

Stress Assessment of Skew Composite Steel I-Girder Bridge

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Abstract - Due to the lack of space required for more traditional right bridges, skewed geometries in urban areas are more efficient to design bridges. Shifting of load from concrete slab to steel girder in a skew steel concrete composite bridge is a multifaceted three dimensional phenomenon. Grillage analysis, finite element analysis method & load distribution method are the popular method of analysis for this type of bridge. Still Finite element analysis is considered to be a precise method, it takes high effort in data preparation, modeling and analysis of structure, and interpretation of results. For skew bridges, AASHTO given a method which too traditional, as it does not consider the fall in girder moments due to skew bridge. On the contrary, AASHTO LRFD equation gives precise results, but it is considered to be bulky in practice. Using different method of analysis, several researchers have investigated the load distribution in skew bridges and presented empirical formulae for moment distribution factors for bridges subjected to AASHTO truck loading. But only a small number of studies have been done on skew composite bridges subjected to IRC load and dead load. Several points in the girder are checked to assure the girder is not over-stressed at any point.

The main aim of this work is to conduct a parametric study to study the key parameters that may control the load stress characteristics of a skew steel-concrete composite bridge. Grillage Analogy based on stiffness matrix approach using "STAAD Pro" has been used for these stress analysis. A wide parametric study is done, in which various skew steel-concrete composite bridge models are analyzed to evaluate their load stress for Bending moment and shear under dead load and IRC live load conditions. The key parameters considered in the study are the span length (20m, 25m, 30m and 35m), skew angle (0 - 50 deg) taken at the interval of 10degree and number of main girders (4 and 5). Bridges with skew angle greater than 450 are rare. Based on the parametric study, bending stresses & shear stresses are determined for skew composite bridges subjected to IRC loading as well as dead load.

Key Words: Skewed bridges, bending stress, shear stress

1. INTRODUCTION

To align the bridge at right angle to the abutment even by provided that long approach roads was a common tendency in the earlier period. Travel distance and many other traffic difficulties had occurred. For grab the necessities of the high speed and severe safety measures of present day heavy highway traffic as well as to reduce the preliminary huge investment in the long curved approach roads, it has to decrease the number of horizontal curves in the highway alignments. There is the requirement of the building of skew bridges at the locations where crossings are at some inclination and not at right angle to river center line.

A skew bridge is the one whose longitudinal axis is not at right angle to the abutment, but makes an angle less than 90 degree. The design of skewed bridges is fetching more customary in the bridge engineering. Skewed bridges are particularly

common in developed areas where alignment issues may manage the design of the bridge rather than economy. Skewed bridges are also quite general in mountainous regions where topographical features might require that the bridge superstructure cannot be at right angles to the abutments and piers. Skewness can also be due to factors such as natural or manmade obstacles, complex intersections, space limitations, or mountainous terrain.

The behavior of a skew bridge is quite dissimilar from that of a straight bridge. In non-skewed bridges, the load path goes in a straight line towards the support in the direction of the span. In skewed bridges, this is not the case. For a solid slab-skew bridge, the load tends to get a short cut to the obtuse corners of the bridge. In addition to introducing problems in the design of details of the deck, skew has significant effects on the deck's behavior and critical design stresses.

1.1 Behavior of Skew Bridges

The behavior of a skew bridge is quite dissimilar from that of a straight bridge. In non-skewed bridges, the load path goes in a straight line towards the support in the direction of the span. The special characteristics of skewed deck slab are:

- Dissimilarity in the direction of maximum bending moment across width, from near parallel to span at edge, to near orthogonal to abutment in the central region.
- Growth of hogging moments in slab near obtuse corners.
- Significant torsion of the deck.
- High support reactions and shear forces developed close to obtuse corners.
- Low reactions and a chance of uplift reaction forces on the acute corners.

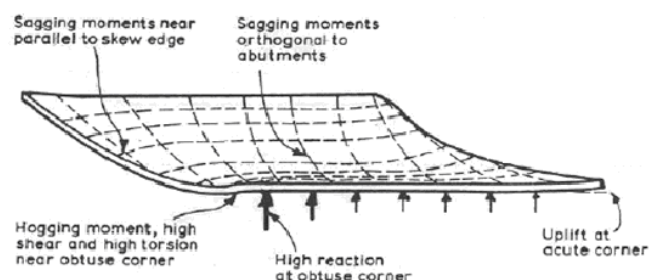


Fig. 1.1 Characteristics of skew decks

1.2 Objectives of Purposed work

1. To carry out a Grillage analogy analysis of skew composite bridges.
2. Development of procedure for the computation of bending as well as shear stresses for different loading

conditions, which can be helpful for the purpose of design.

3. To conduct a parametric study to examine the key parameters that may influence the load stresses of skew composite bridge under IRC loading and dead load.
4. To propose suitable design charts for quick estimation of design forces in longitudinal girders.

