# EFFECTS OF SKEW ANGLE ON BENDING MOMENT'S DISTRIBUTION IN THE SKEW BRIDGE DECK

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## ABSTRACT

In this paper the effect of skew angle on reinforced concrete skew bridges deck is presented by using the grillage analogy. The actual decking system of the bridge is represented by an equivalent grillage of beams. A span 24 m of simply supported right bridge deck with I-section prestressed concrete girders is taken as the case study to obtain the values of the bending moment's distribution for the two types of skewness (types 1 and 2) and the results of skew types are compared against the moments of the right deck span of the bridge. In the skew type 1 the deck span is increased as skew angle increased while in type 2 there is no increase in the desk span. The analysis results for the span are obtained dead and live loads (Iraqi standard load and walkway loading) using STAADPRO computer program. The analysis provided useful information about the variation of moments with respect to change in skewness. It is concluded that in skew bridge deck, the bending moment is increased with increasing the skew angle in skew type 1 while it is decreased with increasing the skew angle in skew type 2 and the negative bending moment in transverse direction and the torsion are increased.

## KEY WORDS

**Skew bridge deck, grillage analogy, bending moment, standard Iraqi load**

## الخلاصة

في هذا البحث تم دراسة تاثير زاوية الانحراف (Skew angle) على الجسور الخرسانية باستخدام طريقة المشبكات (grillage analogy) حيث تم نمثيل نظام الارضية الحقيقية للجسر بشبكة مكافئة من الروافد.ارضية الجسر بالاسناد البسيط وذات الفضاء المستقيم الذي يبلغ طوله ٢٤ متر مع الروافد الخرسانية مسبقة الجهد ذات مقطع عرضي بشكل حرف I استخدمت في هذا البحث لتحديد قيم العزوم الداخلية للجسر بعد تدويره بطرقتين مختلفتين من طرق تدوير الجسور الممستخدمة واقعيا ومقارنة النتائج مع العزوم المستحصلة من الحالة المستقيمة للجسر. النوع الاول من التدوير يسبب زيادة في طول فضاء الجسر وهو قليل الاستخدام واقعيا اما النوع الثاني يبقى محافظا على طول فضاء الجسر وهوالاكثر شيوعا في الجسور. نتائج التحلبل فد حددت تحت تاثير الحمل الميت والحمل الحي (الحمل العراقي القياسي يالاضافة الى الحمل الحي على المماشي الجانبية للجسر) باستخدام برنامج الحاسبة STAAD PRO . التحليل اعطى معلومات مفيدة حول تغيير العزوم قياسا بتغيير زاوية الانحراف للجسر. حيث وجد ان عزم الانحناء يزداد بزيادة زاوية الانحراف وذلك للنوع الاول من انواع التدوير للجسور. كما وجد ان عزم الانحناء يقل بزيادة زاوية الانحراف وذلك للنوع الثاني من انواع تدوير الجسور يرافق هذا النقصان في عزم الانحناء زيادة في عزم اللي (torsion) وكذلك زيادة في عزم الانحناء السالب الذي يظهر بالاتجاه العرضي للجسر.

## INTRODUCTION

Nowadays many of bridge decks are built with some form of skew. The bridge skewness is used in order to increase high speeds and more safety requirements of the traffic, modern as connection of highways with bridges are to be continuous as far as possible. The skew angle is the inclination of the centerline of traffic to the normal to the centerline of the river in case of a river bridge or other corresponding obstruction. The increasing demand for high skew bridges has been accompanied by the development of computer aided methods of analyze, and it is now generally possible to analysis and design a structure at any angle of skewness (Hambly, 1976; Gupta and Misra, 2007).

Many methods are used in analysis of skew bridges such as grillage and finite element methods. Generally, grillage analysis is the most common method in bridge analysis. In this method the deck is represented by an equivalent grillage of beams (Kakish, 2007), the finer grillage meshes, provides more accurate results. The method is applicable to bridge decks with simple as well as complex configurations with almost the same ease and confidence.

The main aim of the present study is to investigate the maximum moments of highway bridges by the use of grillage method to idealize the bridge deck systems under effect of standard Iraqi load UDL (Iraqi Standard, 1978). The present paper is carried out for beam and slab deck system, 14 m in width of deck forming a 9m carriageway and two sidewalks 2.5m each is analyzed for 24 m right span for skew angle of 0, 10, 20, 30, 40, 50 and 60 degrees by using two types of skewness as shown in **Fig. 1**. In the skew type 1 (Cussens, 1975; Gupta and Misra, 2007) the deck span is increased with increasing of skew angle, the span of a skew bridge measured along an unsupported edge of the bridge in plan is the skew span and the perpendicular distance between the two lines of supports is considered the right span. In the skew type 2 (Hambly, 1976; Bakht, 1988) there is no increase in the deck span and the rotation is done in the supported edge, this type of skewness is more efficient than skew type 1 because there is no need to increase in girders and deck slab length.

