Effect of skew angle on longitudinal girder (support shear, moment, torsion) and deck slab of an IRC skew bridge

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This paper presents the behavioural aspects of a skew bridge and compares them with those of the straight counterparts using a 3D Bridge model in Finite Element Analysis software – ABAQUS. To understand the trend clearly, a simply supported RC Bridge was adopted. The results of the bridge model in ABAQUS show that with the increase in the skew angle, the support shear and mid-span moments of obtuse longitudinal girders increase while these parameters decrease in the corresponding acute longitudinal girders. Most importantly, the increasing skew angle rapidly increases the torsional moment in the obtuse angled girder. Such changes in the moment are generally not considered while designing a straight bridge.[1] With increasing skew angle, the slab showed asymmetric bending with increasing deflection at obtuse corner and decreasing deflection at the acute corner.

The present-day traffic situations in many parts of India are such that the option of skew bridges to cater to high speed and efficient traffic movement are being explored more than ever before. However, designing such bridges means performing more intricate analysis to predict their behaviour. The reason is that skew bridges behave differently from their straight counterparts, Figure 1. Such bridges are characterised by skew angles, defined as the angle between the centre line of traffic and the normal to the centre line of the river. Their behavioural difference is attributed to, the longitudinal girders that are not orthogonal to the supporting lines. Despite these facts, the design of skew bridges, for a long time, has not been treated differently from that of the non-skewed bridges. Also, adequate guidelines are not available for designing skew bridges in IRC.

This paper reports the behavioural evaluation of a skew bridge with longitudinal girders and a slab configuration. The load transfer mechanism in skew bridges being different from that in straight bridges, there is a concentration of reaction forces in the former at the obtuse corners and a possibility of negative deflection (uplift) at the acute corners.[2] These responses vary with varying skew angle.

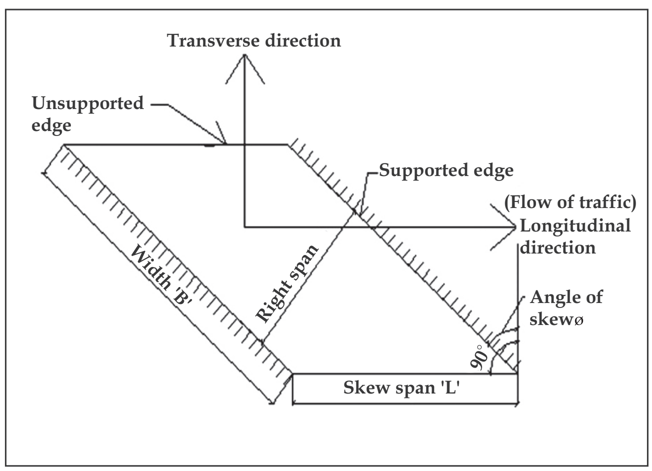


Figure 1. Representation of a skew bridge

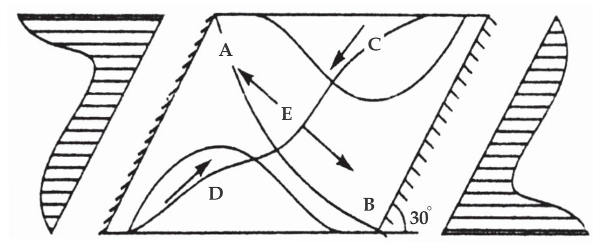
Behaviour of a skew bridge

In a non-skewed bridge the deck behaves orthogonally in flexure i.e. both in longitudinal and transverse directions, with the principal moments being in both these directions where shows the deflection pattern of a non-skewed slab bridge deck.[2] From Figure 2, it is evident that the load from the slab is transferred to supports directly through flexure. The twisting moments at the supports because of bi-directional curvature are small and hence can be neglected.

On the other hand, in skew slabs, the load path tends to take a short cut through the strip of area connecting the obtuse-angled corners and the slab primarily bends along the line joining the obtuse angled corners (Figure 3).[2] The width of this primary bending strip is a function of skew angle and aspect ratio (skew span: width of deck).The areas on either side of the strip do not transfer the load directly to the supports, but only to the strip as cantilever. The load is transferred from the strip to the support over a defined length along support line and then eventually gets redistributed over the whole length (Figure 3).[2]

This 'short cut' load transfer phenomena leads to the following special features in a skew bridge deck:

- Increase in transverse moment
- Decrease in longitudinal moment
- Significant torsional moments in deck slab
- High reaction and torsion near obtuse corner
- Uplift at acute corner



Load transferred from zone C and D to E and then to the supports

Figure 3. Load transfer mechanism of a skew deck

Figure 4 summarises these behavioural differences.

