INFLUENCE OF SKEW ON DESIGN LIVE LOAD SHEAR AND DESIGN LIVE SUPPORT REACTION

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Abstract*— Research has shown that skew bridges designed as straight bridges are unsafe with respect to shear force and support reaction while they are conservative with respect to bending moment. At obtuse corners of skew bridge shear force and support reaction increases while at acute corner, they decrease. This deters the practicing engineers from designing skew bridges. For small skew angle (< 10^0), skew bridge is analyzed as right bridge, ignoring skew angle. But for large skew angle, skew bridges are avoided and straight bridges are provided with long approach roads. This solution is not always feasible due to soaring land acquisition cost in metros and congested cities. This makes the skew bridge imperative in such conditions. Inspite of lot of research done in this area, this not hold much relevance in Indian perspective. Design live load standards and type of bridges built in India are different than that available in research publication. Moreover the work done in this filed does not provide any direct help to practicing engineers in calculating the design forces. In this paper an effort has been made to investigate the effect of skew directly on design live load shear force and design live load reaction in simply supported 2 lane reinforced concrete bridges. Skew angle and span of bridges considered in the study vary from 0^0 to 40^0 and 12 m to 21 m respectively. These spans and skew angles are mostly encountered in practical situations. Hence the study covers almost whole range of RC T beam bridges for Indian scenario. Charts are presented to directly obtain the design live load shear and design live load reaction to help engineers in designing skew bridges without struggling with software analysis.

***Index Terms*—Design shear, design reaction, skew bridge, grillage analogy, RC bridge, IRC loading.**

I. INTRODUCTION

Simply supported bridges with small skew angle (10^0 - 15^0) are frequently observed and generally the skew angle is ignored in the analysis. The bridge can be safely analyzed and designed as right bridge since effect of skew is small at such low skew angles. But at higher skew (>15^0), its effects are pronounced which makes the analysis complicated and the normal load distribution theories are no more applicable. Such bridges are becoming popular in the recent past due to their suitability at oblique intersections especially in congested cities. The reasons are difficulties of land acquisition, escalating land prices and long approach roads. In the present paper influence of skew on live load shear (LLS) and live support reaction (LLR) of reinforced concrete T Beam bridge having skew angle from 0^0-40^0 and span range 12 to 12 m has been investigated for Indian loading conditions. The objective is to provide design bridge engineers ready to use charts for quick estimation of above mentioned parameters and thus obviating the need of software analysis thereby saving huge computational efforts and time. The results have been presented in lucid manner for ease of use.

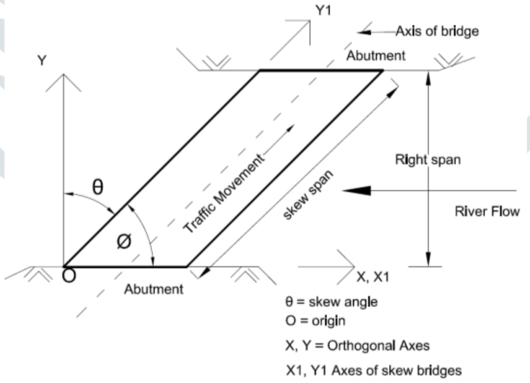

Fig. 1 Skew bridge showing skew parameters

II. BRIEF LITERATURE REVIEW

Baidar Bakht in (1987) analyzed some "Slab on Girder" skew bridges as right bridge using AASHTO loading and presented that the error in analyzing skew bridges as right bridges depends not only on angle of skew but is characterized by two dimensional parameters which depend upon the angle of skew, spacing and span of longitudinal girders and their flexural rigidities. Khallel and Iltani (1990) conducted finite element analysis to determine moments in continuous, normal and skew "slab on steel" girder bridges due to live load for AASHTO loading. Their analysis showed that the maximum moment in the girder of a skew bridge is smaller than that of a normal bridge-approximately by 20%. Pranay Vasantrao Urewar et al. (2006) analyzed simply supported T-Girder single lane, two lane and four lane bridges for IRC Class AA (tracked), IRC Class AA (wheeled), and IRC Class A vehicle. The spans were 15 m for single lane and double lane, and 21 m for four lane bridge. Skew angles in the study were 0^0, 15^0, 30^0, 45^0, and 60^0. His study showed that there was a significant increase in vertical reaction and shear which increased upto 131 % at maximum skew. Trilok Gupta et al (2007) studied the behavior of T-Beam skew bridges with respect to support reaction and Standard IRC 70-R wheeled loading. The study was based on analytical modeling of T-beam bridge by grillage analogy method. The bridges consisted of three longitudinal girders and were simply supported. The spans used were 8 m, 16 m, 24, and 32 m. Skew angles varied from 0^0 to 60^0 at an interval of 10^0. The results show with the increase in skewness that there was significant increase in maximum reaction at obtuse end while negative reactions were observed at the acute end. The negative reactions were pronounced at higher skew angles.

