The Response of a Highly Skewed Steel I-Girder Bridge with Different Cross-Frame Connections

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Abstract-Braces in straight bridge systems improve the lateral-torsional buckling resistance of the girders by reducing the unbraced length, while in horizontally curved and skew bridges, the braces are primary structural elements for controlling deformations by engaging adjacent girders to act as a system to resist the potentially large forces and torques caused by the curved or skewed geometry of the bridge. The cross-frames are usually designed as torsional braces, which increase the overall strength and stiffness of the individual girders by creating a girder system that translates and rotates as a unit along the bracing lines. However, when they transmit the truck's live load forces, they can produce fatigue cracks at their connections to the girders. This paper investigates the effect of using different details of cross-frames to girder connections and their impacts on girder stresses and twists. Field testing data of skewed steel girders bridge under various load passes of a weighed load vehicle incorporated with a validated 3D full-scale finite element model are presented in this study. Two types of connections are investigated, bent plate and pipe stiffener. The two connection responses are then compared to determine their impact on controlling the twist of girder cross-sections adjacent to cross-frames and also to mitigate the stresses induced due to live loads. The results show that the use of a pipe stiffener can reduce the twist of the girder's cross-section adjacent to the cross-frames up to 22% in some locations. In terms of stress ranges, the pipe stiffener tends to reduce the stress range by 6% and 4% for the cross-frames located in the abutment and pier skew support regions respectively.

Keywords-skew bridge; field test; cross-frames; bent plates; pipe stiffener; fatigue

I. INTRODUCTION

Skewed supports occur when the supporting abutments for the girders are not normal to the girder lines but are instead offset by a skew angle which may be required due to the characteristics of the intersecting roadways or the geological terrain. Since skew angles increase the interaction between the steel girders and the braces (cross-frames or diaphragms), the behavior of bridges with skewed supports becomes more complicated than in bridges with normal supports. As the geometry of the bridge deviates from this basic scheme, the functions, and effects that cross-frames and diaphragms have in the structure become more important, up to the point where the structural integrity of the bridge depends on them. Among many other characteristics, horizontal curvature, support skews, large spans and widths, unbalanced construction loads, unequal girder lengths subject the girders to torsion, increasing the significance of cross-frames and diaphragms [1]. Bracing systems force the girders to rotate as a group to accommodate the differential vertical deflections, the interaction between the girders and braces often results in large live load forces in the cross-frames or diaphragms, which can lead to fatigue problems around the brace locations. The severity of the fatigue problem depends on the connection details that are used for the bracing [2].

Historically, AASHTO limited the spacing of cross-frames to 7.62m (25ft) on straight steel bridges. However, the current AASHTO LRFD specifications [3] eliminated the spacing limit and instead allowed a rational analysis to be performed to determine the cross-frame spacing. A major advantage of this clause is the potential cost savings obtained from reducing the number of cross-frame lines in the completed bridge. The use of fewer cross-frame lines is beneficial in reducing both fabrication and erection costs and may result in fewer fatigue-sensitive details on the bridge. However, as analysis techniques become more advanced and bridges become increasingly slender and efficient, it is imperative to fully understand the behavior of the cross-frame systems used and to verify that the braces are providing the restraint necessary to obtain safe structures. AASHTO/NSBA required that the end cross-frame be placed parallel to the skewed support, and hence at an angle to the girders [4]. In order to provide access for welding during fabrication and erection, bent plate connection is often used to connect the cross-frames to the girder and aligned parallel to the skew angle. Such a connection provides little if any warping restraint.

While bent plate connections can simplify fabrication, the flexibility of the plate due to the connection eccentricity may compromise the effectiveness of the cross-frame in stabilizing the girders against lateral torsional buckling. For small skew angles, the bent plate performs adequately, however, problems can occur for larger support skews [5]. The results from laboratory tests and three-dimensional finite element studies have demonstrated that the eccentricity causes out-of-plane

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bending of the members resulting in a reduction in the stiffness of the cross-frame [6]. The eccentric connections lead to member bending that result in uncertain behavior for strength, stiffness, and especially fatigue.

In recent studies on the fatigue performance of existing steel and composite bridges, it has been found that the most common fatigue damage types are caused by secondary effects, i.e. deformation-induced cracking or distortion-induced fatigue cracking. This type of fatigue damage is often the result of secondary restraining forces generated by unintentional or overlooked interactions between different members in the bridge. Poor detailing along with abrupt changes in stiffness at the connections between girders and cross-frames increase the possibility of prone fatigue cracking in such details [3]. Many surveys and reports stated that distortion-induced fatigue, which often occurs in the vicinity of cross-frame to girder connections is the most frequently observed type of fatigue observed [7]. Several studies have explored various specific examples of this phenomenon at cross-frame to girder connections [8-11]. Design codes and evaluation methods generally provide very little guidance on how this kind of fatigue damage should be accounted for or prevented. It is the responsibility of the bridge designer to ensure through good detailing that these secondary effects and the kind of fatigue damage associated with them are avoided.

This study aims to investigate the effectiveness of the cross-frame connection details in terms of structural behavior and responses. This is accomplished using Finite Element Analysis (FEA), validated by field testing results. Two types of connections are investigated: bent plate and pipe stiffener connection. The bent plate connection type is widely adopted in bridges with skew abutments and pier support regions (see Figure 1(a) and 1(b) respectively). It is also used in the bridge of interest of the present study (US13 Bridge). The second and proposed type is the pipe stiffener (see Figure 1(c)). This type of connection was first presented in 1977 [12] and was investigated later numerically and experimentally [5, 13]. The two connection responses are then compared to determine the impacts of each one on controlling the twist of girder cross-sections adjacent to cross-frames and also to mitigate the stresses induced due to live loads. This knowledge can then be applied to assess and optimize the fatigue performance of typical bridges and connection details.

