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Performance of Reinforced Concrete Skewed Slab Bridges According to Egyptian Code

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Abstract: This paper presents study of simple and three-span continuous reinforced concrete skewed slab type bridges. This study is primarily focused on Skew angles which varied from 0 (non-skewed) to 45 degrees and span length which varied from 7.20 to 14.40 meter. The models are analyzed under Egyptian design vehicle loads using finite element analysis program. The investigation presented comparison between skewed and straight bridges in longitudinal moment, torsional moment, deflection and maximum reactions at both obtuse and acute corners. The results have been supported Egyptian code of design skew bridges less than 15 degrees as straight bridge decks. However, some precautions should be takin into consideration for torsional moment, support reactions at obtuse corners in simply supported bridges. Moreover, support reactions at obtuse and acute corners in continuous bridge decks should be analyzed. using finite element method to get safe design and accurate results.

Key words: Bridges · Skew Angle · Solid Slab Decks · Finite Element Analysis (FEA) · Simply Supported · Continuous Spans · Egyptian Code Of Practice (ECP)

INTRODUCTION

Highway Bridge is an infrastructure key to cross intersected ways such as river, road or railways etc. Due to natural obstacles, the highway bridges often are characterized by the angle between crossing ways and named right bridges and skewed bridges. The skew angle can be defined as the angle between the normal to the centerline of the bridge and the centerline of the abutment or pier cap, as described in Figure 1.

In design of highway bridges, the engineers have to choose the skew option to keep the straight alignment of the highway roads as possible to get more speed and safety in daily traffic. However, behavior of highway bridges under skew angle effect is intricate in design and analysis of bridge deck. AASHTO LRDF. [1] recommends that bridges with a skew angle less than or equal 20° be designed similar to normal bridge with the skew span without modifications. However, if the skew angle exceeds 20°, it suggests the use of an alternate superstructure configuration. The parametric study of Menassa *et al*. [2] supported the AASHTO standard specifications to use suitable method for analyzing the bridge decks with skew angle more than 20°. However, Ibrahim *et al*. [3] disagreed with this recommendation and advised to use 3D finite element models for analysis and design.

Studies of skewed bridges performance led to a clear view on significant factors of design and analysis.

In previous investigations, the researchers considered longitudinal bending moment had been the major factor of design. So, several studies focused on it and concluded that longitudinal bending moment diminish with increasing of skew angle. With investigation of simply supported skewed bridges, Ansuman kar *et al.* [4] concluded the same decreasing result of longitudinal bending moment but found torsion moment of deck increased. Trilok Gupta *et al*. [5] reported that support reactions increase with increasing of skew angle specially at obtuse corners and reach to uplift at acute corners. Patrick Théoret *et al*. [6] curried out parametric study of simply supported bridges and concluded that shear forces and maximum support reactions concentrated at obtuse corners and should be taken into consider when design of skew slab bridges.

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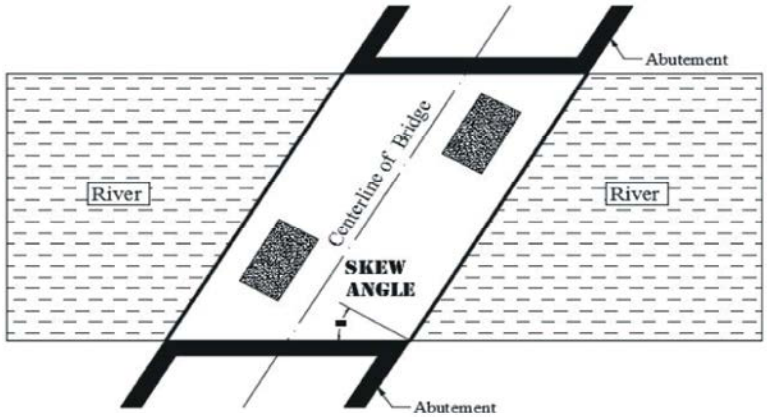