1.3 Methods of Analysis

The methods available for the analysis of bridge decks may be classified into two broad groups:-

- i. Simplified Methods: The simplified methods are derived and used for right bridges only. There is no such similar method for the design of skew bridge decks. However, according to the IRC, skew bridges with skew angle less than 20 degrees can be designed as a right bridge of the effective span. In fact, before the initiation of microcomputers, skew bridges were designed using the simplified methods only.
- ii. Rigorous Methods: Basically for right bridges many rigorous methods of bridge analysis have been developed (i.e., for bridges of zero angle of skew). By adapting them to the analysis of bridges with skewness is quite dull and often complicated. Orthotropic plate method, Finite Difference Method, Grillage Analogy Method, Finite Element Method (FEM), Finite strip method Semi continuum method are the Examples of such rigorous methods.

2. LITERATURE REVIEW

Load Distribution Factors (LDF) have been used in bridge design for many decades as a relatively simple method to estimate live load effects on bridge members for the design and evaluation of bridges. The load-distribution factor concept allows the design engineer to consider the longitudinal and transverse effects of wheel loads as two separate phenomena, thus simplifying the analysis and design of the bridge. The LDF is a function of parameters such as bridge geometry, relative stiffness of components, and nature of the loads.

(AASHTO Standard, 1930): Introduced an “S-over” equation for the load distribution factor (LDF), which was a function of girder spacing only. This code does not consider the effect of skew angle and bridge continuity. Finite element studies, however, have shown it to be unsafe in some cases and too conservative in others.

(Bakht, 1988): Examined that those methods of bridge analysis that are developed basically for right bridges are also sometimes used for analyzing (skew bridges provided that the angle of skew is less than 20°. It is proposed that bridges having $(S \tan \alpha / L)$ less than 0.05 can be analyzed as equivalent right bridges, where S, L and α are the girder spacing, bridge span, and angle of skew, respectively. [3]

(OHBDC, Ontario, 1992): The Ontario Highway Bridge Design Code (OHBDC) (Ontario 1992) accounts for longitudinal and transverse rigidities of bridges in addition to the girder spacing. However, the method is limited to simply support and small-skew-angle bridges. Several researchers have investigated the load Stresses in skew composite bridges,

presenting empirical formulae for moment distribution factors for bridges subjected to AASHTO truck loading.

(Ebeido and Kennedy, 1996): investigated the influence of skew angle, as well as other design parameters, on the moment, shear and reaction distribution factors of continuous, two-span, composite steel-concrete bridges and showed that the interior girders are more susceptible to a change in the skew angle than the exterior girders. They also concluded that bridge aspect ratio has an influence on the moment distribution factor. The effect of aspect ratio increases with increase in the skew angle. [6]

(Khaloo and Mirzabozorg, 2003): using the finite-element analysis method (FEA), analyzed 3-D, simply supported, skewed bridges with different span lengths, skew angles, girder spacing, and arrangements of internal transverse diaphragms. It was concluded that load distribution factors of AASHTO Standard Specifications are up to 43.1% higher than those found by FEA. The authors suggested that girder live load distribution factors should be re-evaluated for skewed bridges. [17]

(Junyi Meng Hamid Ghasemi Eric M.Lui, 2004): An experimental study of a skew bridge model conducted at the Federal Highway Administration Turner-Fairbank Highway Research Center. Details of the design, construction, instrumentation, testing and data processing of the model bridge are described. Results for static displacements, natural frequencies, mode shapes and damping of the model bridge will be presented. [16]

(Peter Kocsis, P.E., M.ASCE, 2004): This paper evaluates the American Association of State Highway and Transportation Officials (AASHTO) line load and live load distribution factors. The standard AASHTO formulas for live load in some cases underestimate the live load moments by as much as 40%. This paper shows how more reliable distribution factors can be obtained for line loads, AASHTO truck loads, and non-AASHTO live loads. A user-friendly computer program for calculating distribution factors is discussed.

(Conner, S., Huo, X. S., 2006): Study about significant discrepancies in girder distribution factors have been observed between actual bridge field-testing results and AASHTO code predictions. To study the effects of parapets and aspect ratios, 34 two-span continuous bridges with a 0° or a 45° skew angle and with varied structure parameters are analyzed using the finite element method. [10]

(C. Menassa; M. Mabsout; K. Tarhini; and G. Frederick, 2007): The effect of a skew angle on simple-span reinforced concrete bridges is presented in this paper using the finite-element method. The parameters investigated in this analytical study were the span length, slab width, and skew angle. The finite-element analysis (FEA) results for skewed bridges were compared to the reference straight bridges as well as the American Association for State Highway and Transportation Officials (AASHTO) Standard Specifications and LRFD procedures. A total of 96 case study bridges were analyzed and subjected to AASHTO HS-20 design trucks positioned close to one edge on each bridge to produce maximum bending in the slab.