Objective

Although many studies have been conducted on the behaviour of skew deck slabs, no significant information could be found in the literature about the behaviour of longitudinal girders (with increasing skew angle) that support the skew slab. This paper attempts to quantify the trends of the skew slab with increasing skew angle.

These include longitudinal girders of a 16 metre span simply supported bridge with increasing skew angle, from 0 to 65^{o}. The parameters considered are support shear, longitudinal and transverse bending moments and torsion of the longitudinal girders, along with deflection and stresses for the skew slab.

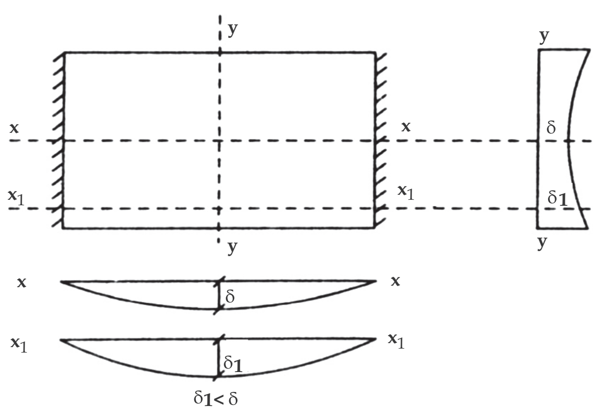


Figure 2. Deflection profiles in a non-skewed bridge

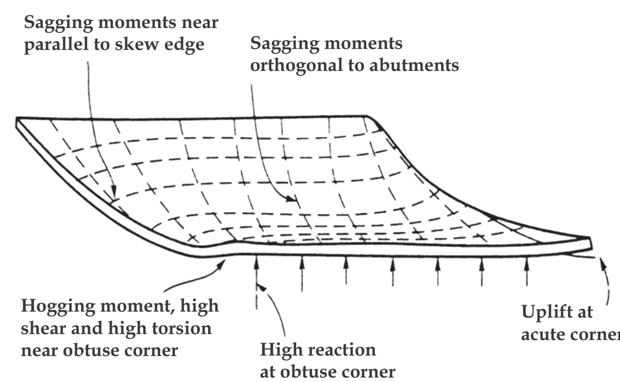


Figure 4. Behaviour of a skew bridge deck

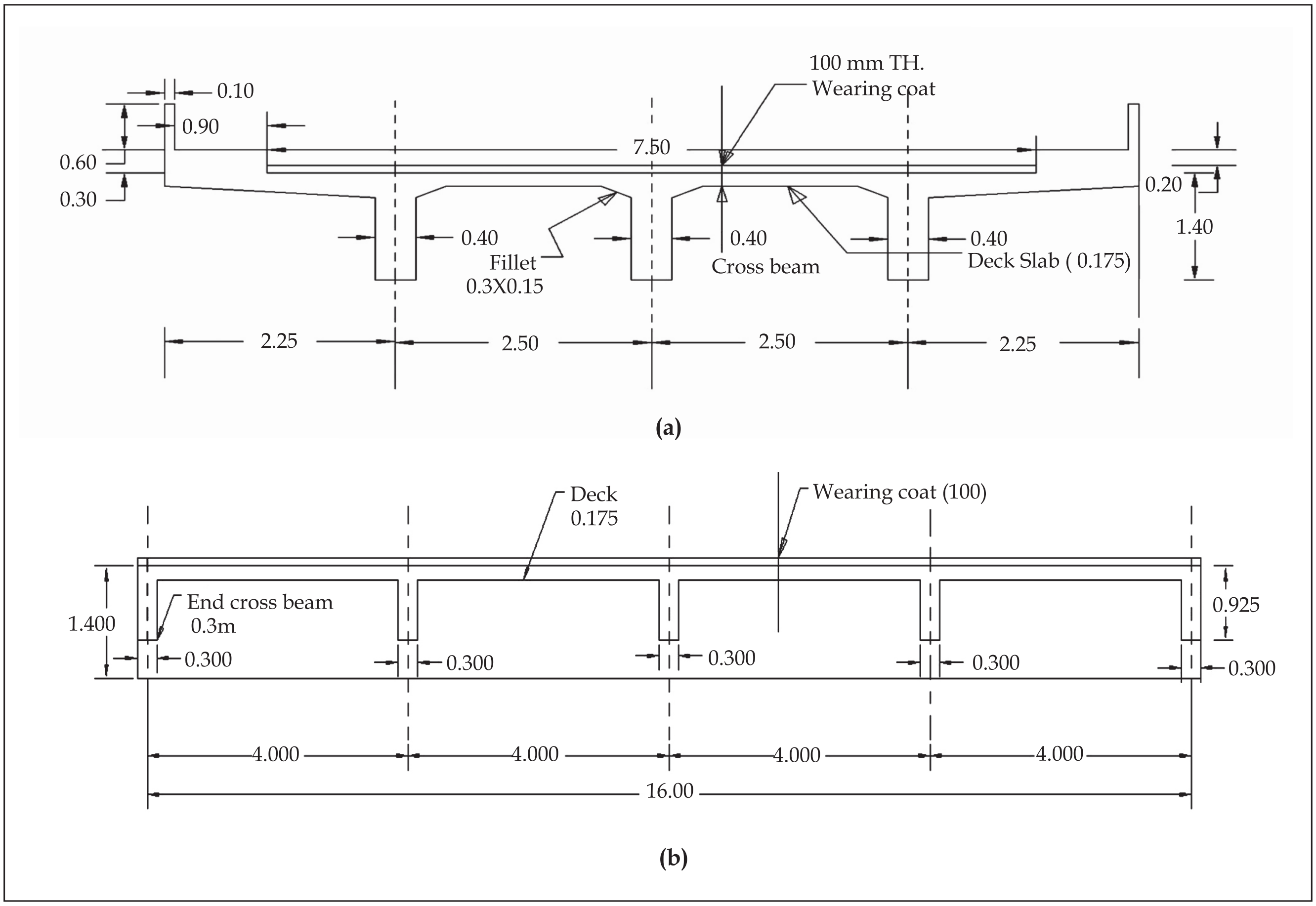


Figure 5. (a) Bridge cross section (b) Longitudinal section of bridge

Methodology

Design

A two-lane simply supported RC bridge of 16 metre span with the following details was manually designed following Indian Road Congress (IRC) code:

Clear roadway = 7.5 m

Total width including parapet = 9.5 m

Assumed three T-beam spaced @ 2.5 m intervals.

Effective span of T-beam = 16 m

Assumed five cross diaphragms @ 4m intervals with preliminary dimensions as shown in Figure 5(b).

M-25 grade concrete & high yield deformed bar of Fe-415 grade are used.

Other dimensions are as shown in Figure 5.

The following important factors were considered:[3]

- The cross girders were provided perpendicular to the longitudinal girders.
- In addition to dead load, IRC Class AA tracked vehicle load was included as live load to produce the maximum moment and considerable shear following manual design calculation.

Modelling

Next, the bridge was modelled in ABAQUS with all its details.[1]

The concrete bridge and flexural reinforcements in deck and girders (both longitudinal and cross girders) were modelled with 3D deformable solid extrusion elements. Both were meshed using quadratic hexahedral elements of type C3D20R.The shear reinforcements

