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GUIDELINES FOR DESIGN AND SAFE HANDLING OF CURVED I-SHAPED STEEL GIRDERS

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TxDOT Project 0-5574: Curved Plate Girder Design for Safe and Economical Construction

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GUIDELINES FOR DESIGN AND SAFE HANDLING OF CURVED I-SHAPED STEEL GIRDERS

PURPOSE:

The purpose of this set of guidelines is to summarize recommendations from work completed as part of the Texas Department of Transportation (TxDOT) Research Project 0-5574 entitled "Curved Plate Girder Design for Safe and Economic Construction." The research included field tests, three-dimensional finite element parametric studies, and software development. The full report for the study will be submitted by October 31, 2009 and includes a more detailed explanation of the recommendations given within this document.

The development of general guidelines to ensure girder stability during lifting, erection and early stages of construction is complicated by the wide range of variables that impact the behavior of the girder system. These variables include girder proportioning, partially installed bracing, crane positioning, the use and positioning of temporary supports, as well as several other factors. To aide in assuring girder stability, two analytical tools were developed as part of this research project. The analytical tools consist of a spreadsheet program (UT Lift) for evaluating girder behavior during lifting, and a finite element program (UT Bridge) for analyzing the behavior of I-girder bridges at various stages of erection and during construction of the concrete bridge deck. While the guidelines presented herein have been developed to assist in producing a stable system, the reader is encouraged to use the analytical tools, UT Lift and UT Bridge, or other suitable analytical packages, to evaluate bridge girder systems during construction.

CROSS SECTIONAL PROPORTIONING:

One of the major topics studied in the research investigation was the effect of cross sectional proportioning on the stability of curved girders during construction. Several parameters were identified including flange width to depth (b_f/D), length to depth (L/D), and radius of curvature (R). One of the catalysts for the research study was differences in the limiting b_f/D ratios commonly applied by TxDOT and the AASHTO Guidelines. According to the *AASHTO LRFD Bridge Specifications 4th Edition* (2007) the minimum b_f/D ratio is one-sixth

(Eq. 6.10.2.2-2). However, TxDOT's *Preferred Practices for Steel Bridge Design, Fabrication, and Erection* (2007) states that "for curved girders, flange width should be approximately one-third the web depth and no less than 30 percent of the web depth. The extra width for curved girders enhances handling stability and helps keep lateral bending stresses within reason." Although the AASHTO minimum limit of 1/6 for b_f/D, is relatively slender, there is no research justification for the TxDOT recommendation of twice the AASHTO value. The limit of one-third the web depth is twice as wide as the one-sixth limit specified by AASHTO.

Torsional loads have a significant contribution to the behavior of curved girders. Therefore, ensuring that girders have sufficient torsional stiffness and strength is an important consideration in proportioning the girders. For open cross sections, such as I-shaped girders, the warping stiffness has a considerable contribution to the torsional stiffness. The most significant contribution to the warping stiffness of the section is the width of the flanges (b_f). Thus, lower values of the b_f/D ratio significantly reduce the warping stiffness of girder cross sections.

For improved economy, engineers may choose to reduce the width of girder flanges because the completed bridge will have a number of cross frames and a hardened deck to brace the girders. However, during the construction process, many of the braces are not connected, which leaves the bridge vulnerable to stability related issues without proper analytical checks. Analytical studies bounded by the typical bridge configuration utilizing by TxDOT and measured by L/D and R that considered the impact of the b_f/D ratio showed that while the TxDOT recommended minimum value of 1/3 was generally conservative, values close to the AASHTO limit of 1/6 often resulted in excessive torsional flexibility that can lead to problems during construction. The studies showed that reducing the minimum b_f/D value to 1/4 often resulted in reasonable behavior throughout the construction process. Designers are also encouraged to make use of analytical tools such as UT Lift and UT Bridge to evaluate the behavior during the construction process.