II. BRIDGE FIELD TESTING

A. Bridge General Description

The US13 Bridge, is a 65° heavily skewed steel I-girder bridge in Delaware, USA (Figure 2). Twin spans carry the north- and southbound lanes. The bridge consists of 2 continuous spans of equal 50m (165ft) lengths. There are 5 girders spaced 2.9m (9.5ft) on center with exterior girders spaced 0.86m (2.83ft) and 1.16m (3.83ft) away from the outer edge of the bridge concrete guard wall on the west and east sides respectively. Therefore, the total width of the bridge is 13.37m (44.67ft), carrying two 3.65m (12ft) lanes, a 3.65m (12ft) shoulder on the west side, and a 1.82m (6ft) shoulder on the east side. The concrete guard wall located on each bridge side has 0.4m (1.34ft) width and 0.86m (2.83ft) height.

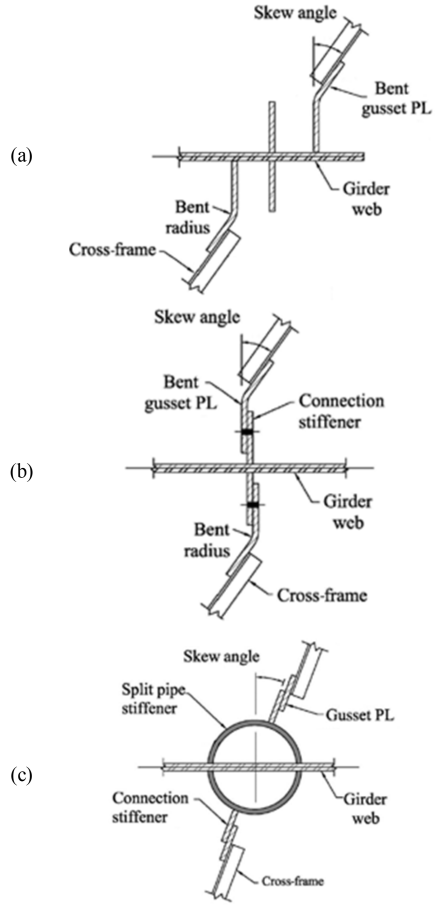

Fig. 1. Cross-frames connection details investigated in the present study: (a) bent plate connection in US13 Bridge abutment skew support, (b) bent plate connection in US13 Bridge pier skew support, and (c) proposed pipe stiffener connection.

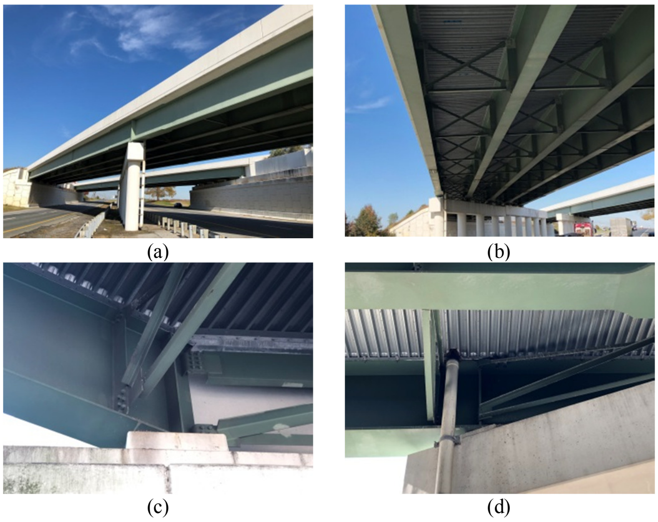

Fig. 2. US13 Bridge in Delaware state, USA, (a) general view, (b) perpendicular cross-frame configuration, (c) bent plate connection in skew abutment support, and (d) bent plate connection in skew pier support.

The bridge contains inline X-shaped cross-frames (between girders and at pier location) oriented perpendicular to the girders' longitudinal axes, as shown in Figure 2(b), which are connected to the girders using full-depth connection plates. Also, inline K-shaped cross-frames are used in the vicinity of the abutment supports and connected to the girder's web using bent plate connection (Figure 2(c)), while inline X-shaped cross-frames used in the pier supports and connected to the girder's bearing plates stiffener using bent plate either (Figure 2(d)).

B. Instrumentation Layout and Loading Pattern

Bridge Diagnostics, Inc. ST-350 strain gauges (BDI gauges) [14] and their associated data-acquisition system were used in the field test. Specifically, 12 strain gauges were installed on the 3 girder cross-sections labeled G1, G2, and G3 (Figure 4). Each of these girder cross-sections was instrumented with 4 strain gauges (Figure 3). One pair was placed 5cm (2in) from the outer edges of the bottom surface of the bottom flange. These cross-section positions are labeled as BF-1 and BF-2. The other pair was placed on opposite sides of the web at approximately mid-height of the web and its members were labeled as W-1 and W-2 [15] (Figure 3). Four different truck passes, with 24km/hr (15mph) speed, were conducted for the load test (Figure 5). Pass#1 had the loaded truck travel down the center of the left lane. This position was intended to maximize the stress and induce differential deflection in Girder #4. Pass#2 was designed to produce a high level of stress in both Girder #3 and Girder #4, while Pass#3 had the truck travel with the left side wheels aligned with the centerline of the two lanes, intending to maximize differential deflections between the instrumented girder and the adjacent one [15]. Pass#4 is a new one implemented using FEA and had the loaded truck travel in the center of the left shoulder with 24km/hr. This pass was intended to produce a high level of twists in the instrumented sections.

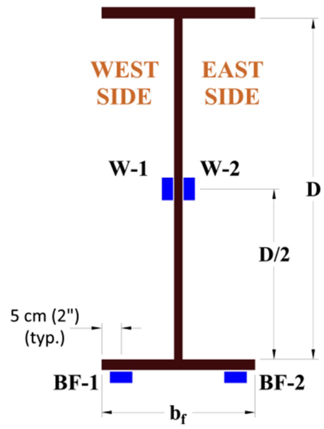

Fig. 3. Cross-section locations for field and FEA data.