It is tangible from the literature review that most of the skew bridge studies have been carried out for 'slab on girder' bridges using AASHTO loadings. However there is lack of similar study for small spans between 12 m to 20 m with respect to IRC loadings and RC T-Beam bridge system, which is mostly used in Indian scenario. Study carried out by Trilok Gupta et al (2007) is for Indian loading condition and considers only IRC 70 R loading but in actual design IRC class A loading should also be applied. Moreover span of 8 m and 24 m as used in his study prefer slab culvert and PSC construction respectively rather than RC T-Beam configuration. Hence this study is useful only for behavioral understanding of skew bridge under Indian loading conditions and does not provide any direct help to design engineers.

III. RESEARCH METHODOLOGY

Among the various load distribution theories for the analysis of bridges, Courbon's theory, Hendry-Jaegar Theory, Morice-Little Approach, Orthotropic Plate Theory etc. were mostly used in the past. These methods have their inherent assumptions and hence, the results were approximate. As a result these methods are outdated and now replaced by new computer dependent methods like finite element method (FEM), finite strip method, grillage analogy etc. These new methods are very powerful and can perform a highly accurate analysis of any type of problem involving geometric and material complexity of any kind. These methods can handle any type of non-linearity. It has all become feasible due to availability of high end computers with huge computing and storage capacity. On the other hand these computer based methods are often criticized also for their high time and cost required in modeling and analysis using computers. In addition modeling, analysis and interpretation of results need a strong understating of the behavioral aspects of problem. The results can be completely misleading and erroneous (blunder in some cases) if the modelling is incorrect.

FEM and grillage analogy are the two most popular methods used by the current engineers. FEM is numerical integration technique to find the approximate solution of partial differential equations. It was developed with the need to solve complex elasticity and structural analysis problems in aerospace and civil engineering. In this method, the whole structure is discretized into small elements of finite dimensions. These elements are joined to adjacent elements at points called as node. At nodes equilibrium conditions and compatibility conditions are approximately satisfied. A field quantity is allowed to have a spatial variation within the element. The accuracy of finite element analysis depends upon the degree of approximation involved and degree of discretization. Stress-strain constraints are provided along with the material property.

Grillage Analogy Method which has been used in this study presents a computer aided method of analysis which is sufficiently accurate to analyze slab-beam bridges for the estimation of design bending moment, torsion and shear force etc. It is a comparatively simple method to analyze the bridge decks and presents a the wonderful visualization of load distribution along and perpendicular to the span. It is a versatile method and can also take into account the contribution of kerb beams, footpaths and differential sinking of girder ends over yielding supports. However this method do possess some limitations such as inability to take into account the effects like shear lag, warping and distortional effects etc. for which more sophisticated methods like finite element analysis have to be used The method has proved to be reliable and versatile for a wide variety of bridge decks. Further the method is such that it can be easily modeled and facilitates computer aided analysis. STAAD Pro software has been used for this purpose. It considers all 6 degrees of freedom at each joint and analyze the structure with matrix stiffness method. The fundamental equation of equilibrium at member level is given by

$$\{p\} = [\bar{k}]\{\bar{u}\} + \{\bar{q}\}$$

The above equation can be transformed into global level using the transformation matrix

$$[k]_{global} = [T]^T[\bar{k}][T]$$

Where,

$$[T]=\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & c & s & 0 & 0 & 0 \\ 0 & -s & c & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & c & s \\ 0 & 0 & 0 & 0 & -s & c \end{bmatrix}$$

$c = \cos\theta$, $s = \sin\theta$, θ is angle between local x-axis of a member and global X-axis.

[T] = Transformation matrix

$[\bar{k}]$ = stiffness matrix of individual element in local co-ordinate system.

The global equation thus formed at structural level is

$$\{P\} = [K]\{U\}$$

IV. GRILLAGE IDEALIZATION OF BRIDGE DECK

Properties of the gridlines depend upon the size/area of the deck which it represents. If the width of grid is small, then the number of gridlines will be more, and conversely if large size of grid is used, then their number ought to be small. Hence a bridge deck of constant dimensions can be represented by many different grid configurations, depending upon the choice of the size of gridlines. There are no definite guidelines or hard bound rules for selection of size of gridlines and mainly they are selected on the basis of experience. Theoretically finer mesh gives very good results and accurate behavior of the deck. It provides excellent visualization of the distribution of stress resultants in the bridge deck, but making the grid too fine makes the analysis computationally inefficient. There is no thumb rule regarding the size of grillage mesh and the experience of designer is the best judge to decide the fineness of the grid. For the grid size of longitudinal beam, effective flange width of T-Beam of an isolated T Beam as given in IRC 21: 2000 clause 305.15 is used.

$b_e = b_w + l_o / 5$

Where, b_e = effective flange width of T-Beam; b_w = width of T-Beam and

l_o = distance between the points of contra flexure.

Longitudinal and transverse gridlines are provided at the center of each longitudinal and cross beam. Remaining portion of slab is also divided into fine gridlines of reasonable width. Figure 2 and shows a typical grillage idealization in longitudinal direction while figure 3 shows plan view of an bridge modeled with grillage analogy in STAAD Pro.

