Simplified Method to Determine the Effect of Detailing on Cross-Frame Forces

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ABSTRACT

There are several issues that necessitate the use of steel I-girder bridges with skewed supports. Due to skew supports, the axis of rotation of bearing line cross-frames is not in line with the axis of rotation of girders, and connection points of intermediate cross-frames are either at different elevations or undergo different deflections. The consequence of this behavior is that the cross-frames fit between the girders at one loading stage and do not fit between the girders at other loading stages, depending on the detailing method used to detail the cross-frames. Additional structural responses, henceforth called lack-of-fit effects, are developed when cross-frames do not fit between the girders. These lack-of-fit effects can be estimated by different methods of analysis for different detailing methods. In addition to lack-of-fit effects, fit-up forces are required to fit the cross-frames between their connections to the girder during erection, for the total dead load (TDL) fit detailing method. Methods of analysis to estimate fit-up forces are not available.

The objective of this paper is to introduce different methods that can be used to calculate lack-of-fit effects for the steel dead load (SDL) fit detailing method at the TDL stage and the TDL fit detailing method at the SDL stage. A comparison of different methods is done to recommend a single simplified method of analysis that can be used to calculate lack-of-fit effects for both the SDL fit and TDL fit detailing methods with reasonable accuracy. Analysis methods are proposed to estimate the fit-up forces. The main conclusion of this research is that improved 2D grid analysis can be used to estimate lack-of-fit effects for both the TDL fit and SDL fit detailing methods and can also be used to determine fit-up forces for connecting girders and cross-frames detailed with TDL fit.

Keywords: skew, steel bridges, detailing methods, structural response, analysis methods, guidelines.

INTRODUCTION

Although the uses of support lines that are perpendicular to the longitudinal axis of a bridge are highly desirable, there are several issues that necessitate the use of systems with skewed supports, including geometrical constraints of intersecting roadways, geological restrictions of the terrain surrounding the bridge, and other factors. The effects of the skewed supports lead to interactions between adjacent girders and the bracing that can result in significant torsional deformations of steel bridges during construction.

Earlier studies have reported several problems in straight skewed steel bridges during both girder erection and placement of the concrete bridge deck. These problems include excessive twist of the girders, uplift at the support locations, development of flange lateral bending stresses, and difficulty fitting the cross-frames during erection (Grunauer, 2011; Ozgur, 2011; White et al., 2012; Norton et al., 2003; Ahmadi and Henney, 2005). These problems are generally associated with the detailing method used for the girders and cross-frames. In steel dead load (SDL) fit, the cross-frames are detailed to fit to the girders in their ideally plumb, as-deflected positions under the bridge SDL that is load at the completion of the erection. SDL fit is generally used to reduce the forces required to install cross-frames in the field when girders are supported on their self-weight. In total dead load (TDL) fit, the cross-frames are detailed to fit to the girders in their ideally plumb, as-deflected positions under the bridge TDL, that is, dead load at completion of a bridge.

Different methods of analysis that are commonly used for steel bridges with skewed supports include improved 2D grid analysis (GA), traditional 2D GA, and 3D finite element method (FEM) analysis (Grunauer, 2011; Ozgur, 2011; White et al., 2012; AASHTO/NSBA, 2011; Linzell et al., 2010). Currently, 2D GA can be used for the SDL fit detailing method only, and a 3D FEM analysis with initial strains in the cross-frames is required for the TDL fit detailing method.

The objective of this paper is to introduce different methods that can be used to calculate lack-of-fit effect for the SDL fit detailing method at the total dead load stage and the TDL fit detailing method at the steel dead load stage. A comparison of different methods is done to recommend a single simplified method of analysis that can be used to calculate lack-of-fit effects for both the SDL fit and TDL fit

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detailing methods with reasonable accuracy. The simplified analysis method is further utilized to calculate fit-up forces.

DESCRIPTION OF STRUCTURES USED FOR COMPARISON OF METHODS ANALYSIS

Three straight-skewed, simply supported, I-girder bridges having different levels of skew are selected for consideration in this study. All three bridges have girders and cross-frames designed with Grade 50 steel having a modulus of elasticity of 29,000 ksi.

Bridge A is an extreme case of straight-skew bridges and was used to show extreme skew effects in previous studies (Grunauer, 2011; Ozgur, 2011; White et al., 2012). Bridge A has 300-ft-long by 144-in.-deep girders simply supported on 70.4° skewed supports. The girders of Bridge A are braced with X-type cross-frames containing L6×6×1 angles. The bridge uses staggered cross-frames at 22-ft spacing between nine girders at 9.25 ft center-to-center spacing. Framing plans and sizes of the web and flanges of the bridges studied are shown in Figure 1.