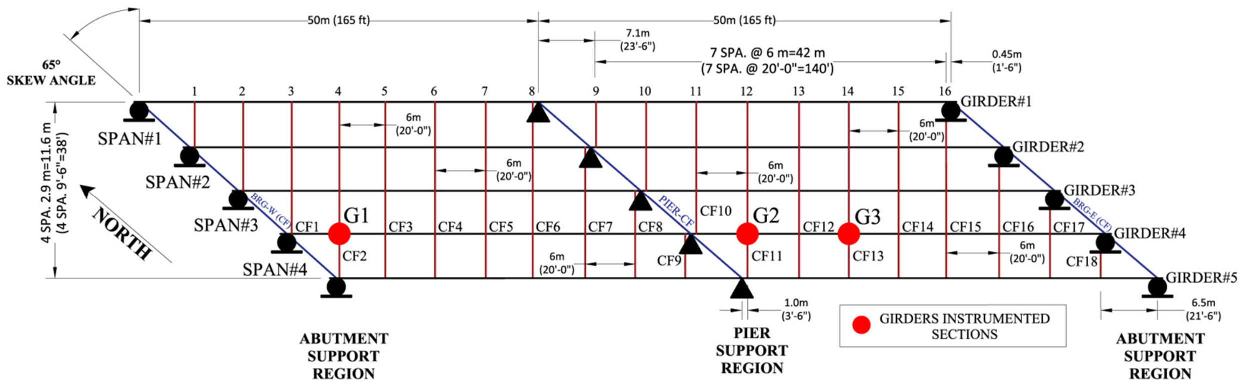

Fig. 4. US13 Bridge framing plan and instrumentation locations.

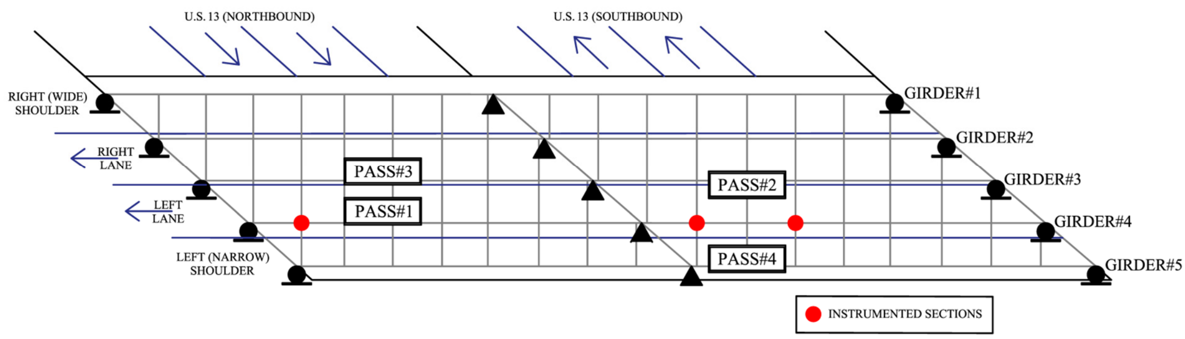

Fig. 5. Truck load passes.

III. Finite Element Analysis

A. Geometry, Meshing, Elements, Materials, and Boundary Conditions

The geometry of the bridge was created according to the structural plans provided by the bridge owner (the Delaware Department of Transportation). Software packages like AutoCAD - 3D, FEMAP, NX Nastran, and ABAQUS/CAE were used to perform the bridge final finite element model [16] (Figure 6). Over 1 million 4-node reduced-integration shell elements [17, 18], were used for modeling all girders, cross-frames, and stay-in-place profiled metal deck forms. For modeling the concrete deck, haunch, and concrete guard wall, 4-node reduced-integration shell elements (S4R) were used. Steel bar reinforcement in the concrete deck slab was defined by Abaqus' rebar option using the actual geometry of the reinforcement and its spacing. In general, the mesh size of both the concrete deck slab and the metal forms were 30cm×30cm (1ft×1ft), while 8 or 12 elements were used across the width of the girder's top and bottom flanges and 28 were used through the height of each web. Linear isotropic elastic material properties were used for the FEA because the applied loads did not cause the proportional limit of the materials to be exceeded. Expansion bearings at abutments were modeled with translation constraints in both vertical and transverse directions at the center node of the bottom flange cross-section of each girder, and only vertical direction constraint for the remaining bottom flange nodes of the abutment cross-sections. Fixed bearings at the pier were modeled similar to the expansion bearing constraints except that the center node of the bottom flange cross-sections was also restrained in the longitudinal direction.

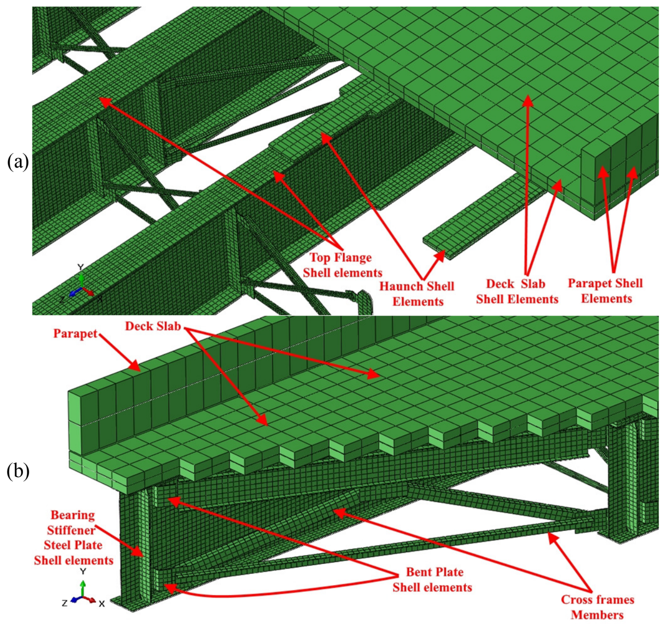

Fig. 6. US13 Bridge Abaqus finite elements model. (a) FEA modeling of bent plates in the pier support region and (b) FEA modeling of bent plates in the abutment support region.

B. Loading (Vehicle Modeling)

The truck load was simulated with a series of static load cases which varied in position to represent a truck traveling across the length of the bridge. Nodal positions of each of these load cases, which were necessary to apply the loads in the model, were computed using a Visual Basic for Applications (VBA) programming routine. To facilitate the use of this routine, the deck element nodes were numbered in ascending order.

