LEAN-ON CROSS-FRAME BRACING FOR STEEL GIRDERS WITH SKEWED SUPPORTS

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SUMMARY

This paper discusses the implementation of a lean-on bracing system, in which several girders "lean-on" a single cross-frame, being used in the design of three skewed steel bridges in Lubbock, Texas. The three bridges utilize two-span continuous straight steel plate girder systems with spans of 140 to 170 feet and have support skew angles of 54 to 60 degrees.

Relatively large live load forces from truck loading can be produced in cross-frames and diaphragms of bridges with significant skew angles, increasing the likelihood of fatigue concerns. By using lean-on bracing systems the magnitude of the cross-frame live-load forces can be minimized and the number of intermediate cross-frames required on the bridge can be substantially reduced.

This paper provides a summary of the research recommendations being used in design of the lean-on bracing systems and an overview of the resulting bracing layout for one of the implementation bridges. In future work on this project, the implementation bridges will be instrumented to monitor the behavior during construction and subsequent live loading

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INTRODUCTION

The design of steel bridge girders during construction is often controlled by lateral torsional buckling. The buckling capacity of the girders is typically increased by bracing the girders using cross-frames or diaphragms positioned at intermediate locations along the bridge length. The Texas Department of Transportation (TxDOT) has sponsored a number of studies of bracing requirements for steel bridges over the past 15 years which have led to the development of design requirements for bracing systems used in steel bridges as well as innovative details to minimize the amount of stability bracing required. A recently completed research project, TxDOT Research Study 0-1772 conducted at the University of Houston, focused on bracing of straight steel bridge girders with skewed supports [6]. The goals of the study included 1) improving understanding of the bracing requirements for steel girders with skewed supports, 2) developing details that would help minimize the number of braces required on these bridges, and 3) reducing the brace forces induced from truck traffic in the completed bridge. One of the recommendations resulting from the research study was to employ lean-on bracing concepts in straight steel bridges so that several girders could be braced using a single cross-frame or diaphragm. By employing lean-on bracing, the cross-frames can be positioned transversely on the skewed bridge in locations that minimize the magnitudes of live-load induced brace forces. TxDOT is currently designing three skewed bridges using these lean-on concepts.

This paper provides a discussion of the lean-on bracing concepts and an overview of one of the implementation bridges on which the bracing is being utilized. Background information on bracing requirements for steel bridges will be presented first followed by a discussion of the recommended bracing details. An overview of the cross-frame layout on the implementation bridge will then be provided along with a discussion of the process used to layout the positions of the cross-frames in the bracing system. Readers should note that this paper addresses bridges with straight girders; additional demands are placed on cross-frames in curved bridges.

BACKGROUND

Lateral torsional buckling often controls the design of steel girders during construction and in this failure mode there is a lateral translation and twist of the girder cross-section. Adequate bracing can be provided to the girders by restraining either the lateral movement of the cross-section, using a lateral bracing system, or twist of the cross-section, using a torsional bracing system. The cross-frames and diaphragms typically used to provide bracing in bridge systems fit into the category of torsional bracing systems since they restrain twist of the girder cross-section.

The AASHTO Specifications have historically been relatively silent with respect to the design requirements for cross-frames and diaphragms. The 25-ft. spacing limit in the AASHTO Standard Specifications for Highway Bridges [2] combined with the typical sizes used for bracing elements generally led to relatively stiff braces that were spaced closer together than necessary. The practice of not specifically designing braces tended to amplify fatigue problems commonly found around the braces since the braces were often larger and more closely spaced than required. The AASHTO LRFD Bridge Design Specifications [3] require that a "rational analysis" be utilized in the design of bracing systems used in bridges but does not provide the design requirements for the bracing. However, prescribed bracing requirements for steel members and frames are provided in The American Institute of Steel Construction (AISC) LRFD Specification [4] and the bracing provisions for torsional systems in the AISC specification are directly applicable to the bracing systems used with bridge girders.

The torsional bracing requirements specified for beams in the AISC LRFD Specification were primarily the result of TxDOT Research Study 0-1239 [7]. The study resulted in expressions for both the stiffness and strength requirements for torsional beam bracing. The stiffness requirement for torsional braces, β_T , in the AISC Specification is given in the following expression:

$$\beta_T = \frac{2.4 L M_u^2}{\phi n E I_y C_b^2} \tag{1}$$

where L is the beam span, M_u is the factored design moment, ϕ is the resistance factor, n is the number of intermediate braces, E is the modulus of elasticity, I_y is the weak axis moment of inertia, and C_b is the moment gradient factor for the braced beam. The stiffness provided by a torsional bracing systems should meet or exceed the required stiffness specified in Equation 1.