Bridge B is another highly skewed bridge, however

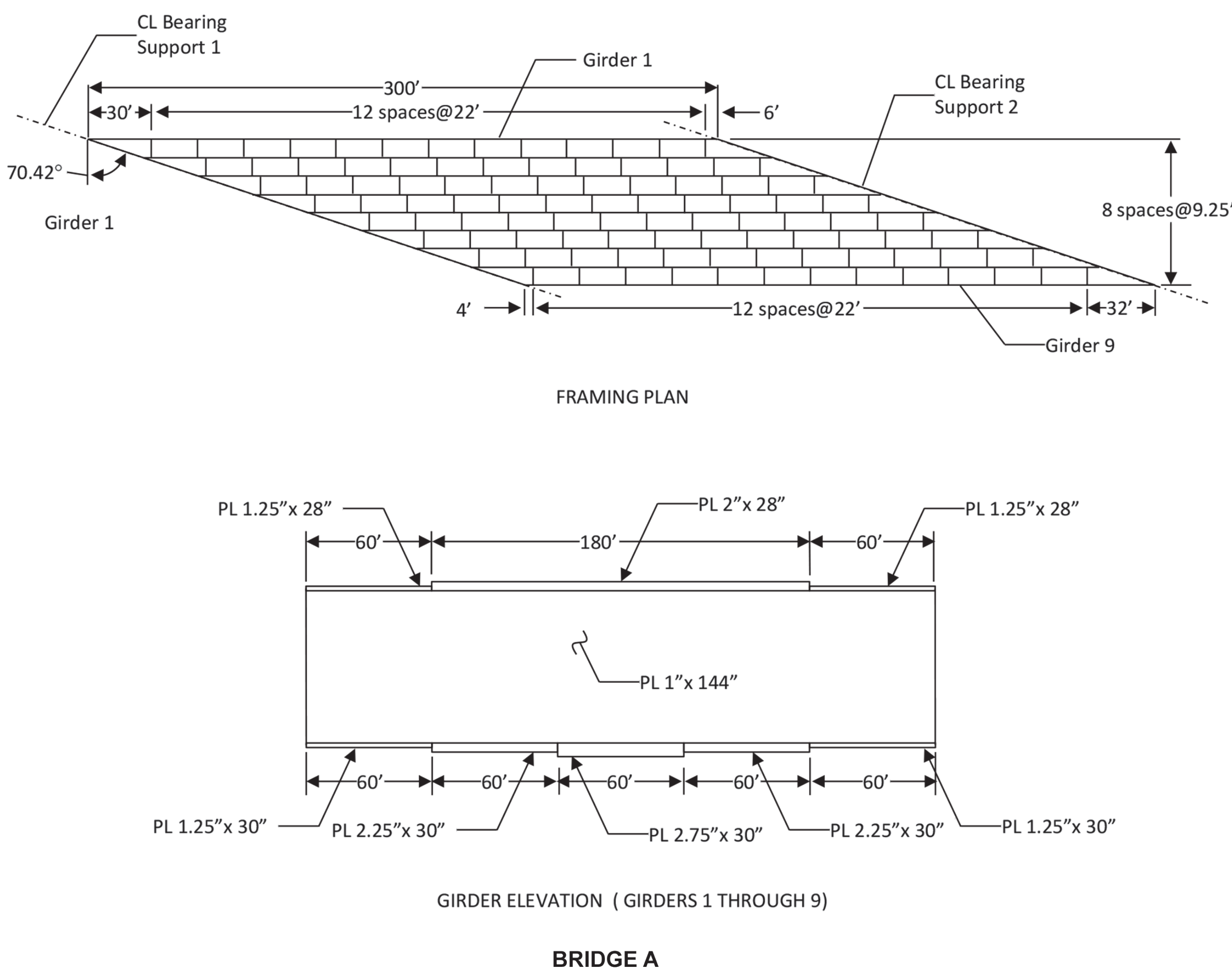


Fig. 1. Framing plan and girder sizes of Bridge A.

the skewed effects in Bridge B are smaller compared to Bridge A. Bridge B has 266-ft-long by 120.5-in.-deep girders simply supported on 62.6º skewed supports. The girders of Bridge B are braced with X-type cross-frames containing L6×6×½ angles. The bridge uses cross-frames at 16-ft spacing between eight girders at 7.26-ft center-to-center spacing. Framing plans and sizes of the web and flanges of the bridges studied are shown in Figure 2.

Bridge C has 150-ft-long by 56.1-in.-deep girders simply supported on 70.0º skewed supports. The girders of Bridge C are braced with X-type cross-frames containing L6×3½×5⁄16 angles. The bridge uses cross-frames at 21-ft spacing between four girders at 8-ft center-to-center spacing. Framing plans and sizes of the web and flanges of the bridges studied are shown in Figure 3.

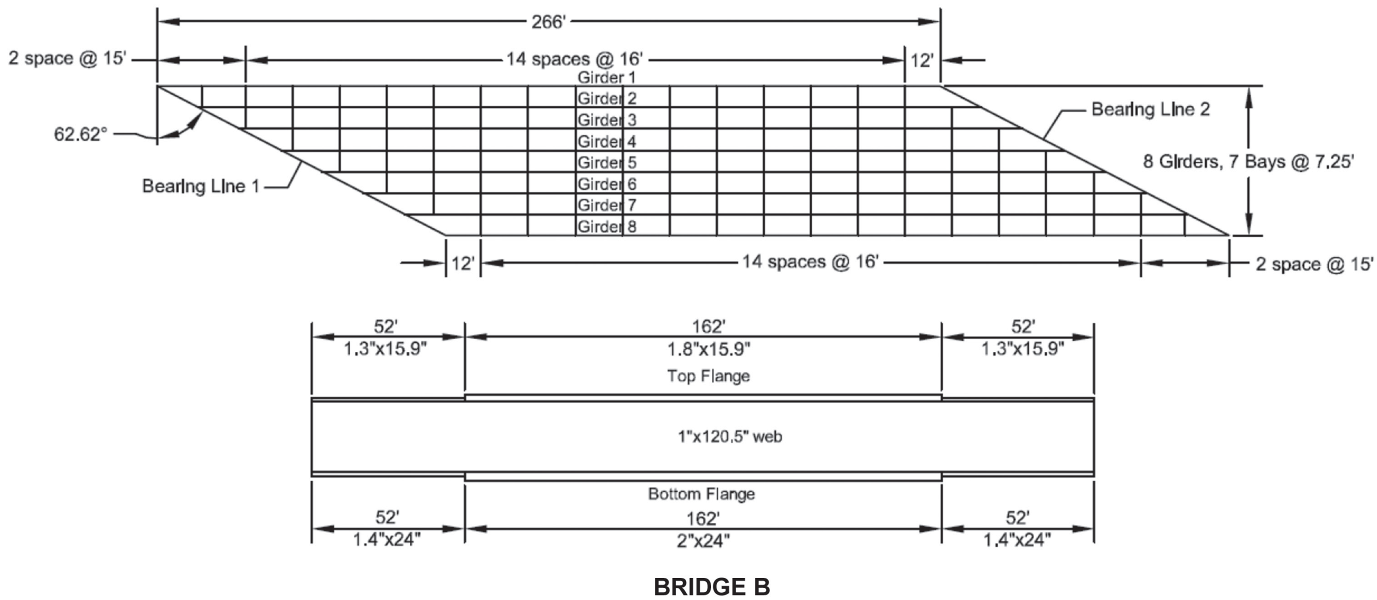


Fig. 2. Framing plan and girder sizes of Bridge B.

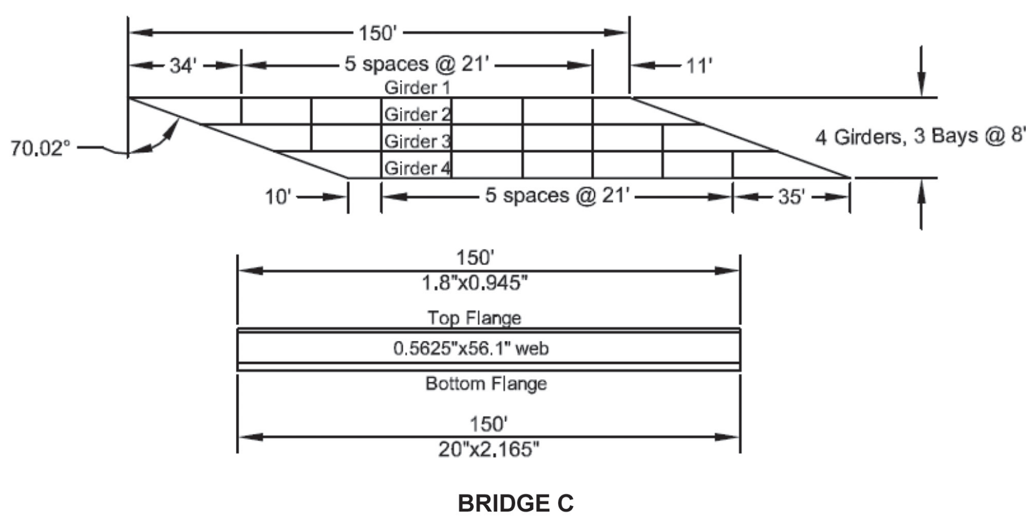


Fig. 3. Framing plan and girder sizes of Bridge C.

SDL FIT DETAILING METHOD

Methods of Analysis

Before discussing different structural responses of skewed steel girder bridges, it is important to discuss different methods of analysis that are used for the calculation of these responses. These methods of analysis are discussed at length in NCHRP 725 (White et al., 2012). A summary is provided here.

1D Line Girder Analysis

In 1D line girder analysis (LGA), the girders are analyzed as line elements without any cross-frame attached to them. In this paper, 1D LGA refers to a line elements model of the bridge girders only.