Fig. 1: Definition of skew angle

Also, Sindhu *et al.* [7] confirmed the significant effect of torsion moment and reactions at obtuse corners of bridge decks. Yogesh Bajpai *et al*. [8] suggested the critical factor for design of skewed bridges had been live shear forces. Field measurement on a skewed bridge (Woodruff Bridge) was performed by Gongkang Fu *et al*. [9] in Michigan boosted the importance of the shear stresses in design. Murat Dicleli [10] indicated that skew generally reduce Live Load effects in main parts of skewed bridges where load is transferred to the supports in their shortest path toward the obtuse corners. Also skew had no effect on Live load distribution in both of interior girders, abutments and piles moment that didn't increased up to skew angle 20 degrees.

Raj and Phani [11] confirmed the skew effect in their study which its conclusions indicated that skewed bridges with skew angle less than 15 degrees could be designed as straight bridges. Also, Results showed maximum stress planes are found at obtuse corners because loads take the smallest path to supports. So, support reactions at obtuse corners more than opposite acute corners. Many studied of skewed bridges were presented according to various standards loads such AASHTO and Indian codes. However, few studies investigated the effect of skew angles in continuous multi-spans bridges. So, skewed bridges need to more investigations to understand the static influence of skew effect on bridge decks.

Egyptian code of bridges 2015 [13] suggests that designers may neglect the effect of skew angle when design the bridges with skew angle less than 15°. Nevertheless, bridges with skew angle exceed 15° should be designed with suitable method such as finite element analysis. Also, it is recommended to avoid bridges with skew angle more than 45° as far as possible. Solid slab bridge is most common choice for engineers in design short and medium spans in Egypt. The main advantage of solid slab bridge deck is less cost where cast in place technic is more practicable in development countries. No need to high proficient to execute this type of decks. Hence, this paper investigated skew angle effect on reinforced concrete slab bridges under standard loads of Egyptian code using finite element analysis. The results The results primarily focused on longitudinal bending moments, deflections, torsion moments and support reactions specially in obtuse corners.

Description of Bridge Cases: This investigation presented a parametric study on solid slab bridges. It included three groups of aspect ratio 1.00, 1.50, 2.00 for spans 7.20, 10.8, 14.40 meter with skew angles 0, 15, 30, 45 degrees and two cases of continuity; one was simply supported single span and the other was three continuous spans (Table 1). In total 24 bridge models were investigated using finite element analysis method.

Total depth (t_s) of deck slab thickness was satisfied standard Egyptian code for design bridges which recommended that maximum deflection don't more than Span/500. Slab thickness were 450mm, 550mm, 700mm for simply supported spans 7.20, 10.8, 14.4 meter respectively and 350mm, 450mm, 550mm for continuous spans 7.20, 10.8, 14.4 meter respectively.

Bridge decks accommodated two traffic lanes width without shoulders to get the worst case may be occurred in practice. Structural lane for design is recommended as three meter in Egyptian code for loads Therefore, only two structural lanes were permitted by deck width. Egyptian code [14] suggests two design

