Skew Effect on Box Girder Bridge

Preeti Agarwal, P. Pal, and P. K. Mehta

List of Notation

θ	Skew angle
BM_{DL}	Bending moment (maximum) due to DL
SF_{DL}	Shear force (maximum) due to DL
VD_{DL}	Vertical deflection (maximum) due to DL
$BMR_{DL(o)}$	Bending moment ratio due to DL for outer girder
$BMR_{LL(o)}$	Bending moment ratio due to LL for outer girder
$SFR_{DL(o)}$	Shear force ratio due to DL for outer girder
$SFR_{LL(o)}$	Shear force ratio due to LL for outer girder
$VDR_{DL(o)}$	Vertical deflection ratio due to DL for outer girder
$VDR_{LL(o)}$	Vertical deflection ratio due to LL for outer girder
BM_{LL}	Bending moment (maximum) due to LL
SF_{LL}	Shear force (maximum) due to LL
VD_{LL}	Vertical deflection (maximum) due to LL
$BMR_{DL(i)}$	Bending moment ratio due to DL for inner girder
$BMR_{LL(i)}$	Bending moment ratio due to LL for inner girder
$SFR_{DL(i)}$	Shear force ratio due to DL for inner girder
$SFR_{LL(i)}$	Shear force ratio due to LL for inner girder
$VDR_{DL(i)}$	Vertical deflection ratio due to DL for inner girder
$VDR_{LL(i)}$	Vertical deflection ratio due to LL for inner girder

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S. Kumar Shukla et al. (eds.), *Advances in Geotechnics and Structural Engineering*, Lecture Notes in Civil Engineering 143,
https://doi.org/10.1007/978-981-33-6969-6_5

1 Introduction

Over the last few decades, numerous bridges have been constructed because of the tremendous development in traffic. The box girder bridge is being constructed/preferred nowadays because of its economy, aesthetics, torsional rigidity, etc. Most of the bridges are supported orthogonal to the traffic direction and are termed as normal bridges. The skewness is introduced mainly because of the existing facilities, site limitations, mountainous territories and complex intersections. Skew box girder bridge is one whose girders may form any angle, except 90° with the abutment. The inner and outer girders of the skew box girder bridge deck are defined based on traffic direction, which is shown in Fig. 1.

Many studies are available on skew bridges, and this study includes a few of these. Brown and Ghali [1] presented a semi-analytic method for the analysis of skew box girder bridges. The results obtained from this method are validated with experimental test results and numerical finite element results. Huo and Zhang [2] studied the effect of skewness, varied from 0 to 60°, on reactions at the piers of continuous bridges subjected to live loads using finite element analysis. Nouri and Ahmadi [3] investigated the effect of skewness on continuous composite girder bridges subjected to AASHTO HS20-44 from the finite element method (FEM). He et al. [4] presented the results of static and dynamic testing of continuous prestressed concrete box girder bridge models (1:8 scale) with 45° skew. Mohseni and Rashid [5] investigated the stresses in the skew multicell bridge, using SAP2000. Yalcin [6] investigated the effect of live load distribution on skewed integral abutment bridges and skewed simply supported bridges. Gupta and Kumar [7] determined the absolute bending moment in a simply supported skew-curved bridge using FEM. Gupta et al. [8]

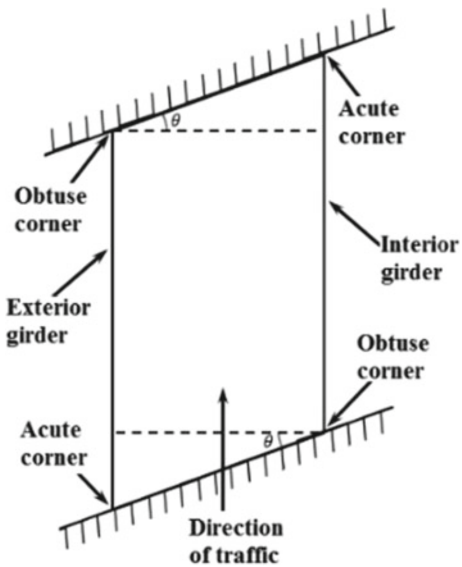


Fig. 1 Skew box girder bridge deck

evaluated frequencies of one, two and three cells RC curved bridge using finite element analysis. Agarwal et al. [9] investigated the maximum bending moment and shear force in a single cell skew bridge using FEM and the effect of the span, girder spacing and span-depth ratio was presented.