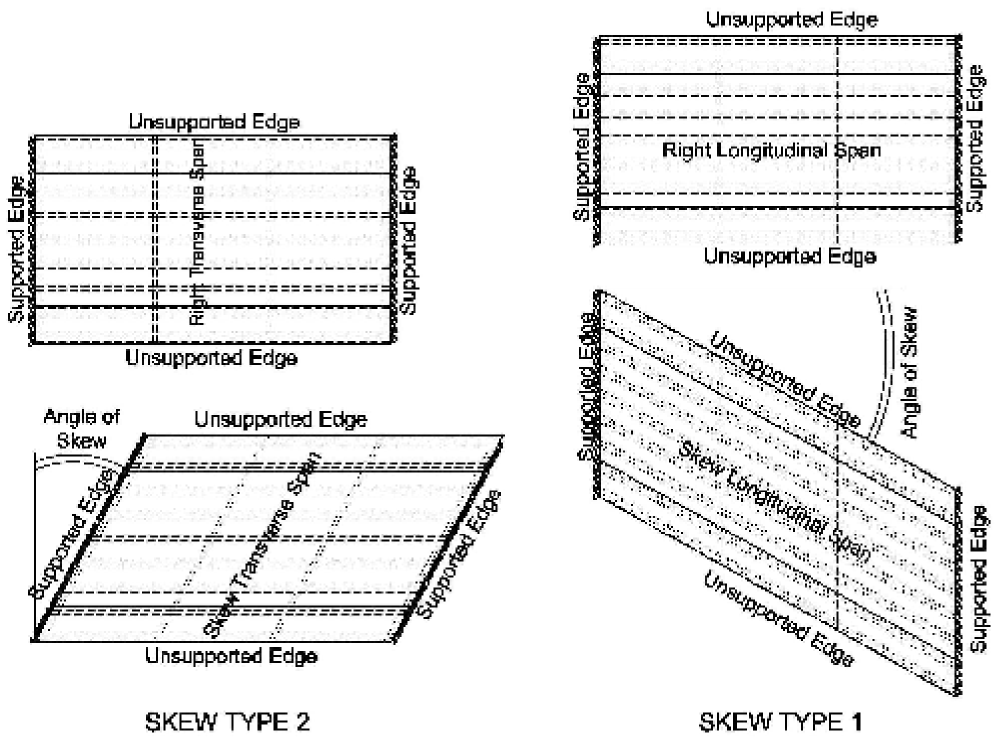


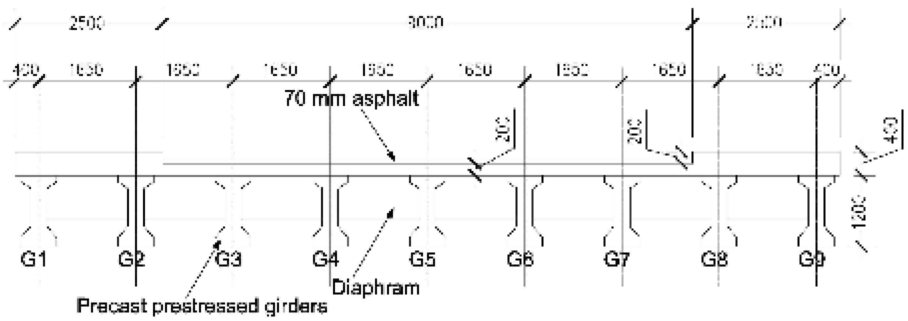

**Fig. 1, Types of skew decks**

## ANALYSIS LAYOUT

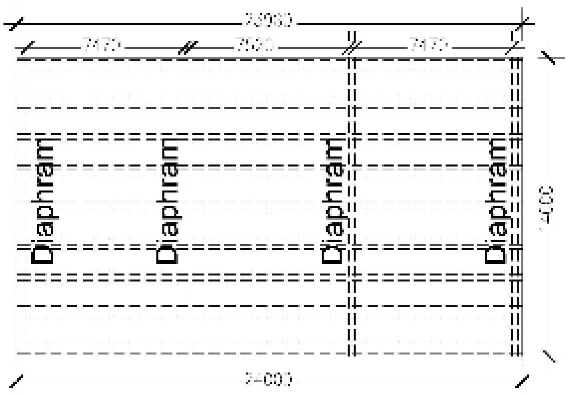
The analysis layout in this paper is relatively inexpensive and has been proved to be reliably accurate for a wide variety of bridges as in below articles.

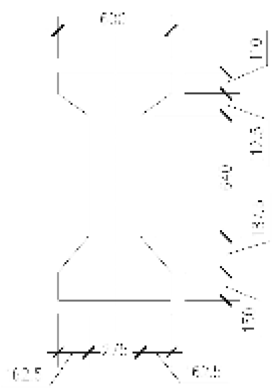
### Information About Selected Bridge

The bridge deck type is a beam and slab deck of simply supported span length (24m) center to center of piers, the total width of deck is (14m), the span of the bridge deck is constructed of the nine precast concrete girders I-cross section with depth (1.2m) which are connected by cast in situ deck slab of thickness (20cm) and four diaphragms as shown in **Fig. 2**. The deck slab is covered by asphalt surfacing layer of (7cm), the slab thickness is increased by additional concrete layer to be (40cm) for (2.5m) width at the two sides of the (9m) carriageway (Al-Sabbagh, 1999).




**a-cross section**



**b-top view bridge deck** **c-girder dimensions details**

**Fig. 2, Selected bridge layouts (Al-Sabbagh, 1999)**

### Idealization of the Bridge by Grillage

The grillage analogy is used in the analysis of the bridge deck (Hambly, 1976). This method is based on representing the actual decking system of the bridge by an equivalent grillage of beams. For the purpose of analysis the distributed bending and torsional stiffness of the decking system are assumed to be concentrated in these beams.