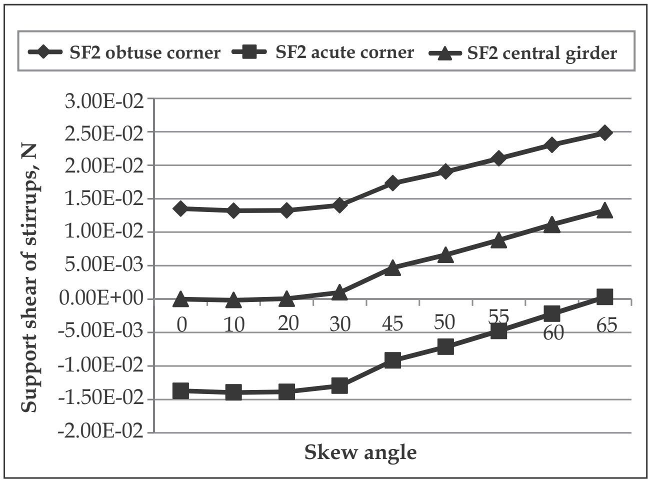


Figure 6. Support shear of longitudinal girders

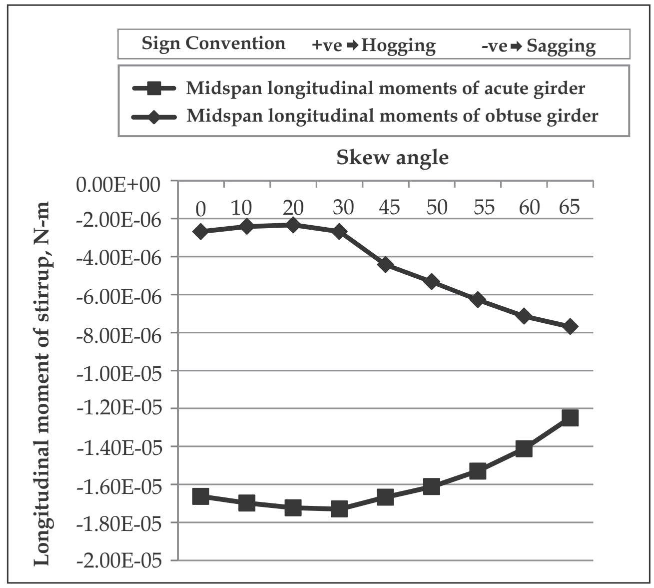


Figure 7. Longitudinal moments of acute and obtuse girders

(stirrups) were modelled as 3D deformable planar wire and meshed with quadratic line elements of type B32. Then, the interaction between the concrete bridge, flexural and shear reinforcements was defined using the interaction module of ABAQUS. The flexural and shear reinforcements (stirrups) were embedded in the concrete bridge at appropriate positions by defining the flexural and shear reinforcements as embedded region and assigning the concrete bridge as the host region.

Dead Load in the form of gravity loading along with IRC Class AA track vehicle loading in the form of pressure loading at the centre of the span acted on the bridge. The model was then rotated from 0 to 65^{o} and analysed.

Results

Effect of skew angle on support shear of longitudinal girder

ABAQUS does not report section forces (shear, moment) for 3D solid elements used for modelling the concrete bridge. However, it reports them these quantities for 3D planar wire (beam) elements used for modelling shear reinforcements (stirrups). As stirrups are embedded in the concrete bridge and are an integral part of the longitudinal girder, they aptly reflect the trend in Section Force as the skew angle increases. Figure 6 presents the trend of Support Shear in a longitudinal girder.

This figure shows that up to the skew angle of 20^{o}, the Support Shear nearly remains constant in all the three girders. However, beyond 20^{o}, it increases steadily for both Obtuse Corner and Central Longitudinal Girder, but decreases for the Acute Corner Girder.

There is a 67% increase in Support Shear for the obtuse corner girder from 30^{o} skew to 65^{o} skew. For the central girder, from being negligible up to 30^{o} skew, the support shear increases considerably. In contrast, there is a great reduction in it for the Acute corner Girder, which is noteworthy. In magnitude, it was nearly equal to that for the Obtuse Corner up to 20^{o} skew, and gradually became negligible at 65^{o} skew. Hence, Support shear in longitudinal girders follows the same trend as the slab's reaction forces.

Effect of skew angle on longitudinal moments of longitudinal girder

As mentioned earlier, ABAQUS does not report the Section Forces for 3D solid elements, the trends in the longitudinal moments are inferred from the trends in longitudinal moments of stirrups.