The total system stiffness provided by a cross-frame or diaphragm system is dependant on not only the stiffness of the braces, but also cross-sectional distortion and the in-plane girder stiffness. The total system stiffness, β_{sys} , follows the classic equation for springs in a series as given in the expression:

$$\frac{1}{\beta_{sys}} = \frac{1}{\beta_b} + \frac{1}{\beta_{\sec}} + \frac{1}{\beta_g} \tag{2}$$

where β_b is the brace stiffness, β_{sec} is the cross-sectional distortion, and β_g is the in-plane girder stiffness. The system stiffness as given by Equation 2 will be smaller than the smallest component on the right hand side of the equation.

An expression for cross-sectional distortion, β_{sec}, is given by Yura [9] and is also provided in the AISC Specification [4]. For partial depth diaphragms, the effects of cross-sectional distortion can be quite substantial and sizeable transverse stiffeners may be required. Since cross-frames tend to be relatively deep, cross-sectional distortion is usually not as critical as with diaphragms.

The effects of in-plane girder stiffness have been discussed in Helwig et. al [5] and Yura [9] and can be approximated with the following expression:

$$\beta_g = \frac{24(n_g - 1)^2 s^2 E I_x}{n_g L^3} \tag{3}$$

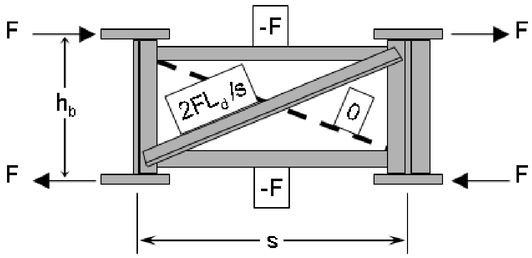

Figure 1 Cross-Frame with Tension Only Diagonal

where n_g is the number of girders through the bridge width, s is the girder spacing, E is the modulus of elasticity of the steel beams, I_x is the strong axis moment of inertia, and L is the beam span. Although the effect of in-plane girder stiffness can be significant for twin girder systems, it is generally not too significant for systems with several girders through the bridge width. Thus, in many cases the brace stiffness, β_b , is the limiting factor for the system stiffness. Yura [9] provides expressions for the brace stiffness of a variety of cross-frame systems, including the typical cross-frame detail consisting of two diagonals forming an “X” along with top and bottom struts as shown in Figure 1.

Since the diagonals usually consist of angles that have a relatively low buckling strength, the compression diagonal is often conservatively neglected. Therefore the system is treated as a tension-only diagonal system for which the brace stiffness, β_b , is as given in the following expression:

$$\beta_b = \frac{Es^2 h_b^2}{\frac{2L_d^3}{A_d} + \frac{s^3}{A_s}} \tag{4}$$

where E is the modulus of elasticity of the cross-frame material, s and h_b are the dimensions indicated in Figure 1, L_d is the length of the diagonal, and A_d and A_s are the respective cross-sectional areas of the diagonal and horizontal struts. Braces that provide adequate stiffness can thus be designed by ensuring the total stiffness provided by the bracing system, β_{sys}, meets or exceeds the required stiffness, β_T, specified in Equation 1.

In addition to satisfying stiffness requirements, effective brace systems must also possess adequate strength. Strength requirements for the braces have been developed using an assumed initial imperfection for the girders consisting of a initial twist of $L_b/500d$, where d is the girder depth. The resulting strength requirements for cross-frames or diaphragms are as given in the following expression [4,9]:

$$M_{br} = \frac{0.024 M_u L}{n C_b L_b} \tag{5}$$

where M_{br} is the moment in the torsional brace, M_u is the maximum factored beam moment, L is the beam span, and L_b is the spacing between torsional braces. The resulting forces in the cross-frame are a function of $F=M_{br}/h_b$ as indicated in Figure 1. By satisfying the requirements specified in Equations 1 and 5, cross-frame and diaphragm systems which have both adequate stiffness and strength can be designed for typical steel girder bridge systems.