2D Grid Analysis

In this paper, 2D grid analysis (GA) refers to a modeling technique in which each node has six degrees of freedom (three translations and three rotations), but the entire structural model of the bridge is in a single horizontal plane. This paper uses two types of 2D GA: simplified methods that are used by some commercial programs, hereafter referred at as traditional 2D GA, and an improved 2D GA recommended in (White et al., 2012).

The torsional stiffness of the girders is estimated by the St. Venant term using the torsional constant, J, in traditional 2D GA. In the improved 2D GA, the torsional stiffness of the girder is modeled by using an equivalent torsional constant, J_{eq}, that considers both the St. Venant and warping terms in the calculation of the torsional stiffness. A detailed expression for obtaining J_{eq} for I-sections is given in the literature (Ahmed and Weisberger, 1996) and presented here in Equations 1 and 2. Equation 1 is based upon the assumption that both ends of the unbraced length, L_b, are fixed, while Equation 2 is based upon the assumption that one end of the unbraced length is fixed and the other is pinned.

$$J_{eq(fx-fx)} = J\left\{1-\frac{\sinh(pL_b)}{pL_b}+\frac{[\cosh(pL_b)-1]^2}{pL_b\sinh(pL_b)}\right\}^{-1} \quad (1)$$

$$J_{eq(fx-pin)} = J\left[1-\frac{\sinh(pL_b)}{pL_b\cosh(pL_b)}\right]^{-1} \quad (2)$$

where

$$p=\sqrt{\frac{GJ}{EC_w}}$$

G is the modulus of rigidity and can be approximated by $G=\dfrac{E}{2(1+\nu)}$, E is the modulus of elasticity, ν is Poisson's ratio, and C_w is the warping constant.

Cross-frames are modeled using a beam element with a moment of inertia, I_{eq}, that matches the flexural stiffness of the truss representation of the cross-frame. The beam also has a cross-sectional area, A_{eq}, that matches the axial stiffness of the cross-frame system. The traditional 2D GA uses the Euler Bernoulli beam stiffness matrix, whereas the improved 2D GA employed here uses an equivalent beam stiffness that matches the stiffness of a truss idealization of the cross-frames exactly within their plane. Detailed derivations and expressions for these stiffness matrices are provided in Grunauer (2011) and White et al. (2012).

It should be noted that in the SDL fit detailing method, the lack-of-fit effects such as layovers, component of deflection due to lack-of-fit, cross-frame forces, component of reactions due to lack of fit, and flange lateral bending stress due to skew effects are of interest after placement of the wet concrete. Therefore, to carry out an SDL fit analysis using the 2D grid analysis, a complete model of the structure is constructed with cross-frames attached to the girders followed by activating the concrete dead load.

3D Finite Element Analysis

At the research stage, different three-dimensional FEM models were analyzed using ANSYS (ANSYS, 2009). Three-dimensional finite element analysis (3D FEM) can be used with different levels of modeling techniques. For example, in a 3D FEM, the flanges can be modeled using either beam elements or shell elements with or without bearing pads. Three-dimensional FEM analyses carried out as a part of NCHRP 725 modeled the flanges using beam elements without bearing pads. In this study, flanges are modeled using shell elements with a bearing pad model. The bearing pads were modeled with solid element of ANSYS (ANSYS, 2009) using an equivalent modulus of elasticity of 10 ksi.

Three-dimensional FEM for the SDL fit detailing method can be accomplished by following the same steps used for 2D GA.

Comparison of Different Methods of Analysis

Different methods of analysis discussed in the preceding sections are used to evaluate lack-of-fit effects for the SDL fit detailing method at the TDL stage. These lack-of-fit effects include layovers, component of deflection due to lack of fit, component of reaction due to lack of fit, flange lateral bending stress, and cross-frame forces. Table 1 shows maximum values of lack-of-fit effects; each lack-of-fit effect is obtained from different methods of analysis and compared to recommend a method of analysis for calculating the lack-of-fit effects. Detailed comparison of the results is provided in research reports by Gull and Azizinamini (2014a, 2014b).

The lack-of-fit effects compared in Table 1 are layovers; component of vertical deflection due to lack of fit, D_{Y2};

Table 1. Comparison of Lack-of-Fit Effects from Different Methods of Analysis—SDL Fit at TDL Stage									
	Absolute Maximum Value of Lack-of-Fit Effect								
	Bridge A			Bridge B			Bridge C		
Lack-of-Fit Effect	3D FEM	2D GA Imp	2D GA Trd	3D FEM	2D GA Imp	2D GA Trd	3D FEM	2D GA Imp	2D GA Trd
Layovers (in.)	2.5	2.3	2.6	1.7	1.8	1.8	1.7	1.8	1.9
D_{Y2} (in.)	2.1	2.4	0.3	0.6	0.7	0.6	1.0	1.0	0.8
R_{Y2} (kips)	278	427	7	56.8	66.5	54.5	17.9	21.6	18.1
f_l (ksi)	14.0	35.9	0.3	2.2	3.6	0.2	2.2	5.1	1.1
Cross-frame forces (kips)	96	193	3	28.9	37.0	36.3	14.9	18.7	17.1

Note: 2D GA Imp = improved 2D grid analysis and 2D GA Trd = traditional 2D grid analysis.

component of vertical reaction due to lack of fit, R_{Y2}; flange lateral bending stress, f_l; and cross-frame forces. D_{Y2} can computed by subtracting vertical deflection of isolated girder under certain dead load from the vertical deflection of bridge frame (girder and cross-frames connected) under the same dead load. Essentially, D_{Y2} is the component of the deflection caused by interaction of the cross-frames and girder and is directly impacted by the detailing methods. Similarly, R_{Y2} can be computed by subtracting the vertical reaction of the isolated girder under a certain dead load from the vertical reaction of the bridge frame (girder and cross-frames connected) under the same dead load. Essentially, R_{Y2} is the component of the reaction caused by the interaction of the cross-frames and girder and is directly impacted by the detailing methods.

Traditional 2D GA provides poor estimates of lack-of-fit effects for Bridge A and good estimates of lack-of-fit effects for Bridge B, except f_l as shown in Table 1. This is because of the staggered framing used in Bridge A compared to the straight framing used in Bridge B. In staggered framing, a cross-frame connects only two girders and forces in the cross-frame in the adjacent bays must be transferred through the girders. In contiguous framing, forces can be transferred directly from the cross-frames in adjacent bays. Therefore, in staggered framing, lack-of-fit effects are dependent on the torsional stiffness of the independent girders. Because traditional 2D GA does not model the torsional stiffness of the independent girders, in the case of staggered framing Bridge A, the lack-of-fit affects are not estimated correctly by traditional 2D GA. In contiguous framing, cross-frames in a contiguous line can directly transfer the forces among each other without relying on torsional stiffness of the girders. Therefore, lack-of-fit effects (except for f_l) are not affected by torsional stiffness of the independent girders.

Note that Bridge A is a parametric bridge and has been designed to maximize the skew effects. Therefore, the R_{Y2} for Bridge A is exceptionally large along with some other lack-of-fit effects that have unusual values for this bridge.

TDL FIT DETAILING METHOD

Methods of Analysis

Different methods of analysis can be used to calculate lack-of-fit effects for the TDL fit detailing method at the SDL stage. These methods are:

- Reversing 2D GA results for the SDL fit.
- 3D FEM using initial strains.
- 3D FEM using Birth and Death cross-frames.

