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Influence of Skewness on Flexural Response of RC Slab Bridges

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Abstract

Normally, straight slab bridges are preferred in any road network due to simplicity in design and construction. However, in some circumstances, it becomes necessary to provide the skew slab bridges owing to geometrical considerations. The structural behaviour of skew slab bridges differs significantly as compared to right slab bridges unless the skew angle is small. In this paper, attempts have been made to investigate the influence of skewness on flexural response of two-lane slab bridges of different spans ranging between 4 m to 8 m at in interval of 1 m and the skew angle has been varied from 0° to 45° in the multiple of 15°. In this study, the linear-elastic three-dimensional finite element analysis of slab bridges has been carried out using the STAAD_Pro. In order to investigate the effect of skewness on flexural response five different span slab bridges, the longitudinal moment, transverse moment, twisting moment, and the maximum deflection produced in skew slab bridges are normalized with the corresponding parameters in the right slab bridges. The study showed that the normalized longitudinal moment decreases significantly with the increase in angle of skew from 15° to 45°, in contrast, an excessive rise in the normalized transverse moments was observed.

Keywords: Skew, Slab Culvert, Slab Bridge, Flexural Response, deflection, Finite Element Method, Staad_Pro, IRC Class-70 R loading.

1. Introduction

Bridges are the key element in any road network. Based on span length, broadly the bridges are classified as small span bridges and large span bridges. The bridge structures with individual spans not more than 10 m are referred as small bridges, however, the bridges having span length less or equal to 6 m are called culverts [SP13, 2004]. RCC solid Slabs are the simplest form of the superstructure and they are widely used in small span bridges. Normally, right (straight) slab bridges are adopted for small spans due to simplicity in design and construction, however, in some circumstances, it becomes necessary to provide skew slab bridges due to geometrical considerations. The angle between the normal to abutment axis and the longitudinal axis of the bridge is referred as skew angle. The effect of skewness on flexural response of simply supported bridges having the angle of skew 15º – 20º is generally found trivial and an approximate method of analysis and design may be adopted and they are found reasonably correct [Chen and Duan, 2014]. For simplified analysis of slab bridges having skewness up to 15º, slab may be treated as one-way right slab having span equal to the distance between the abutments measured along the centreline of bridge. The reinforcement in the slab to be provided along the centreline of bridge may be calculated corresponding to maximum moment at mid-span of equivalent right slab bridge. Moreover, for the temperature effects, cross reinforcement which is usually taken as 0.2 percent of the effective cross section of the slab is placed parallel to supports (IRC 112, 2019). With the increase in skewness in slab, the transverse and twisting moments in the slab become significantly high and the skew slabs cannot be designed as one-way slabs. The increase in skewness in the slab beyond 15º – 20º results in (i) alteration in the direction of maximum longitudinal moment across width of slab, changing from near parallel to span at edges to near orthogonal to abutment in the central regions, (ii) occurrence of considerable torsion in the slab, (iii) high reactions and shear forces near the obtuse corner, (iv) hogging moments near the obtuse corner, and (v) low reactions and possible uplift in acute corner. Due to coupling of these characteristics, the overall structural response of skew slab becomes complex. The structural response of skew slabs depends on degree of skewness, width of slab, and the span of slab. For the simple and quick analysis of bridge having skewness beyond 20º, the equivalent-beam method is normally used. Nevertheless, this method gives conservative results, however, it is still used in American Association of State Highway Officials (AASHO) and the Canadian Standards Association (CSA) specifications. Théoret et al. (2012) derived a series of equations for the equivalent-beam method in order to incorporate the effect of skewness for calculating