C. Interaction Mechanisms and Analysis

Tie constraints were used to simulate all connections between the steel components of the bridge (e.g. between cross-frame members and vertical connection plates on the girders). The metal decking and the top flange were connected via merged nodes with all degrees of freedom constrained. Timoshenko (shear flexible) beam elements [17] with circular cross-sections and 6 degrees of freedom (3 translation and 3 rotation) at each node to represent the shear studs and an isotropic friction model with a coefficient of friction of 0.4 at the steel-concrete interface were used to model the steel-concrete interaction mechanism. Surface-to-surface tie constraints were used to model the connection between the haunch and the slab. The analysis was performed by using an Expert Subroutine System programmed to extract key information from the Abaqus output result file [16]. This was implemented using the Caviness High-Performance Computing (HPC) cluster at the University of Delaware, USA. The static analysis was performed using Abaqus standard implicit static analysis while Abaqus explicit dynamic analysis was used for the dynamic models.

D. Finite Element Modeling of the Pipe Stiffener

A new FE model for US13 Bridge was implemented using ABAQUS/CAE but with the use of a pipe stiffener instead of the bent plate to investigate the effectiveness of using this type of connection in enhancing the structural behavior of the bridge through increasing the connection warping restraint, buckling capacity and reducing the end cross-frame twist. The pipe stiffener model was used in two locations across the bridge. The first one in the west and east abutments skew supports as shown in Figure 7. In this region, the thickness of the pipe stiffener plate was taken as the same as the thickness of the web's bearing stiffener plate (2.25cm (7/8in)), while the diameter of the pipe was taken equal to the width of the bottom flange [46cm (18in)]. The second location is at the pier skew support (Figure 8), the thickness and diameter of the pipe stiffener plate used in this region are 3.85cm (1½in), and 76cm (30in) respectively.

IV. Finite Element Validation

Figures 9 and 10 illustrate the maximum tensile and compressive stresses, recorded from the field test and the FEA data for the strain gauges located in the Bottom Flange (BF) and Web (W) respectively. Generally, the FEA reproduces accurately the general behavior observed in the field testing and a favorable quantitative comparison is obtained in most cases, especially for the gauges located in the BFs of the instrumented sections. The difference between the FEA and field test for the experienced tensile and compressive stresses of the bottom flange attained 7.7 and 10.6%, during Pass#1, 10.5 and 14.8% during Pass#2, and 13.4 and 18.9% during Pass#3 respectively. Accordingly, a weaker correlation was expected and achieved when comparing the compressive stress results due to the fact that the concrete is in tension in this situation and the concrete deck was modeled as a linear elastic material with infinite tensile strength for modeling efficiency. For the webs, the best overall correlation between results was achieved during Pass#1 at G2.

(a)

(b)

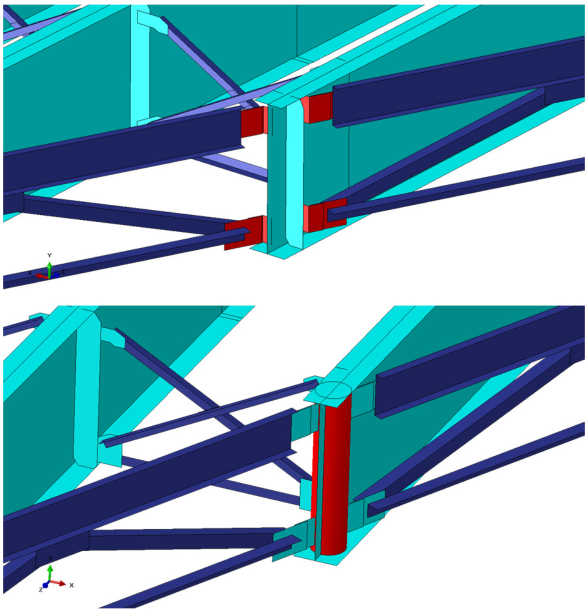

Fig. 7. Abutment skew support region connection details: (a) FE modeling of the existing connection (bent plate), and (b) FE modeling of the new proposed connection (pipe stiffener).

(a)

(b)

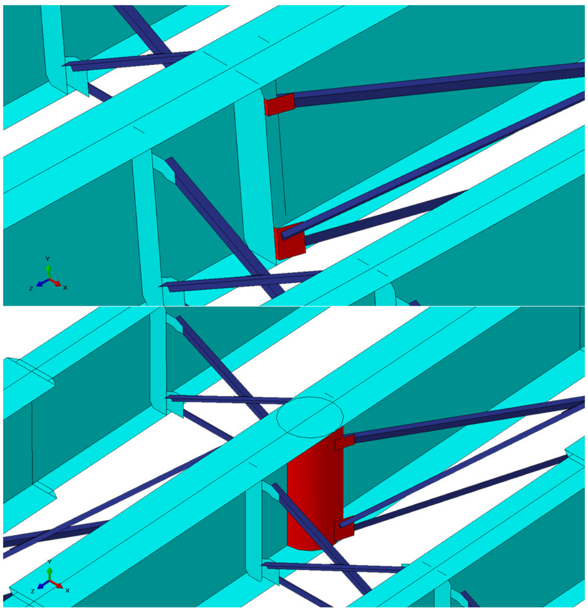

Fig. 8. Pier skew support region connection details: (a) FE modeling of the existing connection (bent plate) and (b) FE modeling of the new proposed connection (pipe stiffener).