STEEL I-GIRDER BRIDGES WITH SKEWED SUPPORTS

The stiffness and strength expressions presented in the prior section were developed assuming both the bridge supports and braces are oriented normal to the longitudinal axis of the girders. Effects of support skew on the bracing behavior were not considered in the development of these expressions. For bridge systems with skewed supports, large live load forces can be induced in the cross-frames and diaphragms in the completed bridge as a result of the relative vertical deflection between adjacent girders under truck loads. The larger live load brace forces in bridges with skewed supports increase the potential for fatigue concerns where these braces frame into the girders. One reason for the removal of the maximum spacing limit for cross-frame and diaphragms in the AASHTO LRFD Specifications was due to fatigue problems that have occurred in the vicinity of bracing elements. Many of the fatigue issues have since been mitigated by modifications in the transverse stiffener details that require the stiffeners at the brace locations to be connected to the girder flanges. However, for systems with significant support skew, large live load forces can still be produced in the braces from truck traffic and hence there is an increased risk for fatigue concerns.

TxDOT Project 0-1772, conducted at the University of Houston, focused on improving understanding of the bracing behavior in bridge systems with skewed supports [6]. The research study included examinations of bracing systems oriented both parallel to the skew as well as cases where the intermediate braces were framed perpendicular to the longitudinal axis of the girders. The bracing strength and stiffness expressions presented in the prior section, which were developed for bridges with normal supports, were also modified to account for the impact of brace or support skew angles as discussed by Helwig and Wang [6]. Alternatively, detailed 3D finite element analyses of the bridge system can be utilized to assist in sizing bracing members for normal or skewed bridges.

In addition to modifying the bracing design expressions to account for the impact of support skew, details were also recommended in TxDOT Study 0-1772 to both reduce the number of intermediate braces required and also lessen the forces induced in these braces due to truck traffic. The recommended details employ lean-on bracing concepts that have been presented by Yura and Helwig [8]. The application of the lean-on concepts results in a single cross-frame providing bracing to several girders as shown in Figure 2. Top and bottom struts can be used to permit several girders to lean on a single cross-frame.

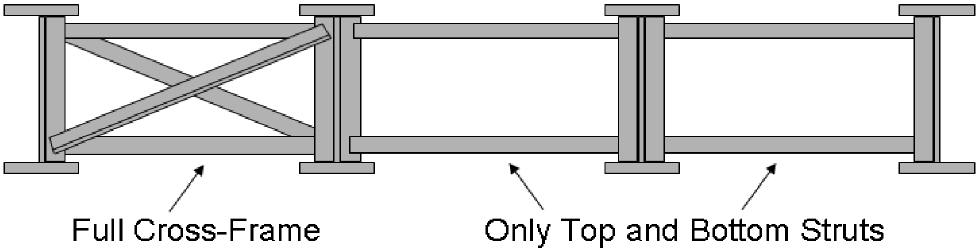

Figure 2: Lean-on Bracing System Allows Four Girders to be Braced by One Cross-Frame

The lean-on concept also gives the engineer the flexibility of selecting positions for the cross-frames within a given bracing line to minimize the cross-frame forces induced by truck traffic in the completed bridge. Figure 3 shows a plan view of a 4-girder system with a skewed support utilizing the lean-on bracing system. Full lines of cross-frames must be provided at support locations, however lean-on concepts can be used on the intermediate (between the supports) bracing lines. The position of the cross-frame within a given intermediate bracing line is indicated by an “X” in both the plan and bracing line views. To minimize the forces induced in the cross-frames by truck traffic, the transverse position of the cross-frames should be selected such that they are as far away from the support as possible. Cross-frames that are nearer the support connect girder locations with relatively little or no live load deflections to adjacent girder locations with larger vertical deflections. For cross-frames positioned near support locations, this relative deflection across the cross-frame induces large cross-frame forces. By positioning the cross-frames away from the supports at locations with smaller relative vertical girder deflection the brace forces induced from live loading can be reduced.