(Trilok Gupta and Anurag Mishra, 2007): A study on the behavior of T-beam skew bridges with respect to support reactions under standard IRC-70R wheeled loading is presented and the study was based on the analytical modeling of T-beam bridges by Grillage Analogy method. Effects of support reactions for different spans have been studied. The analysis provides the useful information about the variation of support reactions with respect to change in skew. The negative reactions were observed with increase in the span and skew angles. It was found that in skew T-beams bridges, the high positive and negative reactions develop close to each other. [24]

(X. Sharon Huo and Qinghe Zhang, 2008): This paper presents a study of the skewness effect on live load reactions at the piers of continuous bridges. Two prestressed concrete I-beam bridges and one steel I-girder bridge were selected for the study. To evaluate the skew effect, the skew angle of the bridges was varied from 0 to 60°. Live load reaction at support and shear at the beam ends of the selected bridges were determined using finite-element analysis. The comparison of the distribution factors of live load reactions and shear revealed that the distribution factor of reaction at piers was higher than that of shear at beam ends near the same support. The increase in the reaction distribution factor was more significant than that in the shear distribution factor in the interior beam line when the skew angle was greater than 30°. [25]

(AASHTO LRFD, 2010): The current AASHTO LRFD Bridge Design Specifications (AASHTO LRFD, 2010) recognize that the LDF is a function of girder spacing, span length, slab thickness, and beam stiffness and so they introduced a new LDF equation, based on elastic finite element analysis (FEA). The LDFs are specified differently for exterior and interior girders, for shear and moment, and for one-lane loaded and two-or-more-lane loaded cases. AASHTO LRFD Specifications, introduce reduction factor for LDF as function of skew angle, respectively. [1]

(Gholamreza Nouri and Zahed Ahmadi, 2012): The design of skewed bridges is becoming more customary in the engineering community. In this paper, the effect of the skew angle on continuous composite girder bridges is presented using three-dimensional finite-element analysis. Seventy-two models of two-span bridges with various span ratios ($N \frac{1}{4}$ 1, 1.55, and 1.82), skew angles (0–60°), and various arrangements of intermediate transverse diaphragms are analyzed. All models were subjected to AASHTO HS20-44 loading. Results for skewed bridges are compared with the reference non skewed bridge, as well as to the AASHTO standard specifications and AASHTO LRFD specifications. The results show that as the skew angle increases, the support moment in interior and exterior girders rapidly decreases. It decreases about 10% when the skew angle is less than 20° and reaches 33% for a 45° skew angle. The shear force increases in the pier support at the exterior girders and decreases at the interior ones with increasing skew angle. [30]

(Manjunath K1, HR Prabhakara, M.M Achar, 2016): The presence of skew in a bridge makes the analysis and design of bridge complex. Design of bridges by considering skew angle is becoming more customary in the engineering community, so

there is a need for more research to study effect of skew angle on the behavior of skewed bridges such as bending moment, shear force, torsion and other parameters. This study mainly focuses on the effect of skew angle on the design of composite super structures in bridges. Six models have been developed and analyzed by using Finite element-based software CSI Bridge 2015 (Advanced Version). Skew angles are taken as 0, 10, 20, 30, 40 and 50 degree, and all models were subjected to IRC class A and IRC class 70R vehicle loading. Results for skewed bridges are compared to the straight or non-skewed bridges. [28]

(Ajay D. Shahu¹, S.V. Joshi², P. D. Pachpor³, 2018): The paper includes different techniques and the related work that has been done for skew angle on skew bridges. Work has been done to understand the effect of skew angle in skew bridges and is primarily focused on IRC Loadings. Paper has shown the intervals of skew angle taken for analysis are 10°, 15°, 20° and 30°. To optimize the result interpretation and variation in values of parameters for different skew angle, the interval of skew angle is kept as 5°. Therefore skew angle increases from 0° to 60° at an interval of 5°. This would help to understand the variation in result for different parameter more precisely. Also, when we plot a graph; say, max Bending Moment value for each skew angle versus skew angle value would reflect smooth variation. Paper provides the detailed study of normal and skewed reinforced cement concrete bridges, various loading criteria on bridges as per Indian Road Congress (IRC) 6 and amendments made recently, different parameters like bending moment, twisting moment, shear force under different skew angles from 0° to 60° at an interval of 5°. [29]

3. METHODOLOGY

Bridges are frequently designed with their decks skew to the supports, tapered or curved in plan. The behavior and rigorous analysis are significantly complicated by the shapes and support conditions but their effects on grillage analysis are of inconvenience rather than theoretical complexity. The mesh of the space frame in plan is identical to the grillage, but various transverse and longitudinal members are placed coincident with the line of the centroids of the down stand or up stand members they represent. For this basis, the space frame is sometimes referred to as down stand Grillage. The longitudinal and transverse members are joined by vertical members, which being short are very stiff in bending.

When a bridge deck is analyzed by the method of Grillage Analogy, there are essentially five steps to be followed for obtaining design responses:

- i. Idealization of physical deck into equivalent grillage
- ii. Evaluation of equivalent elastic inertia of members of grillage
- iii. Application and transfer of loads to various nodes of grillage
- iv. Determine force responses and design envelopes and
- v. Results Interpretation.

In this study of stresses, a bridge is idealized as a single longitudinal girder and analyzed for one train of loading, regardless of the transverse dimensions and properties of the bridge. The forces developed in this system are determined

using basic structural analysis method. Bending Stress is equal to bending Moment (M) divided by elastic section modulus (Z).

$$\sigma = MG / Z$$

Z_t=section modulus for top of the concrete slab

Z_t=section modulus for top of the girder or junction of concrete slab & steel girder

Z_b=section modulus for bottom of the steel girder.

