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Variation of Design Live Load Moment with Skew on RC Bridges

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***Abstract:** Most of the study carried out in the field of skew bridges is of theoretical nature and does not provide any direct help to engineers designing bridges specially, for Indian loading conditions. Therefore an effort was made to help such engineers in the quick calculations of design live load moments (LLM) for small span skew RC bridges. For these bridges of practical dimension and skew angle as used by design engineers in Indian conditions are selected for the study. Two lane RC simply supported T-Beam bridges with varying skew angle (0^0 to 40^0 at 10^0 interval) and varying span (12 m to 21 m at 3 m interval) were analyzed in STAAD PRO software using grillage analogy method. Two lane bridges mostly have three longitudinal girders and are simply supported on three bearings. The same has been used in the study. IRC vehicles (70R Tracked, 70R Wheeled and Class A as per IRC 6) are used to simulate loading conditions for Indian bridges. Effect of skew is observed on design live load moment at critical location (mid span region) in the girders and the same is presented in charts to ease the calculation. With an increase in skew angle, a reduction in design live load moment (LLM) was observed for outer longitudinal girders while, for middle longitudinal girder, design LLM was not much affected. This trend was observed for all spans from 12 m to 21m. This suggests that skew bridges designed ignoring the skew effects are conservative with respect to the bending moment.*

***Keywords:** Bending Moment, Grillage Analogy, Skew Angle, RC T-Beam Bridge, STAAD Pro, Design Live Load Bending Moment, IRC Loading.*

I. INTRODUCTION

Most of the bridges in older days were straight, and skew bridges were averted as far as possible. Lack of knowledge about the structural behavior and construction difficulties were obvious reasons contributing to the designers' choice to favor straight bridges rather than skew bridges. But in the current scenario, with the increasing population, high cost of land acquisition for approach roads and other practical constraints, there is an increasing trend of providing skew bridges at oblique intersections. Also,in congested cities due to lack of space, bridges have to be skew in nature if the intersection is not orthogonal. Hence there is need to study the behavior of skew bridges so as to facilitate quick estimation of design LLM, shear force and support reactions and thus obviating the need of a rigorous analysis. The results have been presented in the form of ready to use design charts.

II. WORKING STRATEGY

In today's era, highly sophisticated soft ware is available to perform a near exact analysis of any complex problem. Commercially available software packages like ANSYS, ABAQUS, SAP etc. has made it possible to use the methods of Finite Element Analysis, etc. with much ease. But still such exact analysis is performed at the cost of high computational and modeling efforts. However for practical design of bridges such a high accuracy in analysis is not required due to inherent safety in the design theories to cater for such minor approximations. Hence grillage analogy was used instead of FEM to carry out the study. It presents a sufficiently accurate method to analyze slab-beam bridges for estimation of design bending moment, torsion, shear force etc. It is a comparatively simple method to analyze the bridge decks and gives an excellent visualization of distribution of forces among different longitudinal and transverse girders in a bridge. It can easily handle complicated geometric features of a bridge such as skew, edge stiffening, and deep haunches over support, continuous and isolated supports etc. with ease. It do possess some limitations such as inability to take into account the effects like shear lag, warping and distortional effects for which more sophisticated methods like FEM has to be used.

Basically grillage analogy method uses stiffness approach for analyzing the bridge decks. The whole bridge deck is divided into a grid of longitudinal and transverse beams. Slab is assumed to be rigid in its own plane and hence there are 3-Dofs namely,1- vertical translation and 2-rotations about the axes in plane of the bridge deck. The properties of cross-section of beams such as moment of Inertia about their principal axes, Tensional constant, Effective area etc. are calculated and the grid is solved for the unknown degrees of freedom using the matrix stiffness method. The overall equations of equilibrium are given below.

{F} = [K]{ U} At Structural Level

{f} = [k]{ u} At Member Level

Where, F represents the unknown reaction/load vector (BM, Torsion, SF), K is the structure stiffness matrix and U is the vector of nodal displacement.

The solution of grillage mesh involves a large no. of equations, which is beyond the scope of the manual calculation. Hence it becomes mandatory to take aid of computer programs in the grillage analogy method. Commercially available software package like STAAD Pro are very helpful in analyzing bridges with grillage analogy method considering all the 6-DOFs i.e. 3 translations and 3 rotations per node. The use of same has been made in this study.