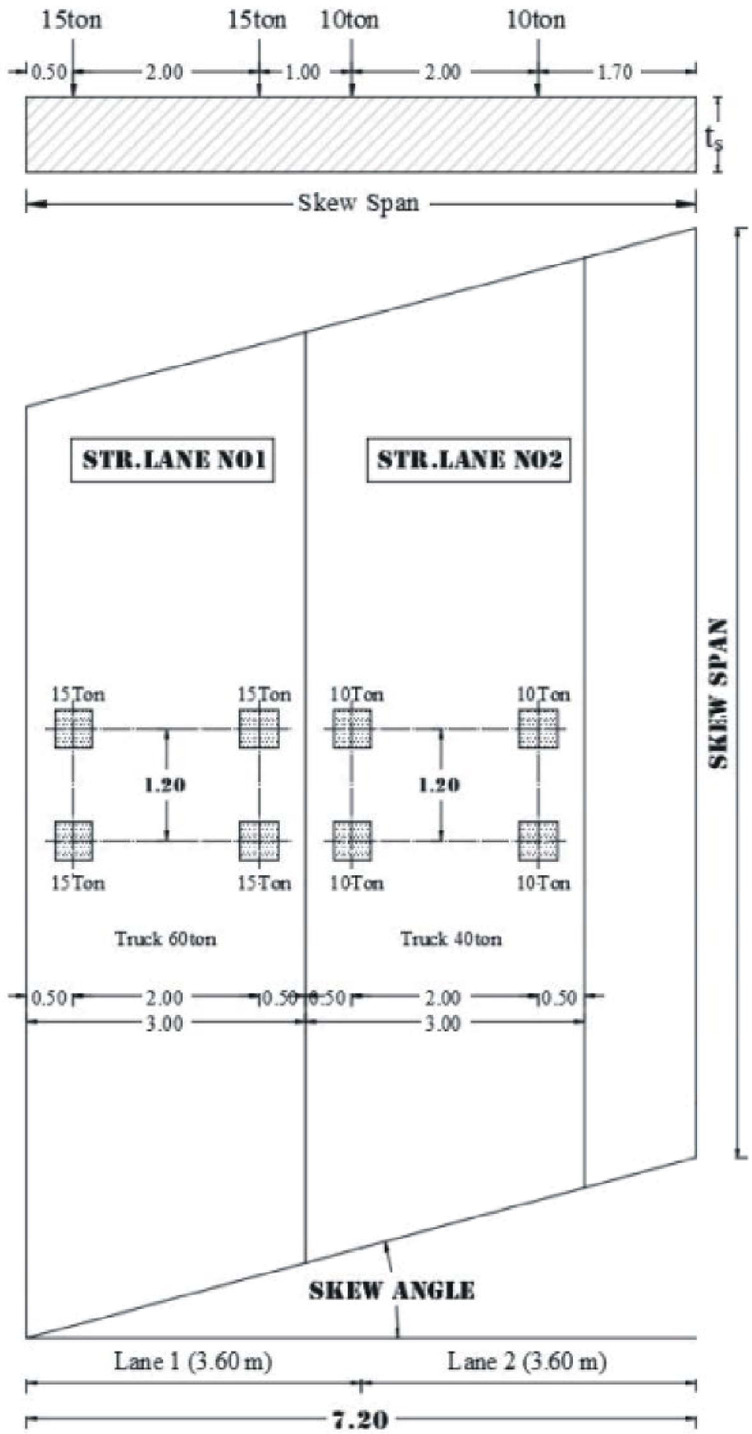

Fig. 2: Loading case of vehicles position in the study

vehicles (truck 60 ton, truck 40 ton) where its centerlines coincide with structural design lane centerlines. For critical loading case of adjacent vehicles position, left wheel load of left vehicle (60 ton) was sited at half meter from free edge but adjacent vehicle (40 ton) was placed at one-meter distance as shown in Figure 2. The study neglected the distributed live and dead loads.

Table 1: Investigated models of Slab bridge decks

Group	Span Length (L)	Width(B)	Continuity case	Skew angle (degrees)
Aspect ratio (span/width) = 1.00	7.2	7.2	Simple	0°
(8 bridge models)				15°
				30°
				45°
			Continuous	0°
				15°
				30°
				45°
Aspect ratio (span/width) = 1.50	10.8	7.2	Simple	0°
(8 bridge models)				15°
				30°
				45°
			Continuous	0°
				15°
				30°
				45°
Aspect ratio (span/width) = 2.00	14.4	7.2	Simple	0°
(8 bridge models)				15°
				30°
				45°
			Continuous	0°
				15°
				30°
				45°