From Figures 7 and 8, it can be inferred that longitudinal bending moments follow a trend similar to Support Shear, except for the Central Girder. Longitudinal bending moments did not change appreciably for all the three girders up to 20^{o} skew, after that however the Obtuse Angled Longitudinal Moments show a rising trend, whereas Acute Angled and Central Girder Longitudinal Moments continue to fall. The rise in longitudinal moments of obtuse girder is critical, because it more than doubles from 30^{o} to 65^{o}. Also, the longitudinal moments of Acute and central girders reduces by 25% and 14% for 30^{o} and 65^{o} respectively. Here, it should be noted that the trend of mid-span longitudinal moments of the girders

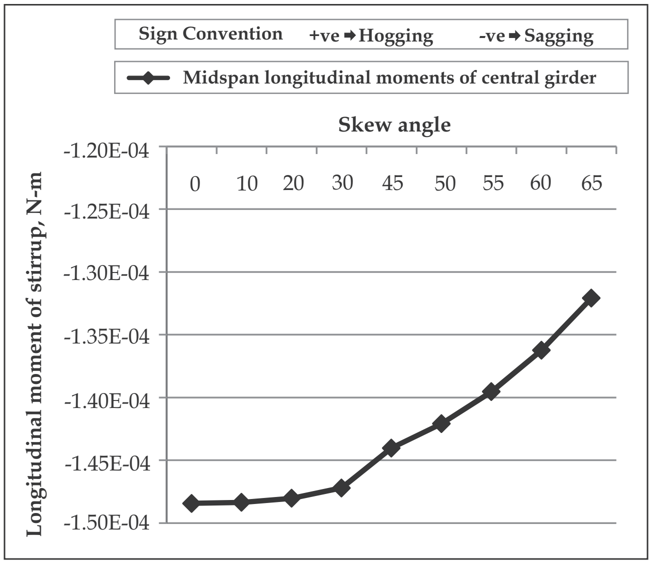


Figure 8. Longitudinal moments of central girder

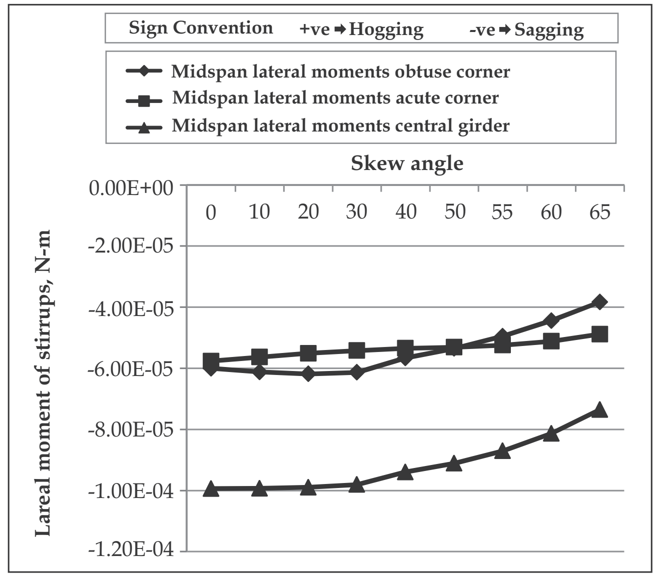


Figure 9. Lateral moments of longitudinal girders

do not exactly follow the behaviour of the slab. The longitudinal moments of the slab are expected to reduce irrespective of position, whereas for obtuse longitudinal girders, the mid-span longitudinal moments more than doubles itself from 30^{o} to 65^{o}.

Effect of skew angle on lateral moments of longitudinal girder

For the reasons already stated earlier, the lateral moments of the longitudinal girders are also reported from corresponding stirrups. Figure 9 shows the trends of lateral moments.

Figure 9 explicitly shows that till 30^{o} skew angle, the lateral moments nearly remain constant. However, from 45^{o} onwards, they start to reduce. The reduction is relatively small (15%) for Acute angled Girder, but becomes appreciable for obtuse angled (35%) and central girders (25%). These findings are in contrast with the behaviour of the skew slab. The anticipated trend for slab is that the transverse moments should increase with increasing skew angle (Figure 4), whereas here a reduction of transverse moments for all three girders with skew angle of 30^{o} and more was observed.

Effect of skew angle on torsional moments of longitudinal girder

The Trend in the torsional moments of the Stirrups is shown in Figure 10.

The torsional moments of the longitudinal girders show an interesting trend. Torsion increases rapidly for both obtuse and central girders; 50% increase from 0 to 20^{o} for obtuse girder and tripling at 65^{o} skew. For other section forces (support shear, longitudinal and transverse moments), the changes in corresponding parameters were insignificant till 20^{o} skew. Though the torsional moments of the acute girder reduce with increasing skew angle, the change in the nature of torsional moment (from negative to positive) after 30^{0} skew should also be noted.