III. PROPERTIES OF GRIDLINES, THEIR SIZES, LOCATION AND PLACEMENT [11]

Gridlines are the beams representing the discredited stiffness and other structural properties of the slab and beam portions which it replaces. Hence gridlines are provided at the center of each longitudinal beam (fig. 1)and transverse beam. Remaining portion of slab is also divided into no. of gridlines. Dense grid is provided near edges and corners. Gridlines are also provided along the lines joining the isolated bearings. For bridges with skew angle less than 15^{o} transverse girders are provided parallel to the support lines so the gridlines should also be parallel to the support lines. But for skew angles exceeding 15 degrees, transverse diaphragms perpendicular to the longitudinal girders are provided as they are found to be more efficient in transverse load distribution. Hence transverse gridlines should be perpendicular to the longitudinal beams (fig. 2). Aid from IRC 21: 2000 clause 305.15 can also be taken to decide the size of grid. The choice of grid fineness and location is best judged by experience of the designer. Table 1 gives the cross sectional details of longitudinal and transverse beams modeled as grid lines.

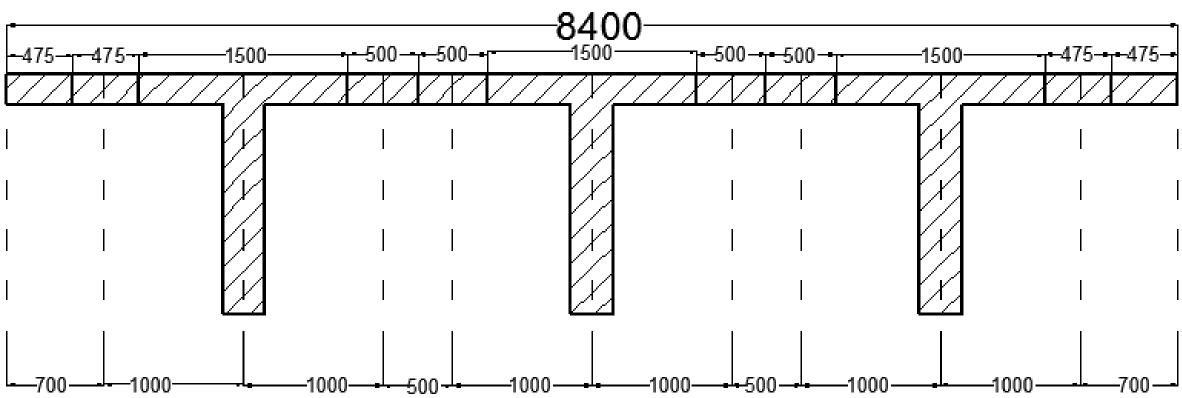

Fig. 1 Grillage idealization in longitudinal direction (All dimensions in mm)

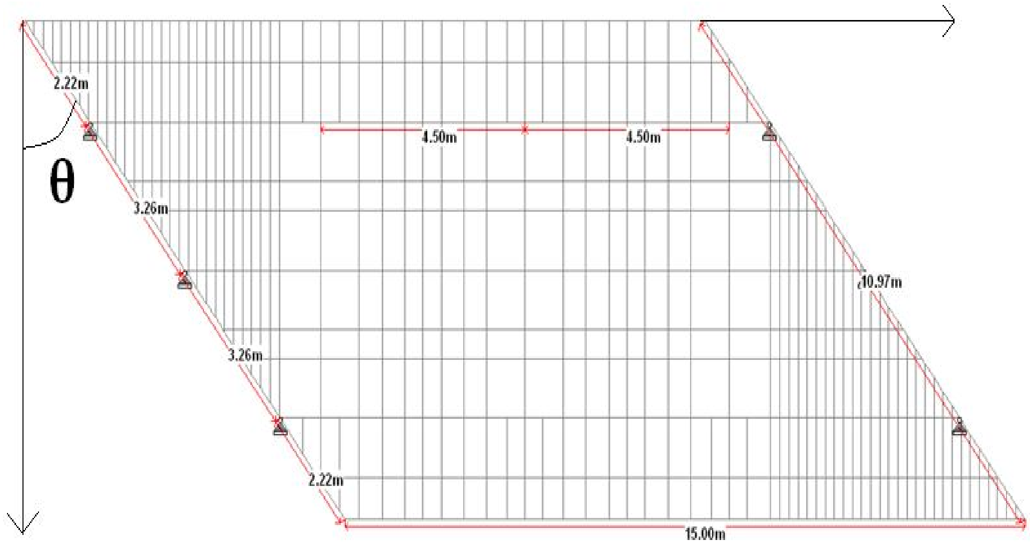

Fig. 2. Typical plan of grillage model of 15 m span (skew bridges, $\theta \geq 15^{0}$)