LIFTING OF CURVED I-GIRDERS:

Lifting Options:

The lifting of curved I-girders is an important stage of the construction process and significant progress was made in Project 0-5574 in understanding and predicting the behavior of girders during lifting. There are several options available to contractors when deciding how to lift the I-girders into place. They include:

A) Single crane with a single lift point
B) Single crane with two lift points and spreader bar
C) Two cranes with two lift points
D) Two cranes with four lift points and two spreader bars
E) Three or more cranes

The least desirable of the above options is Case A with the single lift point as there is little control of the girder deformations, and it is recommended that it not be used for any sizable bridge girder. The scenarios in Cases B and C that use either a single crane with a lifting beam (spreader bar) or two cranes with two lift points is a reasonable option and was the focus of much of the research. The research also included a survey of erectors to determine commonly used lifting practices, and Case B was the most widely used method for lifting girders. Although the geometry of the curved girders results in torsion on the girder system, the two points of support can be positioned to provide a stable system during lifting. However, since the erector does not generally have the spreader beam with the ideal length to prevent rigid body rotation of the girder segment being lifted, the effects of rotations due to both rigid body motion and torsional deformations should be considered when evaluating the lifting behavior. Lifting the girders with the Case D scenario that makes use of two cranes and four lift points results in improved stability compared to Cases B and C due to the larger number of lift points as well as a more favorable distribution of bending moment. The four lift points provide better resistance to girder twist compared two lift points, and the four lifting reactions also lead to a reduction in the maximum bending moment. While the use of two lifting cranes can improve the girder stability, this option is often reserved for relatively long girder segments due to the cost of the extra crane, but the cost can sometimes be overcome if two cranes can complete the work more efficiently than one. Similarly, the use of three or more cranes is uncommon due to the added equipment costs, difficulty in coordinating crane movement, and variations of crane forces during the lift. The source of the variable lifting force when using more than 2 cranes results from the lifted girder being an indeterminate system. With all lifting options, two limit states should be checked to ensure safety of the girders and the workers during the lifting process: a strength limit state and a serviceability limit state, both of which are discussed in the following sections.

Strength Limit State:

Maximum stresses occurring during construction should be limited so as to preclude yielding on the cross section. Premature yielding on the cross section is affected not only by the stresses induced from applied loading but also due to the presence of residual stresses on the cross section. Depending whether Allowable Stress Design (ASD) or Load and Resistance Factor Design (LRFD) methodologies are used the following limits should be checked:

ASD: Service Loads with an Allowable Stress of $F_y/1.67$.

LRFD: Use Factored Loads (Load Factor of 1.5) with a stress limit of ϕF_y ($\phi = 0.9$).

For the ASD approach, the service loads will typically be the self weight of the girder and any attached cross frames. For the LRFD approach, these service loads are multiplied by the Load Factor, as indicated above.

Serviceability Limit State:

A serviceability limit state that limits the total girder rotation to less than 1.5 degrees is recommended to prevent excessive deformation of girders during erection. The rotational limit is used to facilitate the lifting process and to aid in the aerial girder field splice connection. Additionally, excessive deformations provide an indication of a general lack of sufficient stiffness and can also indicate an impending problem with girder stability. The limit of 1.5 degrees was recommended based on information obtained from a nationwide survey of contractors, engineers, and fabricators (Farris 2008). A rotational limit larger or smaller than 1.5 degrees can be selected by the engineer; however, for larger values, the engineer should consider the complications on connection fit-up. For rotations significantly smaller than 1.5 degrees the contractor may be find it practically difficult to achieve.

Stability of Girder during Lifting:

The number of lifting points and their location is the most important factor to consider when designing the lifting plans for curved girders. If two lifting points are used, then there is a specific location where the defined line of support will pass through the center of gravity of the girder resulting in zero rigid body rotation. However, stability of the girder is maximized by lifting in the vicinity of the quarter points of the girder where the moment gradient of the girder is greatest. Schuh (2008) and Farris (2008) recommended *Cb* factors that can be applied to the buckling solutions derived for uniform moment loading utilizing the entire length of the girder segment for the unbraced length, L_b. The C_b expressions are applicable to girders lifted at two locations. It is conservatively recommended that for nonprismatic girders the cross sectional variables (I_y, J, C_w) should be calculated for each cross section and the resulting minimum M_{cr} should be used for design. For doubly-symmetric sections, making use of Timoshenko's (1961) buckling solution results in the following expression:

$$M_{max} < \phi M_{cr} = \phi\, C_b \frac{\pi}{L_b} \sqrt{E I_y G J + E^2 I_y C_w \left(\frac{\pi^2}{{L_b}^2}\right)} \qquad \textbf{\textit{Equation 1}}$$

Where:

$M_{max} = Factored\ Maximum\ Moment\ From\ Static\ Analysis$

$M_{cr} = Critical\ Buckling\ Moment$

$\phi = Reduction\ Factor = 0.9$

$C_b = Lift\ Adjustment\ Factor$

$L_b = Unbraced\ Length = L$

$E = Modulus\ of\ Elasticity\ (ksi)$

$I_y = Weak\ Axis\ Moment\ of\ Inertia\ (in^4)$

$G = Shear\ Modulus\ (ksi)$

$J = Torsional\ Constant\ (in^4) = \sum \frac{bt^3}{3}$

$C_w = Warping\ Constant\ (in^6) = \frac{I_y h^2}{4}$

The C_b factor that was developed based upon the work of Schuh (2008) and Farris (2008) is given in the following expressions:

$$C_b = 2.0 \quad for \quad \frac{L_{\overline{Lift}}}{L} \leq 0.225$$

$$C_b = 6.0 \quad for \quad 0.225 < \frac{L_{\overline{Lift}}}{L} < 0.3 \qquad \textbf{\textit{Equation 2}}$$

$$C_b = 4.0 \quad for \quad \frac{L_{\overline{Lift}}}{L} \geq 0.3$$

Where:

$L_{\overline{Lift}} = Average\ Length\ from\ the\ Lift\ Points\ to\ the\ Ends\ of\ the\ Girder$

The equations above provide a reasonable estimate of the buckling capacity for straight girders and for curved girders with a relatively large radius of curvature (central angle subtended by the girder length (*L*/*R*) is less than 3 degrees). Where *L* is the total length of the girder and *R* is the radius of curvature of the girder. For most curved girders, however, the equations overestimate the buckling capacity. Although the buckling solution in Eqs. 1 and 2 tends to overestimate the capacity for horizontally curved girders, computational studies showed that girders for which buckling was a problem were typically controlled by torsional deformations. In these cases, applying the 1.5 degree rotational limit discussed in the last section usually governed the lifting behavior. When this limit was enforced, buckling was not a problem.

UT Lift:

As mentioned earlier in this document, the program UT Lift is an Excel spreadsheet for evaluating the behavior if curved I-girders during lifting. The spreadsheet provides an analytical tool to determine girder rotation and to give information to an engineer when deciding the safety of a horizontally curved steel I-girder during lifting with two lift points. The spreadsheet input that is required consists of basic information readily available to the engineer such as the thicknesses and lengths of the girder plates that make up the cross section, as well as the weight and spacing of the cross frames. The center of gravity and optimum lift locations for minimizing rigid body rotation are calculated in the spreadsheet. For a given lifting scheme, the spread sheet will calculate the total rotation of the girder being analyzed including both the rigid body rotation and the cross-sectional twist. A stability check and several graphs are also provided for additional information that can be used to assess girder performance.

Recommendations:

Various lifting options are available for the erection of curved girders, but it is advisable to use the maximum number of lift points possible due to the increased stability and the decreased deformations that accompany such lifting configurations. However, economic considerations require a minimum number of cranes to be utilized most of time. Applying the strength and stiffness limits described earlier will generally result in a safe system that avoids problematic deformations during lifting. Although straight girders will not generally be limited by the 1.5 degree rotational limit presented earlier, the buckling solutions from Schuh (2008) and Farris (2008) had good correlation with three-dimensional finite element solutions. The optimum location to lift a girder is between the point at which the line of support passes through the center of gravity and the girder's quarter points. For a horizontally curved segment with a prismatic cross section, lifting at the quarter points will maximize the buckling capacity, while lifting at a distance 21% of the segment length from the ends will result in no rigid body rotation, thereby minimizing the torsional deformations.

PARTIALLY CONSTRUCTED BRIDGES:

Critical Stages of Bridge Constructions:

The critical stage for girder stability generally occurs during construction. The most critical situations to check include:

I. The case where a single girder segment has been erected.
II. The girder system after a holding crane or shore tower is removed.
III. The first concrete placement stage on a span.

Typically, the first girder lifted at a particular cross-sectional location will have a significantly longer unbraced length than the final configuration and can exhibit stability problems. Once the next girder is constructed and cross frames are attached, the stability of the combined system is significantly improved. However, if a holding crane was used during the first stage of erection and then removed, the new configuration should be checked. Any change in the bracing or support conditions can present potential problems for bridges as can stages where the temporary supports are removed. Accordingly, if any of these conditions occur, stability of the system should be checked. Once the concrete has cured, it provides considerable bracing for the girder system, but during the first concrete placement stage, a large load is added to the bridge without adding bracing. Anytime concrete is placed on a span without previously hardened concrete, the entire system should be checked for stability and excessive deformations.