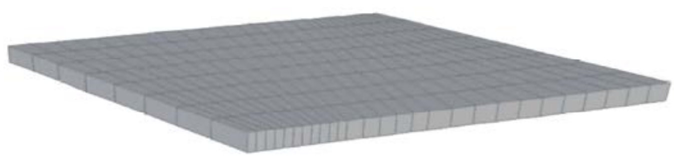

Fig. 3: 3D finite element model of simple support bridge deck

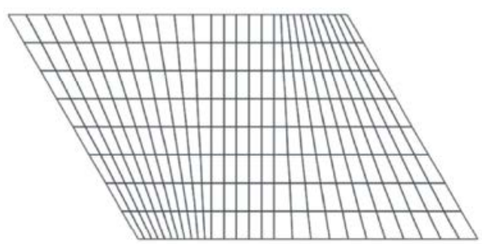

Fig. 4: FEA discretization of solid slab bridge deck using CSI bridge

Finite Element Analysis: The famous FEA program CSI bridge [15] gives a suitable method for design bridges partially in complex manually analysis. It presents three dimensional (3D) finite element models for reinforced solid slab bridge (Figure 3).

Finite element modeling of twenty-four skew slab bridges was made in elastic linear analysis and carried out to obtain the results under the action of moving concentrated loads. FEA discretization of slab bridge deck using CSI bridge are shown in Figure4 indicated that lines of dividing the meshes match with Egyptian code recommendation of bridge decks reinforcement arrangement.

The maximum segment length of deck span was 0.4 meter with maximum sub mesh area 0.4meter square. Wheel load was applied as concentrated loads instead of effect area of wheel as mentioned in Egyptian code to be square area with 0.4 meter for side to obtain maximum results in bridge decks. Roller was defined as fixed displacement at vertical and transverse direction but free in longitudinal direction. On the other hand, Hinge was defined as fixed displacement in three directions. For simply support bridge, Roller was assigned for bearing at one side and hinge at the other side. For three continuous spans decks, Rollers were assigned to the two end supports and one of the intermediate supports but the other support was assigned as hinge to prevent longitudinal movement of bridge deck. The used material for modeling bridge decks was reinforced concrete with compressive strength 35 MPa. Modulus of elasticity was calculated according to Egyptian code ($2.6x10^4$) MPa. Also, Poisson ratio was 0.2. This paper focused on the effect of skew angle on maximum longitudinal moment, maximum deflection, maximum torsional moment in addition to maximum reactions in acute and obtuse corners.

RESULTS AND DISCUSSION

FEA results of skewed bridges are compared to straight reference bridges (non-skewed). Results are plotted in curves to indicate relation between different forces and skew angles. Maximum results location is different along bridge spans based on moving loads locations. Ratios of $M\alpha/M_0$, $D\alpha/D_0$, $T\alpha/T_0$, $R\alpha/R_0$ "Acute corner" and $R\alpha/R_0$ "Obtuse corner" represent maximum longitudinal moment, maximum deflection, maximum torsional moment, maximum support reactions at acute and obtuse corners respectively.

Maximum Longitudinal Bending Moment: General trend of longitudinal bending moment is decrease with increase of skew angle at both simply supported and continuous bridges. Reduction in maximum moment is very small at skew angle 15 degrees for all aspect ratios comparing to results for straight reference bridges (1511.1, 2407.4 and 3305.6 KN. m for span to width ratios 1.0, 1.5 and 2.0 respectively in simply supports case). By increase of skew angle in simply supported bridges, moment decreases in different trends based on span and width of bridge deck. Moment decreased to 77%, 74% and 73% at skew angle 45 degrees for aspect ratios 1.0, 1.5 and 2.0 respectively as shown in Figure 5.

In other side, skewness effect is different in continuous case. At skew angle 30 degrees, reduction in maximum moment is 15% for aspect ratio 1.50 and 2.00 comparing to results for straight reference bridges (990.0, 1611.5 and 2231.9 KN. m for span to width ratios 1.0, 1.5 and 2.0 respectively) as shown in Figure 6. However, maximum moment has small increase at aspect ratio 1.00. At skew angle 45 degrees, maximum moment has small difference for all aspect ratios. It can be concluded that span and width of slab bridge play major effect on load distribution ant its direction. That confirmed Patrick Theoret (2012) equation of moment reduction factor that depend on span, width and skew angle value.