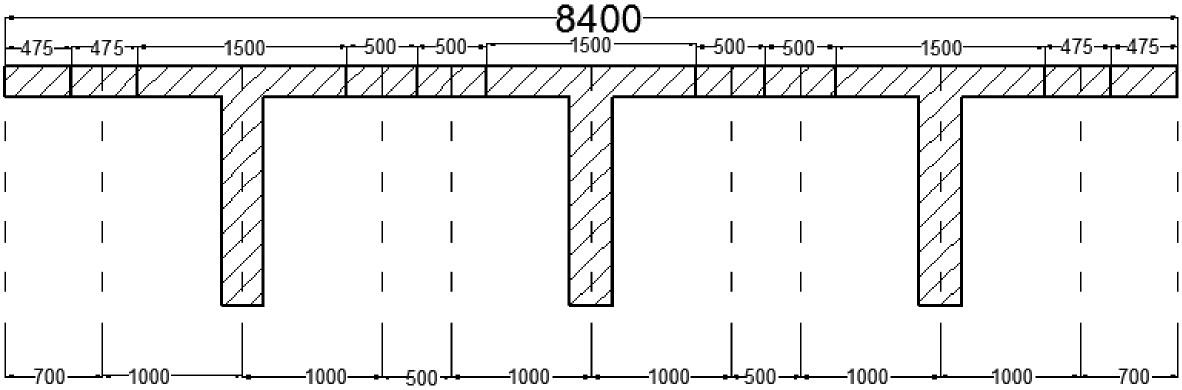

Fig. 2 Grillage idealization of bridge in longitudinal direction (Dash lines represent grids) (All dimensions in mm)

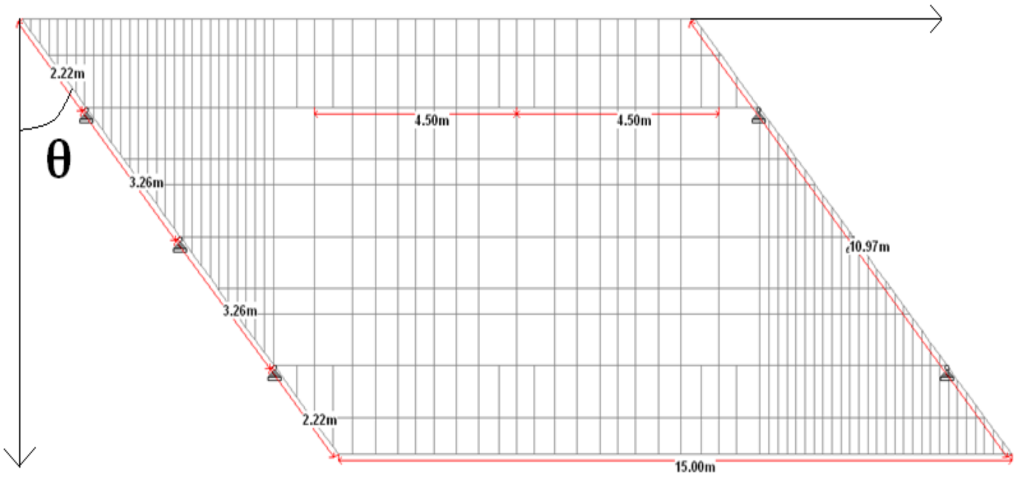

Fig. 3. Typical plan of grillage model of 15 m span (skew bridges, θ ≥ 150)

V. GEOMETRIC PROPERTIES OF BRIDGE UNDER STUDY

A reinforced concrete 2 Lane T Beam bridge is used for the study. 3 longitudinal girders (fig. 4) have been provided to support the deck. The distribution of live loads amongst the longitudinal girders depends on their relative stiffness, transverse stiffness of cross girders and the eccentricity of load. If the stiffness of all longitudinal girders is same, there is little effect of their individual stiffness on the distribution of live loads, provided transverse stiffness is adequate. Cross Girders spacing in the study is kept between 4.5 m to 6 m which is generally used in practice. Skew angle has been varied between 0^0 to 40^0.For skew bridges of 0^0 and 10^0, the cross girders (& transverse gridlines) are parallel to the abutment, while for 20^0, 30^0, and 40^0, the cross girder (& transverse gridlines) are provided orthogonal to longitudinal girders for achieving better transverse rigidity. The bridge is supported on 3 bearings, one below each longitudinal girder where the reaction values are observed. Taking into account practical considerations, the cross sectional dimensions of the bridge are selected (Fig. 4) This cross section has been used for all the spans under investigation i.e. 12m, 15m, 18m and 21m. The depth of longitudinal girders has been kept as span/10 while, the depth of intermediate cross girders is kept as 80% of the depth of longitudinal girders. The depth of end cross girder is kept equal to the depth of longitudinal girder but in practical construction it is slightly less to facilitate the placement of bearing or jacking up for replacement of bearings during the service life. The geometric parameters of bridges under investigation are tabulated below in table 1 and table 2.