Shore Towers:

Shore towers are primarily used to control deformations and stresses as well as provide bracing for the girders during erection. The location of a shore tower affects the behavior of the girders as well as required design forces on the shore tower. The specific location where a shore tower can be placed, however, is affected by many nonstructural restrictions such as site access, construction methodology, and girder stiffness variations. Nonetheless, it is recommended that shore towers be placed at locations where the maximum positive bending moment occurs between permanent supports. This positioning will have the greatest effect on minimizing the total deflections, and in general, it places a tower near the position where it will be required to support the least load of any position along the girder. It should be noted that adding a shore tower results in a large concentrated force and it is thus advisable to place the shore tower under a stiffener location, or alternatively, to check local yielding and stability of the girder web at the shore tower location.

A final issue on the use of shore towers is the load height effect associated with their use. A shore tower supports the girder from the bottom flange which is below the girder's center of gravity. If the girder is not properly braced and the girder is allowed to rotate, the reaction force of the shore tower results in a disturbing force. This disturbing force causes secondary moments on the cross section and increases the deflections predicted by a linear structural analysis. This lack of conservatism should be known to the designers and erectors that use a linear analysis to predict the behavior of curved girders during construction. The previous assessment neglects the tipping restraint that is often present in actual structures which provides stability and reduces the disturbing force. Tipping restraint is the beneficial effect that happens when cross-sectional twist is restricted by stiff contact surfaces between the girder and a load/reaction point. Although load position on the cross section can have dramatic impacts on the buckling capacity, the girder must be able to rotate at the load or reaction point (no bracing) for load position to have any effect. Consequently, problems associated with the disturbing force of the shore tower can be eliminated by properly bracing the girder against rotation at its support on the shore tower.

Holding Cranes:

In lieu of a shoring tower, temporary holding cranes also provide a valuable method of supporting curved I-girders during erection. Although cranes represent expensive equipment on the job site, there are a number of benefits to using holding cranes. There are many situations where traffic demands below the bridge may not permit the use of a shore tower that will often remain standing for lengthy periods of time. The benefit of the holding crane is that the equipment is often only required during lifting of the first few girder segments. The location of a holding crane will affect the recommended load and the effectiveness of the crane to perform its primary function of controlling the deformations and the stresses of the girders it is supporting. The specific location of the holding crane can be affected by many constraints such as site access, construction methodology, and girder stiffness variations, but the recommended location is the same as the shore tower; the location of maximum positive intermediate bending moment (i.e., between the permanent supports). Additionally, the lifting load held by a holding crane significantly affects the behavior of the girder it is supporting. It is recommended that the crane hold a load that would be equivalent to a rigid support directly under the girder. This load will maintain the vertical web and minimize deformations for ease of construction fit-up. A lifting load that varies from this recommended load will result in the girder rotating and could induce unintended stresses. Parametric finite element analyses conducted on TxDOT Project 0-5574 showed that changing the location of the holding crane from the optimum position generally has a less detrimental effect on predicted displacements and stresses than a variation of the lifting load. Small deviations in the lifting force applied by the holding crane can significantly affect a girder's displacements and stresses.

Unlike shore towers, a holding crane will normally be attached to the girder's top flange and will provide an upward force above the girder's center of gravity. Therefore, if the girder rotates, a component of the crane force acts as a restoring force causing a secondary moment that decreases the deflections predicted by a linear structural analysis. This phenomenon is conservative and should be known to the designers and to the erectors that use a linear analysis to predict girder behavior. The detrimental aspect of using a holding crane is that it does not brace the girder laterally or torsionally as a shore tower can and thus a structural analysis should be performed to ensure significant lateral deflections does not occur when using a holding crane.

UT Bridge:

UT Bridge is a comprehensive three-dimensional finite element analysis software package with a user-friendly graphical user interface (GUI) to input girder geometry and analysis cases. The program has a graphical post-processor that allows an engineer to visualize the construction process and to identify potential problems before field work begins. The program allows for two kinds of construction analyses: girder erection sequence analysis and a concrete deck placement analysis. A linear analysis is performed for each case and if desired, an eigenvalue buckling analysis can also be performed. It should be noted that an eigenvalue buckling analysis approximates the load at which a structure will lose stability by providing a multiplier of the applied loads (factor of safety) known as the eigenvalue. This analysis assumes small deflections of the girder prior to buckling and provides a reasonable approximation for straight bridges. However, the approach over-predicts the buckling capacity of curved bridges that exhibit significant deformations prior to buckling. Consequently, eigenvalue buckling analysis can give unconservative buckling predictions for these types of structures.