To calculate shear stress, it is equal to shear force (F) divided by cross-section area of web (A)

$$\tau = F/A$$

In the present study, STAAD Pro. Software has been employed to carry out computer aided analysis of more than 48 skew composite steel-concrete bridges to evaluate their load distribution factors for moment and shear under dead load and IRC live load conditions. The key parameters considered in the study are the span length (20m, 25m, 30 and 35m), skew angle (0°, 10°, 20°, 30°, 40° and 50°), number of main girders (4 and 5) and the orientation of cross bracings (orthogonal to skew span).

From the results of various sensitivity studies, on composite bridges, it is found that changing concrete deck slab thickness or bottom flange thickness has an insignificant effect on both moment and shear distribution (Sennah 1999). Therefore, the concrete deck slab thickness is taken as 250mm. It is also seen that the vertical web stiffeners have insignificant effect on the load distribution and so they are not considered in the analysis. In practice, X-type bracings as well as top and bottom chords are made from single or back-to-back channels. The entire parametric study is done with ISMC 125 for cross members and ISMC 100 for top and bottom chords. An important thing to be noted is that the span of the bridge in this study means distance between supports along the girder, not the perpendicular distance between them. For all bridge type considered, the span-to-depth ratio of 16 is maintained.

The basic cross sectional dimensions of all bridges, considered in this study are shown in table. The symbols used in the first column in Table represent designations of the bridge types considered: deg stands for skew angle, g stands for number of main girders, and the number at the middle of the designation represents the span length in meters. For example, 5g-25-30deg denotes a simply supported bridge of two-lane five girders with 30° skew angle and 25m span. The cross sectional symbols used in Table are shown in Fig.3.1. The numbers of lanes is taken as two. Number of longitudinal girders ranged from 4 to 5. The bridge width is 12m for two lanes.

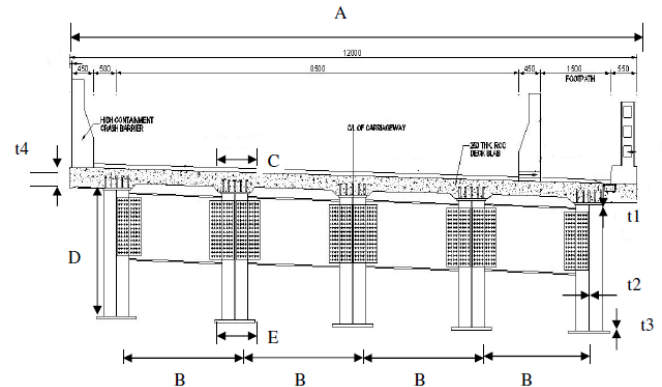


Figure 3.1: The basic cross section configuration of bridge and symbols

3.1 Assumptions

The analysis of a bridge using STAAD Pro. Software is based on the following assumptions:

1. The reinforced concrete slab has complete composite action with the top flange of the steel girder (it is assumed that by using adequate shear connectors, slip is completely prevented).
2. All materials used are elastic and homogeneous.
3. The bridge is simply supported.
4. All loads are in static conditions, and loading is based on IRC loading.

The moduli of elasticity of concrete and steel are taken as 32.5GPa and 200GPa, respectively. The compressive strength of concrete is 40MPa. Poisson's ratio is assumed as 0.2 for concrete and 0.3 for steel. End diaphragms are provided at the supports with minimum thickness and the material for the end diaphragms and the cross bracings are taken to be the same as those for the webs.

Table 1. ANALYSED CASES

S. No.	SPA N(m)	SPACING (m)	SKE W (degr ee)	S. No.	SPA N(m)	SPACIN G(m)	SKE W (degr ee)
1	20	2.5 (or 5 Girders)	0°	25	30	2.5 (or 5 Girders)	0°
2			10°	26			10°
3			20°	27			20°
4			30°	28			30°
5			40°	29			40°
6			50°	30			50°
7		3 (or 4 Girders)	0°	31		3 (or 4 Girders)	0°
8			10°	32			10°
9			20°	33			20°
10			30°	34			30°
11			40°	35			40°
12			50°	36			50°
13	25	2.5 (or 5 Girders)	0°	37	35	2.5 (or 5 Girders)	0°
14			10°	38			10°
15			20°	39			20°
16			30°	40			30°
17			40°	41			40°
18			50°	42			50°
19		3 (or 4 Girders)	0°	43		3 (or 4 Girders)	0°
20			10°	44			10°
21			20°	45			20°
22			30°	46			30°
23			40°	47			40°
24			50°	48			50°

3.2 Loading Conditions

Bridge dead loads and live loads as per IRC specifications are being considered in this study. Four loading cases are considered for each prototype bridge, central and eccentric live load, bridge dead load and SIDL (Superimposed Dead load). It is clear that the trucks are moved in the transverse direction within the lanes in order to yield the maximum moment in both the exterior and the interior girders. The trucks are also moved in the longitudinal direction in order to yield the maximum moments. The third loading case is the dead load of the bridge in which the total weights of the reinforced concrete deck slab, the longitudinal steel girders, and the transverse diaphragms are applied on the bridge as a uniformly distributed load. The fourth loading case is the superimposed dead load in which loads due to crash barrier, railing, wearing coat and footpath are applied according to their location on deck slab.