Maximum Deflection: Figure (7) shows the relationship between deflection reduction factor and the skew angle of the bridge for different aspect ratios. The increased of skew angle results in reduction of deflection for all aspect ratios The maximum reduction reached to 55% at skew angle 45 and aspect ratio 2.0 comparing to deflection of straight reference bridges in simply supported case (11.4mm).

Also, same pattern can be observed for the continuous bridges as shown in Figure (8). Deflection declines down to 47% at skew angles 45 degrees and aspect ratio 2.0 comparing to deflection of straight reference bridges in simply supported case (12.8mm).

Maximum Torsional Moment: In contrast of longitudinal bending moment and deflection, maximum torsional moment increases with skew angle increase specially at obtuse corners. Compared to straight reference bridges in simply supported case (1072.6, 1144.4 and 1180.1 KN. m for span to width ratio 1.0, 1.5 and 2.0 respectively), torsional moment increases up to 134% at skew angle 15 degrees and aspect ratio 2.0. Increase rate reaches to 130%, 158% and 175% at skew angle 15 degrees for aspect ratio 1.0, 1.5 and 2.0 respectively as shown in Figure 9. At skew angle 45 degrees, increase rate is less. So, it can be concluded that skew effect depends on bridge deck span and width with skew angle.

Similar skewness effect is noticed in continuous slab bridges but with less effect. Maximum torsional moment is 1168, 1202.6 and 1219.3 for aspect ratio 1.0, 1.5 and 2.0 in straight reference bridges. It increases up to 113% at skew angle 15 degrees and aspect ratio 1.0 as shown in figure 10. Increase reaches to 120%, 133% and 143% at skew angle 45 degrees for aspect ratios 1.0, 1.5, 2.0 respectively.

Maximum Support Reactions at Obtuse and Acute Corners: Skewness effect on support reactions of simply supported bridges is different based on its locations. While support reaction at obtuse corners increases with skew angle increase, it decreases at acute corners. Comparing to obtuse reactions in straight bridge reference

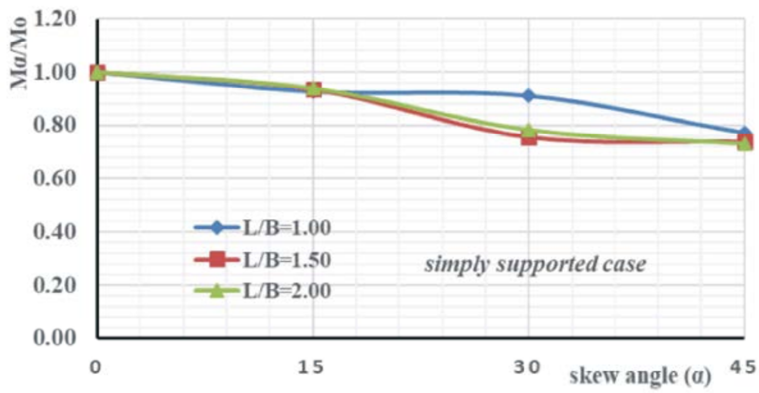

Fig. 5: Maximum longitudinal Bending moment in simply supported slab bridges (Mα/M0 ratio)

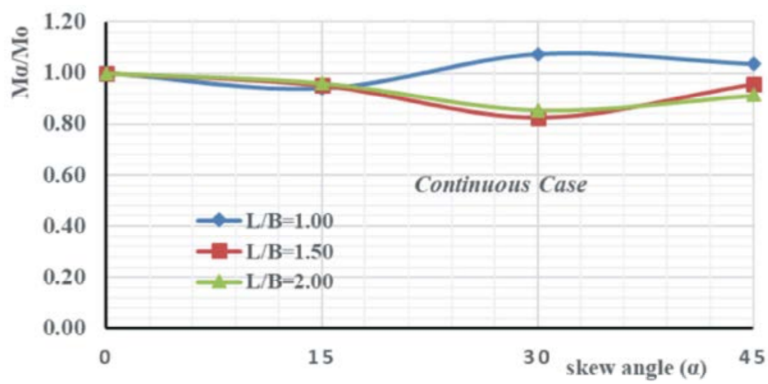

Fig. 6: Maximum longitudinal Bending moment in continuous slab bridges(Mα/M0 ratio)