(a)

(b)

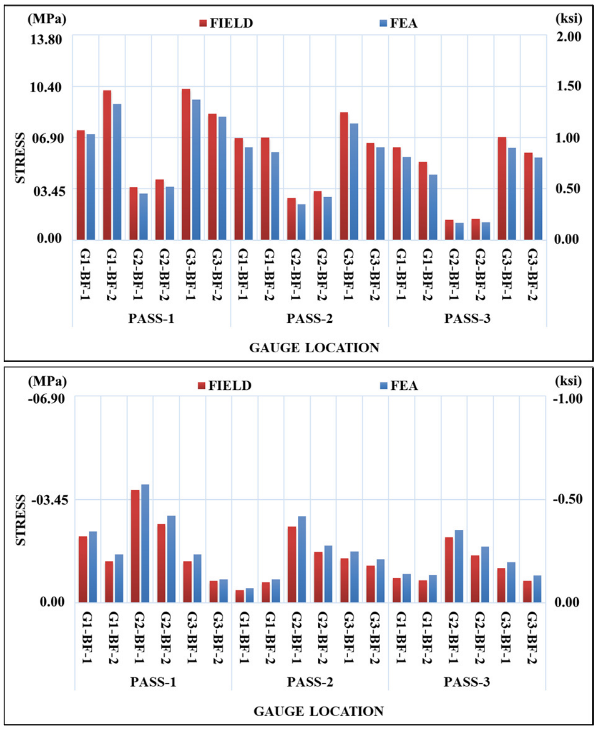

Fig. 9. Field test results vs FEA data for the gauges located in the BF of the instrumented sections (G1, G2, and G3) due to the three field passes, (a) maximum tensile stresses and (b) maximum compressive stresses.

(a)

(b)

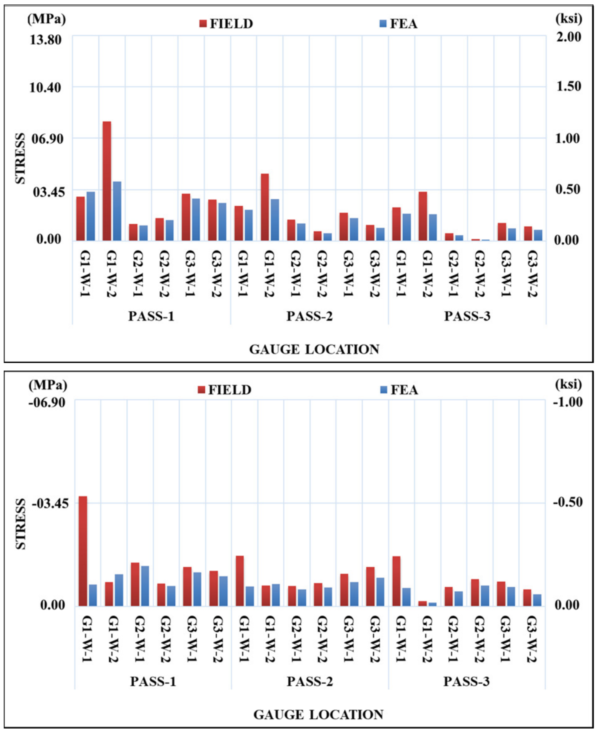

Fig. 10. Field test results vs FEA data for the gauges located in the W of the G1, G2, and G3 sections due to the three field passes: (a) maximum tensile stresses, and (b) maximum compressive stresses.

Figures 11-13 show the field results versus FEA data for the BF gauge positions G1, G2, and G3, in terms of stress versus truck position as it travels across the bridge. These figures show that the FEA results match the expected behavior in stress versus time during the truck passes, including that the FEA also captures accurately the load locations that cause peak stress. In these Figures, the x-axis represents the position of the truck as it travels over the two spans of the bridge. The value (0) of the x-axis declares that the truck is over the left support (west abutment support), the value (0.5) indicates that the truck reaches the intermediate support (pier support), while the value (1) shows that the truck is over the right support (east abutment support).

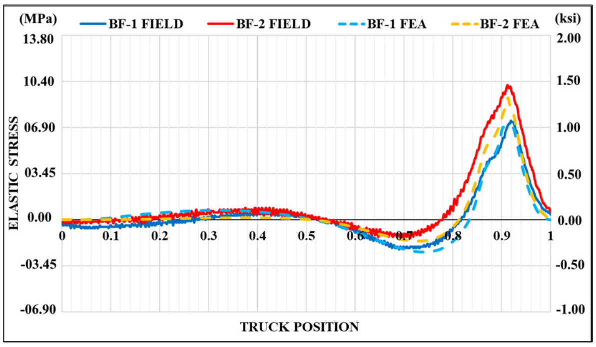

Fig. 11. Field vs FEA stresses influence line for the pair of BF gauges located in the bottom flange of the instrumented section G1.

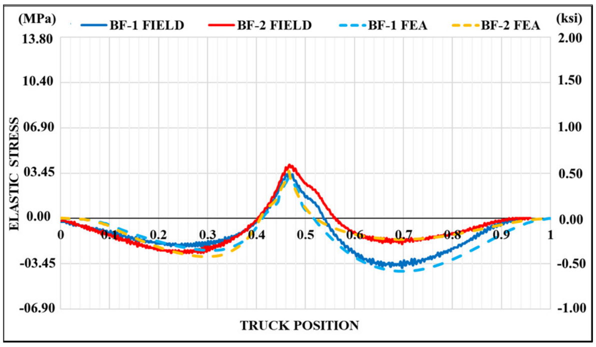

Fig. 12. Field vs FEA stresses influence line for the pair of BF gauges located in the bottom flange of the instrumented section G2.

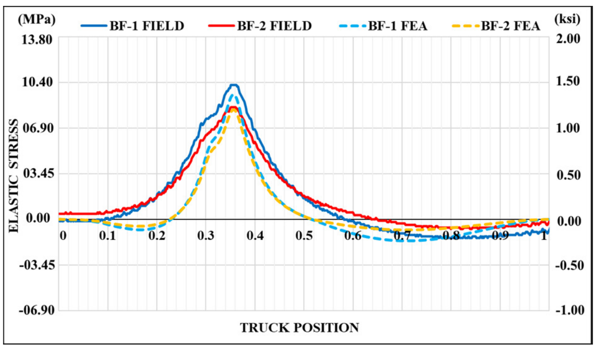

Fig. 13. Field vs FEA stresses influence line for the pair of BF gauges located in the bottom flange of the instrumented section G3.

