EFFECTIVENESS OF CROSS-FRAME LAYOUT IN SKEW COMPOSITE CONCRETE DECK-OVER STEEL I-GIRDER BRIDGES

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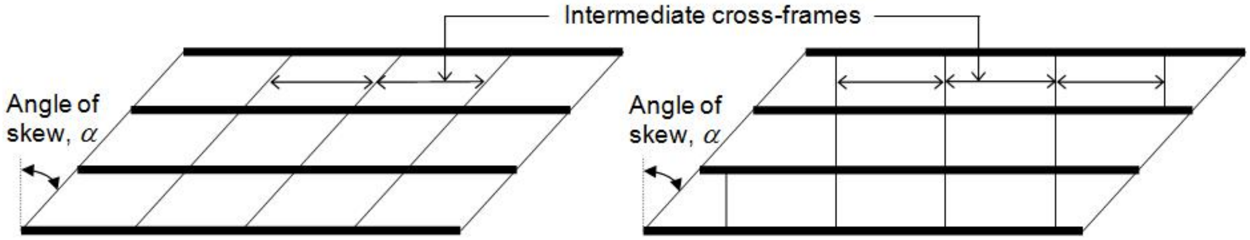
Abstract: The Canadian Highway Bridge Design Code (CHBDC) and AASHTO-LRFD Bridge Design Specifications allow cross-frames to be parallel to the skew angle if less than 20^0. However, for skew angles greater than 20°, both design specifications require the cross-frames to be perpendicular to the longitudinal axis of the girder. Literature review showed that the evaluation of the effect of cross-frames layout in skew composite concrete slab-over steel I-girder bridges on load distribution among girders is as yet unavailable. In this paper, three cross-frame layouts commonly used in skewed bridges are considered, namely: parallel cross frames to the skew support lines (parallel layout), perpendicular cross-frames to the skew support lines (perpendicular-continuous layout) and perpendicular cross-frames to the skew support line with staggered arrangement between girders (perpendicular-discontinuous layout). A three-dimensional finite-element modeling was conducted to determine the magnification factor for moment and shear in bridge girders with different skew angles, cross-frame layout and stiffness, span length, number of design lanes under dead loading. The finite-element results are presented in terms of cross-frame forces at bridge supports, differential vertical displacement of cross-frame at obtuse corners, girder longitudinal bending moment and vertical support reactions. Results showed that parallel cross-frame layout can be used for skew angles up to 30^0. Also, skew bridges with perpendicular-discontinuous cross-frame layout exhibited better structural performance than the perpendicular-continuous cross-frame layout.

1 INTRODUCTION

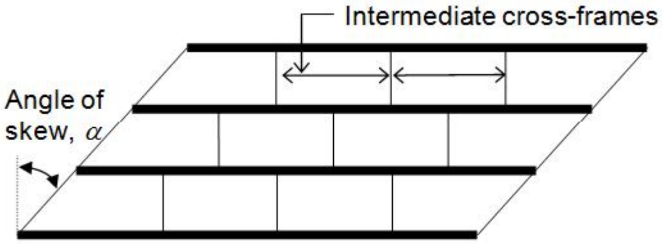
Behavior of skewed bridges is much more complicated than straight aligned bridges with normal supports due to the complex interaction between the steel girders and the cross-frames. This interaction generate large forces in the cross-frames under the truck live loads, thereby augment fatigue cracks commonly found around locations of cross-frames during routine maintenance inspections (Yura et al. 1992; Helwig et al. 1993; Helwig and Wang 2003). The severity of the fatigue problem is dependent on the layouts that are used for the cross-framing. In practice, three cross-frame layouts commonly used in skewed bridges as shown in Figure 1 are: parallel layout, perpendicular-continuous layout and perpendicular-discontinuous layout. If the skew angle is less than 20°, the AASHTO Specifications (2004) and CHBDC (2006) allow the cross-frame to be parallel to the skew angle. For skew angles greater than 20°, both design specifications require the cross-frames to be perpendicular to the longitudinal axis of the girder.

Parallel layouts are generally considered the least susceptible to fatigue induced stresses and differential vertical displacement between girders, because both ends of a cross-frame are attached at the same span point along adjacent girders. However for large skew angles, the cross-frame joint connection flexibilities and lower values of the cross-frame stiffness due to longer braces become an issue. For this reason, perpendicular cross-frame layout (continuous and discontinuous) is recommended (Ozgur 2011; Helwig and Yura 2012). However for cross-frames with perpendicular-continuous layout, the two ends of the cross-frame will develop unequal forces and displacements that can worsen the fatigue problems. Whereas, the behavior of perpendicular-discontinuous layout is similar to parallel layout since the centers of the individual cross-frames are located at approximately the same longitudinal location on the bridge (Helwig and Yura 2012).