Table 1. Dimensions of longitudinal and transverse beams

Longitudinal Beam				**Transverse Beams**			
				Intermediate Cross Beam		End Cross Beam	
S.No	Span(m)	B (mm)	D (m)	B (mm)	D(m)	B(mm)	D(m)
1	12	350	1.2	300	0.96	300	1.2
2	15	350	1.5	300	1.2	300	1.5
3	18	400	1.8	300	1.44	300	1.8
4	21	400	2.1	300	1.68	300	2.1

Table 2. No. of cross beam in bridges under study

Span (m)	**Skew Angle**				
	0^0	**10^0**	**20^0**	**30^0**	**40^0**
12	3	3	3	4	4
15	4	4	4	4	5
18	5	5	5	5	5
21	5	5	5	5	6

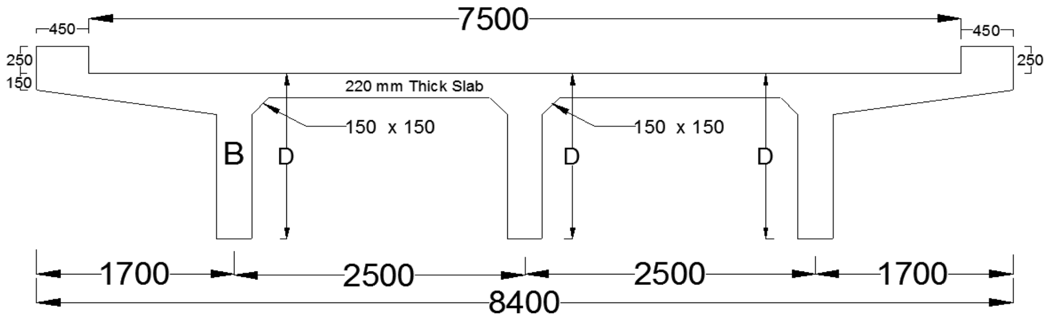

Fig. 4. Typical cross-section of RC bridge for grillage analogy analysis

VI. LIVE LOAD CONSIDERED IN THE STUDY

Bridge deck was analyzed for “Class A”, “Class 70R Tracked” and “Class 70R Wheeled” vehicles. Class 70 R tracked vehicle has been idealized as 20 equal point loads of 35 kN each. As per IRC 6: 2000 Table 2, a two lane bridge should be loaded with either one lane of “Class 70R” or two lanes of “Class A”. For the transverse placement of the vehicle, guidelines of IRC 6: 2000, clause 207 were followed which suggests that the minimum spacing of vehicle form the face of the kerb is 1.2 m for “Class 70R” and 0.15 m for “Class A” loading. Many other trials of transverse placement of vehicles were also made to obtain maximum live load shear (LLS) and maximum live load reaction (LLR) in the bridges. Following observations were made during these trials.

(a) For all Class of loading, the maximum LLS occurs in the outer girder, near the obtuse corner.

(b) For “Class 70R Wheeled” and “70R Tracked” vehicle the maximum LLR occurs in the middle bearing when the vehicle is placed centrally.

(c) For “Class A” vehicle maximum reaction LLR is obtained in the outer bearing at obtuse corner when the vehicle is placed at minimum spacing form the kerb.

The loads were placed accordingly to obtain maximum LLS and maximum LLR in the bridge. The maximum values are the design values and hence only these values are presented here. The results are tabulated below.

VII. RESULTS

7.1 Skew Effect on Design LLS and Design LLR for 12 m Span

It is observed that both LLS and LLR increases with an increase in skew angle. The increase in LLS with skew is 30.66%, 38.3 %, and 27.6% for Class 70 R Tracked, Class A and Class 70 R wheeled vehicle at 40^0 skew. Similar trend is observed for LLR also. The increase with skew is 37.6%, 60.6 %, and 41.27 % for Class 70 R Tracked, Class A and Class 70 R wheeled vehicle as depicted in the figure 5 and figure 6. It can also be seen that there is no significant increase in LLR and LLS upto 10^0, which confirms that skew bridges can be analyzed and designed as right bridges for small skew. The increase in reaction due to class A vehicle is as high as 61%, which suggests that care should be taken while designing the bearings of skew bridge. The values are tabulated below in table 3.

Table 3. Values of LLS and LLR for different skew angle and IRC loading for 12 m span (Refer section VI)

Maximum Live Load Shear (LLS), kN (12 m)				**Maximum Live Load Reaction (LLR), kN (12 m)**			
Skew	**70 R TR**	**CLASS A**	**70 R WH**	**Skew**	**70 R TR**	**CLASS A**	**70 R WH**
0^0	242	193	240	0^0	375.7	256.5	352.3
10^0	248	197	244	10^0	421.9	287.6	389.0
20^0	283.3	230	281	20^0	445	316.4	397.7
30^0	294	255.2	293	30^0	492	364.9	434.4
40^0	316.2	267	306.2	40^0	517.2	412	497.7

