Reaction Response of Horizontally Curved and Skewed Concrete Box-Girder Bridges

Tanmay Gupta and Manoj Kumar

Abstract Concrete box girders are widely used in horizontally curved bridges due to their high torsional rigidity. Certain geographical situation demands skew supports in addition to the curved layout of the bridge and results in complex skew-curve geometry of the deck. The present study focuses on predicting the support reaction response for each unique skew-curve combination of four-cell box-girder bridges via 3D finite element analysis. Central curvature angle for the bridges considered in this paper has been varied from 48° curving left to 48° curving right, at an interval of 12° while the skew angle is swept from 0° to 50° at an interval of 10° to generate feasible combinations possible for skew-curve case. For these unique simply supported multicell concrete box girder bridges, support reactions for dead load as well as for Class-A and Class-70R vehicular live load cases are monitored via large parametric study. Results indicate that uplifting of supports become more prominent in high skew-curve cases at acute corners, while obtuse corner reactions reach as high as 104% of total force transmitting to abutment. Reaction ratio monitored can also be used for deriving skew correction factors for skew-curved bridges.

Keywords Concrete box-girder bridges · Horizontally curved · Skew abutments 3D FEM modelling · Support reaction · Skew correction factor

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1   Introduction

Rapid urbanization and massive growth in infrastructure have created a necessity for complex transportation system for highway bridges, which often leads to unconventional, non-collinear bridge configurations. Presence of skew supports and horizontal curvature together is one such problem which significantly changes the structural response of bridges.

In such situations, concrete/prestressed concrete box-girder sections are often used, to compensate for high torsional moment and bending moment demands arriving from the virtue of geometry. Designing such girders to support a skew-curved bridge is a complex problem since the support reactions, shear and moment demands even due to gravity loads vary significantly across the girders of the bridge deck [1]. For significantly curved bridges (having central curvature angle 12° or more) with sharp skew support edges, generally there exist substantial amount of torsional deformations and potential for uplift at bearings.

Nowadays design engineers have a wide variety of approximate and sophisticated analysis and design methods at their disposal for the analysis of bridge forces. Thus, it becomes very important that the appropriate method is selected for the problem involved considering time and accuracy needed for the project. One-dimensional spine bridge modelling technique, implemented using linear line elements placed along the centre line of the bridge span, still remains the most common technique for bridge analysis in India. Sophisticated and complicated 2D grillage or full fledged 3D finite element analysis for bridges are generally not preferred, for bridges having simple geometric alignment since the spine modelling technique is accurate enough; however, it is unable to capture live load distribution effects especially when the geometry of the girder becomes horizontally curved and skewed at supports.

Capturing the complicated structural response of aforementioned bridges via simplistic spine model is thus not possible; consequently, the need for skew-curve correction factors arrives, which can attenuate the response value of spine model to actual response of the bridge [2]. The present study focuses on capturing the worst support reaction response generated for various combinations of curvature and skewness present in the bridge. As per Indian loading conditions, a case study for 12.5 m wide box-girder bridge is carried out considering unique combinations of central curvature angle (varied from 48° curving left to 48° curving right, at an interval of 12°) and the skew angle (swept from 0° to 50° at an interval of 10°). The 3D finite element models of the bridges are generated and analysed using CsiBridge, to study the effect of skewness in conjunction with curvature on the reactions at obtuse corner. Obtuse corner reactions have been plotted in the form of non-dimensional parameter normalized by total support reactions at that abutment. Results not only give a simplistic way to rectify the obtuse corner reactions obtained from spine model but also provide a deep insight for designers towards girder design for such complicated geometry bridges.

2   Skew-Curve Bridge Force Transfer Mechanism

Structural responses of skew bridges as well as curved bridges are found to differ significantly in comparison with straight/orthogonal counterpart of similar dimensions. By the virtue of geometry, force path in such bridges do not remain as simple as in case of orthogonal bridges; thus, they attract high design forces and moments, which should be aptly considered in bridge modelling.

In case of bridges having only curved geometry, the load is generally transferred along the shortest curved distance between the supports, while for only skewed bridges force tend to take shortcut route via one obtuse corner to other. For combination of skew and curved geometry, however, force path becomes tedious in nature, but in general, it remains heavily towards obtuse corner. Thus, the risk of uplifting at acute corners increases manifold in such cases, especially in case of eccentric vehicular loading, which generates high reactions at obtuse side.