Previous research regarding cross-frames layout perpendicular to the girder line (continuous and discontinuous) is not conclusive as to which layout performs better with respect to effective load sharing among girders and curbing differential vertical displacement at the two ends of the cross-frame. Some studies have concluded that large out-of-plane girder deflections using perpendicular-discontinuous cross-frame layout makes them less effective at distributing gravity loads through cross-frames (Fraser et al. 2000; Barth and Bowman 2001; Hartman et al. 2010). Experimental laboratory testing of both perpendicular cross-frame layouts show that cracks are more common in the continuous layout because back-to-back cross-frames are less flexible, tending to act as one continuous member (Barth and Bowman 2001). Therefore, it may be concluded that perpendicular-discontinuous cross-frame layout perform well to avert fatigue damages because of reduced load transfer, but reduced load sharing between girders may not necessarily be a desirable characteristic for a bridge system.



(a) Parallel (b) Perpendicular-continuous



(c) Perpendicular-discontinuous

Figure 1: Cross-frame layouts for bridges with skewed supports for (a) parallel configuration; (b) perpendicular-continuous configuration; and (c) perpendicular-discontinuous configuration

The objective of the current study is to investigate the effectiveness of cross-frame layout in skew composite concrete deck-over steel I-girder bridges under a uniform distributed load of 10 kN/m^2 by conducting three-dimensional (3D) finite-element modeling. The finite-element results are presented in terms of magnification factors for girder longitudinal bending moment and vertical support reactions, cross-frame forces at bridge supports and differential vertical displacement of cross-frames at obtuse corners for skew angle ranging from 0^o to 60^o. Results showed that the limiting value of skew angle specified in the bridge design specifications (AASHTO-LRFD 2004; CHBDC 2006) to employ parallel cross-frame layout is over conservative and it can be relaxed for skew angle up to 30^0. Also, the adequacy of the perpendicular-discontinuous cross-frame layout for skewed bridges is verified by exhibiting better structural performance than the perpendicular-continuous cross-frame layout.

2 MODELING OF BRIDGE

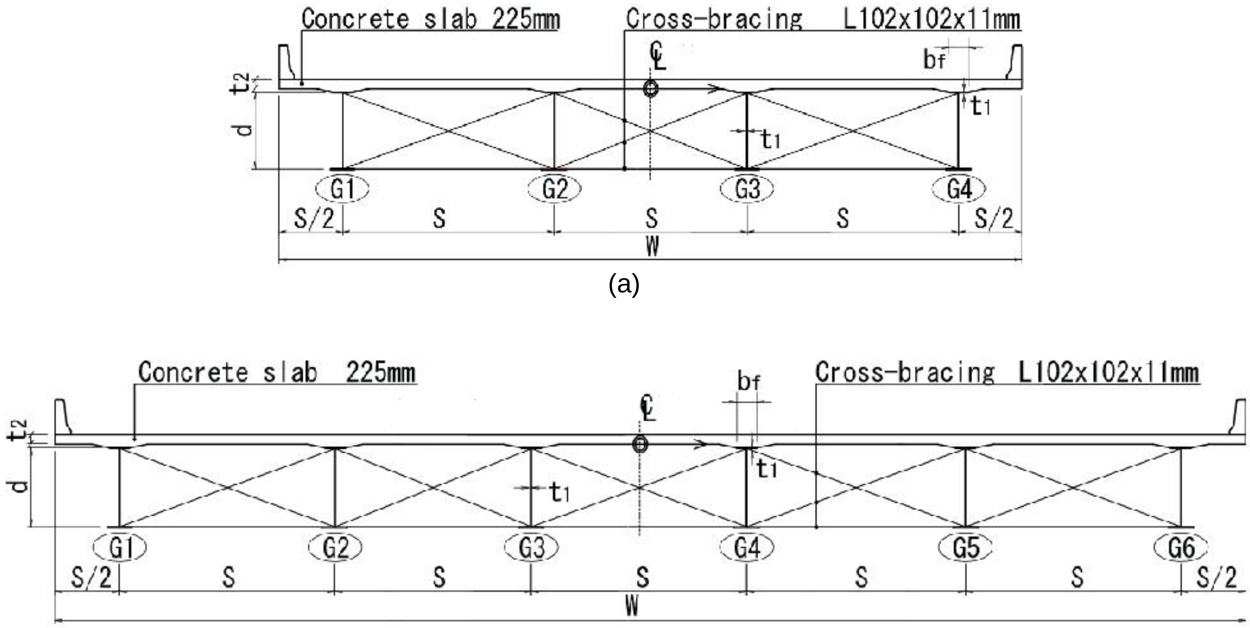
2.1 Bridge Prototype

Figure 2 shows a typical detail of one- and four-lane single span steel-concrete composite girder bridge considered in this study. The bridge structure was idealized using the following assumptions: (1) all materials were elastic and homogeneous; (2) the effects of road superelevation and curbs were ignored;

and (3) the reinforced-concrete deck slab and the supporting steel I-girders were in full composite action; (4) both the deck slab and the supporting I-girders were simply supported at the abutments; (5) transverse intermediate cross-braces were moment-connected to the longitudinal girders. Table 1 presents the basic cross-sectional configurations considered. The modulus of elasticity of the concrete material was 25 GPa with a Poisson's ratio of 0.20, whereas these design values for the steel material were 200 GPa and 0.30, respectively.