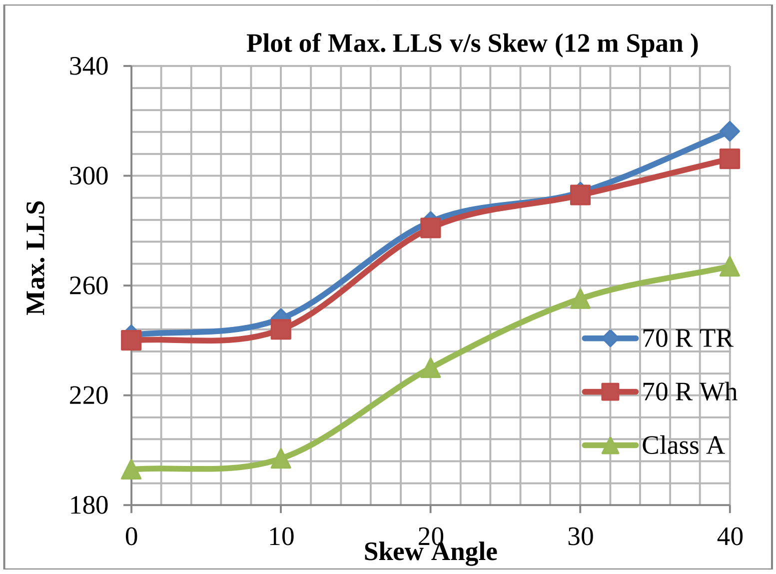

Fig. 5. Effect of skew on LLS for 12 m span bridge

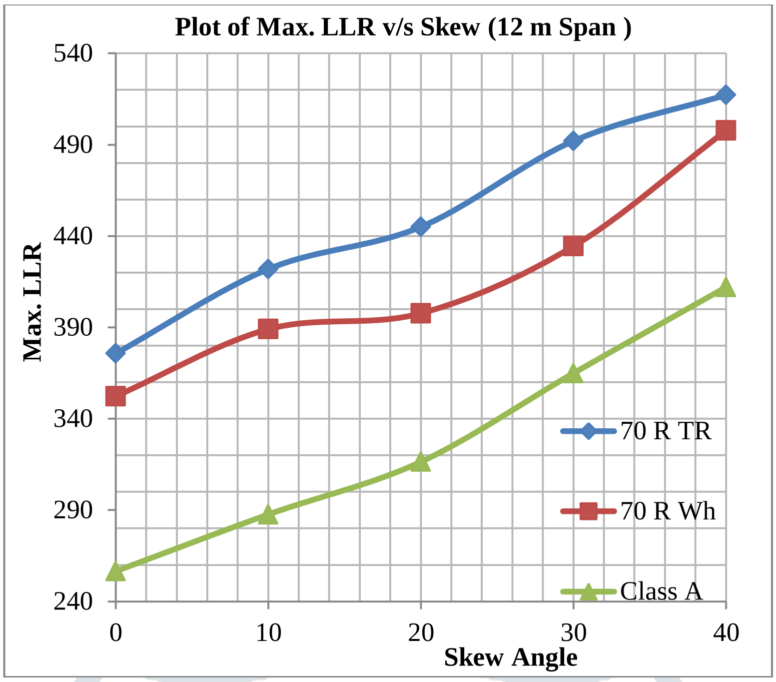

Fig. 6. Effect of skew on LLR for 12 m span bridge

7.2 Skew Effect on Design LLS and Design LLR for 15 m Span

Both LLS and LLR increases with skew in a nearly linear fashion. As in the previous case, the rate of increase in LLS and LLR is slow upto 10^0 but after that slope becomes steep. The increase in LLS is 25.2 %, 28.4% and 21.65% at a skew angle of 40^0 for class 70 R tracked, class A and Class 70 R wheeled vehicles. For LLR the increase is 40 % for 70 R Tracked, 50 % for Class A and 43.4 % for Class 70 R wheeled loading. 70 R wheeled vehicle governs the shear design while 70 R Tracked vehicle governs the design reaction. (Table 4, Fig 7 & 8)

Table 4. Values of LLS and LLR for different skew angle and IRC loading for 15 m span

Maximum Live Load Shear (LLS), kN (15 m)			
Skew	**70 R TR**	**CLASS A**	**70 R WH**
0^0	266	225	291
10^0	272	229	296
20^0	293	253	320
30^0	305	266	333
40^0	333	289	354

Maximum Live Load Reaction (LLR), kN (15 m)			
Skew	**70 R TR**	**CLASS A**	**70 R WH**
0^0	371	288	362
10^0	416	319	396
20^0	458	350	432
30^0	496	391	470
40^0	521	432	519