The positioning of vehicle is an important factor from design point of view. The most critical position, both in longitudinal and transverse direction, on the deck will be one that will result into the maximum value of moment (and shear) in respective direction. The longitudinal placement of loading should be such that it should yield maximum bending moment along span while transverse placement should give maximum moment in that section. In the same way transverse and longitudinal placement of load is so adjusted to get maximum shear in webs. In this study, 70R wheeled vehicle is considered since it produce the maximum moment when compared to other IRC loadings, for span up to 40m. The basic configuration of class 70R and Class A loading is depicted in Figure 3.2 and Figure 3.3

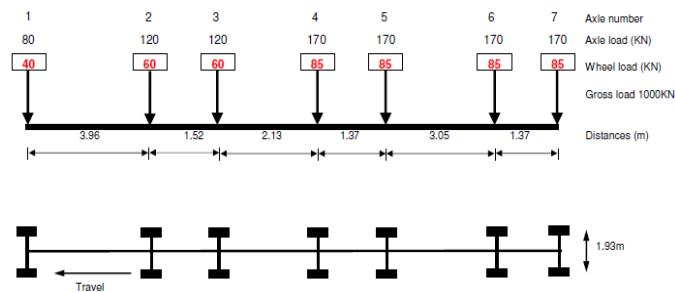


Figure 3.2: The basic configuration of Class 70R train

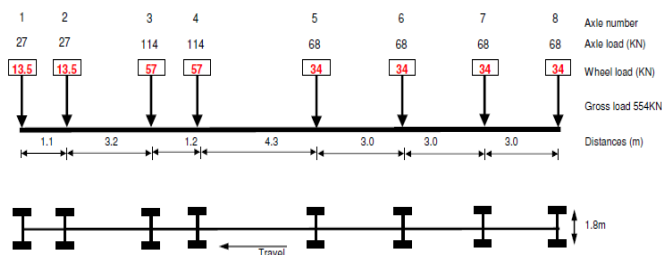
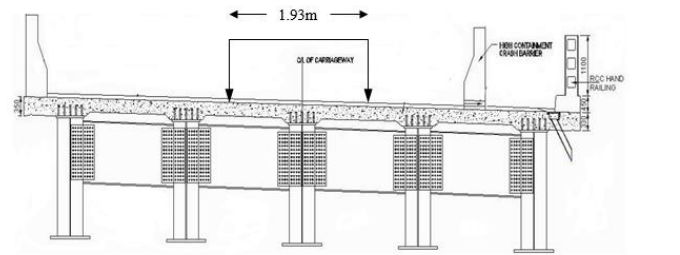


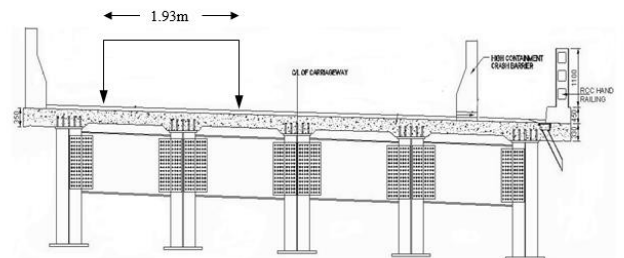
Figure 3.3: The basic configuration of Class A train of vehicles.

The minimum specified clearance between outer edge of the wheel and road way face of the kerb and the minimum clearance between the outer edges of passing or crossing

vehicles on multilane bridge is taken from the codes, in accordance with IRC specification. The transverse placement of load is shown in Figure 3.4 and Figure 3.5.

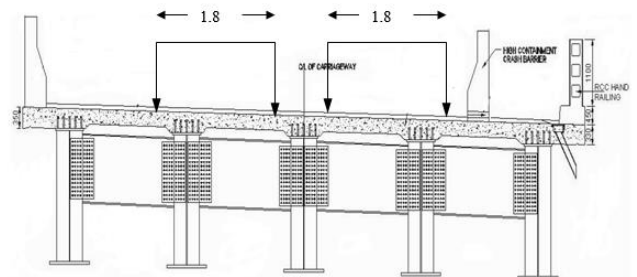


a) Two lane bridge subjected to centrally placed Class 70R train of vehicles

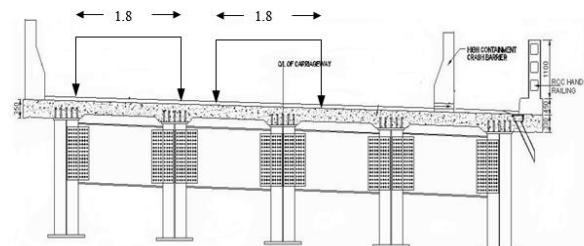


b) Two lane bridge subjected to eccentrically placed Class 70R train of vehicles

Figure 3.4: The transverse placement of IRC Class 70R vehicle



(c) Two lane bridge subjected to centrally placed Class A train of vehicles



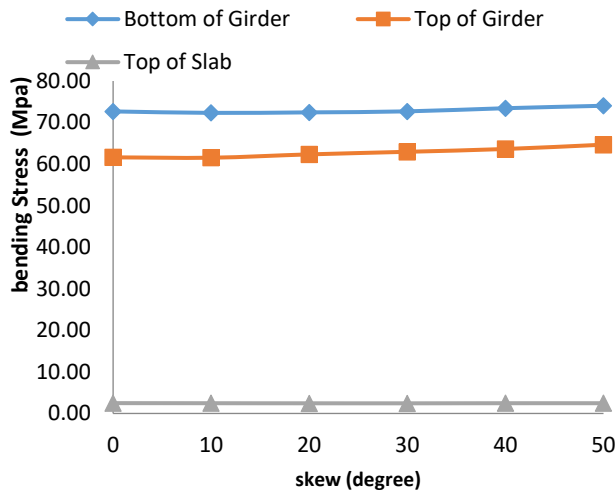
(d) Two lane bridge subjected to eccentrically placed Class A train of vehicles