Figure 1 shows the top slab geometry and force transfer mechanism in a general skew-curved bridge. In the present study, curvature towards right-hand side is considered as negative central curvature angle while bridges curving towards left-hand side are considered as positive central curvature angles. Sense of skew angle is used such that obtuse corner is created towards the outer periphery of curved geometry in the near abutment (towards approaching traffic) for bridges having negative central angle (as shown in Fig. 1), while, for positive central angle case, skew is taken in similar manner, but in this case, obtuse corner remains inward for near abutment.

In general, due to change in force transfer mechanism in skew bridges through the strip of area connecting the obtuse-angled corners, bridge deck primarily bends
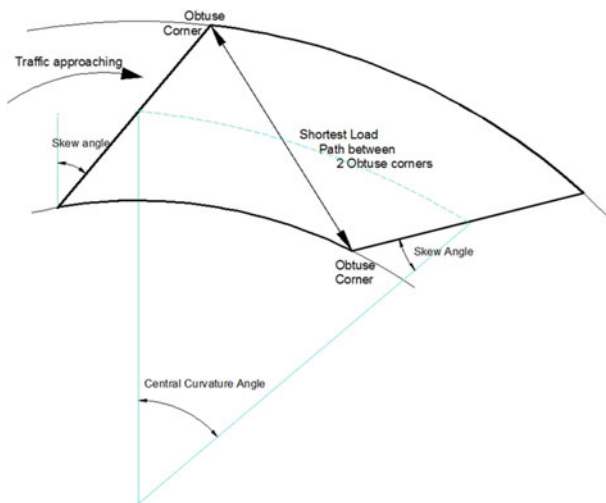
Fig. 1 Schematic diagram of skew-curved bridge showing shortest path for force transfer

along the line joining the obtuse-angled corners. The magnitude of bending moment is considered to be dependent mainly upon skew angle, ratio of the skew span and the width of the deck and the position of load on the span. However, adjacent areas of the force transfer strip in skew bridges, transfer the load only to this obtuse angle joining strip as cantilever rather than transferring the load to the supports directly. Thus, even for dead load case, skew bridges come under considerable torsional moments and unequal reaction forces at bearings. As the skew angle increases obtuse corner tend to come further near, thus generating more twisting in the section. Moreover, due to the presence of curvature in addition to skew, situations get more complicated as curve effect creates additional moments in bridge and more uneven support reaction distribution.

3 Numerical Investigation

3.1 Case Study Description

To investigate the cumulative effect of skew and curvature in concrete box-girder bridges, 54 unique skew-curve combinations are chosen in present case study. As such, box geometries attract high torsional moments; thus cross section for bridge section is chosen as box girder, which has exceptional torsional rigidity. In order to simplify the numerical investigation multi-span bridges are avoided, rather all parametric variations in geometry are applied for simply supported end conditions. The geometrical parameters for the box-girder having cross-section as shown in Fig. 2 and material properties considered in this study are as follows:

Length	25 m
Width	12.5 m
Number of cells	4
Depth	1.22 m
Top slab thickness	0.2 m
Bottom slab thickness	0.2 m
Web thickness	0.3 m
Web spacing (c/c)	2.5 m
Overhang	1.1 m
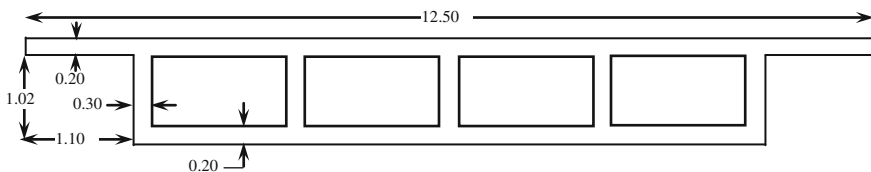
Fig. 2 Box-girder bridge cross section used in present study

Table 1 Parametric variations

Skew angle	Central curvature angle
0°–50° (at an interval of 10°)	−48° to 48° (at an interval of 12°)

Concrete grade	M35
Density	25 kN/m^3
Poisson's ratio	0.2
Elastic modulus	2.958×10^7 kN/m^2

For considering realistic modelling of support bearing, it is assumed to be partially rigid, having a bearing stiffness of 87.5 kN/m. The same base cross section (Fig. 4) has been used for all the skew-curve bridges considered in this study where the skewness and curvature have been varied in accordance to Table 1.

The reactions at the obtuse corner of the box girders considered in present study have been expressed as non-dimensional parameter (in %) normalized by total support reaction at that abutment, and are reported in terms of obtuse corner reaction percentage for gravity (dead) load case and for live loads specified by IRC [3].