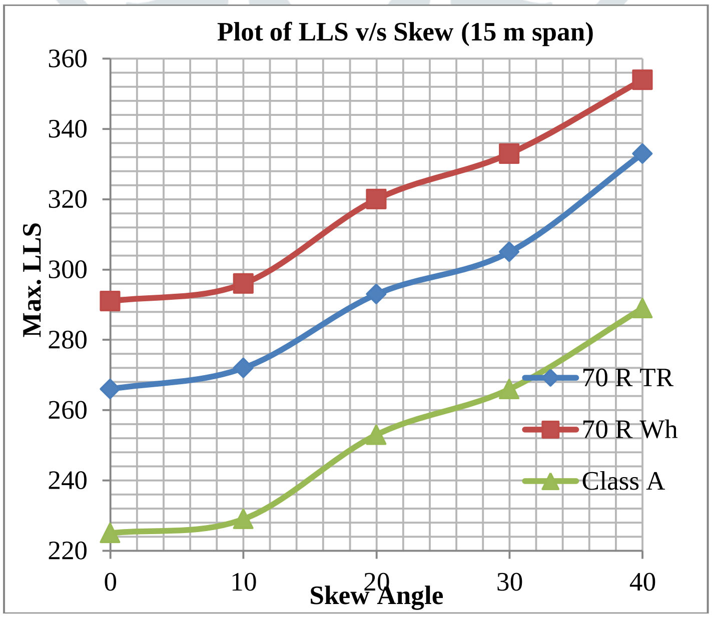

Fig. 7. Effect of skew on LLS for 15 m span bridge

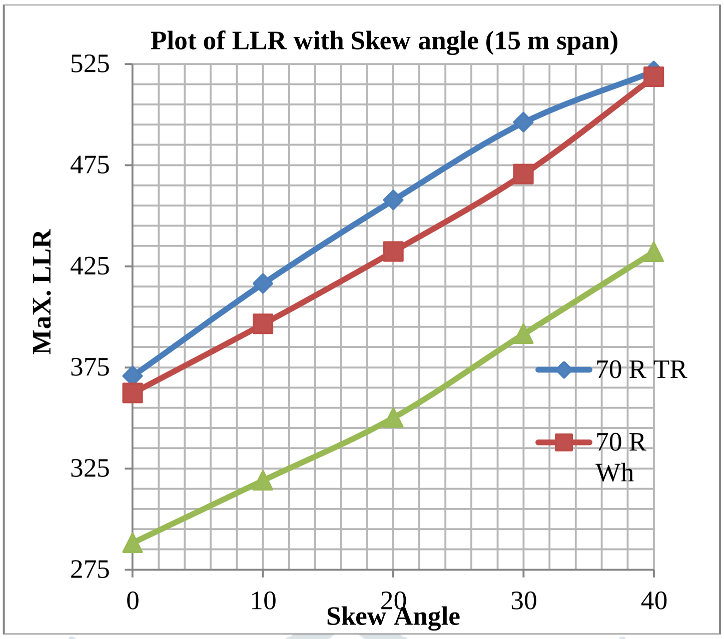

Fig. 8. Effect of skew on LLR for 15 m span bridge

7.3 Skew Effect on Design LLS and Design LLR for 18 m Span

The LLS and LLR shows similar increasing trend as in previous case. For LLS, increase is 22% for 70 R Wheeled loading, 26.5% for class A loading and 21.83 % for 70 R Tracked loading. The maximum increase in LLR is 44.2 % for 70 R Wheeled loading, 40% for class A, and 42.8 % for 70 R Tracked loading. Class 70 R wheeled loading governs the shear design, while there is no fixed trend for design reaction. (Table 5, Fig 9 & 10)

Table 5. Values of LLS and LLR for different skew angle and IRC loading for 18 m span

Maximum Live Load Shear (LLS), kN (18 m)				**Maximum Live Load Reaction (LLR), kN (18 m)**			
Skew	**70 R TR**	**CLASS A**	**70 R WH**	**Skew**	**70 R TR**	**CLASS A**	**70 R WH**
0^0	284	260	328	0^0	362	318	371
10^0	290	264	332	10^0	408	345	402
20^0	308	288	355	20^0	450	375	435
30^0	325	313	377	30^0	490	411	475
40^0	346	329	400	40^0	517	445	535