In the aforementioned literature, the investigators mostly studied the composite I-girder skew bridge considering AASTHO loading, and only a few studies are available on skew box girder bridge. Also, the effects of both dead load (DL) and live load (LL) on skewed bridges are not considered in the analysis. Additionally, there are only a few studies available on Indian loading. In view of the above, the present investigation aims to evaluate the effect of the skew angle on the RC bridge due to DL and LL. The statistical approach deduces many equations to evaluate the bending moment ratio (BMR), the shear force ratio (SFR) and the vertical deflection ratio (VDR) under DL and LL. Here, the BMR is the ratio of maximum BM for any skew bridge (θ) to the maximum BM for a straight bridge. Similarly, other ratios are defined in this study.

2 Validation

Figure 2 shows the RC box girder bridge which is used for validation. This similar model was presented by Gupta and Kumar [7]. In finite element modelling, four noded shell element with six degrees of freedom at each node is used for analysis.

The cross section properties for the model are as follows: Span—27.40 m; Width—10.80 m; Depth—2.96 m; Kerb on both sides of deck—0.2 m and thickness of top and bottom flanges—250 mm and 280 mm, respectively. The concrete's material properties considered are follows: Grade of concrete = M25; Poisson's ratio = 0.2; Elastic modulus = 2.5×10^4 N/mm^2 and Density = 25 kN/m^3.

The bridge is evaluated for dead and live loads (70R tracked vehicle), implemented at a minimum clear distance of 1.2 m from the kerb edge. The mesh size is considered

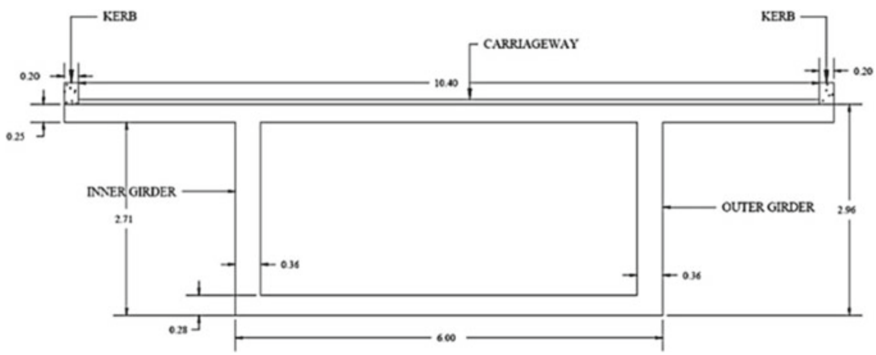
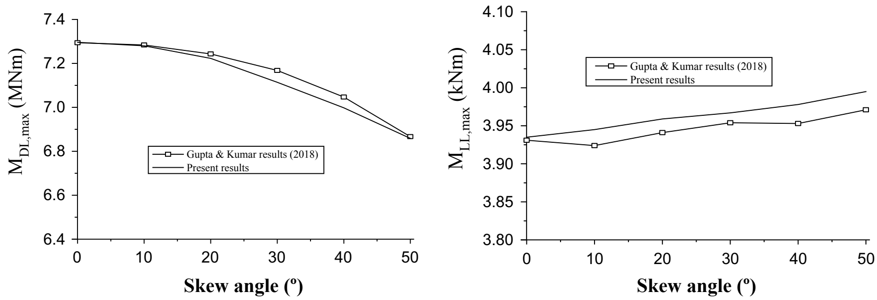
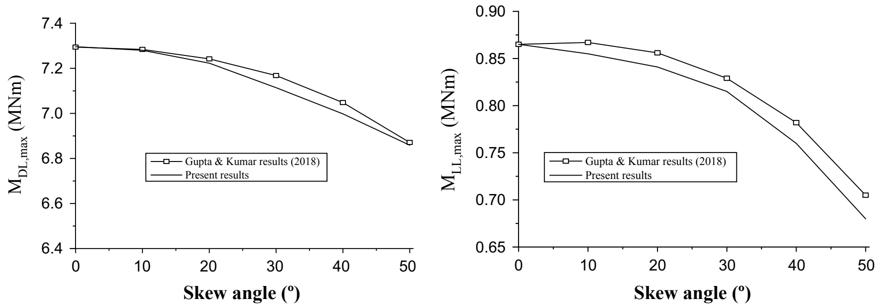