3.2 Finite Element Modelling

For better prediction of results for such complicated geometries, full 3D modelling of bridge superstructure was implemented using well-known finite element analysis and design software CSiBridge. For simplicity, first-order linear elastic analysis is performed for all unique combinations for three different load cases, namely, dead load case, Class-A vehicle moving on three lanes and combination of Class-A loading on first lane and Class-70R vehicle moving on separate third lane. Discretization of the bridge is done using a four-noded 3D shell element having six degrees-of-freedom (three translations + three rotational) at each node. Proper connectivity of top and bottom flange elements with the webs ensures the displacement compatibility. Element size and aspect ratio of the elements have been decided via considering mesh sensitivity analysis for simplified box girder. Based on which a preferred sub-mesh area of 0.25 m^2 was chosen in order to limit the time involved in analysis. Figure 3 depicts a typical finite element model for 30° skew and −36° curved generated in CSiBridge.

3.3 Live Load Placement

The recommendations of Indian Road Congress (IRC) may be used to place the vehicular live load in transverse directions. However, it is not possible to place the
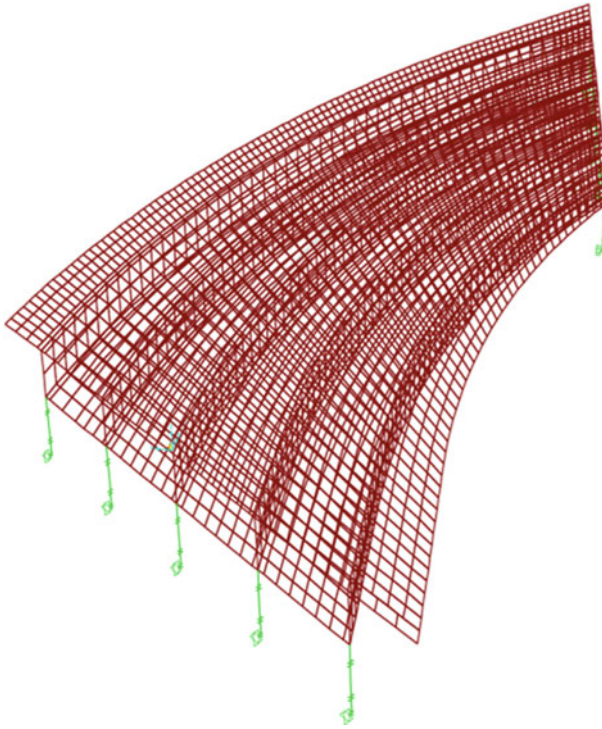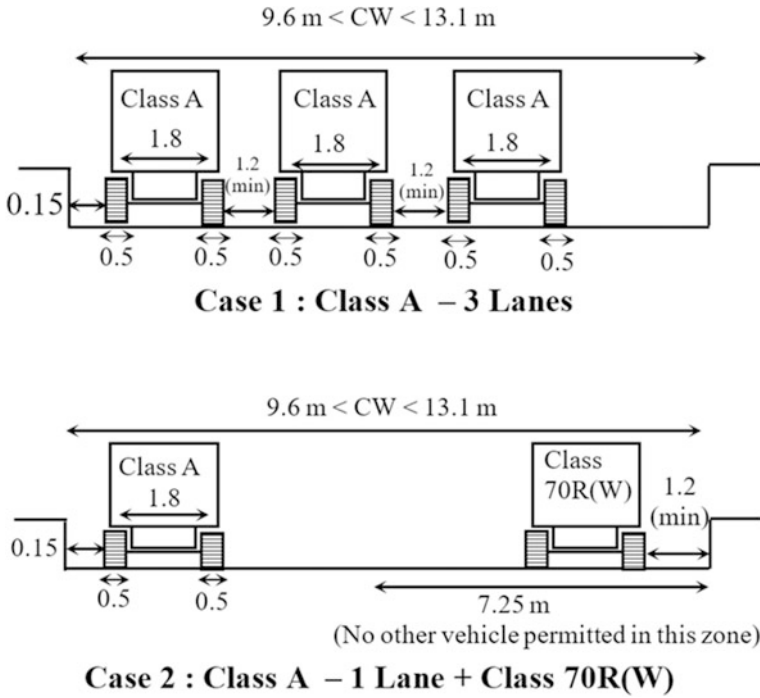
Fig. 3 3D finite element model of a typical skew-curved bridge (curving towards right) showing all discrete elements along the span length

vehicular load in longitudinal direction to develop maximum moment since the rolling load concept can be used only for normal bridges. To mitigate this problem, in the present study, vehicle load is considered to run throughout the span at an average speed of 1 m/s, for which the results of vertical support reactions are captured at an interval of one second. Thus, at every 0.1 m interval, outputs are gathered and finally, all such outputs are compared for finding out the worst condition in all cases.