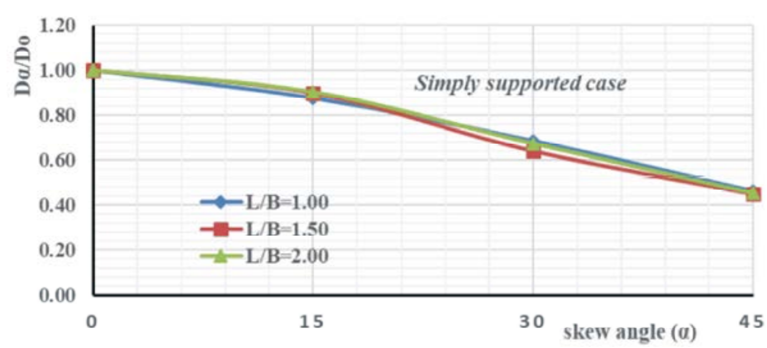

Fig. 7: Maximum deflections in simply supported slab bridges (Dα/D0 ratio)

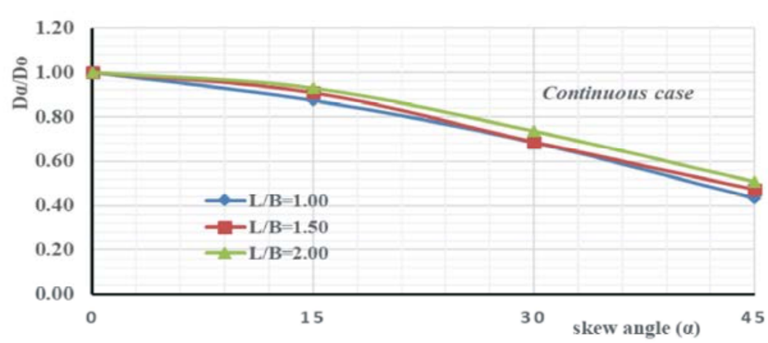

Fig. 8: Maximum deflections in continuous slab bridges (Dα/D0 ratio)

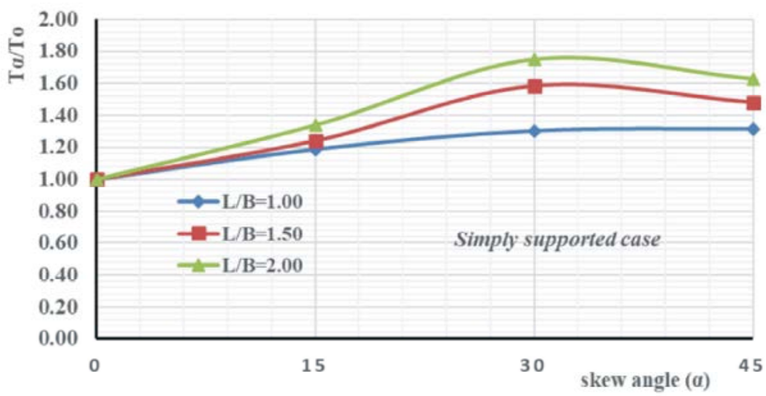

Fig. 9: Maximum torsional moment in simply supported slab bridges(Tα/T0 ratio)

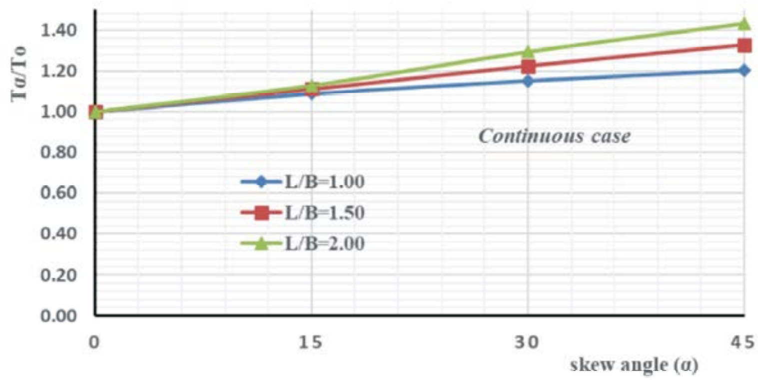

Fig. 10: Maximum torsional moment in continuous slab bridges(Tα/T0 ratio)