Bracing lines near the supports, such as “A” or “E” in Figure 3, should also not be framed directly into the support since doing so ties the cross-frame line to a very stiff support location which will experience no live load girder deflection. By offsetting the first bracing line a few feet (~3 to 4 ft. for typical bridges) from the skewed support the increased girder flexibility near the bracing line substantially reduces the live load forces that develop in the braces while still providing enough stiffness to brace the girders. The lean-on layout also

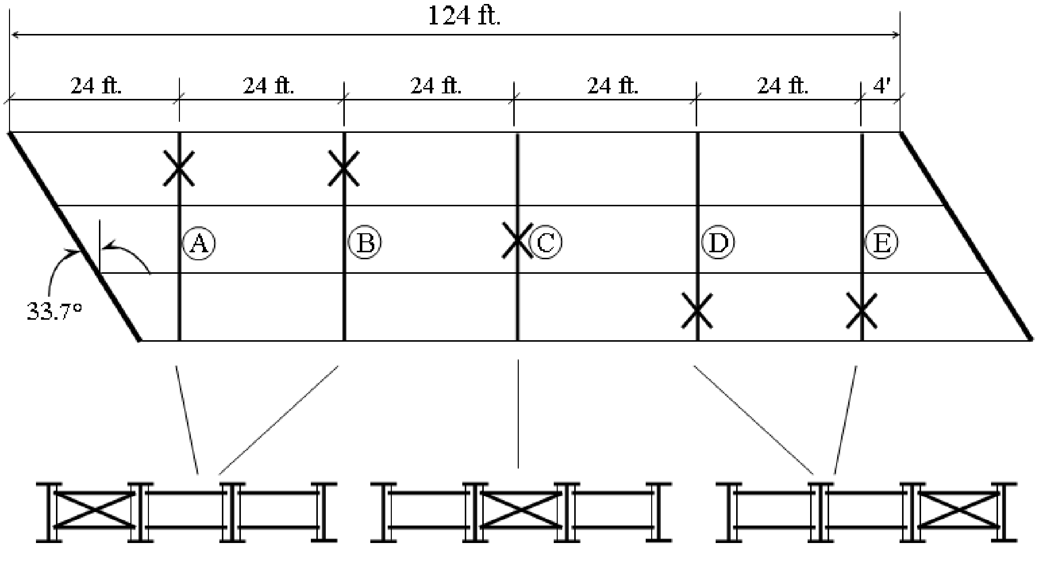

Figure 3: Plan View of Lean-On Layout for Four Girder Bridge

results in a reduction in the total number of cross-frames required on the bridge. A conventional bracing system for the 4-girder system shown in Figure 3 would have included use of 15 intermediate cross-frames; with the lean-on bracing layout the number of intermediate (between supports) cross-frames is reduced to 5.

When utilizing lean-on concepts, the stiffness and strength expressions presented earlier must be modified to reflect the fact that multiple girders will be leaning on a single cross-frame. Using equilibrium for a cross-frame bracing n_{gc} girders (n_{gc} = number of girders per cross-frame = 4 in Figure 4), the general strut and diagonal forces are as given in the following expressions:

$$F_s = (n_{gc} - 1)F \tag{6}$$

$$F_d = \frac{n_{gc} F L_d}{s} \tag{7}$$

where F_s and F_d are the respective strut and diagonal forces and the other parameters are as previously defined. The expressions in equations (6) and (7) were developed for the case where the cross-frame is attached to an exterior girder shown in Figure 4. The equations provide conservative results for configurations where the cross-frame is not attached to an exterior girder.

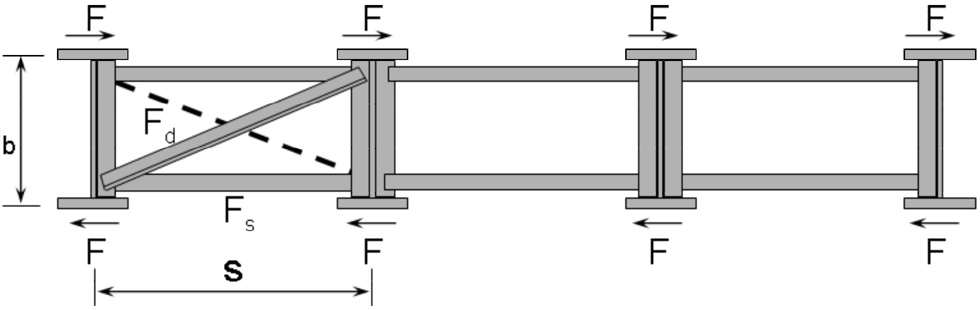

Figure 4:Cross-Frame Forces in Lean-On System

The larger forces in the diagonals and struts also affect the stiffness provided by the lean-on bracing. Modifying the brace stiffness equation to account for leaning several girders on one cross-frame results in the following expression:

$$\beta_b = \frac{E s^2 h_b^2}{\frac{n_{gc} L_d^3}{A_d} + \frac{s^3}{A_s}\left(n_{gc} - 1\right)^2} \tag{8}$$