Since the carriageway width of box girders considered in this study is 12.5 m, which lies in between 9.6 and 13.1 m, as per IRC-6 requirements, this bridge geometry is to be analysed as three-lane bridge. Thus, two live load combinations are implemented in this study which are

1. CASE 1: CLASS-A − 3 LANES
2. CASE 2: CLASS-A − 1 LANE + CLASS 70R (W wheeled or tracked) − 1 LANE
   (these load cases are depicted in Fig. 4)

To generate worst support reaction at obtuse corner on near abutment, heavier loads were kept as near as possible to the obtuse corner following the IRC

9.6 m < CW < 13.1 m

| Class A 1.8 | Class A 1.8 | Class A 1.8 |

0.15

1.2 (min)   1.2 (min)

0.5   0.5   0.5   0.5   0.5   0.5

Case 1 : Class A − 3 Lanes

9.6 m < CW < 13.1 m

| Class A 1.8 | | Class 70R(W) |

1.2 (min)

0.15

0.5   0.5

7.25 m
(No other vehicle permitted in this zone)

Case 2 : Class A − 1 Lane + Class 70R(W)

**Fig. 4** Live load placement (transverse location)

recommendations. The results for IRC Class-70R tracked vehicle are not presented here since the preliminary study indicated that support reactions at obtuse corner due to tracked vehicle are less severe compared to wheeled vehicle.

For present study, it can be expected that approximately 20% of the support reaction (total five supports) will go to each support in the non-curved, non-skewed case under gravity loading, because overhang length of bridge is chosen such as to produce equal distribution of weight among the girder, but same is not true for live load cases as vehicle is kept at minimum clearance from obtuse angle side, thus generating more reaction towards obtuse side even for non-skewed, non-curved cases.

4 Results and Conclusions

4.1 Structural Response Under Dead Load Case

The results compiled in the present study specifically focus on the comparison of proportion (in %) of reaction carried by obtuse corner support bearing with respect to total abutment reaction for each unique combination of central curvature angle

Obtuse corner reaction percentage vs Central curvature angle for skew
angles 0° to 50° for Dead load Case
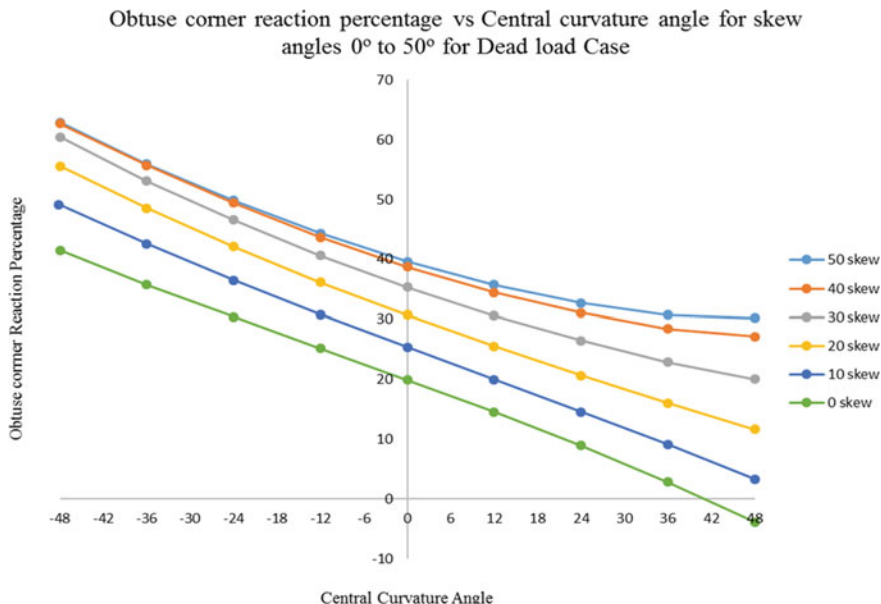
Fig. 5 Obtuse corner reaction percentage under dead load case for each unique skew-curve combination chosen

and skew angle considered. Dead load case results for each unique skew-curve combination are presented in Fig. 5 (negative curvature angle represent curving right while positive for curving left):