While the software was developed as an analysis tool, a designer can utilize its capabilities to design and to check a bridge for a variety of load cases. This would include but is not limited to determining:

I. The optimum location of shore towers,
II. the design load of shore towers,
III. the necessary erection stages for using holding cranes,
IV. when a holding crane can be released,
V. the effects on displacement and stresses of a concrete placement sequence, and
VI. whether a girder will experience uplift at the bearing.

Recommendations:

The critical stage for stability and safety of many steel bridge systems often occurs during construction. All erection stages should be analyzed for excessive deformations, stresses, and buckling considerations. The concrete deck placement produces a large load on the bridge before full composite action can be accounted for and the stabilizing effects of the hardened deck can be achieved. Thus, each concrete stage should be analyzed for excessive deformations, stresses, and buckling considerations. Both shore towers and holding cranes can be used to reduce the deformations and redistribute stresses. Shore towers can be used to brace girders laterally and torsionally if the bracing is adequately strong and stiff. The optimum location for shore towers or holding cranes is the location of maximum positive bending moment between permanent supports. UT Bridge is a user-friendly 3-D finite element program that can be used to analyze partially constructed bridges and to provide valuable information to engineers and contractors in the assessment of the safety of a bridge at various construction phases. Additionally, UT Bridge can be used to locate the optimum location of shore towers and provide the design loads of the shore towers.

ERECTION AND CONSTRUCTION CALCULATION RECOMMENDATIONS:

The design and construction of curved I-girder bridges can be complicated. Therefore, it is important for design submittals to be standardized to ensure safety during construction. The AASHTO/NSBA Steel Bridge Collaboration produced the *Steel Bridge Erection Guide Specification* which provides guidance for the minimum submittal that should be provided by the contractor prior to the beginning of construction. These recommendations have been included below with some modifications as a recommendation for TxDOT's standard construction submittal for horizontally curved steel I-girder bridges.

Drawings:

1) A plan of the work area including permanent substructure units, roads, railroad tracks, waterways, overhead and underground utilities, and other information pertinent to erection,
2) The erection sequence for all members (girders, cross frames, diaphragms, etc.). The location of any temporary support condition, such as holding cranes or shore towers, should be noted along with the design load for the shore towers and/or the prescribed lifting force of the holding cranes. Member reference marked on the erection drawings should be the same as those used on the shop detail drawings.
3) The primary member (girder) delivery location and orientation.

4) The location of each crane for each primary member pick, showing radius and crane support (barges, mats, etc.).
5) The capacity chart for each crane configuration and boom length used in the work.
6) Details, weight, capacity, and arrangement of all rigging for primary member picks.
7) The lifting weight of the primary member picks, including all rigging and pre-attached elements to correspond to erection sequence.
8) Details of any temporary lifting devices to be bolted or welded to permanent members, including method and time (shop or field) of attachment, the capacity, and the method, time, and responsibility for removal.
9) Lifting and handling procedure for each primary member including the center of gravity, the method of lifting (single crane, multiple crane, etc.), and the number and location of lifting apparatus.
10) Blocking or bracing details for girders at permanent supports before cross frame members are attached at temporary supports.
11) Shoring tower (or falsework) design details, including the tower structure, footings, top beams, tower bracing, and all connections between erected girders and top beams and another major portions of the tower.
12) Safety measures detailed for special event such as “Hurricane Season”, if applicable for projects in effected regions.

Calculations:

1) Design calculations indicating the rotational deformations and the maximum stress of all primary girders during lifting procedures. This information should include rigid body rotation and cross-sectional twist for the rotational deformations. The maximum stress should include strong-axis bending, weak-axis bending, and warping normal stresses.
2) Design calculations indicating the load capacity and stability of temporary supports (shore towers and cranes) for each pick and release. Considerations for the wind load effects on temporary supports should be included.
3) Calculations to substantiate the structural adequacy and stability of girders for each step of bridge assembly and concrete deck placement.

4) Calculations to verify adequate capacity of contractor-fabricated rigging such as lifting beams, welded lugs, spreader beams, beam clamps, etc. Submit manufacturers' certification or catalog cuts for pre-engineered devices.
5) Calculations indicating structural integrity of any partially bolted primary splices after release of external support system
6) Calculations to substantiate structural integrity of abutments and retaining walls affected by surcharge from crane.

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