Fig. 2 Cross section of box girder bridge deck (all dimensions are in metre)



(a) For dead load (b) For live load

Fig. 3 Variation of MBM with skew angle in outer girder



(a) For dead load (b) For live load

Fig. 4 Variation of MBM with skew angle in inner girder

as 20 cm. The maximum bending moment (MBM) due to DL and LL is calculated and compared. The present results are found to be in close agreement with Gupta and Kumar's result [7]. The modelling process is therefore appropriate and can be applied with varying parameters for further investigation. Figures 3 and 4 illustrate the maximum bending moment (MBM) for outer and inner girders under DL and LL, respectively, having different skew angles. The percentage variation between these two results is within 5%. The modelling process can be accepted and is applied with varying parameters for further investigation.

3 Results and Discussion

3.1 Methodology

The steps involved in modelling the bridge are shown in Fig. 5, where the input parameters considered are the geometrical properties, material properties, boundary conditions and loading conditions. The outputs are the effects of skew angles on bending moment, shear force and vertical deflection.

The behaviour of box girder bridge decks is examined for various skew angles. The relevant deck data considered for the analysis are as follows: Total width = 11.5 m consisting of roadway = 7.5 m; Kerb = 0.45 m on both sides and Footpath = 1.5 m on both sides. Figure 6 displays the box girder bridge deck model. The material properties of M40 grade of concrete used in bridge models are as follows: Poisson's ratio = 0.2; Density = 25×10^3 N/m^3; Elastic modulus = 3.16×10^4 N/mm^2 and Modulus of rigidity = 1.31×10^7 MPa. The material properties of Fe500 grade of reinforcing steel are as follows: Density = 78 kN/m^3; Yield strength = 500 N/mm^2; and Elastic modulus = 2×10^5 N/mm^2; and Modulus of rigidity = 7.69×10^7

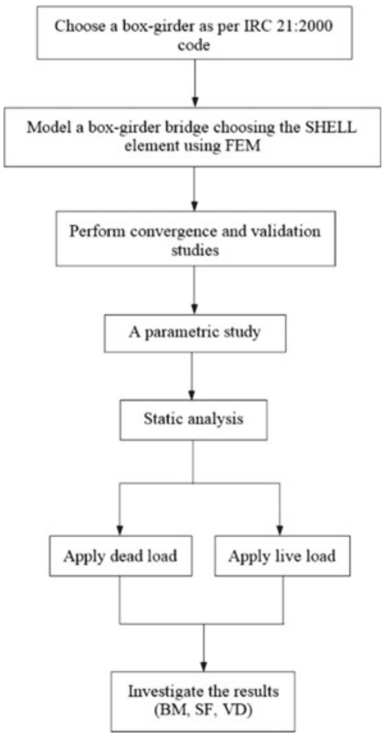


Fig. 5 Flow diagram for modelling

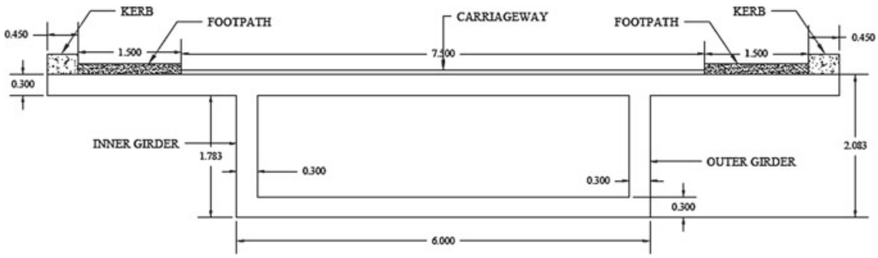


Fig. 6 Model of bridge deck system (dimensions are in metre)