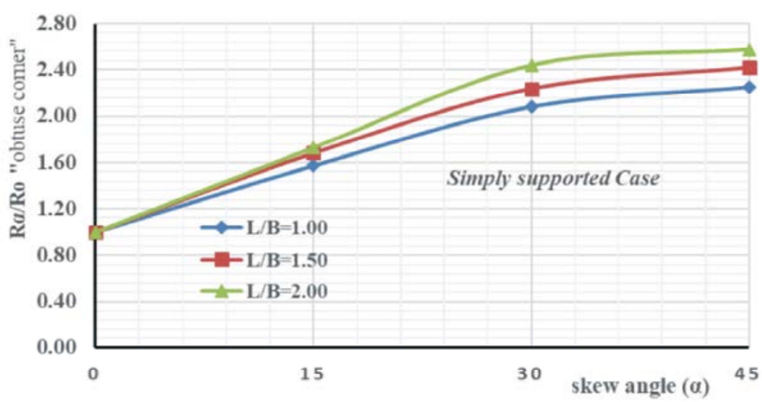

Fig. 11: Maximum reaction at obtuse corner in simply supported slab bridges(Rα/R0 ratio)

(105.2, 132.9 and 156.8 KN for span/width ratio 1, 1.5 and 2 respectively), reaction is 1.57 times at bridge with ratio 1.00 and skew angle 15 degrees. Obtuse corner reactions reach to 2.25, 2.42 and 2.57 times for aspect ratios 1, 1.5 and 2.0 at skew angle 45 degrees as shown in Figure 11. On the other acute corner, reactions decrease to half value compared with straight reference bridges (385, 411.6 and 431.1 KN for span/width ratio 1, 1.5 and 2 respectively) as shown in Figure 12. That explains how load distribute in deck slab where most load goes towards nearest support at obtuse corner due to skewness geometry of deck. Also, results match with (Sindhu 2013) concept "In skewed bridges, the load tends to take a shortest path to the nearest support (obtuse corners of the bridge)".

In continuous bridges, intermediate support reactions increase at both obtuse corner and acute corner of middle span due to skewness effect. Based on the straight reference bridge (113, 127.1 and 132.5 KN for

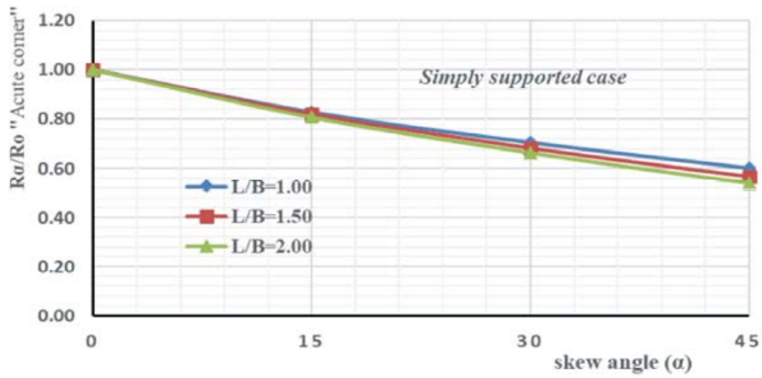

Fig. 12: Maximum reaction at acute corner in simply supported slab bridges(Rα/R0 ratio)