The concrete bridge span is idealized by substituting it by (162) longitudinal grillage members located along the webs centerlines and (152) transverse grillage members as shown in **Fig. 3**. The grillage members were rigidly connected at the intersection joints and the span is supported at its ends on the line of supports as in

**Fig. 3**. A linear elastic analysis was used. The recommendations suggested by (West, 1973) were used to compute the properties of the grillage members. The required section properties are the flexural inertia (I), the torsional inertia (J), the cross section area (A) of each grillage members, the cross section area is used to include the shearing deformation in deflection calculations. The grillage members were classified into nine (T1-T9) types for this span according to the section type. **Table 1** shows the grillage members properties, where I and J are calculated by using the computer program PROKON.

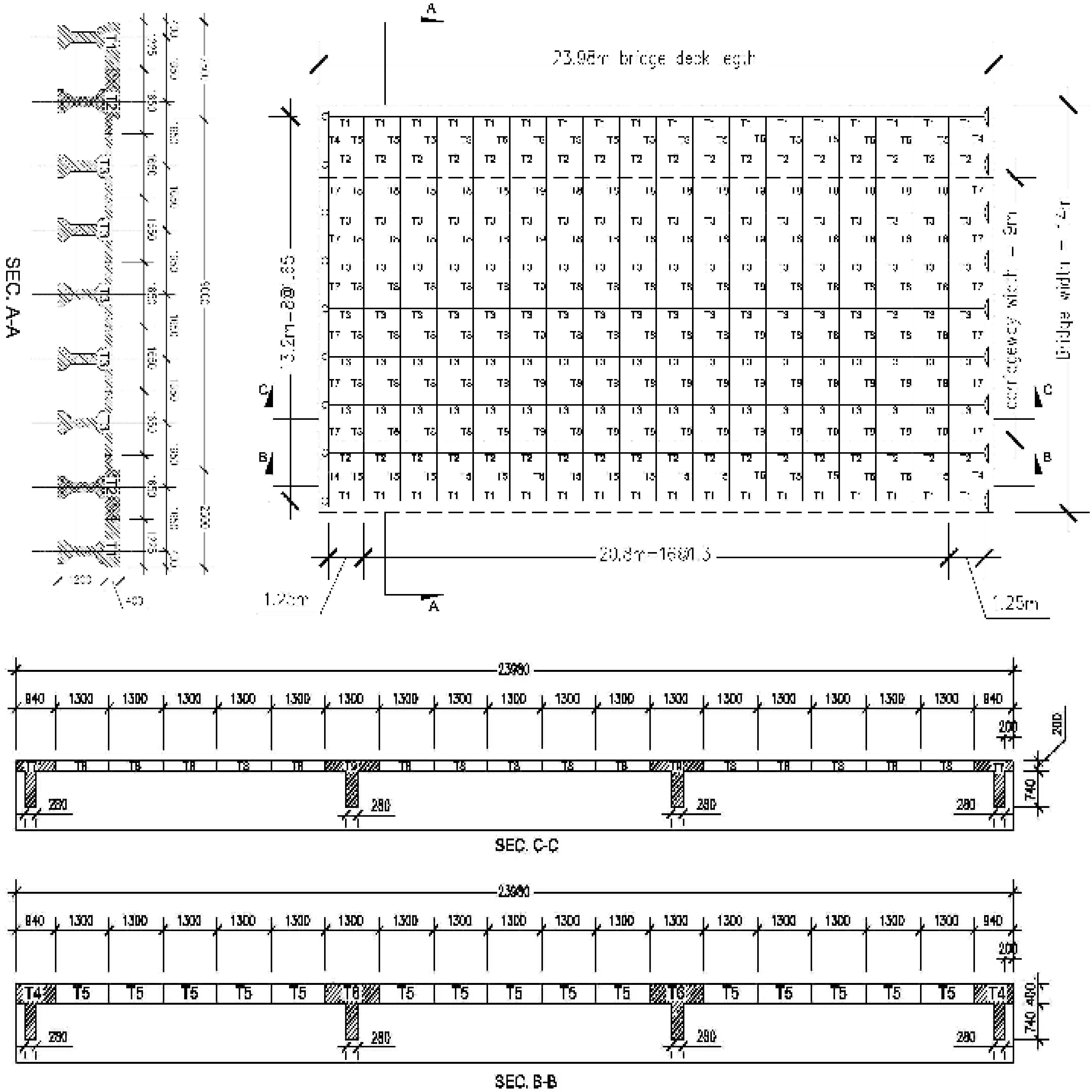



**Fig. 3, Grillage mesh and types of its members**

**Table 1, Grillage member properties**

| Member type | I ($mm^4$) | J ($mm^4$) | A ($mm^2$) |
|---|---|---|---|
| **1** | $226.58 \times 10^9$ | $43.1 \times 10^9$ | 890050 |
| **2** | $234.68 \times 10^9$ | $46.3 \times 10^9$ | 985050 |
| **3** | $165.79 \times 10^9$ | $17.5 \times 10^9$ | 730050 |
| **4** | $57.871 \times 10^9$ | $22.4 \times 10^9$ | 583200 |
| **5** | $6.9333 \times 10^9$ | $22.4 \times 10^9$ | 520000 |
| **6** | $64.527 \times 10^9$ | $8.86 \times 10^9$ | 727200 |
| **7** | $31.855 \times 10^9$ | $7.97 \times 10^9$ | 395200 |
| **8** | $866.67 \times 10^6$ | $3.16 \times 10^9$ | 260000 |
| **9** | $35.793 \times 10^9$ | $8.86 \times 10^9$ | 467200 |

The (T1-T9) types can be divided in longitudinal and transverse members, where the first group represent the main girders composite with deck slab, and the other group represent the deck slab itself in the transverse direction. The spacing of transverse grillage members has been selected, so that, it does not exceed (1.5) times the spacing of longitudinal members.