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the longitudinal shear forces and bending moments, for both dead and live load cases. In order to improve the accuracy of results, grillage method and the finite element methods are used to analyse the skew slab bridges. In the finite element method, the slab bridges may be modelled using plate elements or shell elements. Menassa et al. (2007) studied the flexural behavior of skewed slabs subjected to HS20 loading using the finite element method and concluded that with the increase in skewness in slab, the longitudinal moment decreases whereas the transverse-moment increases. Raghav and Tripathi (2019) used the Finite Element program SAP 2000 to examine the effect of skewness on various moment components in the skew slab bridges under the IRC Class-A loading. Based on their study they concluded that up to 20° skewness there was no significant variation in longitudinal moment, however, with the increase in skewness the longitudinal moments reduced monotonically, nevertheless, the transverse moments were found to increase rapidly with increase in skewness. Sharma et al. (2019) experimentally investigated the behavior of skewed slab and proposed a theoretical formulation to predict the ultimate flexural strength of skew slabs. Based on experimental data and Finite element analysis results, Miah and Kabir (2005) observed that with the increase in skew angle, the stiffness of slab decrease. Moreover, they concluded that for the same aspect ratio and skew angle, the ultimate load carrying capacity of skew slabs were higher when the loads were distributed across the width rather than concentrated at single point located at centre of slab. Doullah and Kabir (1997) carried out experiments on skew slabs and compared the experimentally observed deflections and ultimate loads with those predicted by finite element method using the layered shell element. They concluded that the layered shell element may adequately be used to model the reinforcing bars in the skew slabs. Ismai (2018) used the ABAQUS to the perform the 3-D non-linear finite element analysis of single lane skew slab bridges and studied the influence of skewness on the stress variation in the slab. Moreover, they concluded that the ABAQUS may be used for detailed analysis of skew slab bridges. Furthermore, they recommended that slabs containing the skew angle 60° or more should be considered as severely skewed as these slabs may have higher tendency of cracking compared to analogues right slab. Sharma et al. (2020) proposed a generalized analytical model to design the skew slabs and validated the analytically predicted ultimate flexural capacity with the experimental results. Moreover, they noticed that the skew slabs with a ratio of short diagonal to span less than unity and subjected to point load at center of slab exhibits the uplifting of acute corners and recommended to avoid the construction of skew slabs with such geometrical configurations. Lipari (2020), reviewed the various codal provisions for the design of RC skew slabs for shear and proposed the modified guidelines for the shear design of skew slabs subjected to concentrated loads close to supports. Moreover, he pointed out that the use of design methods based on the effective width, which are acceptable for right (straight) slabs, may lead to unsafe results in case of skew slabs. Furthermore, regarding the reinforcement detailing he recommended to place the main reinforcement perpendicular to the support line. Kankaml and Dagher (1995) performed the nonlinear finite analysis of RC rigid frame skewed slab bridges to study the effect of reinforcement detailing on the flexural strength of skew slab. They pointed out that a skewed slab bridge with more reinforcement near the obtuse corner than near the acute corner exhibits higher ultimate strength compared to analogues bridge designed with uniform reinforcement. Though, several studies have been made in past to understand the behaviour of skew slab bridges under different vehicular loads, however, no study appears in the context of IRC Class 70 R loading.

This study aims to employ the finite element software STAAD_Pro to investigate the influence of skewness on the flexural response of two-lane simply supported skew slab bridges under the IRC Class 70R tracked vehicular loads. To this end the span of the bridge is varied between 4 m to 8 m at the interval of 1 m and for each span the skewness is introduced up to 45° in the multiples of 15°. In this study the flexural response of bridges has been assessed in term of longitudinal moment, transverse moment, twisting moments and deflection. In general, concrete slab bridges are directly supported on abutments by inserting a kraft paper between them. As a consequence of it, the slab cannot freely rotate and translate at supports (abutments) and a partial fixity is experienced by the slab. Nevertheless, in the finite element analysis, the concrete slab is assumed simply supported and boundary condition used in analysis differs from actual boundary conditions. In order to suppress the discrepancy between the actual and modelled boundary conditions, the flexural response parameters for skew slab bridges are normalized with the analogues flexural parameters corresponds to right (non-skew) slab bridges.

2. Description of Slab bridges and Loading

The two-lane highway bridge considered in this study has carriage way width 5.3 m and 225 mm wide kerbs have been provided on both sides of carriage way. In order to investigate the effect of skewness on the flexural response of the two-lane, the thickness of the slab is assumed to be dependent on span and it is considered as (span/12) irrespective of skew angle. The span of slab is varied from 4 m to 8 m at an interval of 1 m and the slab bridges have assumed simply supported at abatements. In order to introduce the skewness in a slab bridge of span L, keeping the distance between the mid-width of abutments as L, the abutments have been rotated to achieve desired skewness.