IV. PARAMETRIC STUDY OF RC BRIDGE

A 2 lane RC T-Beam bridge has been chosen for the study. Spans have been varied from 12m to 21 m with an increment of 3m. The no. of longitudinal girders has been kept as three. Cross girders are hindrance in the speed of construction as they pose practical problems in construction. So their spacing is generally kept not less than 4 m and for this reason the spacing of cross girders is kept between 4.5 m to 6 m. 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 the reason explained in above section. The cross-section shown in fig.3 has been chosen. The sizes of longitudinal and cross beams chosen for study is given in Table 1

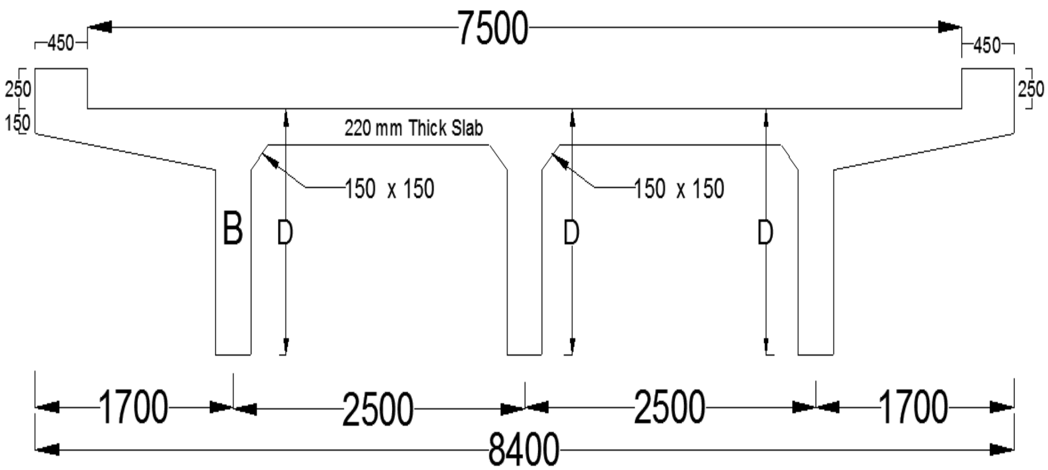

Fig.3. Typical cross-section of bridge for grillage analogy

Table1. Dimensions of longitudinal and transverse girders

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

V. LIVE LOAD APPLICATION ON THE BRIDGE

The bridge deck was analyzed for “Class A”, “Class 70R Tracked” and “Class 70R Wheeled” vehicles. As per IRC 6: 2010 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: 2010 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 the transverse placement of vehicles were also made to obtain maximum LLM in the bridges. Following observations were made during these trials.

A. For “Class A”, “Class 70R Wheeled” and “70R Tracked” the maximum bending moment in the bridge is always obtained in the outer girder when the vehicle is placed at minimum spacing from the kerb.

B. For maximum LLM in the middle girder the vehicle is placed both eccentrically and centrally as it does not always occur for same transverse placement of loads. The loads were placed accordingly to obtain maximum LLM in the bridge.

VI. IDEALIZATION OF VEHICLE

The details of vehicles have been given in IRC 6: 2010. Class 70 R Tracked vehicle has been simulated as train of 20 equal point loads as shown below in fig. 4. The load values shown in the longitudinal details are the axle loads and since there are two wheels on each axle, so the values are halved when seen in the transverse view.

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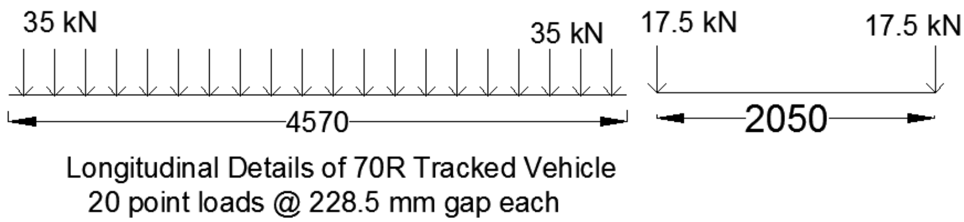


Fig.4. Idealized 70R Tracked

VII. RESULTS AND DISCUSSION

Bridges of span 12 m, 15 m, 18 m and 21 m were analyzed for skew angles 0^0, 10^0, 20^0, 30^0 and 40^0. The vehicles were placed as explained in section 5 and LLM was obtained in G1, G2 and G3 where,

G1 is the outer longitudinal girder on the eccentric side near to live load vehicle.