The following sections provide a discussion on each method.

Reversing 2D GA Results for the SDL Fit

Recent study has shown that the lack-of-fit effects for the TDL fit detailing method at the SDL stage are equal and opposite to the lack-of-fit effects for the SDL fit detailing method at the TDL stage (Gull et al., 2017; Gull, 2014). Lack-of-fit effects for the SDL fit detailing method at the TDL stage can be obtained from grid analysis and reversing their sign shall give the lack-of-fit effects for the TDL fit detailing method at the SDL stage.

3D FEM Using Initial Strains

In this procedure, initial strains are used to model lack of fit at the SDL stage for the TDL fit detailing method. The configurations of cross-frames and girders to calculate the initial strain are shown in Figure 4 for the intermediate cross-frames perpendicular to web and in Figure 5 for the cross-frame parallel to skew. Configuration 1 represents a real situation in which cross-frames do not fit between the girders at the SDL stage for the TDL fit detailing method. Configuration 2 represents an imaginary condition in which cross-frames are deformed to make the connections that were not established in Configuration 1. Configuration 2 is an imaginary high-energy configuration of the system.

Once the system can establish equilibrium it attains its lowest energy state. After equilibrium is established, the system has real configuration of steel framing after attaching the cross-frame for the TDL fit detailing method at the SDL stage.

The initial strain, $\varepsilon_{initial}$, in any cross-frame member can be calculated using the following formula:

$$\varepsilon_{Initial} = \frac{L_1 - L_2}{L_2}$$

where L_1 is the length of the cross-frame member in Configuration 1 and L_2 is the length of the cross-frame member in Configuration 2.

The two configurations of the cross-frames are shown in Figure 4, for the cross-frame that are perpendicular to web and in Figure 5 for the cross-frames parallel to skew. The length of the cross-frame members that are perpendicular to the girder web in Configuration 1 as shown in Figure 4 can be calculated as follows:

$$L_{TC_1} = L_{BC_1} = S$$

$$L_{D1_1} = L_{D2_1} = \sqrt{S^2 + h_b{}^2}$$

where L_{TC_1}, L_{BC_1}, L_{D1_1}, L_{D2_1} are, respectively, lengths of top chord (TC), bottom chord (BC), diagonal 1 (D1), and diagonal 2 (D2) members of the cross-frame in Configuration 1; S is the spacing between the girders; and h_b is the height of bracing.

Similarly, the length of the cross-frame members that are perpendicular to the web in Configuration 2 of Figure 4 can be calculated as follows:

$$L_{TC_2} = L_{BC_2} = \sqrt{S^2 + \Delta^2}$$

$$L_{D1_2} = \sqrt{S^2 + (h_b - \Delta)^2}$$

$$L_{D2_2} = \sqrt{S^2 + (h_b + \Delta)^2}$$

where L_{TC_2}, L_{BC_2}, L_{D1_2}, L_{D2_2} are lengths of TC, BC, D1, and D2 members of the cross-frame in Configuration 2, respectively.

Here, Δ is the difference in elevation of the girders'

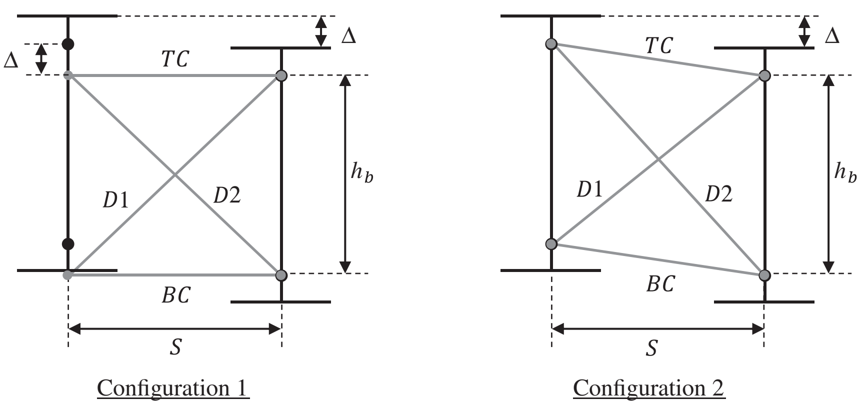


Fig. 4. Configurations to calculate initial strain in the cross-frames that are perpendicular to girder web.

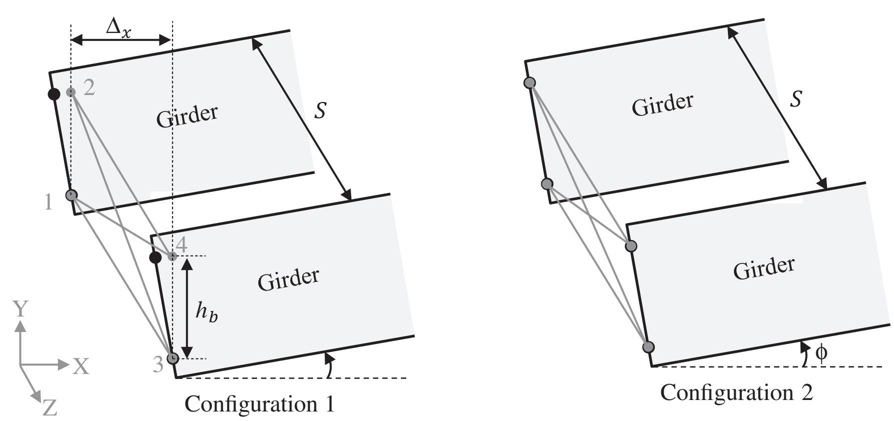


Fig. 5. Configurations to calculate initial strain in the cross-frames that are parallel to skew.

section connected by the cross-frame and can be obtained from the concrete dead load camber calculated from LGA or isolated girder analysis (IGA). It is worth noting that Δ is obtained from the concrete dead load camber calculated from deflection of the system of girders and cross-frames attached together in NCHRP 725 (White et al., 2012). This is an incorrect way of calculating Δ for the TDL fit detailing method at the SDL stage as explained elsewhere (Gull et al., 2017; Gull, 2014).

It should be noted that Δ is the difference in elevation of girders to calculate the initial strains that will simulate lack of fit due to concrete dead load and is different from the real value of Δ that will exist between the girders at the SDL stage.

Lack of fit in the cross-frames that are parallel to the skew supports occurs due to major axis bending rotation of the girder section as shown in Figure 5. Figure 5 illustrates the configuration of the cross-frames parallel to the skewed support at the bearing lines, however, the intermediate cross-frames parallel to skew have similar configurations. Configuration 1 in Figure 5 shows that the cross-frame does not fit between the girders due to major axis bending rotation, ϕ, of their ends. In configuration 2, the cross-frame is deformed to establish the connections as described previously for the cross-frames perpendicular to the girder web.