V. STRESS RANGE CONCEPT

The stress range concept was adopted in the present study to investigate the effect of the use of the different connections (bent plate vs pipe stiffener), as it is a key metric affecting the fatigue performance for the detail of interest. The stress range for each gauge is evaluated by finding the difference between the maximum and minimum stresses. Figure 14 describes the stress range concept in which it represents the relation between the stress (plotted on the y-axis) and the truck position (plotted on the x-axis). Figures 15 and 16 show the stress range for the gauges located in the BF and W respectively, of the instrumented sections G1, G2, and G3, due to the three-field passes.

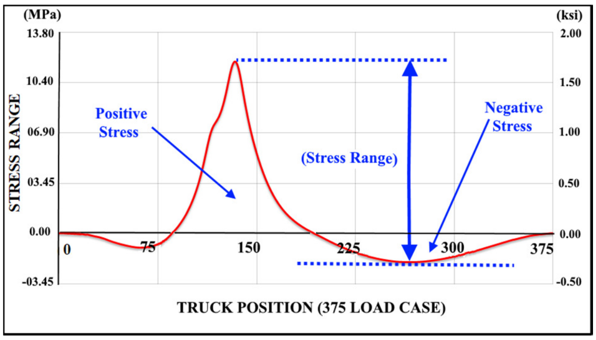

Fig. 14. Illustration of the stress range concept.

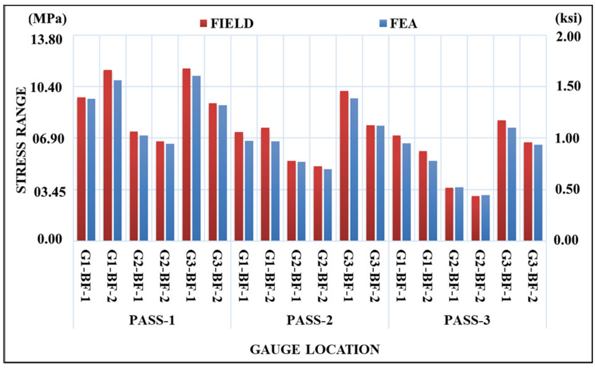

Fig. 15. Field vs FE stress range for the gauges located in the BF of the instrumented sections (G1, G2, and G3) due to the three field passes.

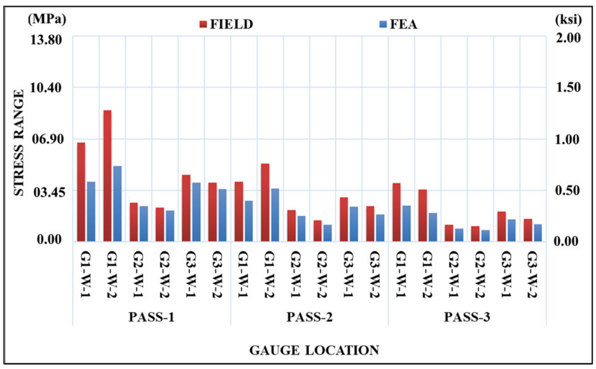

Fig. 16. Field vs FEA stress range for the gauges located in the W of the instrumented sections (G1, G2, and G3) due to the three field passes.

VI. Results

A. Pipe Stiffener vs Bent Plate (Stress Range Comparison)

The preliminary investigation of Field vs FEA stress range results (Figures 15 and 16), revealed that the gauges located in the BF of the instrumented sections G1, G2, and G3 due to all the three-field passes experienced higher stress range than the ones located in the W. Based on this, the stress range for BF-1 and BF-2 locations (see Figure 3), at the intersection of each cross-frame along the length of girder#4 will be used to investigate the effectiveness of using the pipe stiffener instead of the bent plate in terms of stress range due to Pass#1 and Pass#4 only. It is worth mentioning that Pass#4 is an FEA pass that had the loaded truck traveled in the center of the left shoulder with 24km/hr and was designed to produce a high level of twists in G1, G2, and G3.

(a)

(b)

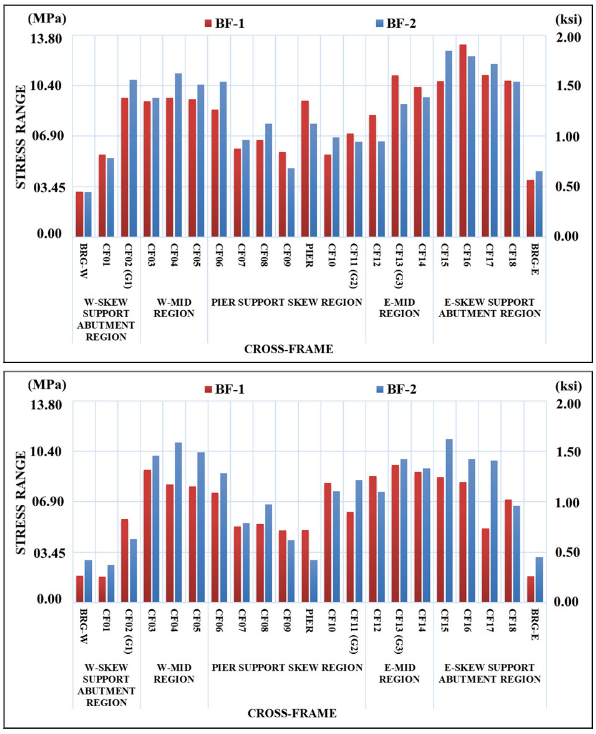

Fig. 17. FEA stress range for BF-1 and BF-2 locations at girder cross-sections adjacent to cross-frames connected to girder#4, for the case of using bent plate connection detail due to (a) Pass#1, and (b) Pass#4.

Figure 17 illustrates the stress range results for BF-1 and BF-2 at the intersection of all cross-frames along the length of girder#4 for the current case of US13 Bridge with the use of bent plate connection detail and due to Pass#1 and Pass#4, while Figure 18, shows the stress range results for the same locations and due to same passes but with the use of pipe stiffener. The comparison between Figures 17 and 18 show a slight difference (enhancement) due to the use of the pipe stiffener in terms of stress range. The stress range in the west abutment K-Type cross-frame (BRG-W) is reduced due to the use of pipe stiffeners by 3% and 6% respectively, during Pass#1 and Pass#4. While in the east abutment K-type cross-frame (BRG-E) the overall reduction was 3% and 5% during Pass#1 and Pass#4 respectively. In the pier X-type cross-frame, the reduction attained 2.5% during Pass#1 vs 4% during Pass#4. In the other cross-frames located at girder#4, the decrease of the stress range is almost insignificant, especially the ones located in the middle region of girder#4 (away from both the skew abutment and pier regions). In general, the reduction of the stress range using pipe stiffener due to Pass#4 is higher than Pass#1 since Pass#4 induced more warping and lateral bending compared to Pass#1.