The in-plane girder stiffness is also affected by using the lean-on bracing system. In the discussion of the in-plane girder stiffness given in Equation 3, it was mentioned that this term can dominate the system stiffness in twin girder systems. Helwig and Wang [6] recommended that the X-bracing be distributed across the bridge width similar to the layout shown in Figure 3 to tie the girders together and lessen the impact of the lean-on system on the in-plane stiffness term. Helwig and Wang recommended that the stiffness given by Equation 3 be reduced by 50% when using a lean-on system to account for fewer cross-frames at each brace line, however it was important that each girder have at least one intermediate cross-frame connected directly to it such as the system shown in Figure 3.

IMPLEMENTATION OF LEAN-ON SYSTEM

TxDOT has been using the recommendations from Project 0-1772 [6] in the design of the bracing systems for three skewed bridges to be constructed in Lubbock, Texas and one bridge with normal supports to be constructed in Austin, Texas. The three skewed bridges are all two-span continuous systems with severe support skews of 50 to 60 degrees. One of the skewed bridges is a nine-girder system and the other two skewed bridges are six-girder systems. The implementation bridges will be monitored by research personnel from the University of Houston during erection and construction, and after the bridges are completed live load tests will also be conducted to measure the forces in selected cross-frames using the lean-on bracing system.

The layout of the bracing used in one of the implementation bridges (Figure 5), which is a nine girder system with a support skew of 54 degrees, will be discussed in this section. It should be noted that whether or not a lean-on bracing system is used for intermediate (between supports) brace lines, cross-frames should be positioned between every girder at support locations as shown in the plan view of the bridge system in Figure 5. The X's in the figure denote the locations of full cross-frames (struts and diagonals). Only top and bottom struts are used at other locations at intermediate cross-frame lines as shown in the section views displayed at the bottom of the figure. As suggested in the recommendations detailed in the prior section, the bracing lines in the support regions were not framed directly into the support locations but were instead offset by 4 ft. from the support to reduce the magnitude of live load forces induced in the bracing.

As shown in Figure 5, the final layout for the braces in the lean-on system used in the implementation bridge includes cross-frames between each girder arranged to form a path of continuity across the bridge. For the cross-frame lines nearest the supports, the transverse locations of the cross-frames are such that the cross-frames are positioned as far from the supports as possible. A pair of cross-frames is also provided at mid-width of the bridge near the midspan location of each span. The cross-frames in the remaining cross-frame lines provide a path connecting the cross-frames between the exterior and middle girders, such that there is at least one cross-frame between each and every girder.