Table 1: Geometry of prototype bridges

Number of lanes	Span L (m)	Bridge width W (m)	Number of girders	Girder spacing S (m)	Cross-section dimensions (mm)			
					b_f	d	t_1	t_2
1	20	6	4	1.5	400	1040	20	225
4	20	18	6	3	400	1040	20	225



(a)

(b)

Figure 2: Cross-section diagram of a concrete slab over steel I-girder bridge for (a) one-lane; (b) four-lane

The concrete deck slab thickness was 225 mm. The steel web thickness was 20 mm, whereas the top and bottom flange width and thickness were 400 and 20 mm, respectively. The over-hanged slab length was equal to half the girder spacing. The X-type cross-frames at the support and between the span was provided in accordance with the specification stipulated in the manual of standard short-span steel bridges (Theodor and Al-Bazi 1997). Cross-frame members were spaced at equal intervals between the support lines and were made of L102x102x11 steel angles. For comparison purposes three types of cross-frame layouts were used: parallel layout, perpendicular-continuous layout and perpendicular-discontinuous layout. The effect of cross-frame layouts on girder longitudinal bending moment, vertical support reactions, cross-frame forces at bridge supports and differential vertical displacement of cross-frames at obtuse corners were studied by varying the skew angle between 0^o and 60^o by increment of 10^o. Straight bridges with zero skew angles served as a reference for comparison with skewed bridges. In total, 38 bridge cases were analyzed and assessed using finite-element analyses (FEA).

2.2 Finite Element Modeling

The general FEA program, CSiBridge (CSI 2013), was used to generate the 3D finite-element models. CSiBridge (CSI 2013) is an object-based interface that converts bridge objects to a finite-element model to be analyzed using SAP2000 (CSI 2007) structural analysis techniques. The concrete slab and web of steel girders were modeled using four-node 3D elastic shell elements with six degrees of freedom at each node. The top and bottom flanges of longitudinal steel girders were modeled using two-node 3D elastic beam elements with six degrees of freedom at each node. The transverse diaphragm cross-frames were simplified and modeled using the same beam elements. The shell and beam elements were connected by rigid link elements. These elements were used to model the composite action between the deck and the girders by connecting the nodes of the deck elements with the beam and shell elements. The connections between the girder and cross-frame elements were fixed. Details of the finite-element modeling of composite girder with cross-frame are shown in Figure 3. Simple supports at the ends of bridges were modeled using boundary constraints in which the lower nodes of the girder web ends were restrained against translation in such way to simulate temperature-free bridge superstructure (Lee 1994). Figure 4 shows typical boundary conditions considered for one-lane and four-lane bridges respectively. To improve the accuracy of the finite-element modeling and to make the design more efficient and cost-effective, the aspect ratio of the shell elements was adjusted less than 4. Logan (2002) proved that as the aspect ratio rises above 4, the inaccuracy of the solution increases.

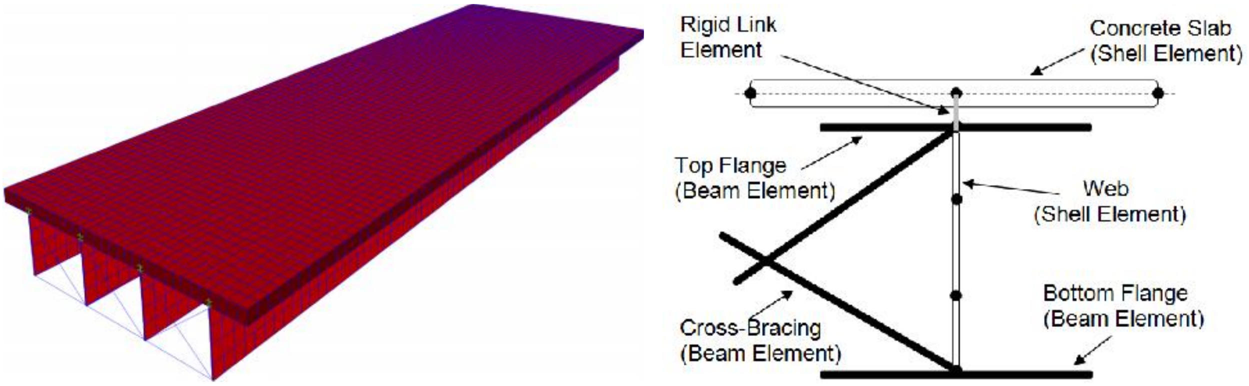
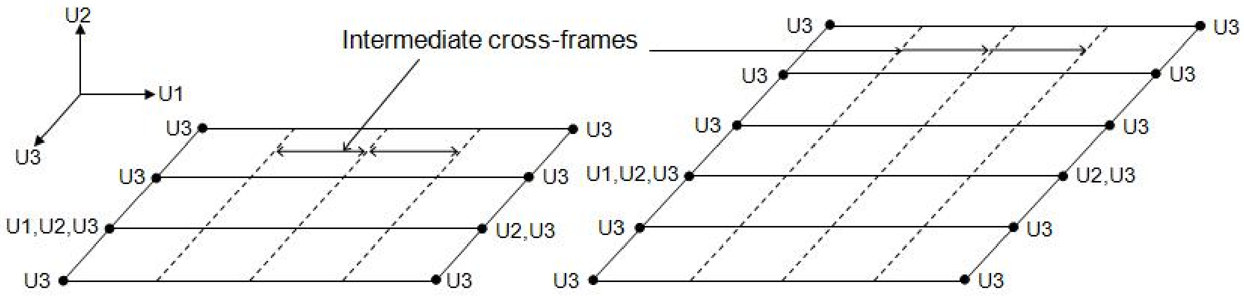