- From Fig. 5, it is evident that the obtuse corner reaction for the non-curved case reaches 40% at about 50° skew angle which just about doubled from non-skew non-curve bridge case.
- The curve effect greatly influences reaction response, which can be observed via uplift at corners occurring around +40° central angle case when the bridge is not skewed. It implies high central curvature itself is sufficient for uplifting even towards the obtuse side.
- For bridges curving right (+ve central angle) with high central angle and high skew, the coupled skew-curve effect is dominant, which is evident from the fact that the curve for 40° skew crosses the curves next to it (50° skew curve). Thus, it can be concluded that at higher skew angle (greater than 40°) obtuse corner tend to attract reaction at slower rate as compared with skew range of 0°–40°.
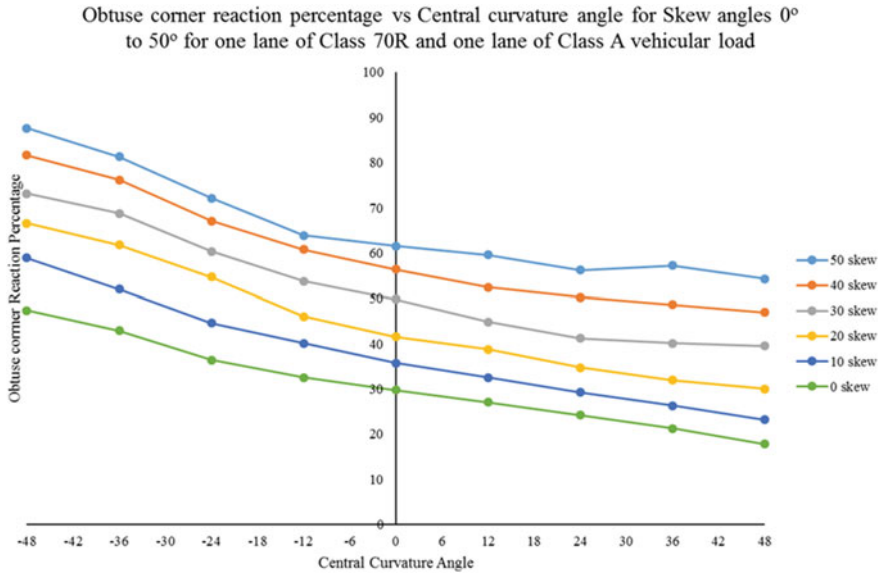
4.2 Structural Response Under Live Load Cases

The results for obtuse corner support reaction for live load case 1 (Class-A vehicle running on three lanes) and case 2 (Class70R on one first lane and Class-A on third lane) are presented in Figs. 6 and 7, respectively. As all the results are compiled for near abutment (abutment towards the incoming traffic flow) thus by changing the curvature direction from right to left, obtuse corner experiences significantly low support reactions, reason being, for right curved bridge obtuse corner remain on outer periphery while for left curved, it falls towards inside periphery of curve. Furthermore, some significant observation from Figs. 6 and 7 are as follows:

- It can be evidently seen for non-curved cases that, as the live load is eccentric, obtuse corner reaction percentage distribution in skew 0°–50° again doubles but this time from 30% to near more than 60% in both live load cases. Case 1 shows a steeper rate of increase than case 2 indicating that for higher skews as the vehicle weight gets more distributed, it tends to attract more reaction at obtuse side, while for lower skews, heavy vehicle (Class 70R in present case) running near to obtuse corner will dominate the support reaction.
- As the live load is always modelled to run near obtuse corner, no uplift occurs near obtuse side with the change in curvature from right to left for both the cases.
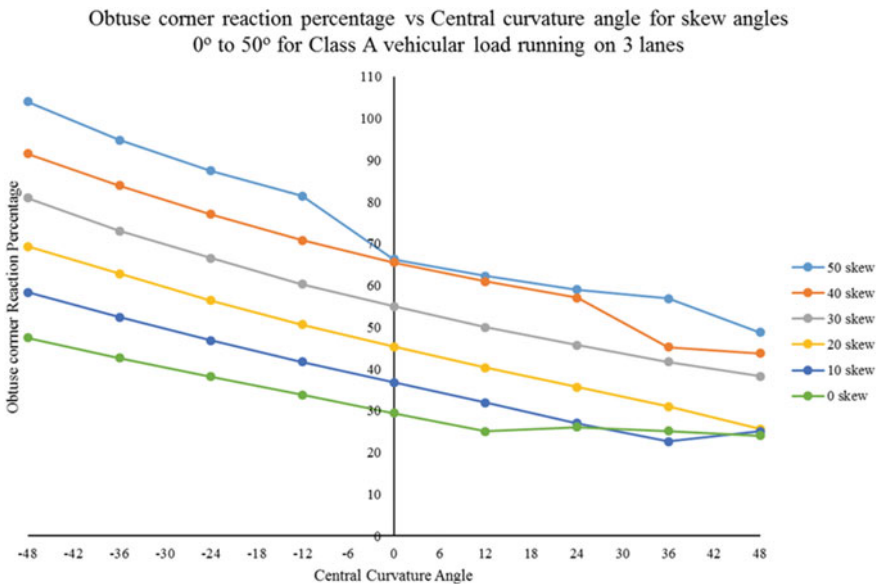
Fig. 6 Obtuse corner reaction percentage under live load case 1 for each unique skew-curve combination chosen