The analysis is accomplished by the software program "STAAD PRO" for grillage structure. This program is the most popular structural engineering software and the program enables the user to input the difference level of the neutral axes of the grillage members at each start and end joints of a member. **Table 2** gives the offsets of the grillage members (all offsets are in the vertical direction on grillage plane). Grillage member type (3) is assumed to be at level 0.0 in x-z plane. So, the offset values for other member types have been measured according to this level.

**Table 2, Grillage members offset (in mm)**

| Grillage member types | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| **Member offset (mm)** | 127 | 155 | 0.0 | 297.5 | 500 | 337.6 | 153.6 | 400 | 191.6 |

**Application of Loading**

In the analysis all cases are considered for both dead and live loadings which are applied on the deck that was modeled by grillage meshes and the bridge deck responses are determined.

The dead load of the bridge deck can be calculated according to the deck cross section, where the precast girder, deck slab, diaphragms and asphalt are considerable in the dead load calculations with concrete density = 25 $kN/m^3$ and asphalt density = 22 $kN/m^3$, these dead loads were applied for the concrete span and the responses are obtained.

In the live load applications, two types of loadings which are taken into consideration, the first is the Iraqi specifications of highway bridge loading issued by the Development Board in June 1962 and revised in 1972 and 1978 and adopted for global analysis (Iraqi Standard, 1978). The standard loading (S.L) as uniformly distributed lane loading (UDL) per linear meter of notional lane. This load is to be decreased as the loaded length and lane width are increased. In addition to (UDL) a concentrated knife-edge load (KEL) which is uniformly distributed across the width of the notional lane is also considered. The carriageway of the bridge is divided into three notional lanes each of (3.0m). Full S.L is to be applied to two notional lanes and one-third of S.L to other lane. Two cases of standard loading distribution were considered as shown in **Fig. 4**, the values of nominal lane loading for the effective length (23.3m) of the span as follows:-

$$S.L = 10.3\frac{kN}{m^2} \qquad KEL = 39.42\frac{kN}{m}$$

The other type of the live load is the walkway loading that was taken 4 kN/m$^2$, the effect of the critical walkway were added to the effect of the critical standard load by superposition.

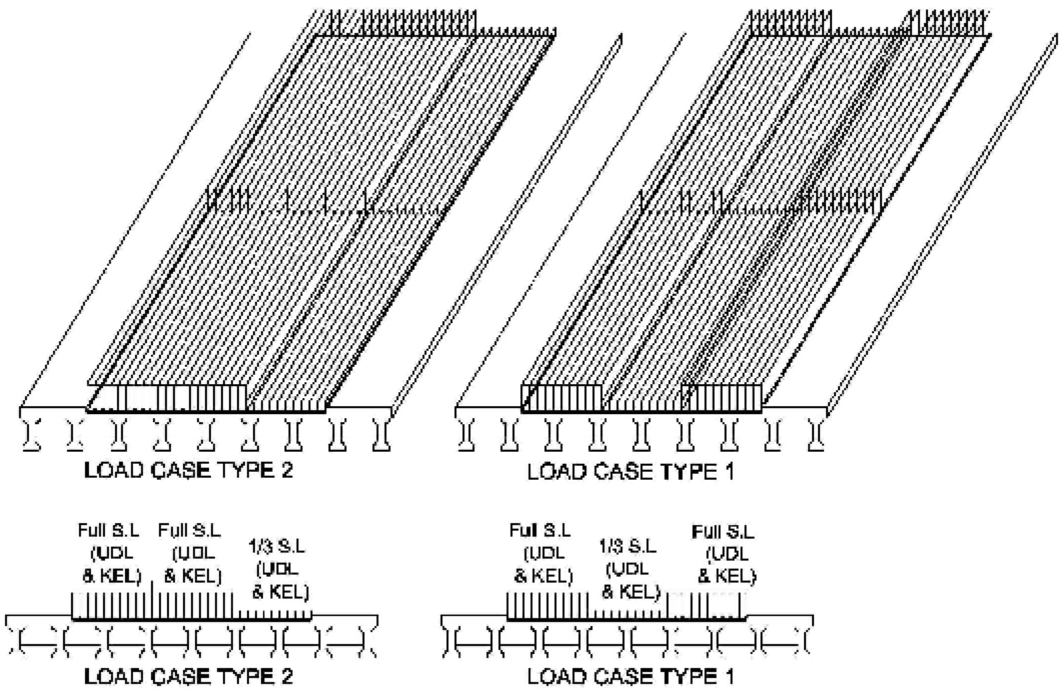



**Fig. 4, Live load cases for Iraqi standard loadings**

## RESULTS AND DISCUSSIONS

To assess quantitatively the effect of analyzing real life skew bridges, several skew angles (0$^o$, 10$^o$, 20$^o$, 30$^o$, 40$^o$, 50$^o$ and 60$^o$) for two types of skewness are analyzed and compared with right bridge to examine the effects on the major principal moments