According to IRC6: 2017, two-lane highway bridges are designed for IRC Class-70R loading on single lane and the design forces are checked for Class-A loading on each of two lanes. The IRC Class 70R loading contains two types of vehicles namely wheeled and tracked and for the design of bridges both the vehicles are considered (one at a time) and the bridges are designed for maximum effects. Thus, the two lane highway bridges are analysed for Class-70R Tracked loading on single lane, Class-70R wheeled loading on single lane, and the Class-A loading on both the lanes and the bridges are designed for maximum moment and shear produced by them. In the present study, for brevity, only the results for class 70R tracked vehicle are presented. The tracked vehicle simulates a combat tank used by the army. The ground contact length of the tracked vehicle is 4.57 m as shown in Fig. 1. In order to determine the maximum bending

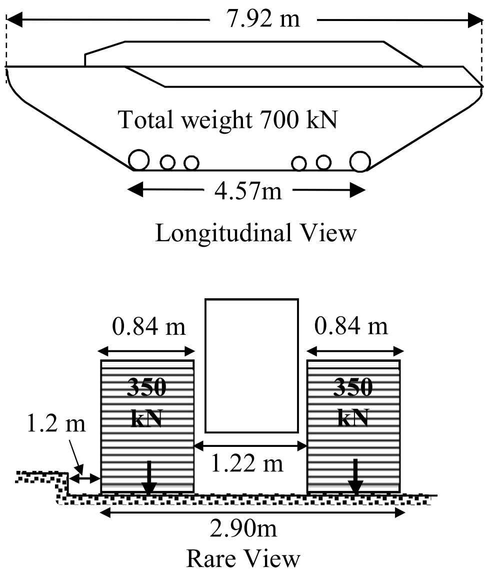

Fig. 1. IRC Class 70-R Tracked Vehicle

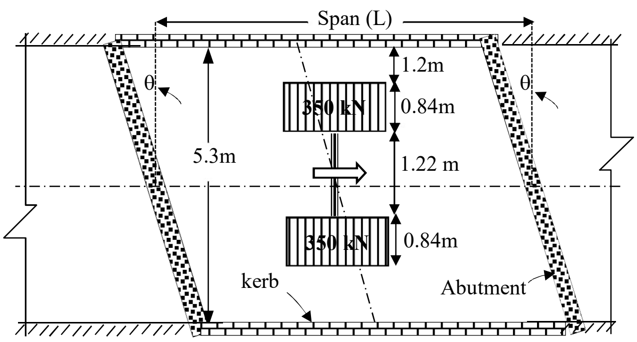

Fig. 2. Typical Geometry of skew slab bridge with Class 70R Tracked vehicle positioned at minimum eccentricity

moment, the IRC Class 70R tracked vehicle is kept at mid-span at maximum eccentricity in transverse direction at clear spacing of 1.2 m from kerb as specified by IRC6 [5]. In the longitudinal direction, the wheel loads were placed such that their centre of gravity acted at the mid-width line drawn parallel to abutment line. The position of Class-70R loading on the deck to produce maximum moment in the bridge is shown in Fig. 2.

3. Finite Element Analysis

In this study, the linear-elastic three dimensional finite element modelling and analysis of slab bridges has been carried out using the STAAD-Pro. The slab bridges are modelled using plate elements available in STAAD-Pro. In finite element analysis performed in this study, the wheel loads were treated as concentrated load acting at the centroid of the wheel. In most of the cases the concentrated loads were lying within the elements rather than at node. Since, in the finite element analysis, loads may be applied at nodes only, the concentrated load acting within the element were converted into equivalent nodal loads using the concept of tributary area (Chen, 1999) where the equivalent load at the i^{th} node due to wheel load P placed within element is determined as $P_i = P(A_i/\sum A_i)$, where A_i is the tributary area associated with i^{th} node and $\sum A_i$ is the total area of element as shown in Fig.3. For the element shown in Fig. 4, if the concentrated load P is applied with in the element located at distance X1 along x-axis and at distance Y1 along the y-axis, the equivalent load transferred to node N_1, may be determined according to Eq. (1).

$$\begin{aligned} P_1 &= P[(X_2 - X_1).(Y_2 - Y_1)/X_2Y_2] \\ &= P[(1 - X_1/X_2).(1 - Y_1/Y_2)] \\ &= P(1-\alpha)(1-\beta) \end{aligned} \tag{1}$$

where, $\alpha = X_1/X_2$ and $\beta = Y_1/Y_2$

In the similar way the equivalent loads at other nodes may be determined. The equivalent loads at all the four nodes are written together in Eq. (2).