(a)

(b)

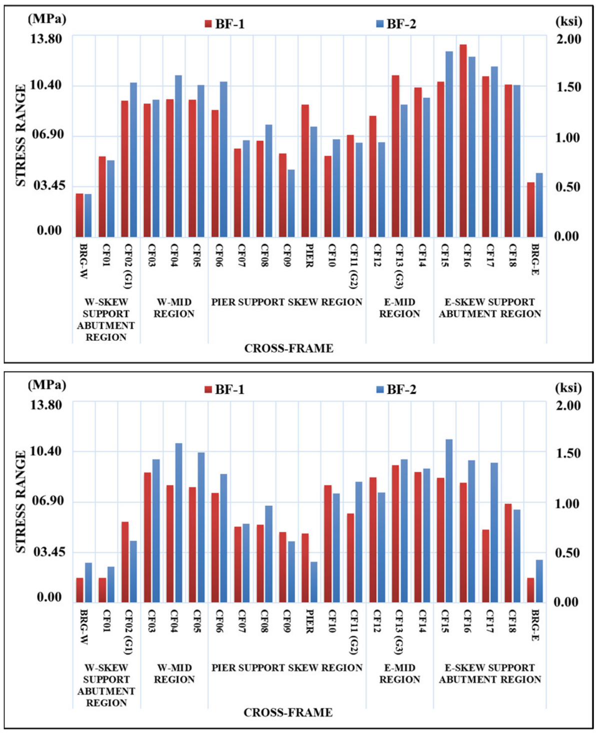

Fig. 18. FEA stress range for BF-1 and BF-2 at girder cross-sections adjacent to cross-frames connected to girder#4, for the case of using pipe stiffener connection detail due to (a) Pass#1, and (b) Pass#4.

B. Pipe Stiffener vs Bent Plate (Angle of Twist Comparison)

Typically, girders in non-skewed bridges experience twists along their longitudinal axis only in one direction (clockwise or counterclockwise). However, it was found that the girders in steel skewed bridges show a torsional rotation profile (twist) in which one part of the girder rotates in one direction and the rest rotates in the opposite direction. In the present study, a positive twist means that the cross-section of interest will be twisted in a clockwise pattern along the longitudinal length of the girder, while in a negative twist, the situation is vice-versa (counterclockwise twist pattern). The Right-Hand-Rule (RHR) is adopted in the present study to determine the sign of the angle of twist. The pipe stiffener provides a more rigid connection between the cross-frame and the girder and is designed to restraint warping, thus it is decreasing the lateral displacements, cross-frame stresses, and end cross-frame twist [5, 13]. Figure 19 illustrates the angle of twist data trending for the girder cross-sections adjacent to cross-frames located at girder#4 due to Pass#1 and Pass#4, for the case of bent plate connection (US13 Bridge status), while Figure 20 shows the results of using the pipe stiffener for the same locations and passes.

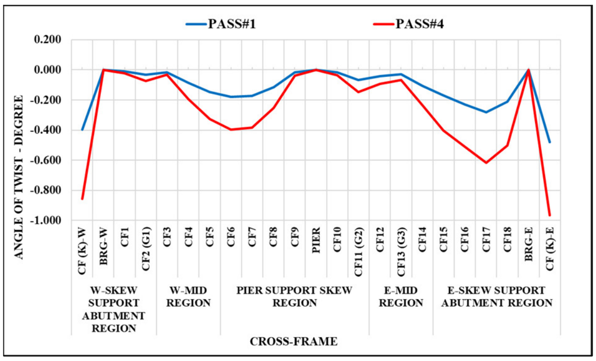

Fig. 19. FEA angle of twist for the girder cross-sections adjacent to cross-frames located at girder#4 due to Pass#1 and Pass#4 for the case of using bent plate connection (US13 Bridge status).

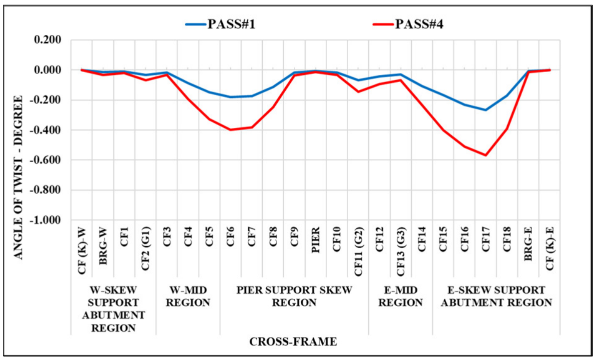

Fig. 20. FEA angle of twist for the girder cross-sections adjacent to cross-frames located at girder#4 due to Pass#1 and Pass#4 for the case of using pipe stiffener connection.

The following conclusions can be drawn through a comparison of the results of Figures 19 and 20:

- In the US13 Bridge abutment region, the bent plate is connected to the girder web after the support bearing stiffener (Figure 1(a)). This eccentric connection led to member bending that results in uncertain behavior for strength [6], and also increased the twist (sway) of the girder cross-section, see sections CF (K)-W and CF (K)-E in Figure 19.
- The round shape of the pipe stiffener allows a perpendicular connection between the skewed support cross-frame and the stiffener for any skew angle and results in minimizing the connection eccentricity caused by the use of bent plate in the abutment skew support region (see Figure 20).
- The use of a pipe stiffener reduces the twist of the girder's cross-section adjacent to the cross-frames near both the skew abutment and pier supports regions. The reduction is relatively proportional to the distance between the pipe stiffener location and the cross-frame of interest. Figures 19 and 20 indicate that the angle of twist for cross-frame (CF18) is reduced by 19% and 22% for Pass#1 and Pass#4, respectively. Meanwhile, during the same mentioned passes, the enhancement achieved 12% and 16% for cross-frame (CF01), 5 and 8% for cross-frame (CF17), and 3 and 7% for cross-frame (CF02) (see Figure 21).

