacity of the bearings from fully developing. When girders are not fully attached at their splice locations in an adjacent span, it is common for out-of-plane and/or uplift forces to be induced at the supports. Decisions such as using tie-downs, allowing free movement, not fully assembling the bearings, or changes in erection sequence can be made by examining the reactions and girder movement at the bearings.

Deck Placement Analysis

The concrete deck placement on steel curved girders generally leads to the greatest stresses and can lead to serious problems if not adequately analyzed and addressed. The understanding of curved girder and concrete curing behavior is particularly important for the selection of a proper placement sequence.

The deck usually is not placed in one stage due to the large concrete volume involved (typically more than 500 cubic yards), uplift at adjacent bearings or the need to control shrinkage. Therefore, multiple sections are placed at different times, which leads to many potential sequence options. However, repeated relocation of concrete placement equipment increases construction costs. It is important to analyze each option to determine the sequence that minimizes stress. In some cases the girders will be adequate to support the deck-placement-induced forces; in other cases, shoring towers will be required.

One of the most complicated aspects of curved girder erection and construction is determining the proper elevation of the shoring towers during the deck placement sequence. This becomes increasingly complex if the towers were also needed during the steel erection as well. The shoring towers should be placed at or below the final elevation of the girders as to not hold the girders above their final position while the concrete is curing. Often shoring towers are placed at the final girder elevation, which will result in the towers loaded with extremely high forces under the weight of the fresh concrete. Typically, it is not necessary to hold the girders at their final elevation because the girders possess additional strength to allow for additional deflection. However, these extremely high construction forces can cause localized overstressing and buckling in the girders and cross frames. In addition, heavy-duty temporary shoring towers and foundations may be required.

The key is to find an elevation at which the girders deflect to a point where stresses are close to allowable limits and providing a load path so that any remaining forces are transferred to the shoring towers. This helps reduce the required capacity of the shoring towers (thereby improving economy) while also helping to prevent localized problems in the girders. Typically, one starts with an estimated deflection within the analysis, and then progresses to a trial and error approach in inputting elevations. The final tower elevations are determined based on their effect on the allowable limits of the girder system. Very subtle adjustments to the tower elevations can greatly affect support reactions.

The shoring tower elevations can be altered within the model using the support offset functions. The supports can be raised or lowered by simply changing the offset until an acceptable configuration is found. If the support reaction is negative, it implies that the shoring tower is pulling the girder down; the tower should therefore be raised to produce a positive reaction or removed to simulate the girder lifting off the tower. It is important to remember that in many curved bridges, especially those with small radiuses, the outer girders will tend to deflect downward and the inner girders will tend to deflect upward. In such cases, shoring towers typically are required only under the outer girders.

Summary and Conclusions

This article has provided a streamlined approach for establishing an idealized erection analysis, which includes methods for determining an adequate erection and deck placement sequence. A relatively quick erection analysis can cut costs by reducing the reliance on shoring towers or extra cranes to support a structure that does not require such efforts. More importantly, analyzing each step of the lifts, erection and deck placement will greatly reduce the risk of accidents due to members being overstressed or becoming unstable.

With the advances in computer technology and with this simplified yet accurate procedure, an entire multi-span curved bridge can be fully analyzed in a matter of weeks rather than months. As an example one state department of transportation performed a full and highly detailed analysis of a curved bridge using a sophisticated nonlinear finite element program. In all areas of the structure the findings of the department's analysis were within 3% of the results found in the idealized structural model.

Structural engineers should become familiar with the behavior of curved structures. This is not a simple analysis in which loads and dimensions are entered and the computer program churns out the answers. Applying this method of analysis relies on engineering judgment with regard to structural behavior of the members, the bearings, and the system as a whole. Many different trials must be run in order to gain an understanding of the performance of the structure under different loading configurations and to understand the finite element program's interpretation of such behavior. The analysis model should be built in a sequential manner following the proper erection sequence. As always, inconsistent or incorrect assumptions will result in inaccurate output and erroneous explanation of data. MSC