$$\begin{aligned} P_1 &= P(1-\alpha).(1-\beta) \\ P_2 &= P(\alpha).(1-\beta) \\ P_3 &= P(1-\alpha).(\beta) \\ P_4 &= P(\alpha).(\beta) \end{aligned} \tag{2}$$

In the finite modelling, all the slabs have been assumed simply supported on two opposite edges. At on one of the abutment all the end nodes of slab are assumed pinned, however, the end nodes of slab at other abutment are assumed roller supported allowing the translation along the central line of slab. For the linear elastic analysis of slab bridges, the modulus of elasticity, Poisson's ratio and density of concrete are taken as 21.67×10^6 kPa, 0.17 and 23.5616 kN/m^3 respectively.

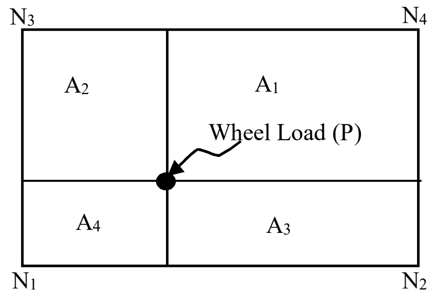

Fig.3. Tributary areas for determination of Equivalent Nodal Loads

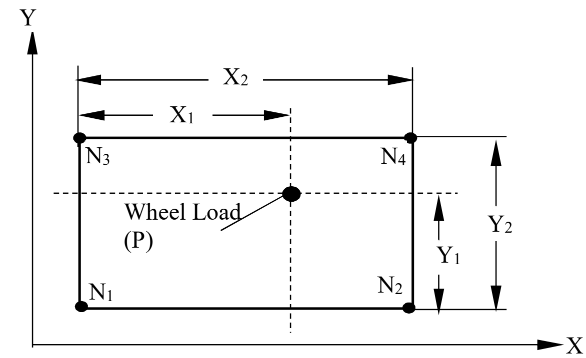

Fig. 4. Distribution of wheel load to nodes

4. Results and Discussions

The aim of the present study was to numerically investigate the effect of skewness on the flexural response of the two lane slab bridges of different spans. To this end the span of the slab was varied between 4 m to 8 m at the interval of 1 m and for each span length the effect of skewness was examined on maximum magnitude of longitudinal moment, transverse moment, twisting moment and the deflection produced in bridge due to IRC Class 70-R tracked vehicle. For each of five spans namely 4 m, 5 m, 6 m, 7 m, and 8 m, three skew angles 15°, 30° and 45° are considered. In order to assess the relative performance of skew slabs compared to non-skew slab, the maximum magnitudes of longitudinal moment (M_x), transverse moment (M_y), twisting moment (M_{xy}) and the deflection (δ) are normalized with the analogues parameter in the context of non-skew slab bridges, M_{x0}, M_{y0}, M_{y0} and δ_0 respectively. The variation of (M_x/M_{x0}), (M_y/M_{y0}), (M_{xy}/M_{xy0}) (δ/δ_0) and (Q/Q_0) with angle of skew for different span skew bridges has been shown in Figs 5-8.

4.1 Maximum Longitudinal Bending Moment

The variations of normalized longitudinal bending moments (M_x/M_{xo}) with skewness in slab bridges having span lengths between 4 m to 8 m measured along the longitudinal axis of the bridges have been shown in Fig. 5. The Fig.5 exhibits that for all spans ranging between 4 m to 8 m, as the skew angle increases, the value of (M_x/M_{xo}) decreases continuously. Moreover, the figure depicts that up to 30° skewness, the (M_x/M_{xo}) ratio for the 5 m and 7 m span bridges remains higher compared to other spans, however, with the increase in skewness it tends to fall rapidly and becomes lowest at 45° skewness. Furthermore, the Fig. 5. indicates that at 45° skewness level, the value of (M_x/M_{xo}) for 5 m span slab bridge becomes lowest as a result the longitudinal moment in the 5 m span bridge becomes approximate 42% of that in no-skew slab bridge.