The length of the cross-frame members that are parallel to the skew supports in Configuration 1 shown in Figure 5 can be calculated as follows:

$$L_{TC_1} = L_{BC_1} = \sqrt{{\Delta_x}^2 + S^2}$$

$$L_{D1_1} = L_{D2_1} = \sqrt{{\Delta_x}^2 + {h_b}^2 + S^2}$$

Neglecting the displacement in the y-direction of the connection points and taking sinθ ≅ θ, the length of the cross-frame members that are parallel to the skew supports in Configuration 2 can be determined as follows:

$$L_{TC_2} = L_{BC_2} = \sqrt{{\Delta_x}^2 + S^2}$$

$$L_{D1_2} = \sqrt{(\Delta_x - \phi . h_b)^2 + {h_b}^2 + S^2}$$

$$L_{D2_2} = \sqrt{(\Delta_x + \phi . h_b)^2 + {h_b}^2 + S^2}$$

and

$$\Delta_x = S \times \tan\theta$$

where, θ is the skew angle and ϕ is the major axis bending rotation due to concrete dead load at the location of the cross-frame; ϕ is positive (counterclockwise) for the bearing line having Girder 1 at the acute corner and is negative (clockwise) for the bearing line having Girder 1 at the obtuse corner.

To get SDL configuration for the TDL fit detailing method, a complete model of the bridge is built with cross-frames attached to the girders. A value of initial strain is assigned to each cross-frame member that can be calculated based on location and orientation of the cross-frame and type of the cross-frame member. Once initial strains are assigned to all the cross-frame members, static analysis is run without applying any external load. In the static analysis, the cross-frame members expand or contract, depending on the initial strain value, and establish equilibrium with the girders. Once equilibrium is established, the steel framing of the bridge achieves its stable lowest possible energy configuration. The geometry of the bridge obtained after the equilibrium is established represents bridge geometry at the SDL stage for the TDL fit detailing method.

3D FEM Using Birth and Death Cross-Frames

Lack of fit at the SDL stage for the TDL fit detailing method can also be simulated by using Birth and Death options for the cross-frame elements.

In the TDL fit detailing method, cross-frames fit between the girders after application of the concrete dead load. Therefore, in this analysis, concrete dead load is applied on the girders to deflect the girders to a position where cross-frames fit between them. Once the girders are deflected by concrete dead load, the cross-frames are made alive. After that, concrete dead load is removed to get the SDL responses for the TDL fit detailing method.

Three-dimensional FEM using Birth and Death cross-frames is a two-step FEM analysis after completing the bridge geometry with cross-frames attached.

Step 1. All the cross-frame elements are killed (using the EKILL command in ANSYS), and the concrete dead load is applied as shown in Figure 6.

Step 2. After the concrete dead load has deflected the girders, all the cross-frame elements are made alive (using EALIVE command in ANSYS), and the concrete dead load is removed (made zero), as shown in Figure 7.

At the completion of step 2, the SDL configuration of bridge framing is obtained for the TDL fit detailing method.

It is worth noting that the Birth and Death method does not involve laborious calculation of initial strain for every single cross-frame member and gives the same results as the method of initial strains.

The next section includes a detailed comparison of different responses obtained from different methods of analysis.

Comparison of Different Methods of Analysis

Different lack-of-fit effects such as layovers; component of deflection due to lack of fit, D_{Y2}; component of reaction due to lack of fit, R_{Y2}; flange lateral bending stress, f_l; and cross-frame forces are compared for different methods of analysis

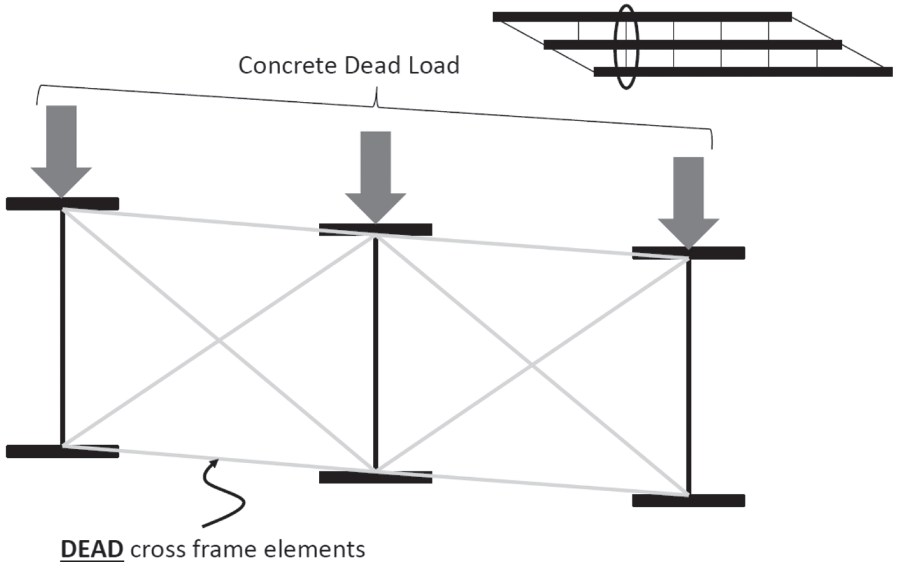


Fig. 6. Application of concrete dead load on girders after killing cross-frame elements.

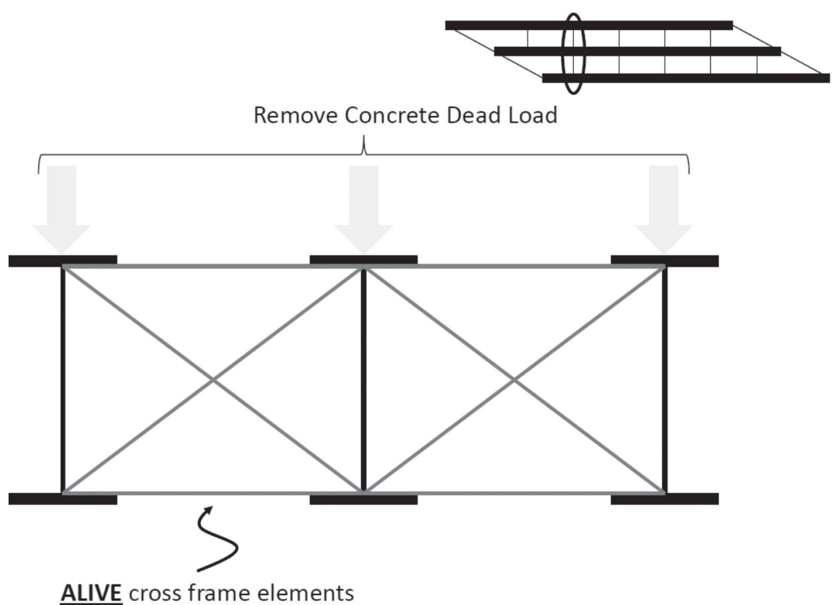


Fig. 7. Removal of concrete dead load from girders after making cross-frame elements alive.