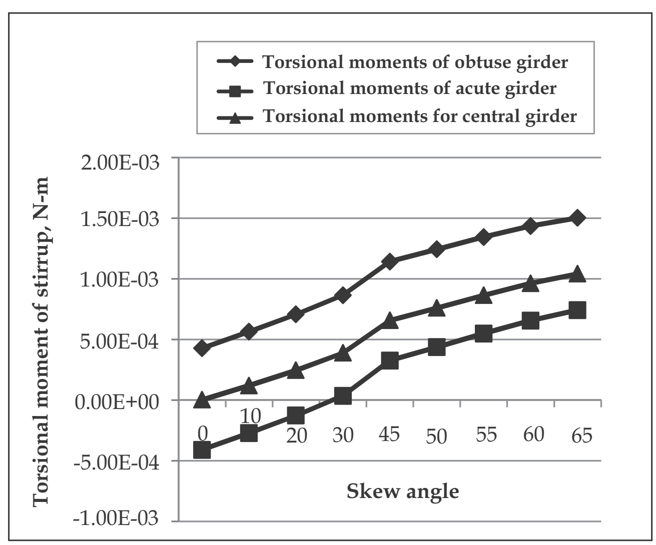


Figure 10. Torsional moments of longitudinal girders

Effect of skew angle on slab deflection

The deflections of the deck slab can be directly reported by ABAQUS. Figure 11 summarises the deflection scenario of deck slab with the increasing skew angle.

Figure 11 clearly shows the anticipated deflection trend of the skew slab. The deflections of the obtuse corner increases gradually till 45^o skew (36% increase from 0 to 65^o), after which it tends to stabilize. In contrast, the deflection of the acute corner continues to fall, reducing as much as 60% from 0 to 65^o skew. Exact values of deflection for both obtuse and acute corners of slab strenghtens the claim for expected symmetric deflection of the right deck (0 skew). Also, increasing deflection for the obtuse corner and decrease of the same in acute corner verifies the probability of S-shaped deflection pattern of the skew deck at higher skew angles.

Effect of skew angle on slab stress

From the trend in deflection pattern shown in Figure 11, it can be inferred that there is a possibility of development of zero stress at the acute angled corner of the slab. Figure 12 summarises the trend in vertical stress of the slab.

As expected, Figure 12 is commensurate with Figure 11 illustrating deflection trend. The possibility of the acute corner becoming a zero stress corner is better reflected in Figure 13, where both Vertical and Shear Stress components (S22 and S13 respectively) tend to become zero.

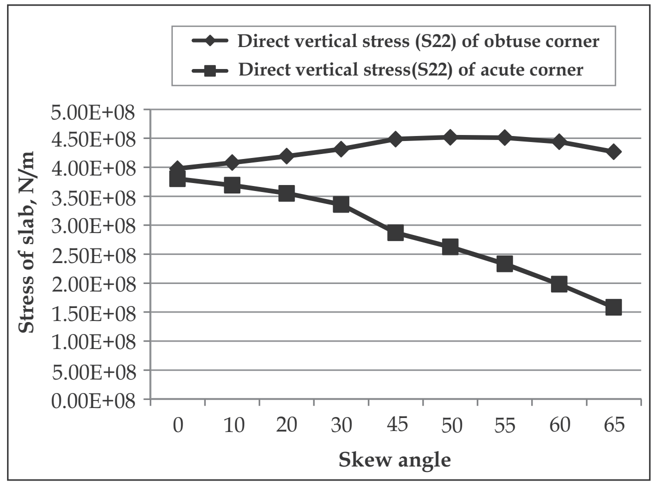


Figure 12. Direct vertical stresses(S22) of slab

Summary and conclusion

The behaviour of an RC simply supported bridge was studied by increasing the skew angle. The parameters investigated were section forces such as support shear, longitudinal, lateral and torsional moments of longitudinal girders and deflection and stresses of slab.

Results show that the skew angle increase results in increasing the support shear of the obtuse longitudinal girder and decreasing that of the acute longitudinal girder. Although the changes are insignificant for inclusion in the design up to 20^o skew, but at higher skew angles the increase is considerable (25% increase for 45^o skew). These changes must be taken into account for correctly designing an obtuse girder.