### Skew Type (1)

In this type of skewness the span is rotated at the required angle and set the abutment at the same arrangement. The analysis is done with the abutment set at the same length (which means the perpendicular distance between girders decreases) for angles (0$^o$ to 60$^o$) with fixing the applied loads and idealization system to find the effect of the skew angle on the maximum moment, then the results from the output of analysis of bridge decks are obtained. The maximum moments have been calculated for this type of skewness under the effect the dead load, the live load and the total load separately. **Fig. 5** shows that the relationship between the maximum moments and the skew angles and also it presents a comparison between the maximum moments obtained from the different types of loadings. The maximum moment under the effect of total loads at $0^o$ skew angle is 2963 kN which increases to 5143 kN at $60^o$ skew angle. The relationships between the ratios of increased maximum moments to the original moment versus the skew angles for different types of loadings are given in **Fig. 6**.

To keep the same traffic width (perpendicular distance to the span) a new mesh is used to idealize the bridge for each skew angle because the horizontal distances between joints are increased which means that the abutment stays in the same arrangement but its length is increased. The relationship between the maximum moments and the skew angles under the total load effect is shown in **Fig. 7**. The maximum moment under effect of the total loads at $0^o$ skew angle is 2963 kN which increases to 10381 kN at $60^o$ skew angle.

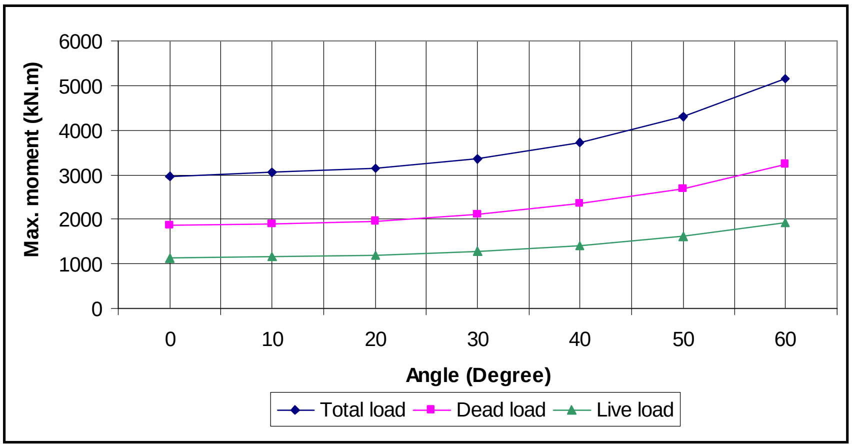



**Fig. 5, Maximum moments for 24 m right span (skew type 1)**

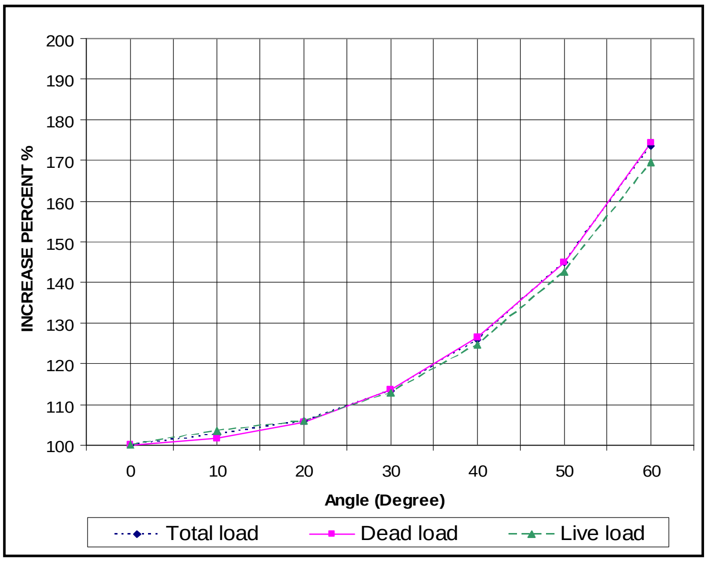



**Fig. 6, Increase percent in the moments for 24 m right span (skew type 1)**

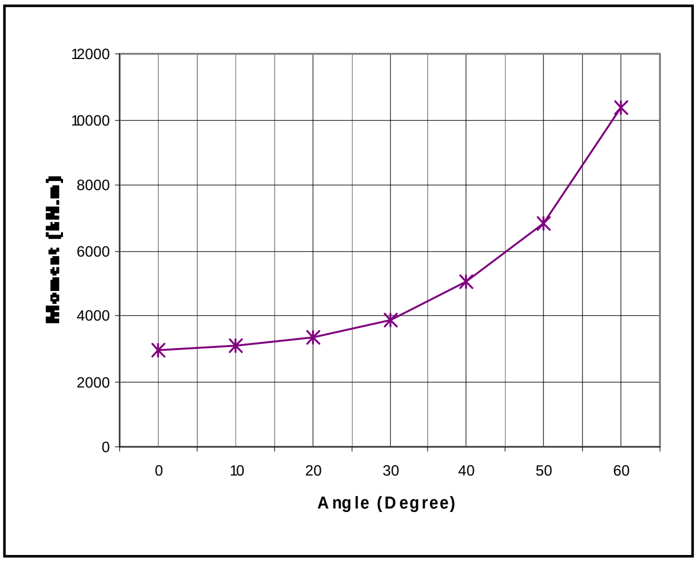



**Fig. 7, Maximum moments for 24 m right span (skew type 1 with mesh modification)**

**Skew Type (2)**

This type of skew has the most publicity and widespread use in the construction of highway bridges. In this type of skewness the abutment is rotated at the required angle with keeping the span between the abutments at the same length.