Figure 3.5: The transverse placement of IRC Class A vehicle

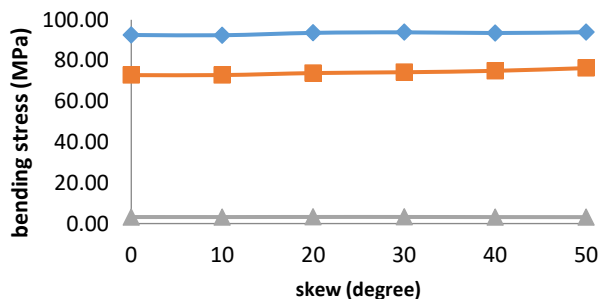
4. RESULTS AND DISCUSSIONS

In order to obtain meaningful results for bridge analysis, i.e. moment or force, an appropriate interpretation of the results is essential. To calculate the stress from the analysis, the moment in the girder section has to be established. The moment at a particular section is the resultant of girder moment in the beam member and deck moment in the cross members. These moment and shear force values are obtained directly from the analysis of bridge using STAAD Pro. Software.

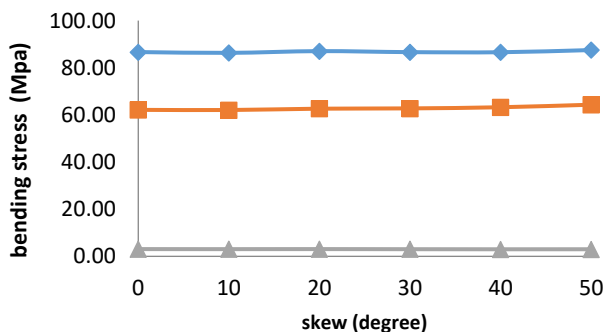
stress in outer girder G1 of 20m span



stress in outer girder of 25m



stress in outer girder of 30m



stress in outer girder of 35m

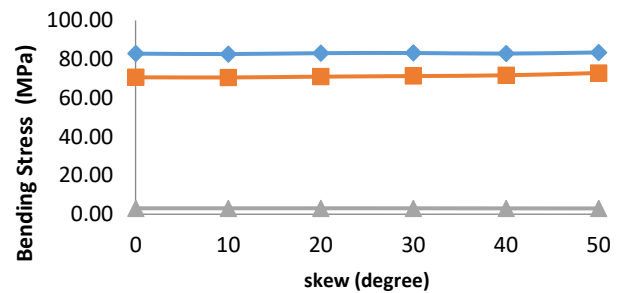
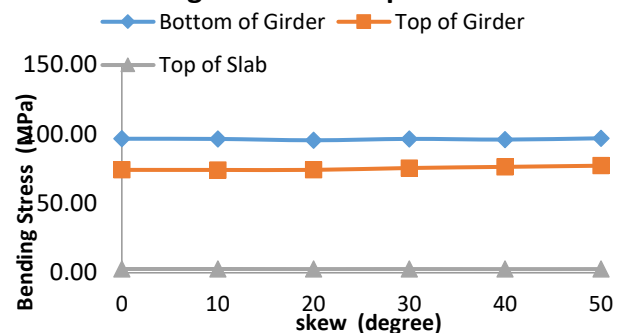
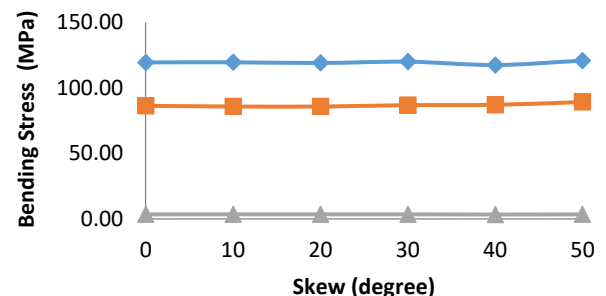


Figure 4.1: Stresses at various Locations of the Outer Girder of 2.5m spacing Bridge for Total Dead load & IRC critical Live load

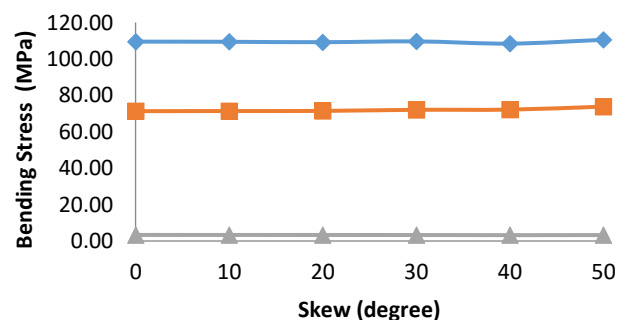
Bending Stress in 3m spacing Outer girder of 20m span