G2 is the middle longitudinal girder

G3 is also the outer longitudinal girder but,on the other side of eccentrically placed load.

A. Effect of Skew on Design LLM for 12 m span

Fig.5, fig.6 and fig.7shows the variation of LLM of G1, G2 and G3 with skew. The LLM for G1 and G3 are obtained by placing the vehicle eccentrically, while for G2 it is obtained by picking the severe values of eccentric and central placement of load. It is observed that for G1 the LLM falls consistently in a nonlinear fashion for all class of loading, while the LLM of G2 remains nearly constant for 70 R Tracked and Wheeled loading. For G3 there is a marginal increment in LLLM with skew angle. At 40^0 skew the LLM in G1 due to 70 R tracked vehicle decreases from 822 kN-mto 702.2 kN-m which is 14.5 % while for 70 R wheeled it decreases from 736kN-m to 608 kN-m which is 17.5 %. For Class A loading the reduction was 10% at 40^0 skew.

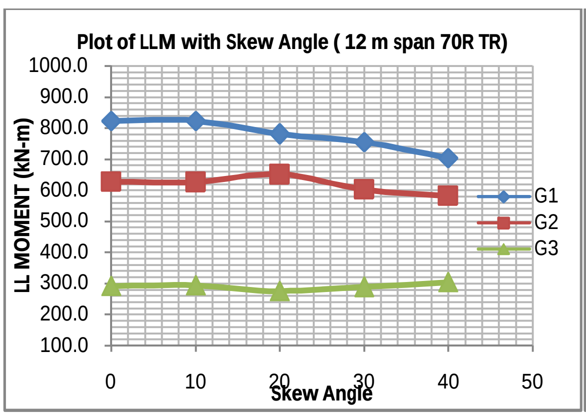


Fig.5 Variation of LLM with Skew Angle (12m span 70 R TR)

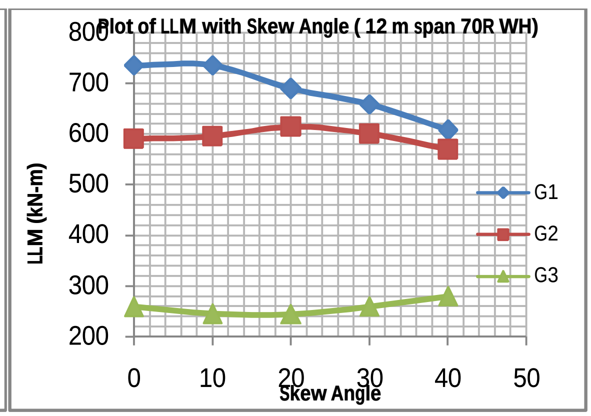


Fig. 6 Variation of LLM with Skew Angle (12 m span 70 R WH)

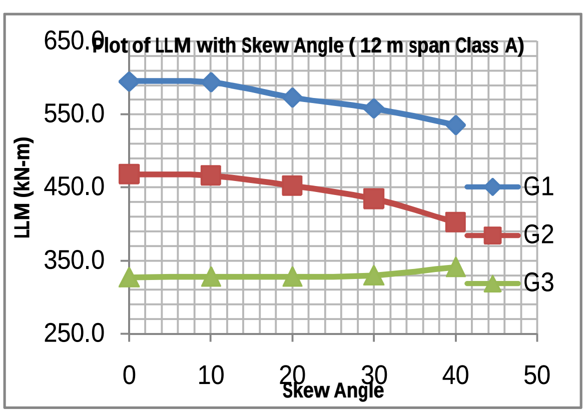
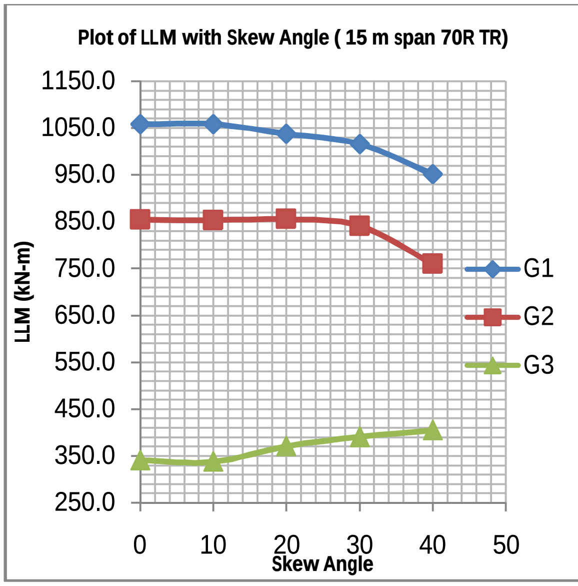