In the present paper, the analysis is done for angles ($0^o$ to $60^o$) to find the effect of the skew angle on the maximum moment then the results from the output of analysis of bridge decks are obtained.

The maximum moments have been calculated for this type of skewness under the effect of dead load, live load and total load separately. **Fig. 8** shows that the relationship between the maximum moments and the skew angles and also it presents a comparison between the maximum moments obtained under the different types of loadings. The maximum moment under the effect of total loads at $0^o$ skew angle is 2963 kN which decreases to 2551 kN at $60^o$ skew angle, and the maximum moment under the effect of live loads at $0^o$ skew angle is 1128 kN which decreases to 981 kN at $60^o$ skew angle. Also the maximum moment under the effect of dead loads at $0^o$ skew angle is 1855 kN which decreases to 1613 kN at $60^o$ skew angle.

The relationship between the maximum torsions and the skew angles under the total load effect is shown in **Fig. 9**. The maximum torque under the effect of total loads at $0^o$ skew angle is 31 kN which increases to 345 kN at $60^o$ skew angle.

The relationship between the maximum negative moment in transverse direction and the skew angles under the total load effect is shown in **Fig. 10**. The maximum moment in diaphragms under the effect of total loads at $0^o$ skew angle is -74 kN which increases to -317 kN at $60^o$ skew angle.

**Table 3** shows the values of maximum moments and torque in longitudinal direction and maximum moment in transverse direction under the effect of live, dead and total loads.

**Table 3, Maximum values of moments and torque**

| angle | Max. moment in longitudinal dir. | | | Torque | Max. neg. moment in transv. dir. |
|---|---|---|---|---|---|
| | Total load | Live load | Dead load | | |
| **0** | 2963.235 | 1127.985 | 1854.526 | 30.734 | -73.951 |
| **10** | 2960.808 | 1126.481 | 1852.617 | 63.486 | -80.83 |
| **20** | 2946.713 | 1119.303 | 1844.03 | 98.364 | -94.186 |
| **30** | 2917.07 | 1105.358 | 1826.701 | 146.942 | -117.542 |
| **40** | 2860.194 | 1079.445 | 1794.436 | 203.624 | -152.918 |
| **50** | 2753.352 | 1032.787 | 1733.861 | 270.509 | -207.453 |
| **60** | 2551.314 | 980.845 | 1612.683 | 344.843 | -316.46 |

**Fig. 11** shows the bending moment diagrams for the girder G1 that is located approximately in the edge span, under the effect of total loads. The relationship between the distance and the average moment in the joints is appearing clearly in this figure for the different skew angles from $0^o$ to $60^o$. The value of moment diagrams are decreased with the increasing of the skew angles in all joints except the joints at supports at which the moment approaches to zero (simply supported span). **Fig. 12** shows the bending moment diagrams for the girder G5 which is located in the mid-span under the effect of total loads. The relationship between the distance and the average moment in the joints is appearing clearly in this figure for different skew angles from $0^o$ to $60^o$. The values of moment diagrams are decreased with increasing the skew angles.

The bending moment diagrams for the diaphragm that is located at first span under the effect of total loads is shown in **Fig. 13**. The relationship between distance (the length of diaphragm) and the moments (two moments at each internal joint) is appearing in this figure for different skew angles from $0^o$ to $60^o$. The bending moment diagrams for the diaphragm that is located at one-third span under the effect of total loads is shown in **Fig. 14**. The relationship between distance (the length of diaphragm) and the moments (two moments at each internal joint) is appearing in this figure for different skew angles from $0^o$ to $60^o$.