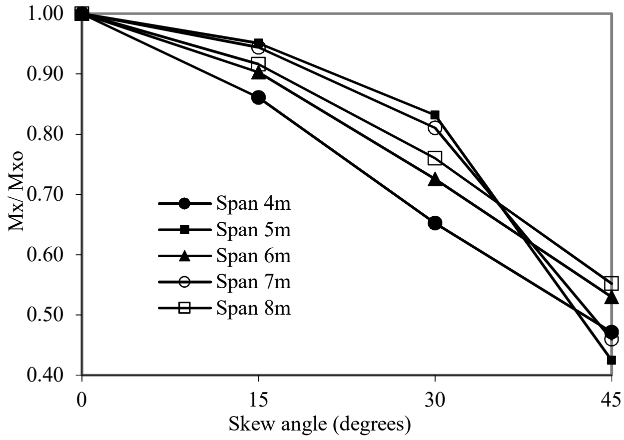

Fig. 5. Variation of Maximum Normalized Longitudinal Moment (M_x/M_{x0}) with skew angle

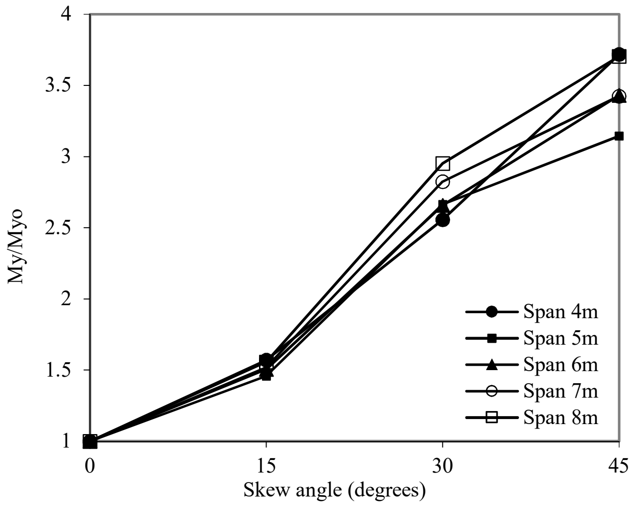

Fig. 6. Variation of Maximum Normalized Transverse Moment (M_y/M_{y0}) with skew angle

4.2 Maximum transverse bending moment

The effect of skewness on maximum normalized transverse moment (M_y/M_{yo}) for all the five span lengths considered in this study are shown in Fig. 6. It may be observed from the figure that in contrast to (M_x/M_{xo}) ratio variation, the (M_y/M_{yo}) ratio increases with increase in skewness. Moreover, it may be noticed from the Fig. 6 that up to 15° skewness, the slab span length has no significant effect on (M_y/M_{yo}) ratio variation, however, for higher skewness, the increase in (M_y/M_{yo}) ratio significantly depends on span length. Furthermore, the Fig. 6 shows that at skew angle 45°, the (M_y/M_{yo}) ratio for the 5 m span length becomes 3.15 while in case of 4 m and 8 m span lengths it reaches up to 3.7 which infers that for the skew angle 45° the 5 m span slab culvert performs better in the context of transverse moment.

4.3 Maximum Twisting Moment

The impact of skewness on the normalized maximum twisting moment in skew slab bridges (M_{xy}/M_{xyo}) is shown in Fig. 6. The figure exhibits that for all the spans considered,

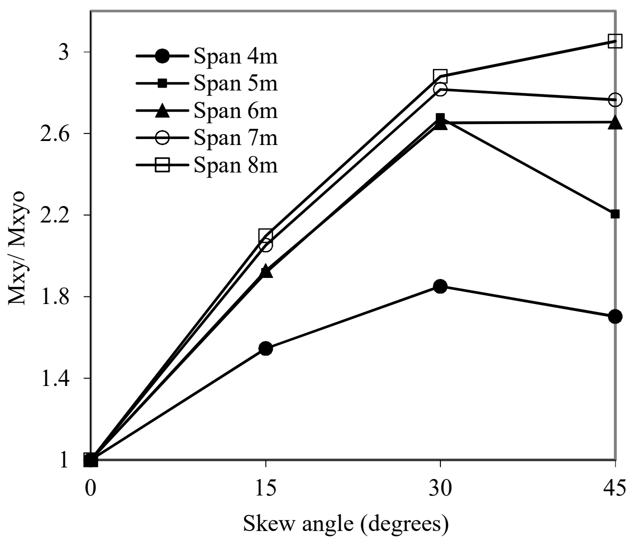

Fig. 7. Variation of Maximum Normalized Twisting Moment (M_{xy}/M_{xy0}) with skew angle