Figure 3: Details of the finite-element modeling of composite girder with cross-frames



(a) (b)

Figure 4: Boundary conditions for single-span bridge models: (a) one-lane bridge; (b) four-lane bridge

2.2.1 Verification of finite element modeling

To validate the finite element modeling technique, available physical load test data from the field testing of the Missouri Bridge A6101 performed in August of 2002 (Wu 2003) was compared against the results of a finite element model of the bridge using the previously described modeling technique. Out of the twelve different truck positions on the bridge span, the girder deflection values for eight truck positions were reported as they were determined by the test team to be the most accurate. Figure 5 presents a comparison of both the physical data from the field test of Missouri Bridge A6101 along with the data from the bridge's finite element model. The comparison indicates that this finite element modeling technique is quite accurate in predicting bridge system behavior and girder response with the largest difference in values is only 0.4 mm, equivalent to a 5% difference.

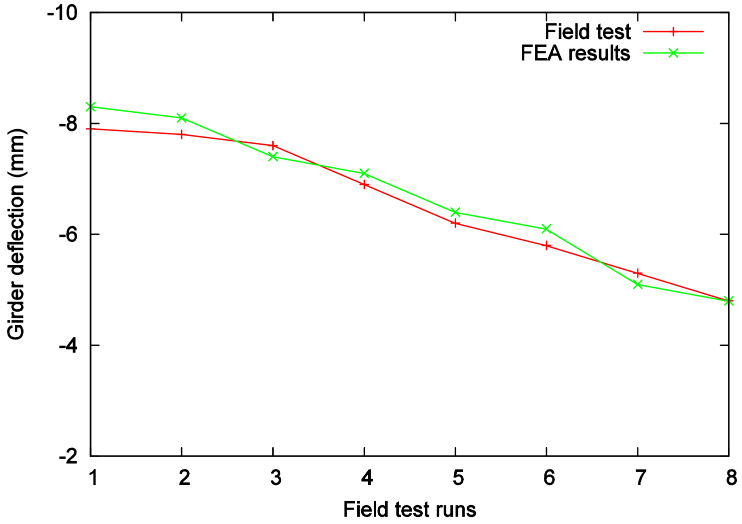


Figure 5: Validation of live load field testing with finite-element modeling results

3 LOADING AND FEA RESULTS

For the purpose of comparing the results of a skewed bridge with a straight configuration, a uniformly distributed load of 10 kN/m^2 was applied to the deck slab of the bridge prototypes analyzed in this study. The uniformly distributed loading case was considered in this study based on the results of previous studies performed on skewed bridges subjected to truck loading (Ebeido and Kennedy 1996a, b; Diab et al. 2011). In these studies, the live loading condition of fully loaded lanes with trucks provided the most critical cases for evaluating the maximum moment and shear in skewed bridges compared with partially loaded lanes with trucks.

The FEA results for the one-lane and four-lane bridges considered in terms of the cross-frame forces at bridge supports, differential vertical displacement of cross-frame at obtuse corners and magnification factors for girder longitudinal bending moment and vertical support reactions are reported subsequently. The maximum FEA bending moment is presented in the form of the ratio M_α/M_o, where M_α is the maximum FEA moment in the bridge for a given skew angle of α (between 0^o and 60^o), and M_o is the FEA moment for a nonskewed bridge (skew angle of 0^o). Similarly, the ratio R_α/R_o is calculated for the support reaction.

3.1 Cross-frame Forces at Bridge Support Line

Helwig and Wang (2003) suggested that the cross-frame lines near supports should not placed directly into the support, but instead be offset by approximately 4 or 5 feet (1.22 or 1.52 m) to reduce the forces induced in the cross-frame. A sensitivity study was carried out to validate this recommendation and the results revealed that placing the cross-frames at an offset substantially reduced the cross-frame forces particularly at the obtuse support corners. Keeping in view, all cross-frame layouts were set at 1.22 m away from the support line.