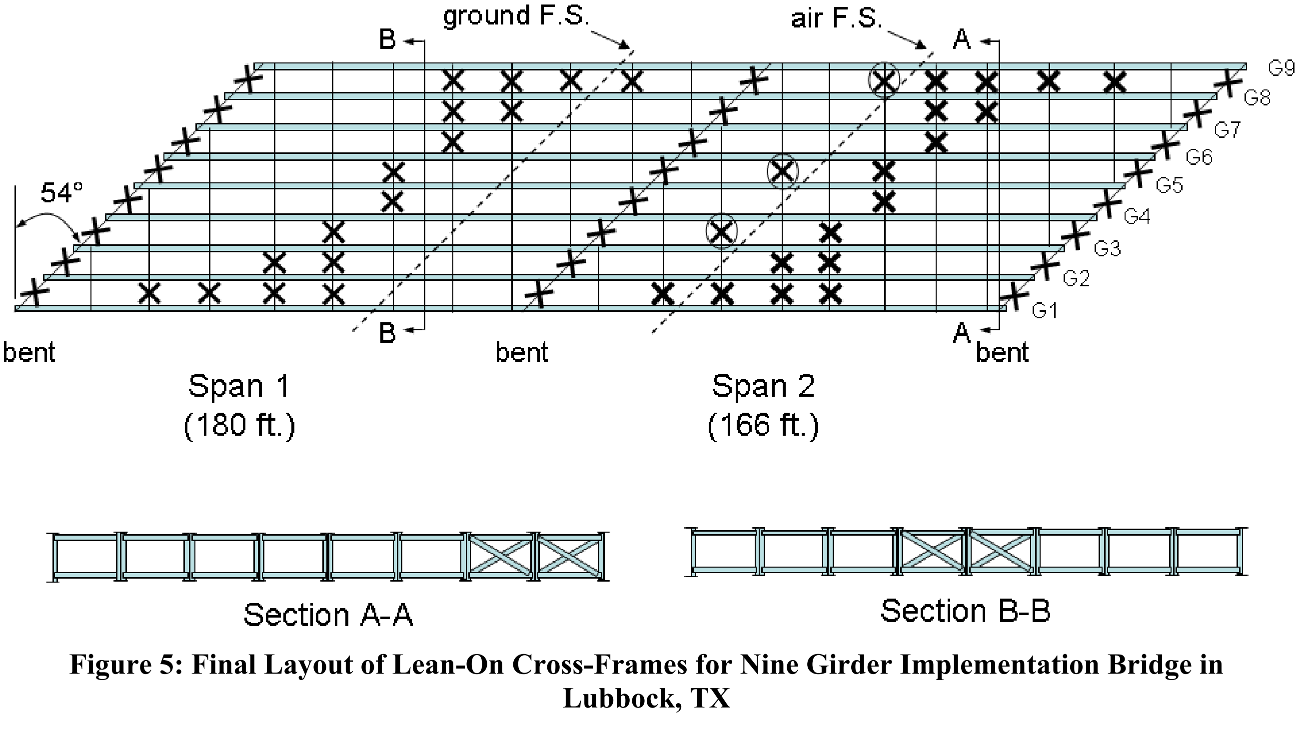

Figure 5: Final Layout of Lean-On Cross-Frames for Nine Girder Implementation Bridge in Lubbock, TX

Using a conventional layout for the cross-frames, with cross-frames across the width of the bridge at every intermediate cross-frame line, the nine-girder bridge would have required 128 intermediate cross-frames. The number of intermediate cross-frames was reduced to 35 using the lean-on system. The sizes of all the struts and the cross-frame diagonals are L5x5x3/4 angles. The same size angles were used for the cross-frames at both the support and intermediate cross-frame locations. If a conventional cross-frame layout (with 128 intermediate cross-frames) had been used smaller L4x4x3/8 angles could have been used in the intermediate cross-frame lines, but the larger L5x5x3/4 angles would still have been required at the support locations due to the long cross-frame member lengths resulting from the support skew. With the lean-on layout, bolted connections will be used at locations that just have struts while the locations with full cross-frames will be welded.

In the lean-on layout shown in Figure 5, three cross-frames, which are circled in the figure, were added to the bridge to facilitate girder erection. The erection scheme for the girders specifies that the field splice (F.S.) in Span 1 will be completed on the ground and the girders in Span 1 will then be erected followed by completion of Span 2. Erection must begin with an exterior girder and proceed across the width of the bridge. The contractor may elect to start erection with either girder G1 or G9. The cross-frames and struts between girders G1 and G2 or G8 and G9 could be installed on the ground and the girders could be lifted as a pair, or the contractor can elect to lift an exterior girder and the adjacent girder one at a time and hold the girders using cranes until the cross-frames and struts can be installed between the two girders. The circled cross-frame between girders G8-G9 was added on the overhang section in Span 2 to facilitate erection of G8 and G9 as a pair.

The erection scheme specifies that an exterior girder pair must be lifted first since there are several cross-frames between each exterior girder and its adjacent girder (4 cross-frames between G1-G2 and G8-G9 in Span 1). Once an exterior girder pair has been erected, this girder pair can then be used as a base on which to "lean" additional girders if the contractor elects to set the remaining girders one at a time. Rather then using single girder lifts the contractor may alternatively elect to lift G3-G4 and G5-G6 in pairs. To facilitate erection of these girders in pairs, the circled cross-frames in Figure 5 between G3-G4 and G5-G6 were added. The circled cross-frames connect the ends of the girders on the overhang section in Span 2. Girder (G7) will be lifted individually whether or not a paired erection scheme is used for the other girders. During the erection sequence, the contractor must install all cross-frames and every other strut between girders (or girder pairs).