Table 2. Comparison of Lack-of-Fit Effects from Different Methods of Analysis—TDL Fit at SDL Stage									
	Absolute Maximum Value of Lack-of-Fit Effect								
	Bridge A			Bridge B			Bridge C		
Lack-of-Fit Effect	3D FEM InStr	3D FEM B&D	2D GA Rev	3D FEM InStr	3D FEM B&D	2D GA Rev	3D FEM InStr	3D FEM B&D	2D GA Rev
Layovers (in.)	2.5	2.5	2.3	1.7	1.7	1.8	1.6	1.6	1.8
D_{Y2} (in.)	2.1	2.1	2.4	0.6	0.6	0.7	1.0	1.0	1.0
R_{Y2} (kips)	279	279	427	58	57	67	18	18	22
f_l (ksi)	13.9	14.0	35.9	2.2	2.2	3.6	2.1	2.1	5.1
Cross-frame forces (kips)	98	98	193	30	29	37	16	15	19

Notes: 3D FEM InStr = 3D FEM analysis by using initial strains.
3D FEM B&D = 3D FEM analysis using the Birth and Death elements.
2D GA Rev = results obtained by reversing the results of improved 2D grid analysis.

in the TDL fit detailing method at the SDL stage. Three-dimensional FEM analysis using initial strains and 3D FEM analysis using Birth and Death cross-frame element gives almost the same estimates of different lack-of-fit effects for Bridge A and Bridge B as shown in Table 2. Reversing the improved 2D GA results obtained for the SDL fit detailing method at the TDL stage gives conservative estimates of lack-of-fit effects for the TDL fit detailing method at the SDL stage. Bridge A, which has staggered framing, has a higher overestimation of lack-of-fit effects by the improved 2D grid analysis compared to overestimation of the lack-of-fit effects for Bridge B and Bridge C that use contiguous framing. Reasonable estimates of lack-of-fit effects are obtained by reversing the improved 2D GA for Bridge B and Bridge C. Bridge A uses staggered framing with a small stagger distance that results in a small unbraced length and overestimation of torsional stiffness of the girder, which consequently results in overestimation of lack-of-fit effects. Detailed comparison of the results is provided in research reports by Gull and Azizinamini (2014a, 2014b).

Fit-Up Forces

In the TDL fit detailing method, the cross-frames are detailed to fit between the girders at the TDL stage. Therefore, these cross-frames do not fit between the girders at the SDL stage or during the erection of steel framing. To fit the cross-frames detailed with the TDL fit detailing method between the girders at the SDL stage or during erection, a force is required to move the girders into a position where the cross-frames can be attached. The girders are both twisted and moved in a vertical direction to fit the cross-frames between the girders. This is accomplished by the application of horizontal and vertical forces at the top and bottom of the girders, henceforth referred to as fit-up forces. In theory, four fit-up forces are required to move a girder for attaching the cross-frames: two vertical forces acting on the top and bottom of the girder, F_y^T *and* F_y^B, and two lateral forces acting on the top and bottom of the girder, F_z^T *and* F_z^B, as shown in Figure 8.

Knowledge of the fit-up forces allows the bridge steel erector to make arrangements for application of the fit-up force. High fit-up forces are not desirable because these high forces may require special equipment and could slow down construction of the skew bridges.

Proposed Methods of Calculating Fit-Up Forces

Two methods are proposed to calculate the fit-up forces required to fit the cross-frames detailed with the TDL fit detailing method between the girders during erection:

- Cross-frame forces method.
- 3D erection simulation method.

The cross-frame forces method requires less effort and is

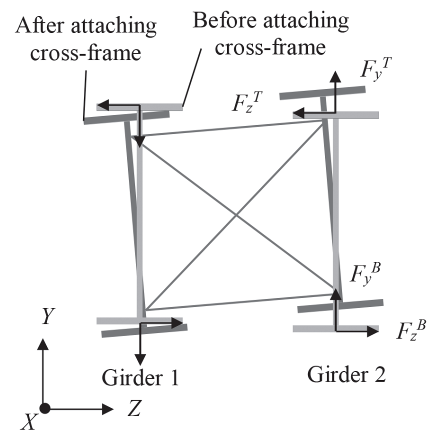


Fig. 8. Fit-up forces required to attach the cross-frames to the girders.

less accurate compared to the 3D erection simulation method, which is more accurate but requires more effort.

The following sections provide details of each method.

Cross-Frame Forces Method

Cross-frame forces at the SDL stage for the TDL fit detailing method are indicative of the fit-up forces. This is because the cross-frames are holding the girders into the twisted positions or are responsible for the lack-of-fit. Recent research (Gull et al., 2017; Gull 2014) has shown that cross-frame forces for the TDL fit detailing method are equal and opposite to the cross-frame forces at the TDL stage for the SDL fit detailing method. Therefore, cross-frame forces for the TDL fit detailing method at the SDL stage can be obtained by reversing the sign of the cross-frame forces for the SDL fit detailing method at the TDL stage. Cross-frame forces for the SDL fit detailing method at the TDL stage can be obtained from improved 2D grid analysis (2D GA), thereby avoiding the use of 3D finite element FEM analysis.

Once cross-frame forces are obtained, they are resolved into vertical and lateral components at the connection points as shown in Figure 9. The fit-up forces in the vertical direction, F_y, and the lateral direction, F_z, at a connection point can be calculated by resolving the cross-frame forces into vertical and lateral components at the connection. For example, Equations 3 and 4 can be used to calculate fit-up forces at the top of Girder 2.

$$F_y^T = -F_{D1} \sin\theta \tag{3}$$

$$F_y^T = -F_{TC} - F_{D1} \cos\theta \tag{4}$$

where, F_{BC}, F_{TC}, F_{D1} and F_{D2} are forces in the bottom chord, top chord, diagonal 1 and diagonal 2 members of the cross-frames, respectively.

Three-Dimensional Erection Simulation Method

Three-dimensional erection simulation attempts to mimic the erection of steel framing in practice. In this simulation, the cross-frames are erected one by one following a particular erection sequence similar to the erection of a real bridge in practice. It is important to note that with the erection of cross-frames detailed with the TDL fit detailing method, both stiffness and geometry of the bridge framing change continually. The change in bridge geometry is considered in erection simulation by updating the geometry after creating each cross-frame element. The change in stiffness of the framing is automatically considered in the erection simulation by the creation of cross-frame elements.

A step-by-step procedure for the erection simulation is described here:

- FEM model of girders cambered using line girder analysis/isolated girder analysis is completed.
- Initial strains (INSTRN) are calculated for a cross-frame to be erected. The initial strains are obtained from the lengths of cross-frame members and the lack-of-fit (the distance between the cross-frame connection holes and girder connection holes). Each cross-frame member is assigned a value of INSTRN as shown in Figure 10.
- After assigning INSTRN to each cross-frame member, static analysis is run to get the cross-frame forces in the erected cross-frame. Fit-up forces are obtained from the cross-frame forces obtained as explained earlier.
- Once the fit-up forces are obtained for the erected cross-frame, the initial strains in the next cross-frame are calculated based on updated geometry of the bridge. The procedure is repeated until all cross-frames are erected.

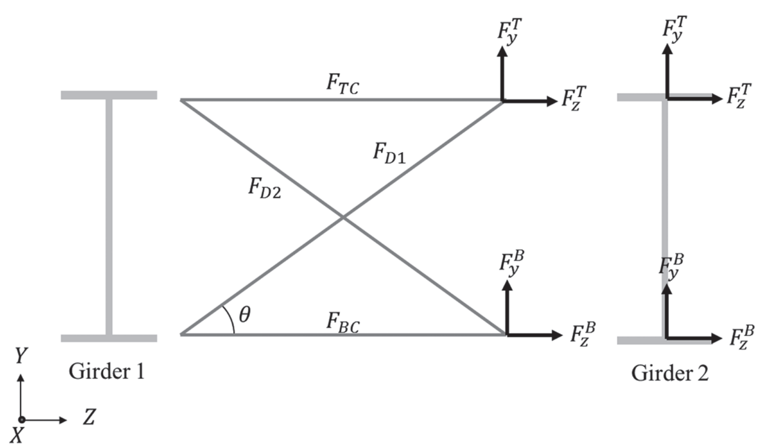


Fig. 9. Fit-up forces by resolving cross-frame forces at connection points.