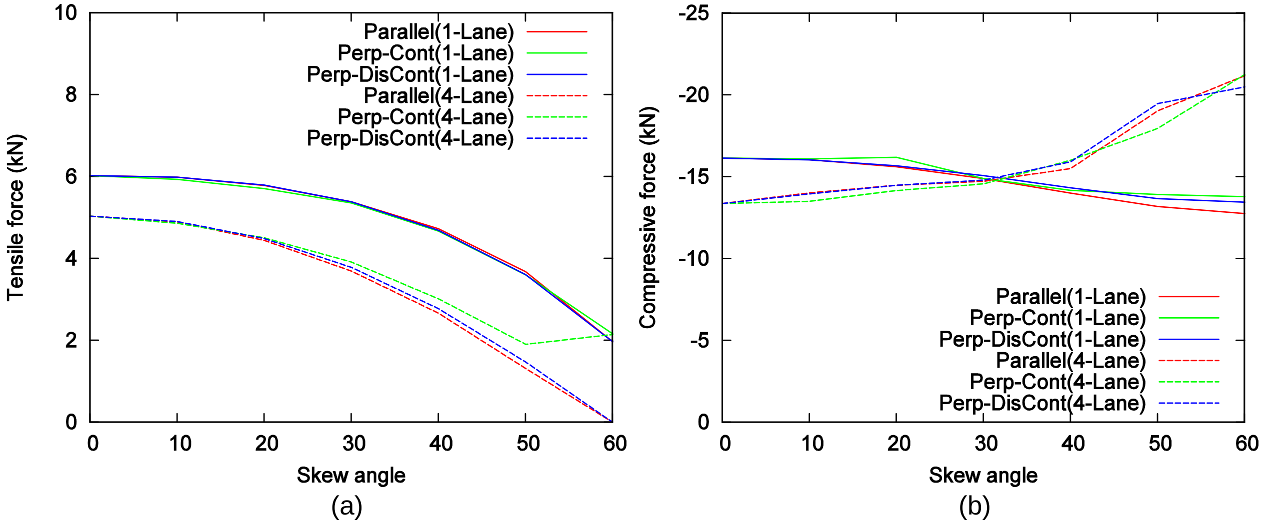


Figure 6: Cross-frame forces at obtuse corner of multi-lane bridge: (a) tensile force; (b) compressive force

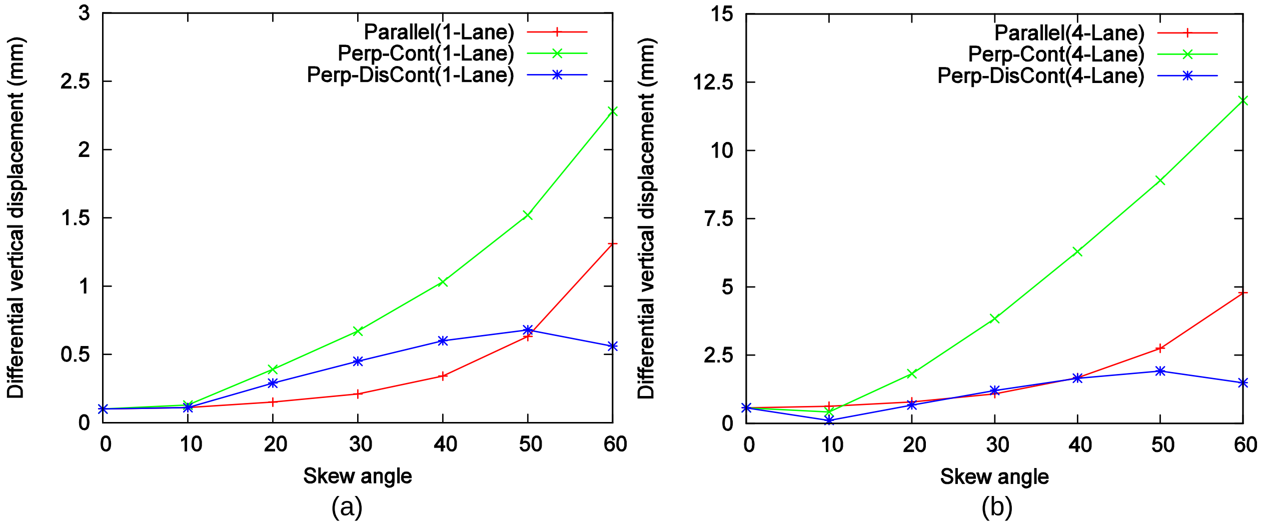


Figure 7: Differential displacement of cross-frame end members for: (a) one-lane; and (b) four-lane bridge