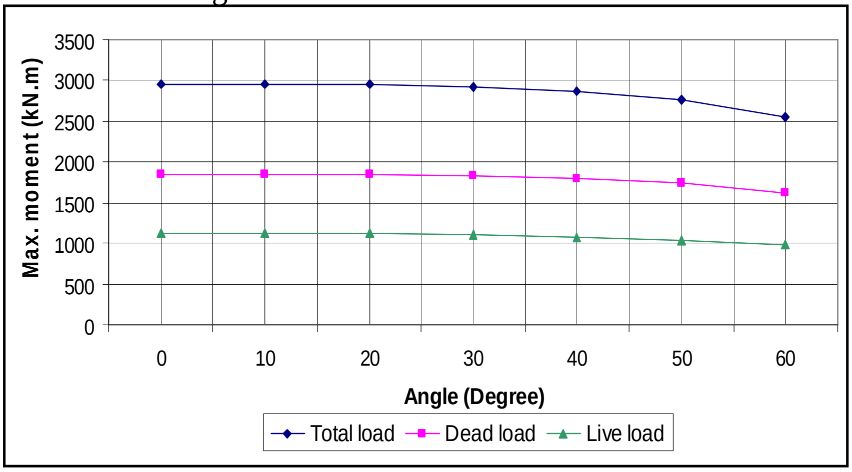



**Fig. 8, Maximum moment for 24 m right span (skew type 2)**

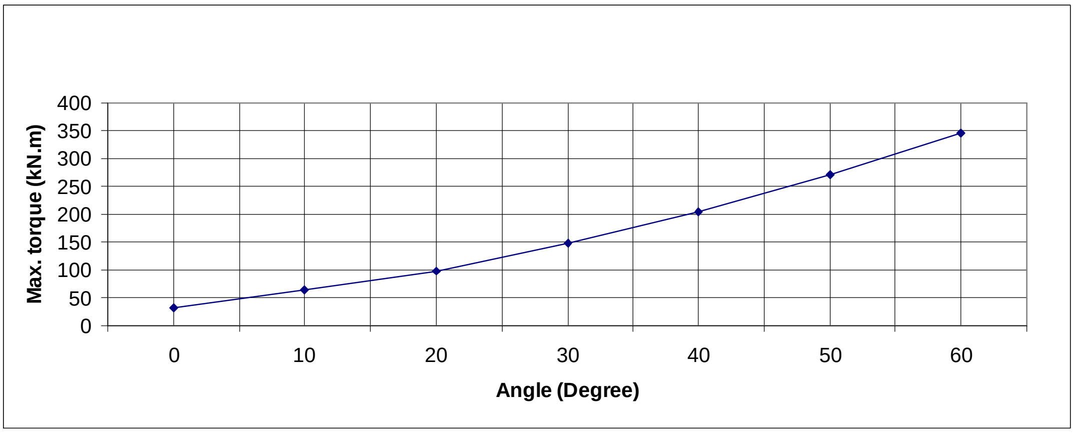



**Fig. 9, Maximum torque for 24 m right span (skew type 2)**

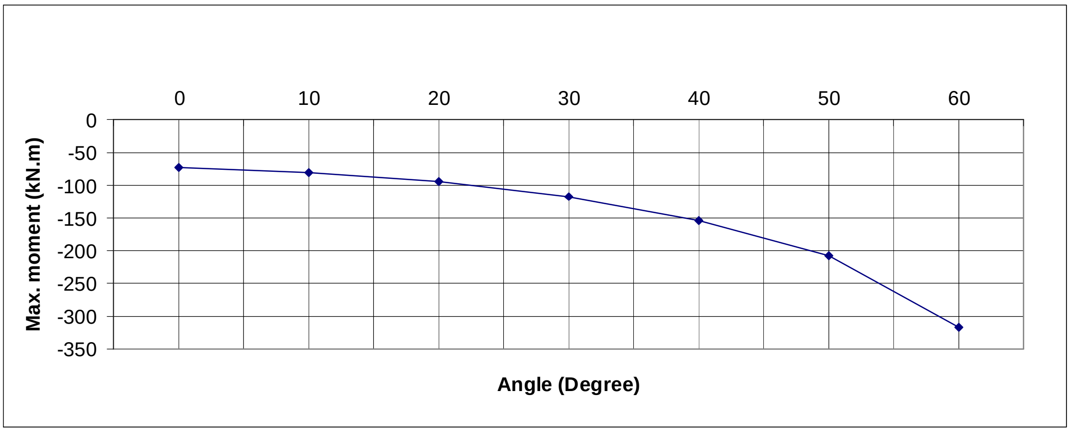


**Fig. 10, Maximum negative moment in transverse members for 24 m right span (skew type 2)**

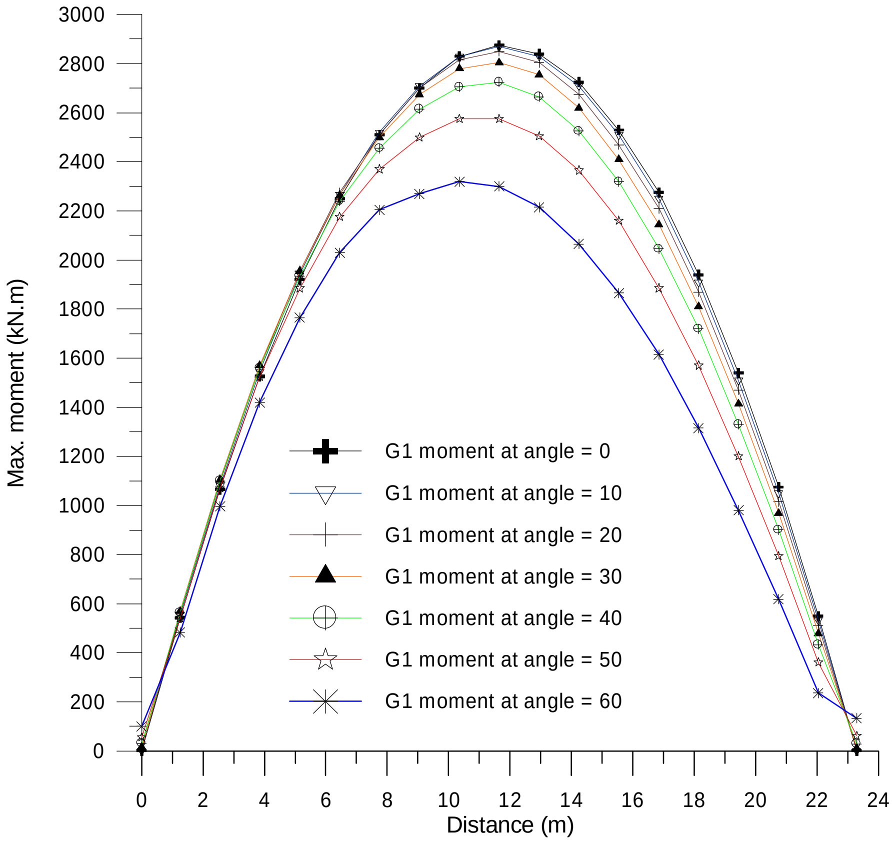