The erection scheme for the implementation bridge specifies that Span 1 will be erected first. If the erection scheme did not call for Span 1 to be completed first, then additional cross-frames (like the circled cross-frames in Span 2) should be added in Span 1. Thus if the contractor chose to follow a paired erection scheme starting with Span 2 there should be cross-frames positioned at the ends of the girder overhangs into Span 1 to facilitate erection. If the designer wishes to provide even more flexibility in the erection scheme cross-frames could be positioned between each girder on either side of the field splice in both spans to permit the contractor to start construction with either span and allow any adjacent girders to be lifted in pairs (rather than specifying G3-G4 and G5-G6 as paired lifts and G7 as an individual lift). Though the erection scheme for the implementation bridge was controlled by the positioning of the cross-frames, there will be significant oversight by both TxDOT and the researchers during erection of the implementation bridge. The researchers recommend that when designers use a lean-on bracing system for other bridges that they strongly consider laying out the lean-on bracing system to provide as much erection flexibility as possible. The designer should thus position cross-frames between each girder in the areas bordering field splices as noted above. Doing so will increase the number of cross-frames on the bridge but will still utilize significantly fewer cross-frames than would a conventional layout while providing more erection options for the contractor. The designer should show at least one erectable scheme and if the contractor wants to use a different scheme the alternate erection scheme should be reviewed.

CONTROLLING RELATIVE GIRDER DEFLECTION DURING CONSTRUCTION

In the preliminary planning for the implementation bridges, the researchers investigated many different lean-on layouts. One of these preliminary layouts is shown in Figure 6. An important deficiency in the layout shown in Figure 6 is the absence of intermediate cross-frames between some adjacent girders. For instance, there are no intermediate cross-frames between G2-G3 and G7-G8 in Span 1, and no intermediate cross-frames between G2-G3, G6-G7, and G7-G8 in Span 2. Although the bracing layout shown in Figure 6 provides adequate construction stability under the steel and concrete dead loads plus the construction live load of 50 psf used by TxDOT, there is a potential for an unusual deflection profile across the width of the bridge during the deck cast with this layout.

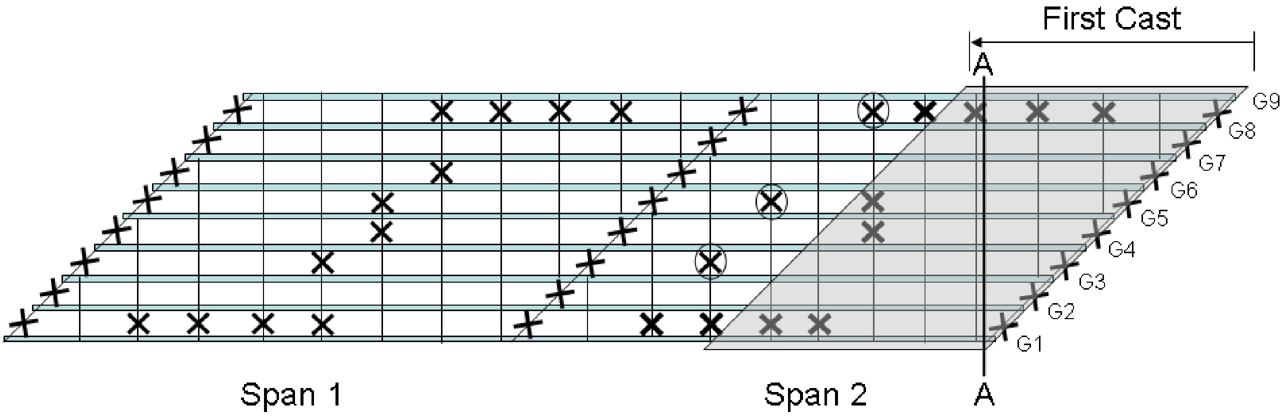

Figure 6: Preliminary Layout of Lean-On Cross-Frames

The response of the bridge with the preliminary cross-frame layout shown in Figure 6 was evaluated during deck casting. The deck casting sequence that will be used will begin with a first cast in Span 2 as shown in Figure 6. The deck will be cast parallel to the skew starting from the exterior support. The vertical deflection of each girder at Section A-A shown in Figure 6 was obtained from a three dimensional finite element model of the implementation bridge. Girder deflections at Section A-A were evaluated for bridge systems with a conventional bracing layout (128 intermediate cross-frames), the final lean-on layout shown in Figure 5, as well as the preliminary lean-on layout shown in Figure 6. The vertical deflection of each girder at three locations (outside edge of top flange, midwidth of top flange, and inside edge of top flange) at Section A-A are plotted in Figure 7. The x-axis of the figure shows the distance from the edge of the deck overhang at G1. The labels at the top of the figure (G1, G2, …) indicate the location of each girder. As shown in the figure, both the conventional layout and the final lean-on layout show a relatively smooth shape across the width of the deck at Section A-A. But with the preliminary layout there is a noticeable kink in the deck profile in between girders G7 and G8. Due to the lack of intermediate cross-frames connecting girders G7 and G8 these girders experience a noticeable relative deflection difference as shown in the plot. There are several cross-frames between girders G8 and G9, so this pair of girders deflects and rotates as a unit. There are also relatively short girder lengths from the end support to Section A-A for girders G1, G2, G3 and G4, as well intermediate cross-frames between G1-G2, G3-G4, G4-G5, and G5-G6 in Span 2 and G6-G7 in Span 1. However, there were no