FEA results demonstrated that cross-frame diagonal members exhibited compressive force while tensile force was generated in the bottom chord members. Results also confirmed that the cross-frame members at obtuse corners experienced highest axial forces than the rest of the members at bridge support. Figure 6(a) shows that both bridge configurations showed a decreasing trend of tensile forces with an increase of skew angle from 0^o to 60^o. However, Figure 6(b) illustrates a maximum of 20% decrease and 59% increase in compressive force for one-lane and four-lane bridge system respectively with the variation of skew angle from 0^o to 60^o. Also, Figure 6(b) depicts that the variation of response is about 7% for one-lane and 9% for a four-lane bridge system when the skew angle changes from 0^o to 30^o and beyond that up to 60^o skew angle this variation intensified and resulted in 13% decrease for one-lane and 50% increase for four-lane bridge system. Furthermore, it has also been demonstrated in Figure 6(b) that both the bridge configurations exhibited a maximum of 21% difference at 0° skew angle, then converged at 30° skew angle and finally departed to the maximum of 67% at 60° skew angle.

3.2 Differential Cross-brace Vertical Displacement

Helwig and Yura (2012) reported that for cross-frames parallel to the abutments, the two ends of the cross-frames experienced similar vertical displacement during truck live loads. However, for cross-frames normal to the girder lines, the two ends of the cross-frames had different vertical displacements. This differential displacement resulted in large cross-frame forces, which intensified fatigue problems.

The results from 3D FEAs revealed that the differential vertical displacement at the obtuse corners of the intermediate cross-frame members increased significantly in case of perpendicular-continuous cross-frame layout in comparison with parallel and perpendicular-discontinuous layouts for multi-lane bridges, as shown in Figure 7. Moreover, the result showed that the perpendicular-discontinuous layout performed well in reducing the differential vertical displacement at the cross-frame ends significantly.

3.3 Longitudinal Bending Moment Magnification Factor

The longitudinal bending moments for the interior and exterior girder of multi-lane bridges were evaluated and the corresponding magnification factors (M_α/M_o) are presented in Figure 8 and 9 respectively.

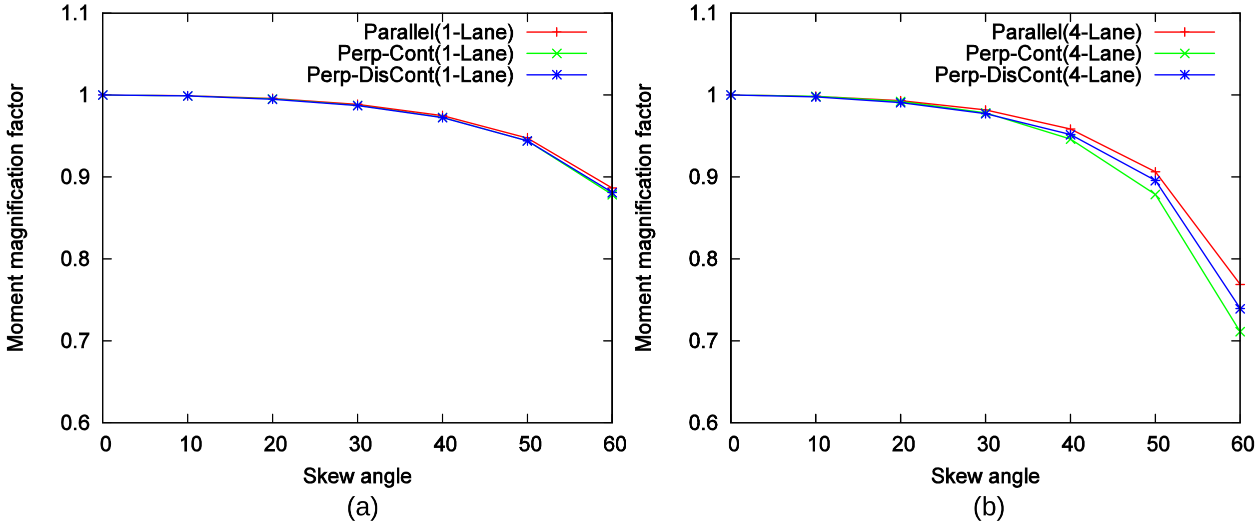


Figure 8: Moment magnification factor for interior girders of bridge system for: (a) one-lane; (b) four-lane

The FEA results of an interior girder of multi-lane bridges were quantified in term of the ratio M_α/M_o as follows:

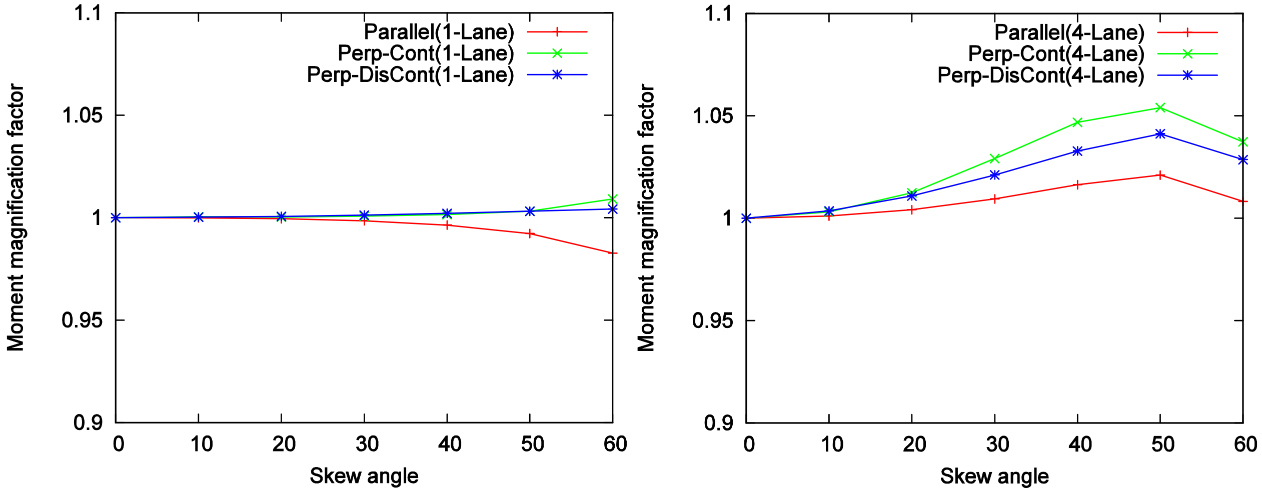
a) For one-lane bridge, all cross-frame layouts resulted in about 12% decrease in longitudinal internal girder moment with the variation of skew angle from 0° to 60°.

b) For four-lane bridge, all cross-frame layouts experienced a similar trend of 2% decrease of internal girder moment up to 30° skew. Subsequently, this reduction in the internal girder moment increased significantly and experienced a decrease of 23%, 29% and 25% in case of parallel, perpendicular-continuous and perpendicular-discontinuous cross-frame layouts respectively.

Similarly, the FEA results for an exterior girder were computed as follows:

a) The effects of different cross-frame layouts showed an insignificant effect on exterior girder moment with the variation of skew angle (0^{o} to 60^{o}).

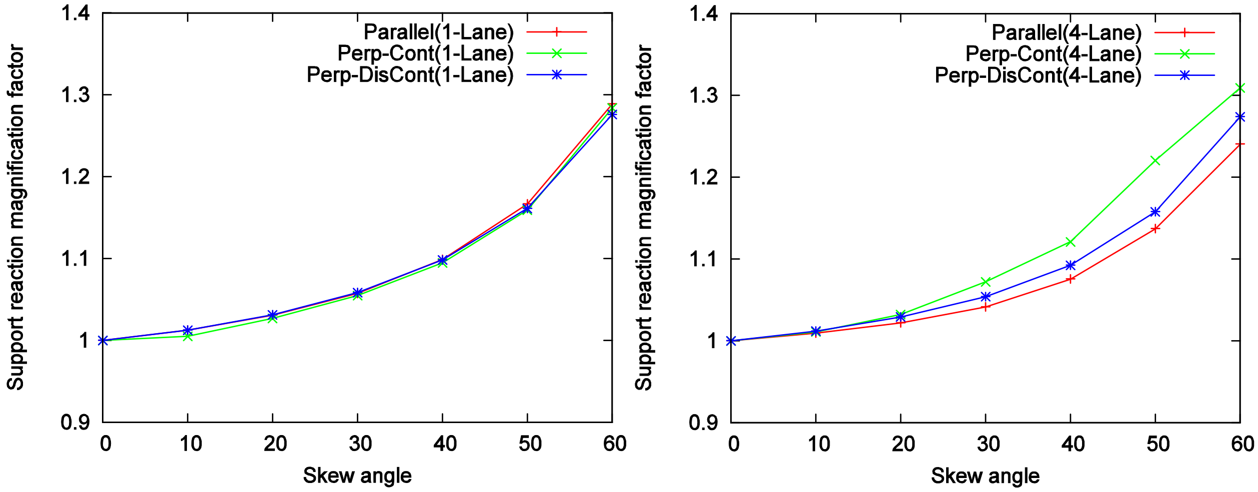
b) For one-lane bridge, parallel bracing system resulted in 2% decrease of exterior girder moment at 60^{o} skew angle. However, in a four-lane bridge system, a maximum of 2%, 6% and 4% increase in exterior girder moment was experienced for parallel, perpendicular-continuous and perpendicular-discontinuous cross-frame layouts respectively.