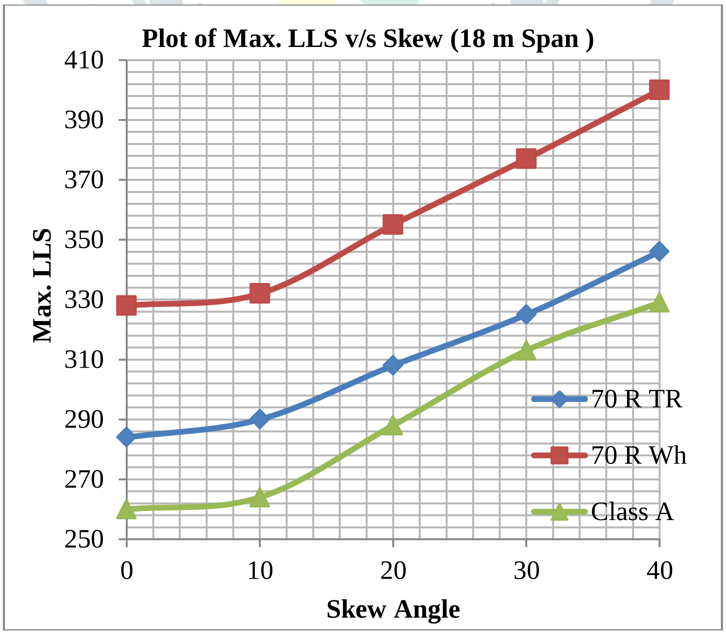

Fig. 9. Effect of skew on LLS for 18 m span bridge

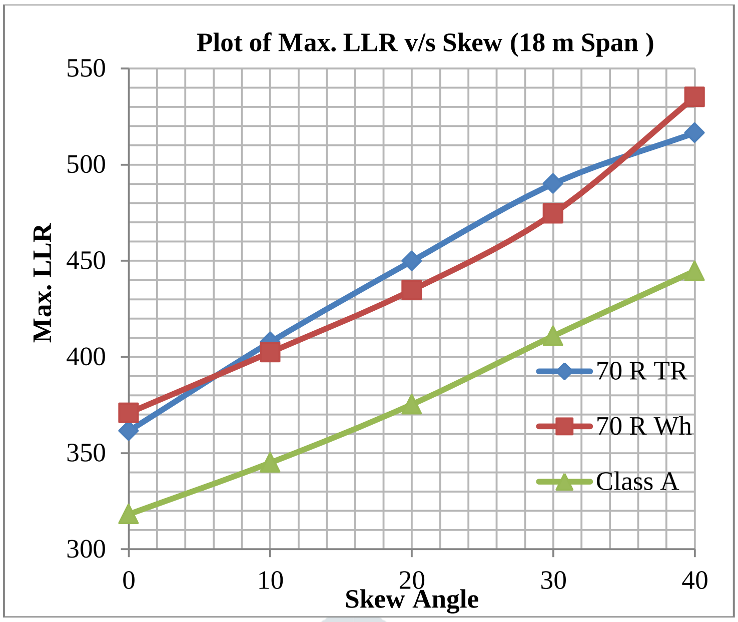

Fig. 10. Effect of skew on LLR for 18 m span bridge

7.4 Skew Effect on Design LLS and Design LLR for 21 m Span

Here also LLS and LLR increase linearly with skew angle. Maximum increase in LLS is 36.2 %, 36.5 % and 38.7 % for 70 R tracked, Class A and 70 R wheeled loading respectively. In LLR, the increase is 25.9 %, 27 %, and 27.5 % for 70 R tracked, Class A and 70 R wheeled loading respectively. 70 R wheeled loading governs the shear design. (Table 6, Fig 11 & 12)

Table 6. Values of LLS and LLR for different skew angle and IRC loading for 21 m span

Maximum Live Load Shear (LLS), kN (21 m)			
Skew	**70 R TR**	**CLASS A**	**70 R WH**
0^0	378	340	393
10^0	419	363	423
20^0	455	389	457
30^0	489	421	491
40^0	515	464	545

Maximum Live Load Reaction (LLR), kN (21 m)			
Skew	**70 R TR**	**CLASS A**	**70 R WH**
0^0	286	282	346
10^0	292	287	352
20^0	312	316	379
30^0	329	335	400
40^0	360	358	441