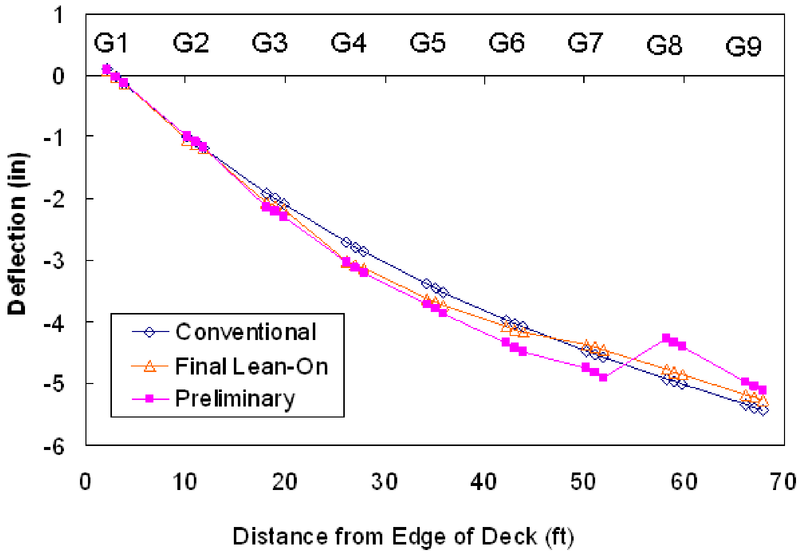

Figure 7: Girder Deflection at Section A-A

intermediate cross-frames connecting G7 and G8 in the preliminary lean-on layout. Consequently G1 through G7 rotate and deflect as a unit and G8 and G9 rotate and deflect together, but there is nothing tying together the system between girders G7 and G8 and the irregular profile shown in Figure 7 results.

The deflection profile for the preliminary lean-on layout shown in Figure 7 has the potential to create problems during the deck cast. The transverse reinforcement in the deck will run parallel to Section A-A, and it is not likely that this reinforcement would be flexible enough to adopt the "kinked" decked profile resulting from the preliminary lean-on layout. This kinked deck profile would most certainly lead to non-uniform cover on the top mat of deck reinforcement, and could possibly even result in scalping of the reinforcement in some areas. It should be noted that kinks in the deck profile were seen with the preliminary lean-on layout at multiple locations along the bridge; the profile at Section A-A is just used as an example to show the issue that may result if intermediate cross-frames are not positioned between every girder at select locations in each span. As long as intermediate cross-frames are placed between each girder, as shown in Figure 5, a smooth transverse profile, analogous to that seen with conventional cross-frame layouts, can be obtained.

SUMMARY

A recent study of the stability bracing requirements for beams with skewed supports has led to a better understanding of the bracing required for such systems and an alternative "lean-on" bracing layout that can be used to reduce the live-load induced brace forces in the completed skewed bridge. With the lean-on bracing system full lines of cross-frames are still required at support locations, but the number of intermediate cross-frames required on the bridge can be substantially reduced. Using a lean-on system, full intermediate cross-frames are positioned at select locations in intermediate cross-frame lines to ensure stability during construction, to control differential deflection between adjacent girders, and for erection purposes. Other full cross-frames, consisting of two diagonals with a top and bottom strut, are replaced by only a top and bottom strut. While two struts are still required in the lean-on bracing system, the connection requirements for the struts are relatively simple and often only require a few bolts.

Lean-on bracing can improve erection, economy, and fatigue performance of skewed bridges. A significant number of cross-frames can be eliminated and the live load forces in the remaining cross-frames can also be reduced using the lean-on bracing layout. TxDOT is currently implementing the lean-on bracing system in the design of three bridges with severe support skew in Lubbock, Texas. In future work on this project, the implementation bridges will be instrumented to monitor their behavior during construction and subsequent live load testing.

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