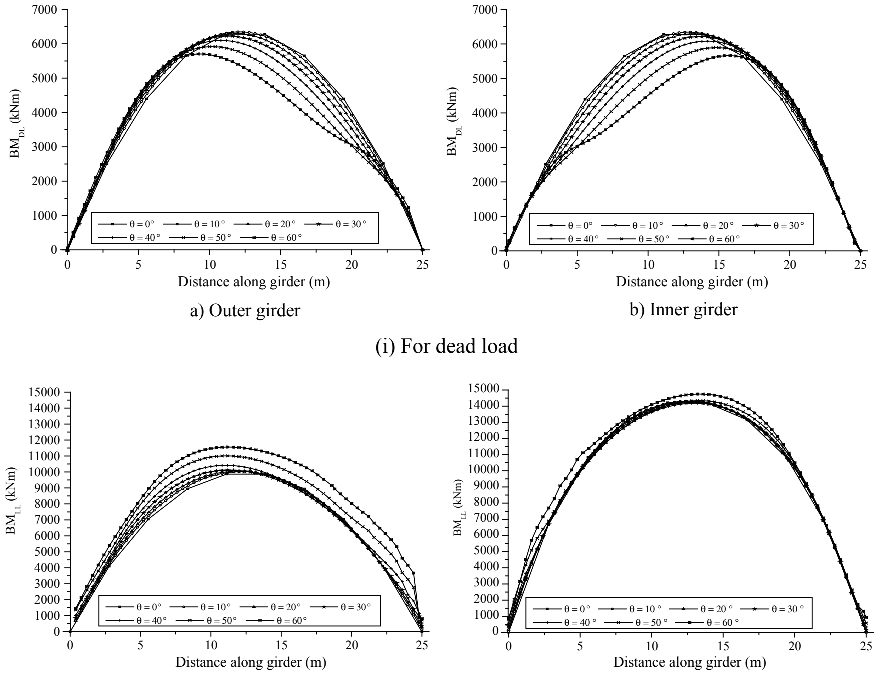
N/mm^2. The analysis is done using CSiBridge v.20.0.0 software [10]. Girders and slab are modelled using the four noded shell element having six degrees of freedom at each node. The section is finalised as per the specifications of IRC 21:2000 [11].

In this study, Class 70R load is used; however, the results of only 70-R track loading are presented because it is found to develop more severe stresses and deflection in comparison with any other IRC loadings. As per IRC-6 specification [12], this load is applied at a distance of 1.2 m from the kerb face. Simply supported boundary condition is used for the analysis of all bridge deck models. In the analysis, it is found that the results are converging at a mesh size of 100 mm, so 100 mm mesh size is used for parametric study.

3.2 Effect of Skew Angle

The effect of skew angle on bending moment (BM), shear force (SF) and vertical deflection (VD) on both the girders of the box girder under DL and LL is investigated. A bridge of 25 m span (L) and span-depth ratio (L/d) 10 is considered for the analysis. Figure 7 shows the variation of BM along outer and inner girders, for different skew angles. It is evident from the figure that DL-BM is the same along both the girders for a straight box girder bridge. In the case of LL, the BM is higher along the inner girder than that of the outer girder because the LL is placed close to the inner girder. When the skew angle varies, maximum BM shifts towards the girders' obtuse corner due to DL and LL. The DL-BM decreases considerably with the increase in skew angle in both the girders. The LL-BM increases with the skew angle. For skew angle, less than 30°, variation in BM is insignificant for both the girders. When the skew angle varies from 30° to 60°, for both the girders, the DL-BM is found to decrease within a range of 2.8–9.1% with respect to those in straight bridges. The LL-BM at outer girder increases in the range of 1.5–19.1% for the skew angle variation from 0 to 60°, with respect to the straight bridge. However, the BM for inner girder is found to be insignificant for a similar variation.

Figure 8 shows the variation of SF along outer and inner girders for different skew angles. It is seen that SF increases with the skew angle at the obtuse corner



a) Outer girder b) Inner girder

(i) For dead load

a) Outer girder b) Inner girder

(ii) For live load

Fig. 7 Effect of skew angle on variation of DL and LL moment

and decreases at the acute corner of both the girders. For both the girders, the DL-SF increases by 6.0, 12.2, 18.3, 24.5, 29.4 and 31.2% for skew angle 10, 20, 30, 40, 50 and 60°, respectively, with respect to the straight bridge. At outer girder, LL-SF increases by 3.8, 8.6, 11.1, 14.1, 15.5 and 16.8% for the skew angle of 10, 20, 30, 40, 50 and 60°, respectively, with respect to the straight bridge. However, there is a change in the behaviour of skewed bridges in comparison with the straight bridge. While for the inner girder, the respective changes are within a range of 1.5–8.2%. There is a change in the behaviour of skewed bridges in comparison with the straight bridge.