Angle of Twist Data (Degree)							
Cross-Frame	Cross-Frames Region	Pass#1		δ	Pass#4		δ
		Bent Plate	Pipe Stiffener	%	Bent Plate	Pipe Stiffener	%
CF (K)-W	W-SKEW SUPPORT ABUTMENT REGION	-0.398	0.000	100	-0.856	0.000	100
BRG-W		0.000	0.000	0	0.000	0.000	0
CF1		-0.010	-0.009	12	-0.022	-0.018	16
CF2 (G1)		-0.034	-0.033	3	-0.074	-0.069	7
CF3	W-MID REGION	-0.015	-0.015	0	-0.034	-0.034	0
CF4		-0.088	-0.088	0	-0.194	-0.194	0
CF5		-0.148	-0.148	0	-0.327	-0.327	0
CF6	PIER SUPPORT SKEW REGION	-0.180	-0.180	0	-0.397	-0.397	0
CF7		-0.174	-0.174	0	-0.383	-0.383	0
CF8		-0.115	-0.114	1	-0.253	-0.248	2
CF9		-0.017	-0.017	2	-0.038	-0.036	7
PIER		0.000	0.000	0	0.000	0.000	0
CF10		-0.016	-0.015	4	-0.035	-0.032	9
CF11 (G2)		-0.067	-0.066	1	-0.148	-0.144	3
CF12	E-MID REGION	-0.043	-0.043	0	-0.095	-0.095	0
CF13 (G3)		-0.030	-0.030	0	-0.067	-0.067	0
CF14		-0.105	-0.105	0	-0.232	-0.232	0
CF15	E-SKEW SUPPORT ABUTMENT REGION	-0.169	-0.169	0	-0.402	-0.402	0
CF16		-0.232	-0.232	0	-0.511	-0.511	0
CF17		-0.280	-0.266	5	-0.618	-0.569	8
CF18		-0.211	-0.171	19.00%	-0.503	-0.392	22.00%
BRG-E		0.000	0.000	0.00%	0.000	0.000	0.00%
CF (K)-E		-0.480	0.000	100.00%	-0.964	0.000	100.00%

Fig. 21. FEA angle of twist data comparison for bent plate verses pipe stiffener due to Pass#1 and Pass#4.

$$\text{Note:}\delta = \frac{\phi_{pipe\ st.} - \phi_{bent\ plt.}}{\phi_{pipe\ st.}} \text{ X } 100\%,$$ where: ϕ is the angle of twist.

Figure 22 shows the effect of bent plate verse pipe stiffener on the angle of twist for cross-frame (CF18) due to both Pass#1 and Pass#4 (i.e., twist envelop for the truck whole journey across the span of the bridge). The use of pipe stiffener enhances (increases) connection torsional stiffness and reduces girder cross-section twist. The pipe stiffener serves as both the bearing stiffener and connection plate, and increases the warping resistance characteristics, and thus improves the buckling resistance of the girder.

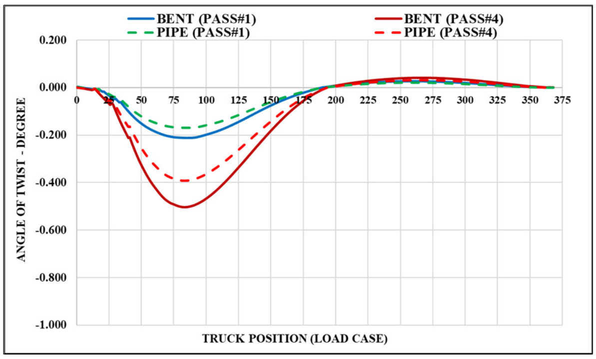

Fig. 22. FEA angle of twist envelop for the girder cross-sections adjacent to cross-frame 18 (CF18), due to Pass#1, and Pass#4, for the cases of using a bent plate and pipe stiffener connections.

VII. CONCLUSIONS

Field testing data of different passes of a weighed load vehicle incorporated with a validate full-scale 3D FEA model of a highly skewed steel girder bridge, created with the FEA software ABAQUS/CAE, were used to investigate the effectiveness of using two different types of connections: bent plate and pipe stiffener connection. The results of this study lead to the following conclusions:

- One of the difficulties in using a cross-frame parallel to the skew angle (case of US13 Bridge) can be the connection details that are used between the brace (cross-frame) and the girders. In many applications, the bent plate may be used to make the connection between the brace and the connection plate (web stiffener for the case of pier skew support region), and/or girder's web (in the abutment skew support region). Such detail allows the fabricator to utilize a connection plate that is perpendicular to the web, however, the bent plate connection can dramatically reduce the effectiveness of the brace due to the flexibility introduced by the eccentric connection. One solution in eliminating the bent plate is orienting the connection plate parallel to the skew angle, however, such a detail can be complicated for larger skew angles, thus a pipe stiffener can be suggested instead.
- The pipe stiffener was used instead of the bent plate connection to enhance the structural behavior of this connection through increasing the connection warping restraint and buckling capacity, and reducing the end cross-frame twist. The pipe stiffener can provide more rigid connection than the traditional bent plates and also it controls the girder end rotations. For example: the angle of twist for CF18 is reduced by 19% and 22% for Pass#1 and Pass#4, respectively. Meanwhile, the percentage reduction (enhancement) was 12% and 16% for cross-frame CF01, due to the same two passes.
- The effectiveness of the pipe stiffener came from its geometry configuration. The pipe stiffener connection can adjust and conform to any skew angle. In addition, it can work as a bearing stiffener plate, and since it is confined to the region of abutment support it can eliminate the need for an intermediate cross-frame to control end rotations and also make the stress distribution more uniformly than using end bent plates.

ACKNOWLEDGMENT

The authors would like to thank Dr. Jennifer McConnell (University of Delaware, Delaware, USA), for her guidance and support during this research.

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