Obtuse corner reaction percentage vs Central curvature angle for Skew angles 0°
to 50° for one lane of Class 70R and one lane of Class A vehicular load

Fig. 7 Obtuse corner reaction percentage under live load case 2 for each unique skew-curve combination chosen

- Combined effect of skew and curve for case 1 generates obtuse corner reaction as high as 104% of the abutment reaction; similarly, in case 2, these values go up to 87%. These values signify that going beyond these limits of skew and curvature for single span bridges will surely create much more challenges for constructions.

4.3 Skew Correction Factors

For the simplified analysis, box-girders are modelled as spine, which comprises of only one single girder. The spine models are unable to capture the non-uniform support reactions in the skew-bridges. Skew correction factors (SCF) can be applied to the support reactions for the corresponding non-skewed bridges to account for the effect of skewness in the bridges analyzed using the simplistic spine modelling of the bridge [2]. Consequently, for superstructure shear design, the use of skew correction factors for obtuse girder regions is required. To quantify skew correction factors AASHTO LRFD [4] specifications give an empirical equation for cast-in-place concrete multicell box as $1 + (0.25 + (12L/70d))\tan\theta$, where L is bridge span in ft., d is the depth of cross section in inch and θ is skew angle. Further, as amendment to this equation in 2014, CALTRANS provided a much simpler estimation of skew correction factor as $1 + (\theta/50)$. As these equations are limited to only skew geometry, these cannot predict the behaviour of SCF for skew-curve cases.
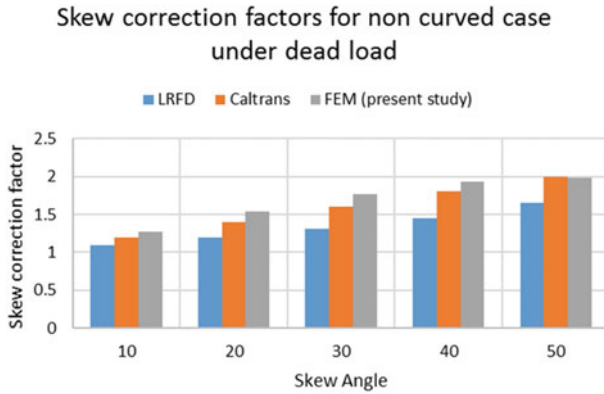
Fig. 8 SCF comparison among LRFD, CALTRANS and present study under dead load

As the nature of the curves presented obtuse corner reaction for various load cases (Figs. 5, 6 and 7) have similar trend, consequently, the nature of curves for absolute reaction (for dead plus live load case) will be almost same. Therefore, these curves may be used to determine the skew correction factors for absolute reaction at obtuse corner. Since there are no direct guidelines available on skewed bent or abutment reactions, sometimes these skew correction factors are also applied to reactions to calculate bearing forces.

Thus, SCF from the present study can be derived for obtuse corner as (obtuse corner reaction percentage/100) * no. of supports. Figure 8 shows a comparison of skew correction factors thus obtained for non-curved case under dead load from these three approaches.

Results show un-conservative values of SCF for lower skew range calculated via LRFD and CALTRANS equations. While there are no guidelines available for SCF calculations in case of IRC loading for either skew or skew-curve cases, thus, present study results can play a pivotal role in bridge design using spine models also. Similarly, for dead load cases, SCF for combined effect of skew curve are rare to find.

In conclusion, present study not only provides obtuse corner reaction response for all unique skew-curve combinations feasible but also presents simple SCF value charts for ease of designers.

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