Fig. 7 Variation of LLM with Skew Angle (12m span Class A)

B. Effect of Skew on Design LLM for 15 m span

The placement of live load is similar to 12 m span. The LLM in G1 falls consistently in a non-linearly manner with skew while for G2 it is almost constant up to 30^0 skew and at 40^0 skew a decrease is observed for 70 R Tracked and 70 R wheeled. The LLM in G2 falls in similar manner to G1 for Class A loading. The reduction in LLM for G1 at 40^0 skew is 10.1% for 70 R Tracked, 12.36 % for 70 R Wheeled and 7.69 % for Class A vehicle. There is an increase in LLM of G3 with skew. (Fig. 8, fig. 9 and fig. 10)



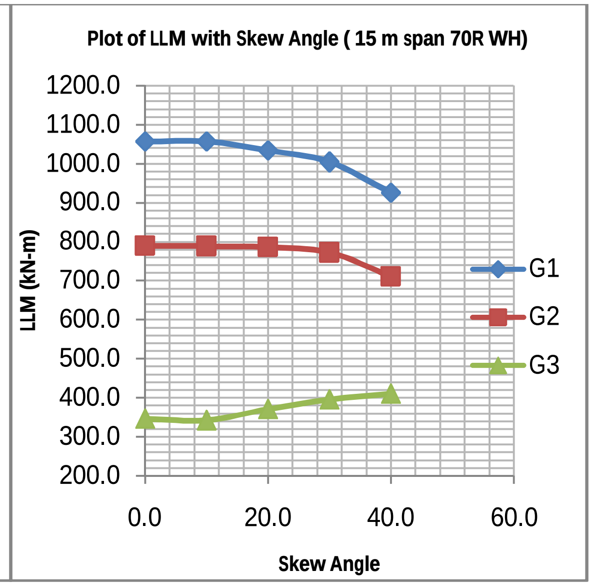


Fig.8 Variation of LLM with Skew Angle (15m span 70 R TR) Fig. 9 Variation of LLM with Skew Angle (15m span 70R WH)

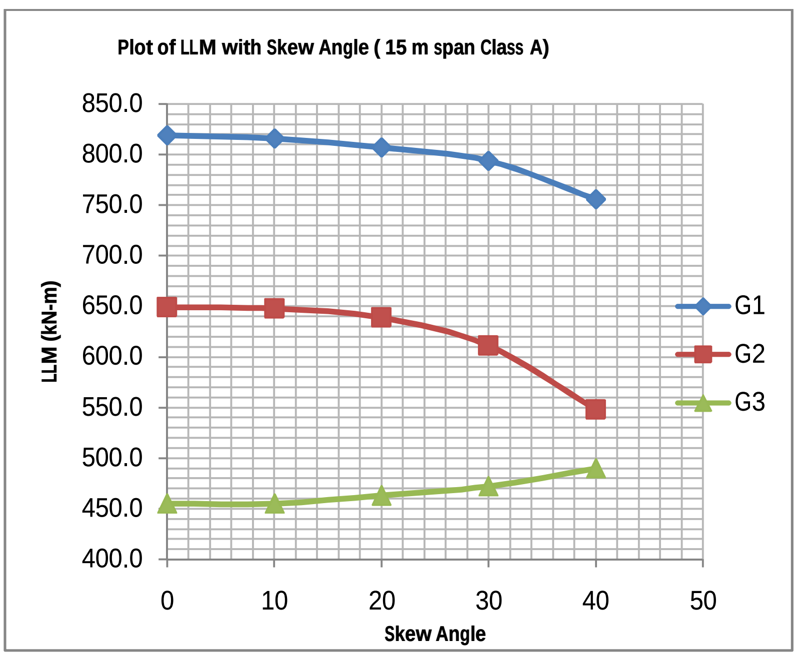


Fig. 10 Variation of LLM with Skew Angle (15m span Class A)

C. Effect of Skew on Design LLM for 18 m span

Similar trends have also been observed as in 15 m span. The LLM of G1 for all class loadings decreases with increasing skew with a maximum fall of 10.5 % for class 70 R Wheeled vehicle. For G2, the LLM almost remains constant for 70 R Tracked and 70 R Wheeled loading. For class A loading the LLM for G2 starts falling steeply after 20^0.(Fig. 11, fig. 12 and fig. 13)