Bridge girders are generally elastic during the erection of steel framing. The final deflected geometry of elastic girders is not affected by attaching cross-frames one by one or by attaching all of the cross-frames at once. Therefore, the geometry of girders at the end of erection simulation (attaching cross-frames one by one) should be same as the geometry of girders attaching cross-frames all at once. Comparison of the geometry of the girders (layovers and girder elevations) at the end of the erection simulation (attaching cross-frames one by one) to the geometry of the girders attaching cross-frames all at once is shown in Figure 11 for Girder 4 of Bridge C. As indicated by Figure 11, attaching the cross-frames either all at once or one by one results in the identical final geometry (layovers and girder elevations) of Girder 4 of Bridge C. Results shown in Figure 11 provide evidence that erection simulation is working properly. Similar results were obtained for other girders of Bridge C, as well as Bridge A and Bridge B.

An alternative approach to 3D erection simulation can be to use the Birth and Death option with cross-frame elements and evaluate cross-frame forces for the TDL fit detailing method at the SDL stage. The details for carrying out analysis using the Birth and Death option with cross-frame elements were provided earlier. Once the cross-frame forces are obtained, the fit-up forces can be calculated by resolving the cross-frame forces in the horizontal and vertical

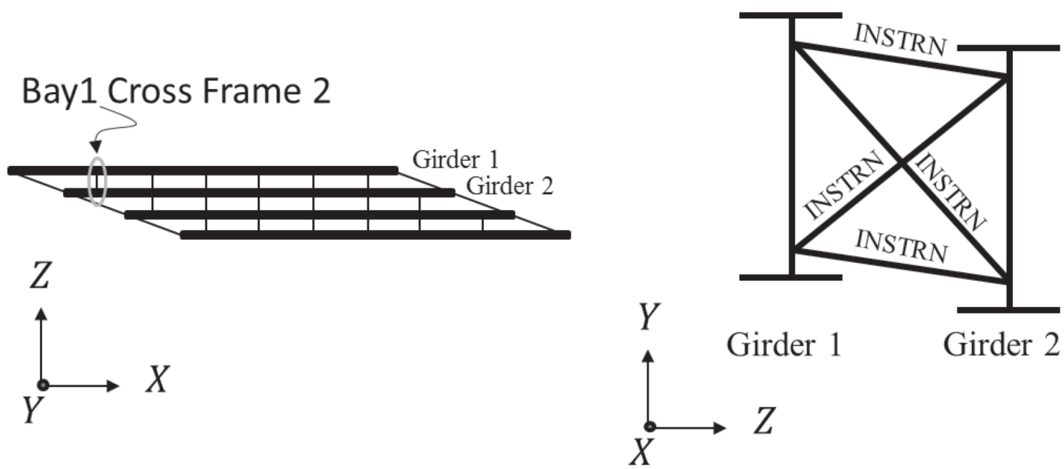
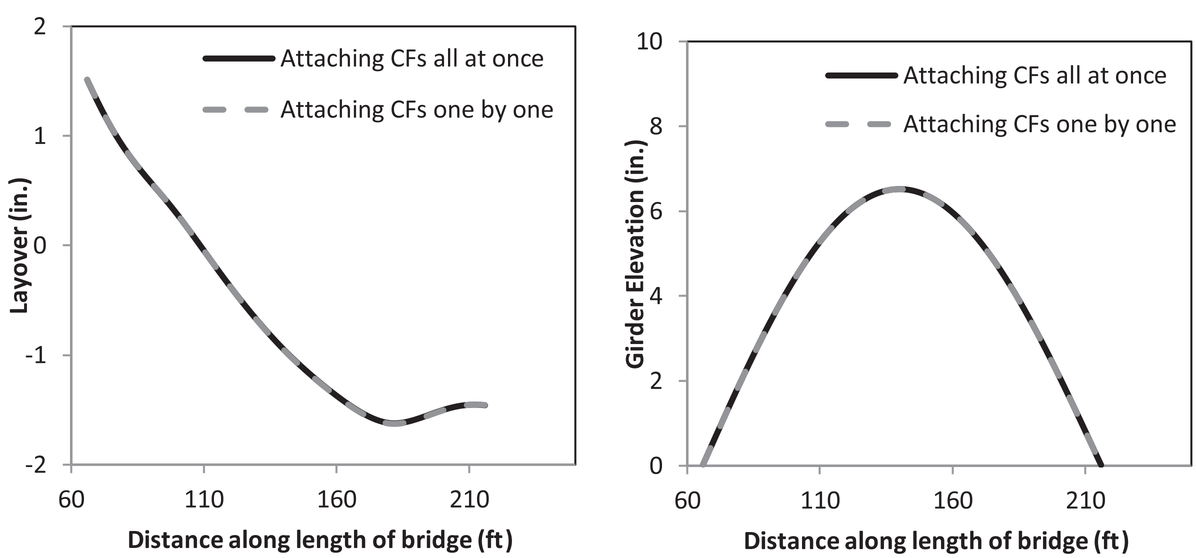


Fig. 10. Steps followed to calculate fit-up forces in erection simulation.



Note: CFs = cross-frames.

Fig. 11. Geometry of Girder 4 of Bridge C after completion of erection.

direction as explained earlier. However, in this case, all the cross-frames are erected at once, and an erection sequence cannot be followed for erecting cross-frames one by one.

Discussion and Comparison of Fit-Up Forces

As discussed earlier, erection of a cross-frame requires both lateral and vertical forces at the top and bottom (F_z^T, F_z^B, F_y^T, F_y^B) to move the girders into a position where connections can be made between the cross-frame and the girders. Comparison of these fit-up forces obtained from the cross-frame force method and the erection simulation method is shown in Figures 12 and 13 for Girder 3 of Bridge C for erecting cross-frames in Bay 3. The results of the erection simulation method discussed in this section are obtained following Erection Sequence 1. The following observation can be made from by inspecting the data presented in Figures 12 and 13.

- Lateral fit-up forces at the top and bottom are in opposite directions, indicating that the girder is required to be twisted to make the connections between a cross-frame and the girders.
- Vertical fit-up forces for the top and bottom are generally in the same direction, indicating that the girder needs to be moved up or down to make a connection between a cross-frame and the girders.
- Both lateral and vertical fit-up forces are relatively high for the first intermediate cross-frame because (1) the distance between the cross-frame and the connection point is largest for this cross-frame, and (2) the girders are very stiff near the supports and require more force for deflection and twisting.
- The highest fit-up force calculated from the cross-frame force method is in good agreement with the highest fit-up force calculated from the erection simulation method.

Typically, the erector is interested in knowing the maximum level of fit-up force required to fit the cross-frames detailed with the TDL fit detailing method between the girders during the erection of a steel bridge. Therefore, the absolute maximum fit-up force in both the vertical and lateral directions is obtained from different methods of analysis for Bridge A, Bridge B, and Bridge C as shown in Table 3. The fit-up forces calculated from cross-frame forces method (obtained from improved 2D GA) are in close agreement with the fit-up forces obtained from the erection simulation method, except for Bridge A. For Bridge A, the cross-frame forces method overestimates the fit-up forces because the cross-frame forces are overestimated by improved 2D GA for this bridge. The overestimation of cross-frame forces by improved 2D GA for Bridge A was discussed earlier. It is also worth noting from Table 3 that Bridge A has a very large magnitude of fit-up forces that will require significant amount of jacking of girders in the field to install the cross-frame; therefore, this bridge should be detailed for SDL fit.