Figure 9 shows the vertical deflection variation with the skew angle. For smaller skew angles (up to 20°), the variation in VD is found to be insignificant. The DL-VD decreases with the increase in skew angle in both the girders. In the outer girder, the LL-VD decreases up to 50°, while in the inner girder, it increases with skew angle. The DL-VD is found to decrease by in the range of 2.7–16.2% in both the girders for skew angle variation from 30 to 60°. In the outer girder, the LL-VD increases by about 5% for skew angle variation from 30 to 60°, while in the inner girder, the respective changes are within a range of 1.9–8.1%.

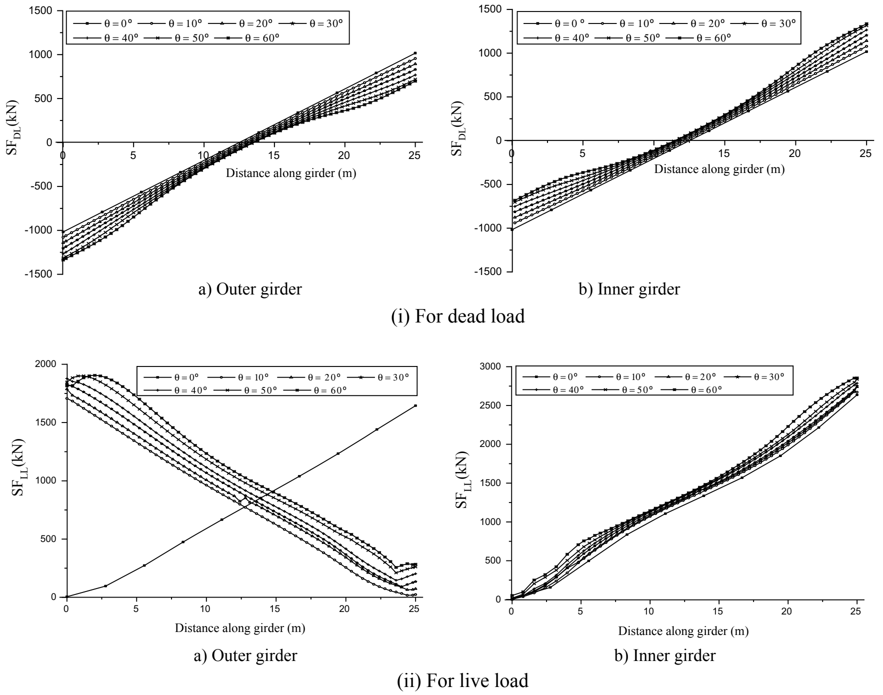


Fig. 8 Effect of skew angle on variation of DL and LL shear force

3.3 *Proposed Equations for Forces and Deflection*

A few equations are proposed to evaluate the effect of skew angle on the BMR, SFR and VDR for both outer and inner girders of the bridge. The two primary loads, i.e. dead load and IRC class 70 R track load, are considered separately for developing the proposed equations. The value of BMR in the outer girder is represented by $\text{BMR}_{\text{DL(o)}}$, while its value in the inner girder due to DL is represented by $\text{BMR}_{\text{DL}(i)}$. Likewise, other ratios also presented. The proposed equations for DL and LL are as follows:

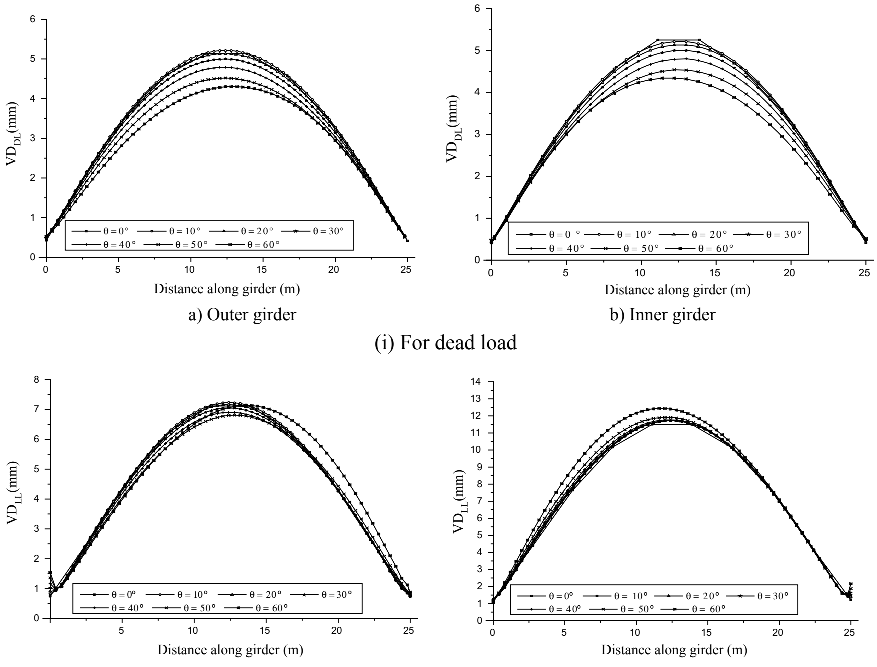
(A) **For DL**

- At outer girder,

$$\text{BMR}_{\text{DL(o)}} = \cos(55.3\theta) \tag{1}$$

$$\text{SFR}_{\text{DL(o)}} = 1 + 0.00587\theta \tag{2}$$

$$\text{VDR}_{\text{DL(o)}} = \cos(0.00962\theta) \tag{3}$$



a) Outer girder b) Inner girder

(i) For dead load

a) Outer girder b) Inner girder

(ii) For live load

Fig. 9 Effect of skew angle on variation of deflection due to DL and LL

- At inner girder,

$$BMR_{DL(i)} = 1 - 4.7012 \times 10^{-7} \times \theta^3 \quad (4)$$

$$SFR_{DL(i)} = 1 + 0.00581\theta \quad (5)$$

$$VDR_{DL(i)} = \cos(-0.00937\theta) \quad (6)$$

(B) For LL

- At outer girder,

$$BMR_{LL(o)} = 1 + 8.2073 \times 10^{-7} \times \theta^3 \quad (7)$$

$$SFR_{LL(o)} = 17.41363/(8.0739 + 17.12901\theta) - 1.15669 \quad (8)$$

$$VDR_{LL(o)} = 1 + 1.29243 \times 10^{-8} \times \theta^4 - 5.16631 \times 10^{-5} \times \theta^2 \quad (9)$$

Table. 1 Verification of the proposed equation

Forces	Girder	Skew angle (degree)	For dead load			For live load		
			Using proposed equation	Using FEM	% error	Using proposed equation	Using FEM	% error
BM (kNm)	Outer	50	5787	5910	2.19	10,878	11,009	1.18
	Inner	50	5909	5896	0.13	14,478	14,428	0.35
SF (kN)	Outer	40	1256	1266	0.79	1861	1877	0.82
	Inner	40	1253	1256	0.90	2785	2787	0.05
VD (mm)	Outer	60	4.304	4.304	0	6.988	7.138	2.09
	Inner	60	4.348	4.347	0.04	12.193	12.435	1.97

- At inner girder,

$$BMR_{LL(i)} = 1 + 0.00037\theta \tag{10}$$

$$SFR_{LL(i)} = 1 + 0.001141\theta \tag{11}$$

$$VDR_{LL(i)} = 1 + 1.67403 \times 10^{-5} \times \theta^2 \tag{12}$$

The effect of skew angle on BM, SF and VD in a single cell bridge under DL and LL is studied. Some of the results obtained from the present analysis are reported in Table 1 for the validation of the proposed equations. In all cases, the outcomes deduced from the equations are found to be very close to those obtained from the finite element analysis.

4 Conclusions

A study was performed to evaluate the behaviour of skew box girder bridges under both DL and LL, and the following conclusions are drawn:

- The skew bridge's influence is insignificant up to 20°, so these bridges can be treated as the straight one.
- For DL, the BM decreases significantly with increment in skew angle, while for LL, it increases.
- SF increases with the skew angle at obtuse corner, while it decreases at the acute corner of both the girders. In the inner girder, the effect of the skew angle on LL-SF is insignificant.

- Under DL, the VD decreases with the increase in skew angle in both the girders. Under LL, in the outer girder, it decreases up to 50°, while in the inner girder, it increases with skew angle.

Acknowledgements The authors acknowledge the financial support offered under TEQIP by the MNNIT Allahabad.

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