(a) (b)

Figure 9: Moment magnification factor for exterior girders of bridge system for: (a) one-lane; (b) four-lane

3.4 Support Reaction Magnification Factor



(a) (b)

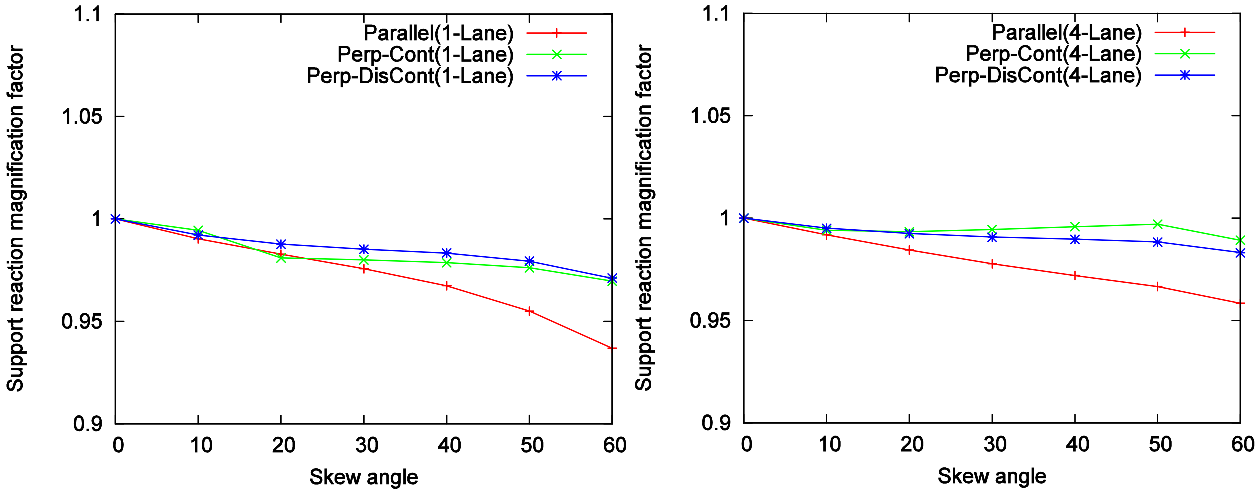
Figure 10: Reaction magnification factor at obtuse corners of bridge system for: (a) one-lane; (b) four-lane

In skewed bridges the behaviour of the structure near the bearings particularly at the obtuse corner requires special consideration. Figure 10 shows the support reaction at obtuse corners for one-lane and four-lane bridge system in term of magnification factor (R_α/R_o) as follows:

a) For one-lane bridge system, all cross-frame layouts resulted in 6% increase in exterior girder support reaction at obtuse corner for skew angle up to 30°. However, an increase of 22% is experienced beyond 30° up to 60° skew.

b) For four-lane bridge system, a maximum of 7% increase in support reaction was experienced at 30° skew for perpendicular-continuous cross-frame layout. However from 30° to 60° skew, the cross-frame layouts having parallel, perpendicular-continuous and perpendicular-discontinuous arrangements exhibited 21%, 26% and 23% increase in support reactions respectively.

Figure 11 revealed that cross-frame layouts have insignificant effect on acute corner support reaction with the variation of skew angle for both bridge configurations. However, parallel cross-frame layout demonstrated a 7% and 4% decrease in response for one- and four-lane bridge system at 60° skew.



(a) (b)

Figure 11: Reaction magnification factor at acute corners of bridge system for: (a) one-lane; (b) four-lane

4 CONCLUSIONS

The effect of cross-frame layouts with the variation of skew angle in a single-span multi-lane steel girder bridges were investigated using 3D finite element analysis. The study involved varying the geometric parameters of a bridge such as number of lanes or bridge width, number of girders, girder spacing and seven distinct skew angles. The cross-frame forces at bridge supports, differential vertical displacement of cross-frame at obtuse corners, girder longitudinal bending moment and vertical support reactions for skewed bridges were calculated and compared to the reference 3D FEA nonskewed bridges. The findings of this study can be summarized as follows:

1. Higher compressive forces in the cross-bracing members arranged at the support line were experienced in four-lane bridge system particularly at high skew angle. An increase of 59% was evaluated with the variation of skew angle from 0° to 60° with an increase of about 9% took place when skew angle less than 30°.

2. For high skew angles, perpendicular-discontinuous cross-brace layout resulted in significant reduction of differential vertical displacement at the two ends of the cross-frame members.

3. The FEA results of the maximum longitudinal interior girder moment for different cross-frame layouts indicated a uniform pattern of decrease with an increase in the skew angle when compared to nonskewed bridge regardless of the number of lanes, number of girders and girder spacing. This decrease was small for skew angle less than 30°, and tends to be significant when the skew angle exceeded 30°. However, the cross-frame layout has insignificant effect on exterior girders.

4. As skew increased, more reaction was transferred towards obtuse angled corners and less on the acute angled corner. The increase was small for skew angle less than 30°, and tends to be significant when the skew angle exceeded 30°.

5. The FEA result showed that the computed responses have insignificant effect with the change of skew angle up to 30°. Therefore, parallel cross-frame layout can be employed for skew angles up to 30°.

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