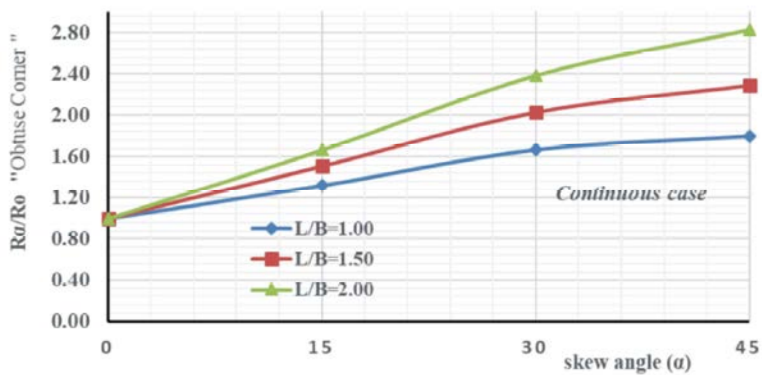

Fig. 13: Maximum reaction at obtuse corner in continuous slab bridges(Rα/R0 ratio)

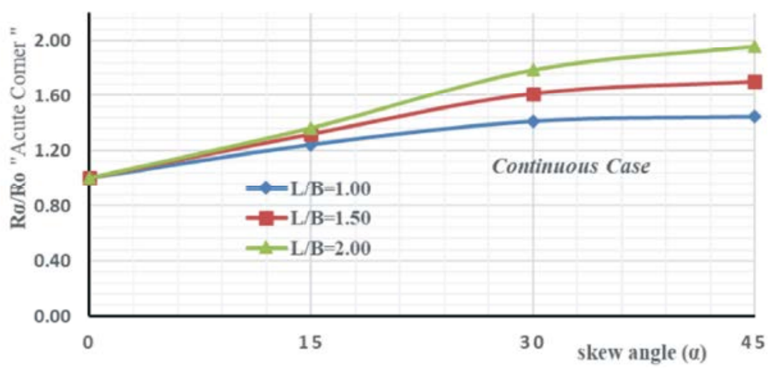

Fig. 14: Maximum reaction at acute corner in continuous slab bridges(Rα/R0 ratio)

span/width ratio 1, 1.5 and 2 respectively), maximum support reaction at obtuse corner in middle span reaches to 1.8, 2.3 and 2.8 times at skew angle 45 degrees for aspect ratios 1, 1.5 and 2.0 respectively as shown in Figure 13.

Also, increase of maximum support reactions at acute corners comparing to results in straight case (396, 414.2 and 425 KN for span/width ratio 1, 1.5 and 2 respectively). It reaches to 1.5, 1.7 and 2.0 times at skew angle 45 degrees for aspect ratios 1, 1.5 and 2.0 respectively as shown in Figure 14. Hambely 1991 confirmed that significant effect at intermediate support region specially at skew angles more than 20 degrees. Presence of obtuse angle at every side give same skewness effect on intermediate support reactions.

CONCLUSIONS

To clearly understand of skewness effect on slab bridge decks, this paper presents investigation of skewed slab bridges in two cases of continuity simply supported and continuous case. The study involved varying the geometric characteristics of the bridges including the span length and slab width with different skew angles. Comparing between skewed slab bridges and straight reference bridge (non-skewed) was in longitudinal bending moment, deflection, torsional moment and support reaction at acute and obtuse corner.

- FEA results indicated that longitudinal bending moment and deflection often decrease with skew angle increase for each simply supported and continuous cases. In contrast, torsional moment multiplied with skew angle increase and concentrated in obtuse corners in simply supported and continuous cases. In the other side support reaction values magnified at obtuse corners in simply supported and continuous slab bridge decks. While support reaction at acute corner declined in simply supported bridges with skew angle increase. But reactions raised higher at acute corner in continuous solid slab bridges.
- Generally, results indicated that skewness effect higher on simply supported solid slab bridge than continuous cases. However, it should be taken into consideration reaction higher at acute corners in continuous bridges. This paper support standard Egyptian code to analysis bridges with skew angle 15 degrees as straight bridges but with some precautions specially in obtuse corners in simply supported and continuous cases.

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