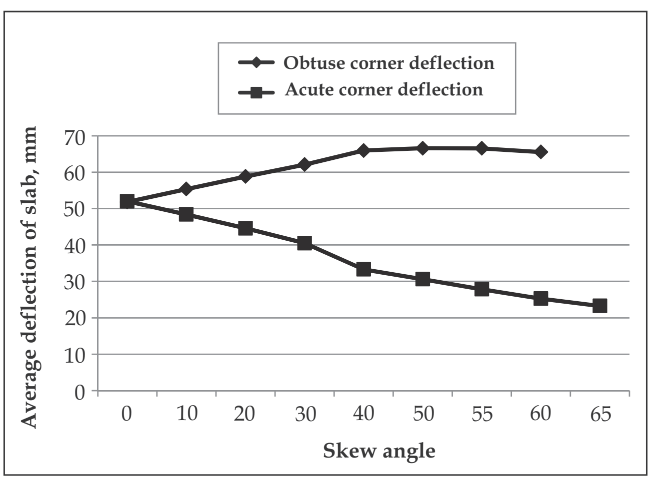


Figure 11. Deflection of acute and obtuse corners of deck slab

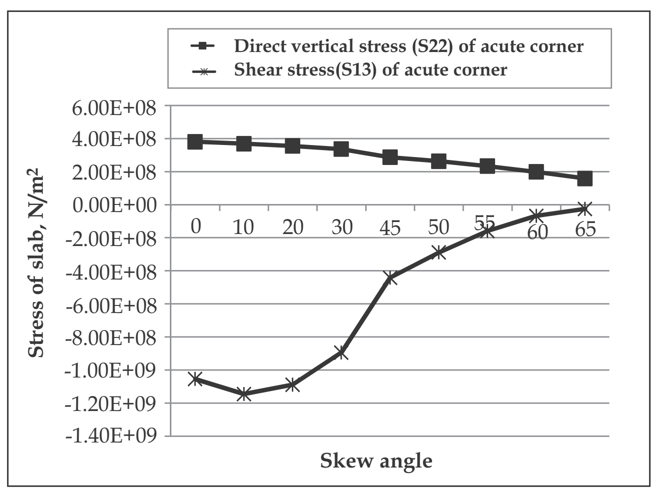


Figure 13. Direct vertical(S22) and shear stress(S13) of acute corner of slab

Similarly, the mid-span longitudinal moment steadily increases with increasing skew angle for obtuse angled girder and decreases for the acute angled one. The changes are again insignificant up to 30^o skew, beyond that the mid-span longitudinal moments of the obtuse girders changes notably, nearly doubles at 50^o increasing further up to 65^o. Again, for a skew angle above 30^o, the design considerations must include these modifications for flexural adequacy of the longitudinal girders.

Also, the mid-span lateral moments of the longitudinal girders, both obtuse and acute, register a reduction with increasing skew angle. These reductions are relatively small (from 0 to 65^o) for Acute angled Girder, whereas they are appreciable for obtuse angled girder (15% and 35% respectively, from 0 to 65^o). These changes can be taken into consideration for economic section design, provided the other factors permit such modification.

Most importantly, with the increasing skew angle, torsional moments rise rapidly in obtuse angled girders. This aspect is generally not considered during the design of right bridges. Torsional moments in the obtuse girder increases by 50% for 0 to 20^o skew. Further, obtuse angled girder registers a voluminous growth in its torsional moments, tripling itself for 0 to 65^o skew. Since torsion is not generally considered for the design of a straight bridge, this factor alone can contribute significantly to the structural failure of a skew bridge designed as a straight one.

For the slab, asymmetric bending is observed with increasing deflection at obtuse corner and decreasing deflection at the acute corner with increasing skew angle. For the slab, it has been observed that with the increasing skew angle, the symmetric deflection profile of the right slab disappears and deflection of the obtuse corner increases but deflection of acute corner reduces significantly, giving rise to a warped deck. Also, the direct vertical and shear stress of the acute corner of the slab becomes nearly zero at 65^o skew, strengthening the possibility of uplift at higher skew angle and giving rise to an S-shaped deflection profile of the deck.

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