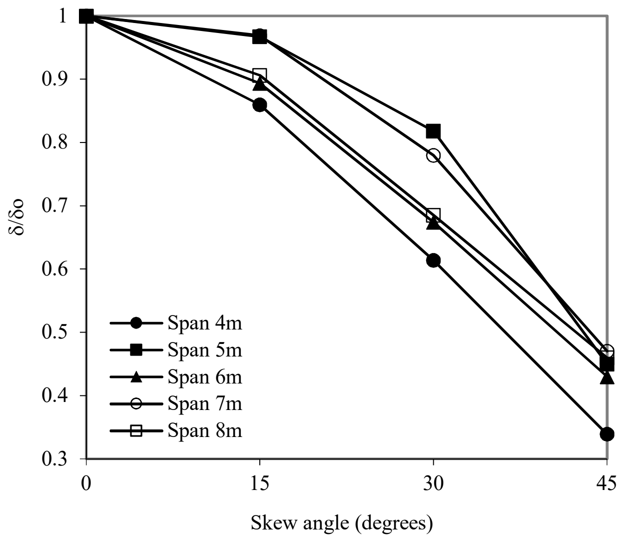

Fig. 8. Variation of Maximum Normalized Deflection (δ/δ_0) with skew angle

the normalized twisting moment (M_{xy}/M_{xyo}) increases with the increase in skewness up to 30°, however, the rise in the (M_{xy}/M_{xyo}) ratio is least for the 4 m span. Moreover, beyond the 30° skewness, the (M_{xy}/M_{xyo}) ratio is little affected by the skewness for all the spans considered except for 5 m span where the (M_{xy}/M_{xyo}) ratio tends to decrease with the increase in skewness. Thus, it may be concluded that up to 30° skewness, the twisting moments in slab bridges increases significantly, however, beyond this skewness limit the increase in twisting moment ratio either remains unaffected or decreases.

4.4. Maximum Live-Load Deflection

The effect of skewness on the maximum normalized live load deflection (δ/δ_o) for the skew slab bridges of span ranging between 4 m to 8 m are depicted in Fig. 8. It may be observed from the Fig. 8 that as the skew angle increases the normalized deflection (δ/δ_o) decreases continuously. Moreover, the Fig. 8 shows that at the skew angle of 45°, the normalized deflection for the 4 m span bridge is minimum which indicates that for this slab geometry, the maximum deflection occurred in slab is approximately 34% of that produced in corresponding non-skew slab bridge. Nevertheless, for the other spans considered in this study (5 m to 8m) and comprising 45° skewness, the maximum deflection in slab bridges is observed 46% of that developed in analogues non-skew slab bridge. Furthermore, it is interesting to note that the trend of variation in (δ/δ_o) ratio is more or less similar to the variation of (M_x/M_{xo}).

5. Conclusions

The aim of the present study was to numerically investigate the effect of skewness on the flexural response of the two-lane slab bridges of different spans ranging between 4 m to 8 m an interval of 1m and for each span length three magnitudes of skewness is introduced up to 45° in the multiple of 15°. To assess the relative flexural response of slab bridges, the maximum magnitudes of longitudinal moment (M_x), transverse moment (M_y), twisting moment (M_{xy}) and the deflection (δ) developed in skew slab bridge are normalized with longitudinal moment (M_{x0}), transverse moment (M_{y0}), twisting moment (M_{xy0}) and deflection (δ_0) produced in similar span non-skew slab bridges. The study showed that the for all the spans considered in this study, with the increase in skewness in slab bridges, the normalized longitudinal moment (M_x/M_{x0}) as well as the normalized deflection (δ/δ_0) were observed to decrease, however, the normalized transverse moment (M_y/M_{yo}) and the normalized twisting moment (M_{xy}/M_{xyo}) were found to decrease. Up to the 15°skewness, the fall in (M_x/M_{x0}) and (δ/δ_0) ratios was moderate, nevertheless, excessive fall in these ratios was observed while introducing more skewness in the slabs. In general, the influence of skewness on all the flexural response parameters considered in this study was found to increase with increase in span of slab. Moreover, this study reaffirms that slab bridges with skew angles less than 15° may be designed as straight (non-skewed) slabs, however, a sophisticated analysis must be performed for the slab bridges containing skewness more than 15°.

Disclosures

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