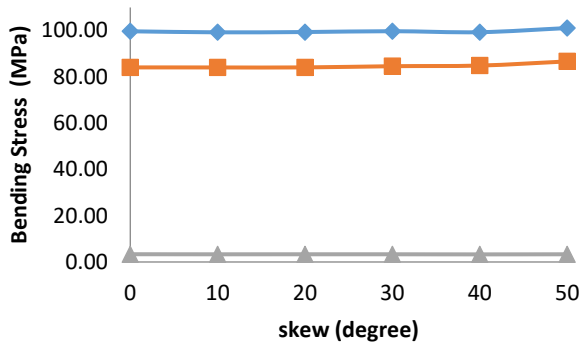
Bending Stress in 25m span



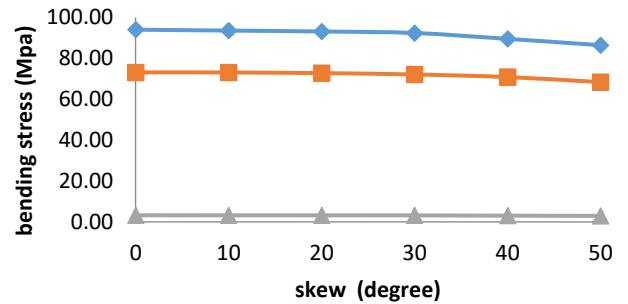
Bending Stress in 30m span



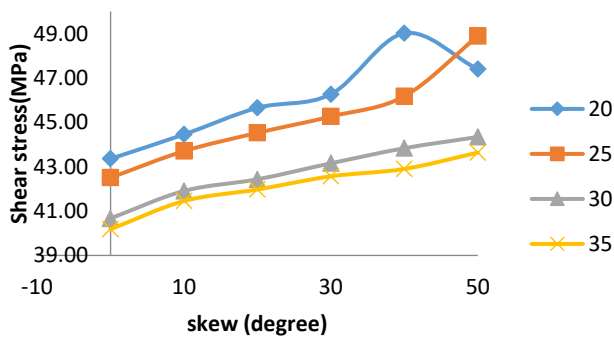
Bending Stress in 35m span



Bending stress in G2 25m span



shear stress for 3m spacing



Bending stress in G2 30m span

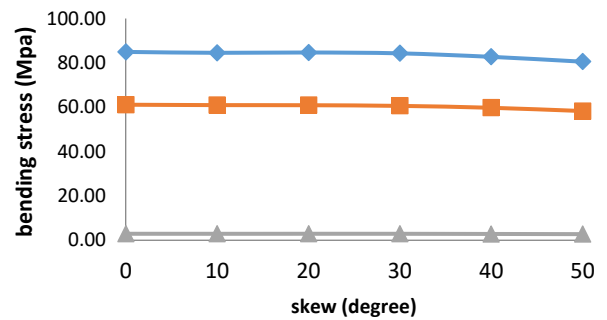
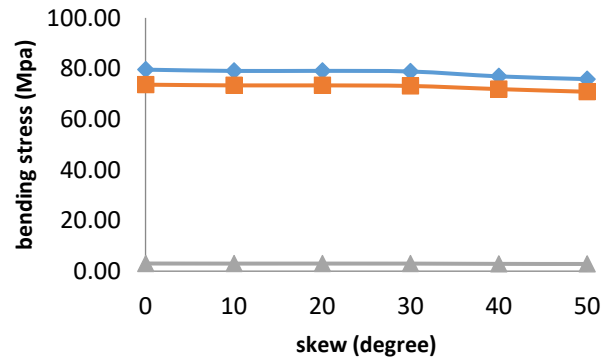


Figure 4.2: Stresses at various Locations of the Outer Girder of 3m spacing Bridge for Total Dead load & IRC critical Live load