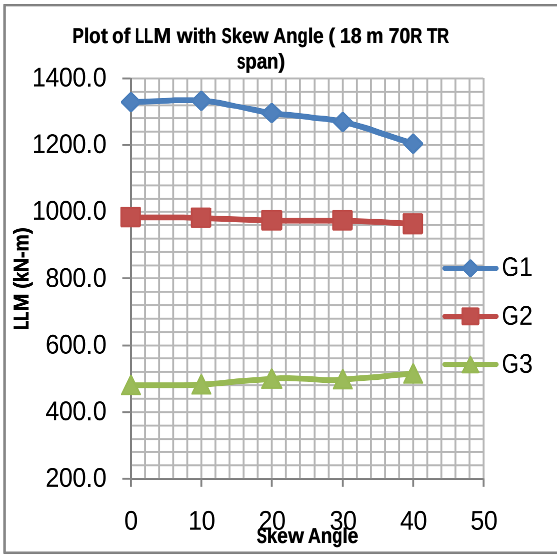


Fig. 11 Variation of LLM with Skew Angle (18 m span 70 R TR)

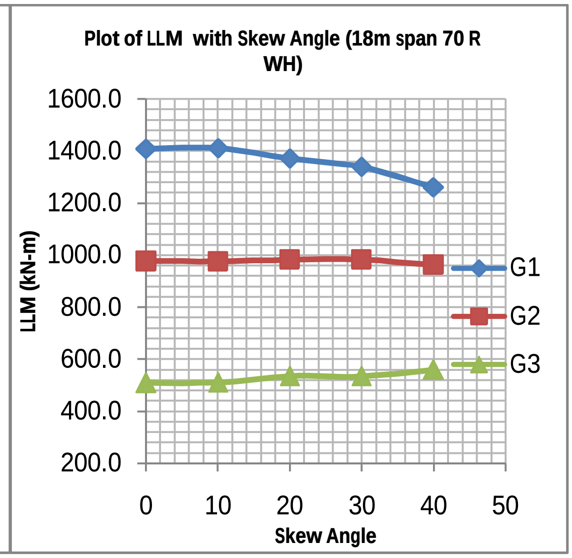


Fig.12 Variation of LLM with Skew Angle (18 m span 70 R WH)

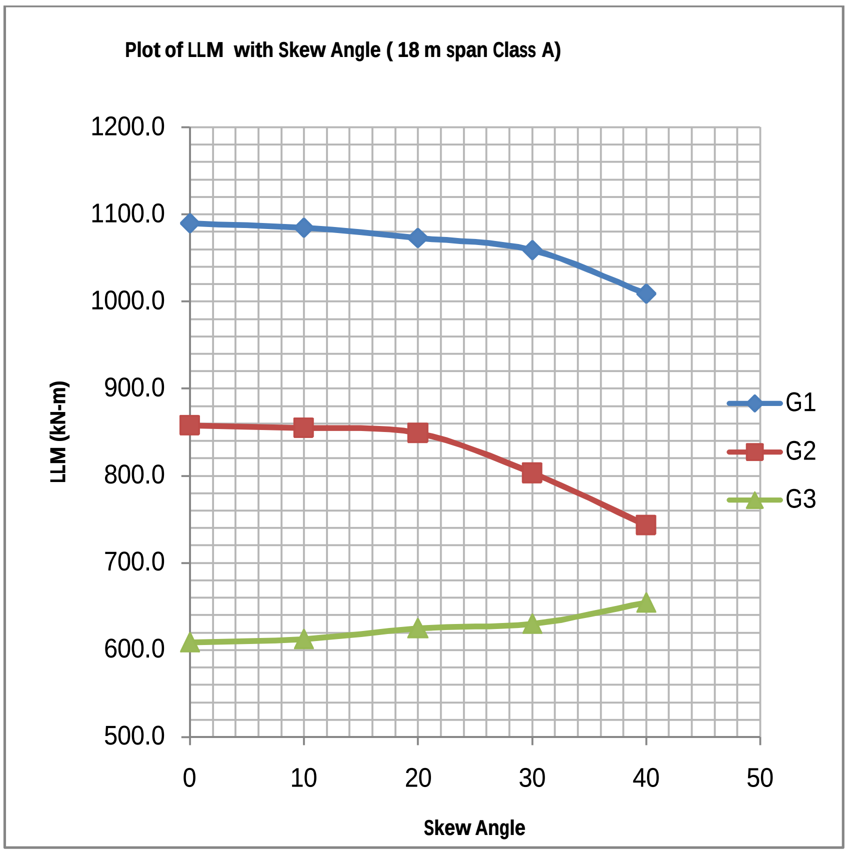


Fig. 13 Variation of LLM with Skew Angle (18m span Class A)