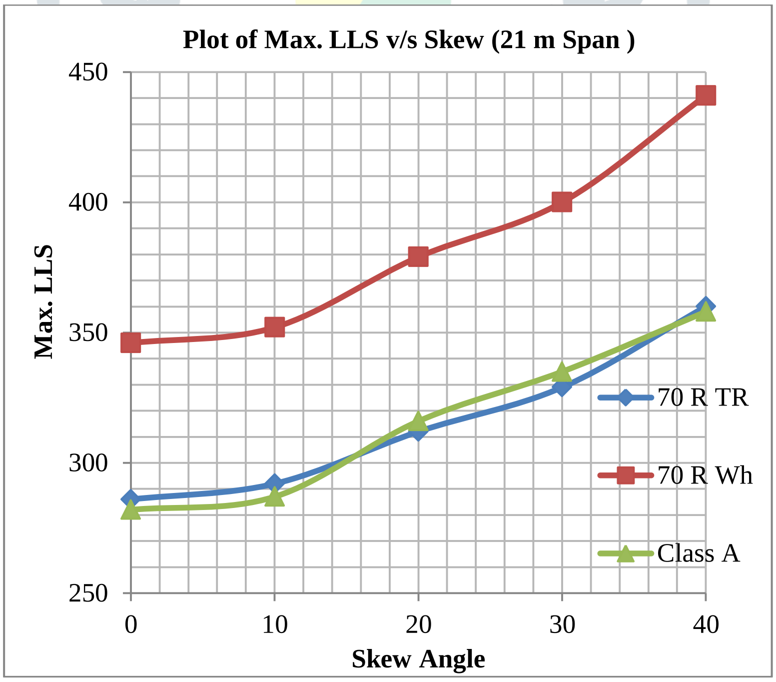

Fig. 11. Effect of skew on LLS for 21 m span bridge

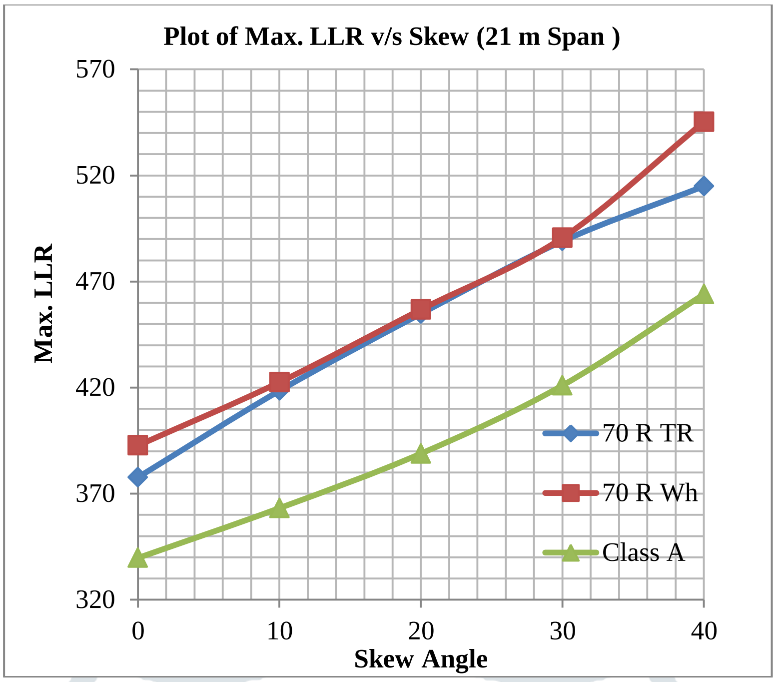

Fig. 12. Effect of skew on LLR for 21 m span bridge

VIII. PROCEDURE TO ESTIMATE MAXIMUM LIVE LOAD SHEAR (LLS) AND MAXIMUM LIVE LOAD REACTION (LLR) IN SKEW BRIDGES

In the design of any skew bridge, analysis is done for dead loads and live loads. Skew angle has little effect on dead load analysis, and hence it can be carried out in the routine way as for right bridges. For live load analysis the study conducted above can be used to directly estimate the maximum live load shear and maximum live load reaction in bridges of same configuration, same cross section, span in between 12 to 21 m and skew angle between 0^0 and 40^0. For this a linear double interpolation has to be performed between span and skew angle. To substantiate the validity of the study three bridges were analyzed in STAAD PRO using grillage analogy method and the results were compared with those obtained from charts. A linear double interpolation was done within the two nearest values of span and skew using the charts and table. Comparisons of results is given below in table 7.

Table 7. Comparison of Analytical and Predicted Values of Design Forces

Case 1	**Span = 20, Skew angle = 20**										
	70 R Tracked				**Class A**				**70 R Wheeled**		
Parameter	**Staad Analysis**	**Charts & Tables**	**% Error**		**Staad Analysis**	**Charts & Tables**	**% Error**		**Staad Analysis**	**Charts & Tables**	**% Error**
Shear (kN)	308	310.8	0.91		301	306.9	1.96		369.1	371	0.51
Reaction (kN)	460.4	453.6	-1.48		380	384.5	1.18		460	450	-2.17
Case 2	**Span = 19, Skew angle = 35**										
	70 R Tracked				**Class A**				**70 R Wheeled**		
Parameter	**Staad Analysis**	**Charts & Tables**	**% Error**		**Staad Analysis**	**Charts & Tables**	**% Error**		**Staad Analysis**	**Charts & Tables**	**% Error**
Shear (kN)	338	338	0.00		334.4	331	-1.02		408.3	400	-2.03
Reaction (kN)	505.25	503.3	-0.39		415.8	433.3	4.21		508.9	509	0.02
Case 3	**Span = 13.5, Skew angle = 25**										
	70 R Tracked				**Class A**				**70 R Wheeled**		
Parameter	**Staad Analysis**	**Charts & Tables**	**% Error**		**Staad Analysis**	**Charts & Tables**	**% Error**		**Staad Analysis**	**Charts & Tables**	**% Error**
Shear (kN)	293.9	294.7	0.27		257.5	251.5	-2.33		307.5	307	-0.16
Reaction (kN)	475.9	473	-0.61		346.2	356.8	3.06		440.7	434	-1.52

IX. CONCLUSIONS

Following major conclusions can be drawn from the above results.

1) As the skew angle increases maximum live load shear (LLS) increases. Upto 10^0 skew, increase is small but after 10^0, it increases significantly and thus skew bridges designed as right bridges are unsafe with respect to LLS. The increase in shear is in the range of 25 to 40%
2) Similar to LLS, live load reaction (LLR) also increases with skew. The maximum increase is as high as 61% for class A and 12 m span.
3) It is observed from above results that, increase in LLR reduces with increasing span. This shows that the skew effect is pronounced on small span bridges. Increasing span, alleviates the influence of skew.

4) The case studies shows that the actual results of LLS and LLR obtained from STAAD analysis are very close to the values obtained from charts. The maximum error in calculating shear values from charts is 2.33 % while in support reactions is 4.21 %. Hence the above charts helps greatly in quick estimation of LLS and LLR for skew and right bridges in the span range of 12 to 21 m and skew angle range of 0^0 to 40^0, hence saving a lot of time.

X. ACKNOWLEDGMENT

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