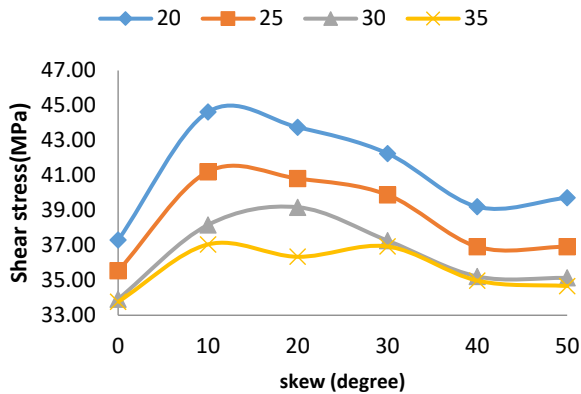
Bending stress in G2 of 20m Span



Bending stress in G2 of 35m span



shear stress in 2.5 spacing G2 girder



σ in 30m span

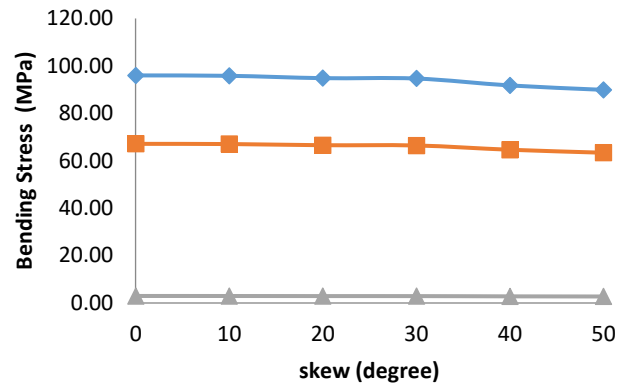
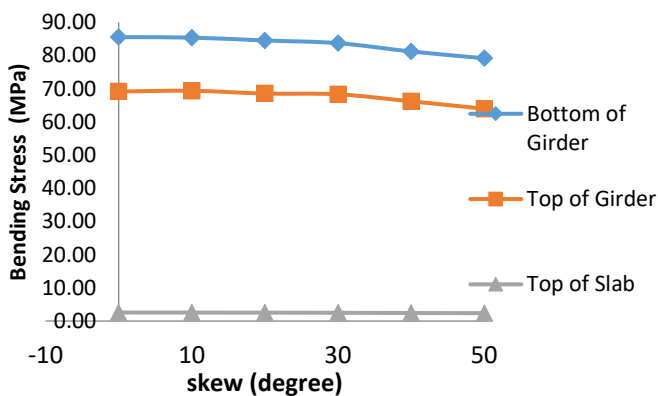
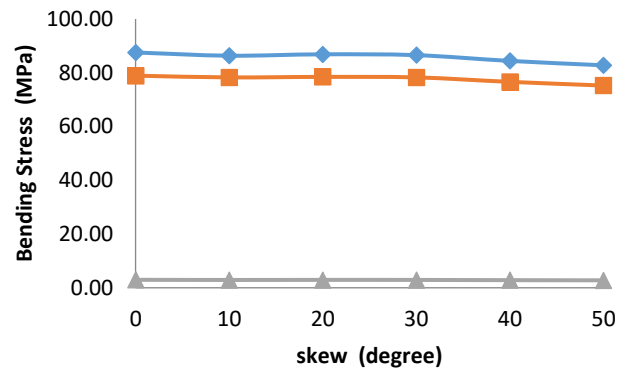


Figure 4.3: Stresses at various Locations of the Inner Girder of 2.5m spacing Bridge for Total Dead load & IRC critical Live load

Bending stress of G2 3m spacing 20m span



σ in 35m span



τ in G2 3m spacing girder

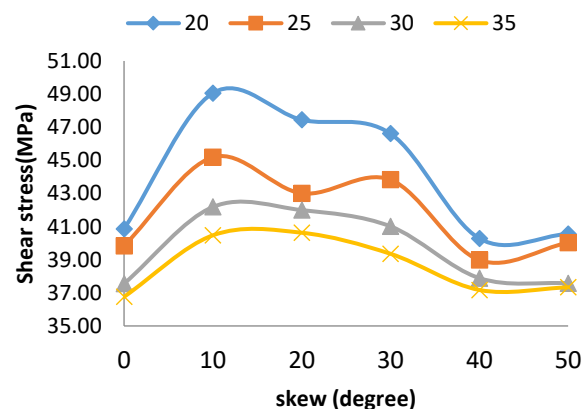


Figure 4.4: Stresses at various Locations of the Inner Girder of 3m spacing Bridge for Total Dead load & IRC critical Live load

From the above it is clear that result of same skew span but varying skew angle are almost same with a maximum difference of 10%. In other words, a structure skew span of 20m and skew angle of 50 degree is interpreted as square span of 13m and same skew angle has almost same result as that of 20m zero degree skew. So it can be concluded that for a skew

structure, the given square span can be transformed into equivalent skew span and analysis may be done considering skew span and square structure with negligible error.

5. CONCLUSIONS

- The results of the study can be used for finding out the Bending stresses and Shear stresses of bridges with intermediate values and the method can be considered as a reliable one also as it is also explained in verification study by taking an example.
- The skew has no significant effect on the load stresses for skew angles between 0 and 20°. However, the load stresses varies significantly with increase in skew from 20° to 50°. (Case no. 1-3,7-9,13-15,19-21,25-27,31-33,37-39,43-45)
- The bending stresses decreases with increases in skewness of the bridge for inner girder while it is reverse for outer girder.
- The Load stress of skew bridges are less than those of right bridges regardless of span length for inner girders. (Case no. 4-6,10-12,16-18,22-24,28-30,34-36,40-42,46-48)
- The bending stresses of skew bridges increases significantly with increase in span for all girders if depth of girder is increasing gradually as per span.
- The sensitivity of load stresses of Inner girders with respect to skew angle is high as compared to Outer girder. (Case no. 13-18)
- The bending stresses generally increases linearly with increase in span length, especially for highly skewed bridges.
- For a skew structure, the given square span can be transformed into equivalent skew span and analysis may be done considering skew span and square structure with negligible error.

6. SCOPE OF FUTURE WORK

- Design expression for Load stresses for moment and shear can be evaluated by extending the present study by increasing the number of bridge prototypes.
- The effect of number of lanes, more number of girders and span length on Load stresses may be included.
- In the present study, the number density and size of cross bracings are kept constant. For future study, this can vary and find out the optimum number and size for a better stresses of loads.
- The results can be verified by the use of other rigorous methods such as finite element method and using other design softwares by modeling whole structure instead of using grillage analogy.

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