D. Effect of Skew on Design LLM for 21 m span

The effect of skew on LLM is less as compared to 12 m span. The fall in LLM for G1 is small and its maximum value is 9.9% for 70 R wheeled loading at a skew of 40^0. For G2 the LLM almost remains constant for 70 R tracked and 70 R wheeled vehicle. For class A it shows a fall after 30^0. The reduction in LLM is higher at higher skew.(Fig. 14, fig. 15 and fig. 16)

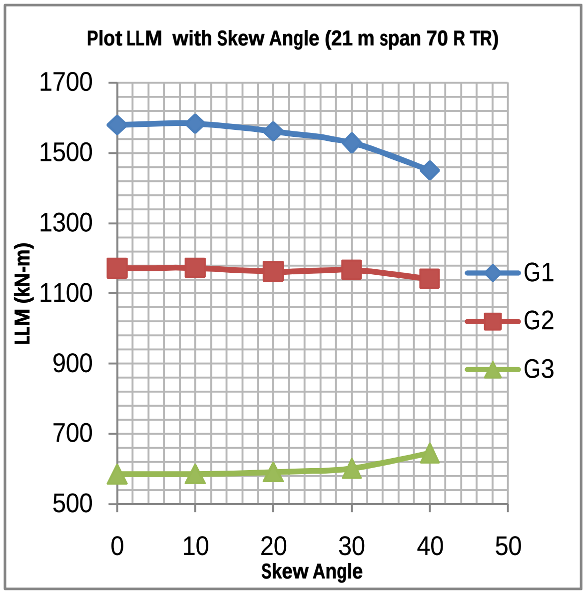


Fig. 14 Variation of LLM with Skew Angle (21 m span 70 R TR)

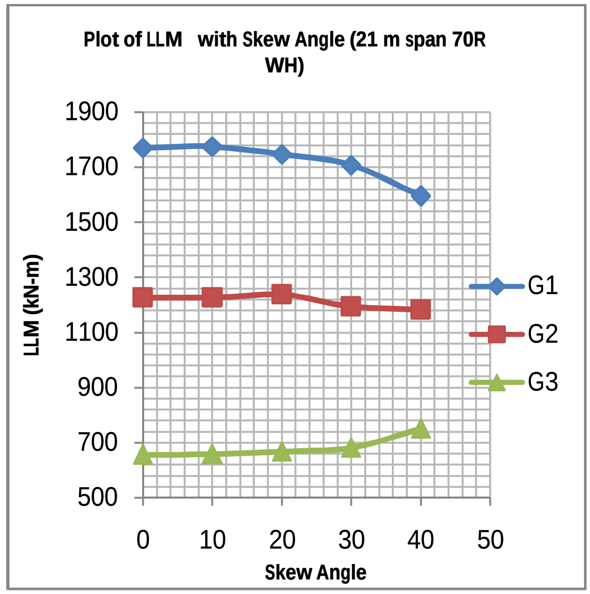


Fig.15 Variation of LLM with Skew Angle (21m span 70 R WH)

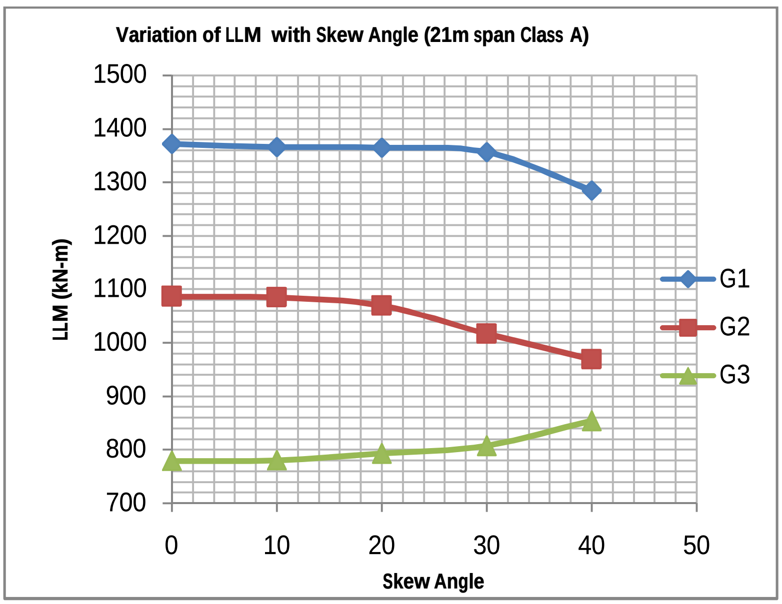


Fig. 16 Variation of LLM with Skew Angle (21m span Class A)