In summary, cross-frame forces obtained from improved 2D GA can be used to estimate fit-up forces required for the TDL fit detailing method at the erection stage.

SUMMARY AND CONCLUSIONS

For the SDL fit detailing method, performance of improved and traditional 2D GA is different for different framing options as follows:

- For bridges with contiguous cross-frames, traditional 2D GA gives reasonable estimates of all responses, except for flange lateral bending stress, and improved 2D GA gives reasonable estimates of all responses.
- For bridges with staggered cross-frames, traditional 2D GA gives erroneous estimates of all the responses, and improved 2D GA gives reasonable estimates of all responses. However, when the stagger distance is small, J_{eq} in improved 2D GA has a very high value, resulting in overestimation of lack-of-fit effects.

Lack-of-fit effects for the TDL fit detailing method at the SDL stage obtained from a method of initial strain shows a very good agreement with the lack-of-fit effects obtained from the method of Birth and Death cross-frames elements. Reversing improved 2D GA results for the SDL fit detailing method at the TDL stage also gives reasonable estimates of the lack-of-fit effects for the TDL fit detailing method at the SDL stage.

The fit-up forces should be considered by the designer as required in the AASHTO LRFD design specification. Designers need to specify the load stage for which the cross-frames should be detailed. The designer needs to consider the effect of the fit and specify the maximum fit-up required in the field to install cross-frames for TDL fit. This paper provides a simplified method to estimate the maximum fit-up forces.

Although layovers do not have any known effect on the strength of girders, they cause additional rotation in the girders and should be considered in the bearing design for SDL fit. For TDL fit, the layovers appear only at the temporary SDL stage and are not significant at the TDL stage.

Two different methods are introduced to evaluate the fit-up forces that are required to erect the framing of a skew bridge: cross-frame forces method and 3D erection simulation method.

It has been shown that cross-frame forces evaluated from improved 2D GA can be used to estimate the fit-up forces required to fit the cross-frames, detailed with the TDL fit detailing method between the girders during erection of a steel bridge.

Table 3. Absolute Maximum Fit-Up Force from Different Methods				
	Absolute Maximum Fit-Up Force (kips)			
	Lateral		Vertical	
Bridges	**CF Forces**	**Erection Simulation**	**CF Forces**	**Erection Simulation**
Bridge A	230	180	104	131
Bridge B	41	38	28	30
Bridge C	25	29	7	10

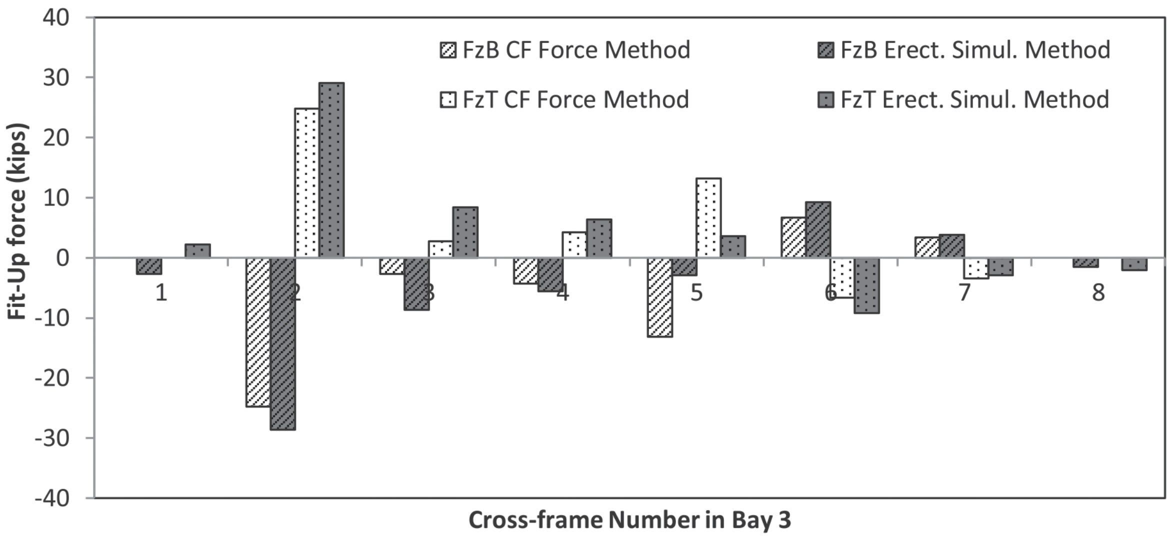


Fig. 12. Lateral fit-up forces applied on Girder 3 of Bridge C for erecting cross-frames in Bay 3.

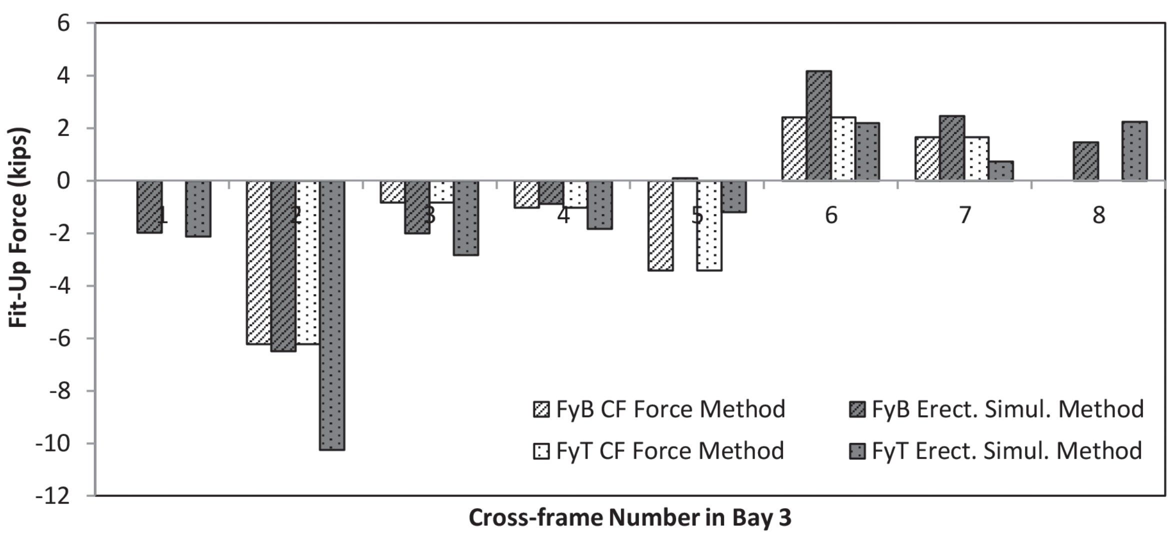


Fig. 13. Vertical fit-up forces applied on Girder 3 of Bridge C for erecting cross-frames in Bay 3.

Improved 2D GA can be used to estimate the lack-of-fit effects for both the TDL fit and the SDL fit detailing methods.

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