VIII. VARIATION OF PERCENTAGE REDUCTION IN LLM WITH SPAN

As the span increases the percentage reduction in LLM (between 0^0 skew and 40^0 skew) for G1 also reduces. Table 2 gives the values of percentage reduction in LLM in G1 for different class loadings with span.

Table2. Percentage Reduction in LLM (in G1) b/w 0^0& 40^0 skew

Span	Class A	70 R TR	70 R WH
12 m	10.08	14.57	17.39
15 m	7.69	10.1	12.36
18 m	7.43	9.4	10.49
21 m	6.34	8.16	9.93

IX. DESIGN PROCEDURE TO ESTIMATE MAXIMUM LLM IN GIRDERS IN SKEW BRIDGES

In the design of any skew bridge, analysis is done for dead load and live load. Skew angle has little effect on dead load analysis and hence it can be carried out in the routine way as for right bridge. For live load analysis the study conducted above can be used to directly estimate the design LLM i.e. in bridges of same configuration and cross section, span in between 12 m to 21 m and skew angle between 0^0 and 40^0. Design of outer girders, G1 and G3 remains same as load can occupy any transverse position on bridge. Design of girder G2 is different from G1 as it is subjected to fewer forces, as observed from above charts. To estimate the LLM, linear double interpolation should be done with respect to span and skew angle.

To substantiate the validity of the results, three bridges were taken whose span and skew angle were different from those considered in the parametric study. They were analyzed in STAAD PRO using grillage analogy method and the results were compared with those obtained from charts proposed in the study (Kamlesh, 2011)[10]. A linear interpolation has been done within the two nearest values given in the charts. Comparison of results is given below. The results are in good agreement and the maximum error is 2.47 % for 19 m span and 35^0 skew and that also in the safer side. This shows that the study is highly useful in quick estimation of design LLM without struggling with the complicated and rigorous computer modeling of skew bridges, thus saving lot of time and computational efforts.

Table 3: Comparison of Analytical and Interpolated Values of Design LLM

Case 1	Span = 20, Skew angle = 20										
	70 R Tracked				Class A				70 R Wheeled		
Parameter	Staad Analysis	Charts	% Error		Staad Analysis	Charts	% Error		Staad Analysis	Charts	% Error
Moment (kN-m)	1471	1462.6	-0.57		1265	1271	0.47		1621	1613.6	-0.46
Case 2	Span = 19, Skew angle = 35										
	70 R Tracked				Class A				70 R Wheeled		
Parameter	Staad Analysis	Charts	% Error		Staad Analysis	Charts	% Error		Staad Analysis	Charts	% Error
Moment (kN-m)	1345.8	1321	-1.84		1143.4	1136	-0.65		1449	1413.2	-2.47
Case 3	Span = 13.5, Skew angle = 25										
	70 R Tracked				Class A				70 R Wheeled		
Parameter	Staad Analysis	Charts	% Error		Staad Analysis	Charts	% Error		Staad Analysis	Charts	% Error
Moment (kN-m)	896.8	905.4	0.96		678.8	688.6	1.44		845.8	849.9	0.48

X. CONCLUSIONS

A. Following Conclusions can be Drawn from above Parametric Study

1) With the increase in skew angle, the maximum LLM in the outer girder G1 reduces for all class of loadings. The reason is that with the increasing skew angle the rectangular bridge takes the shape of parallelogram and load follows the shorter path along the shorter diagonal. This can also be called as reduction of effective span. Hence simply supported T-Beam skew bridges are found to be conservative with respect to the moments even if the skew angle is ignored.
2) For class 70 R Tracked and Wheeled vehicle maximum LLM in girder G2 nearly remains constant irrespective of skew. For Class A, a fall in maximum LLM is observed.
3) The reduction in maximum LLM is nonlinear in nature. At higher skew angle more reduction is observed.

4) With the increase in span there is a fall in the "percentage reduction in maximum LLM" of the bridge, yet no co-relation could be established.

XI. ACKNOWLEDGEMENT

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