**Fig. 11, Bending moment diagrams in the G1 location at edge span (skew type 2)**

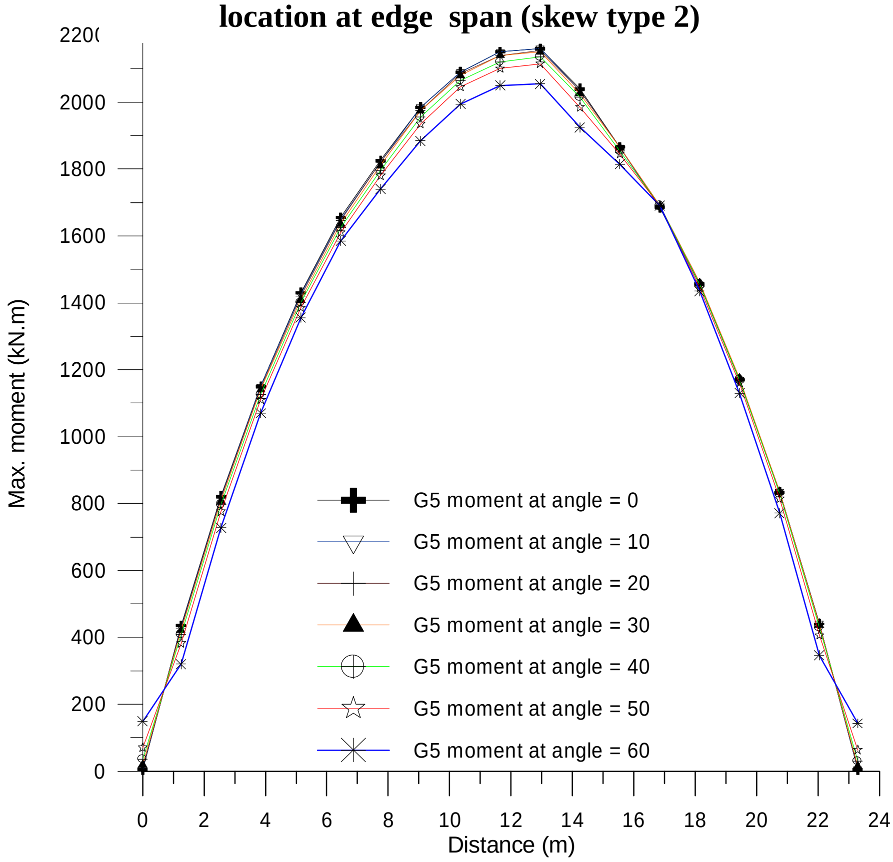



**Fig. 12, Bending moment diagrams in the G5 location at mid span (skew type 2)**

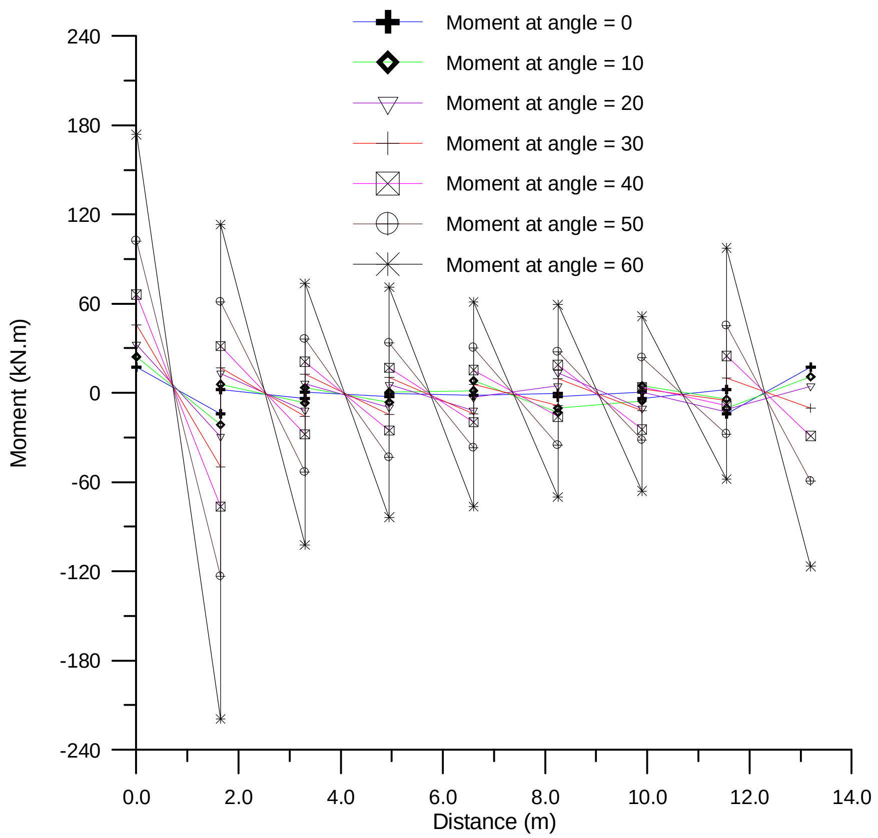



**Fig. 13, Bending moment diagrams in the diaphragm location at first span (skew type 2)**

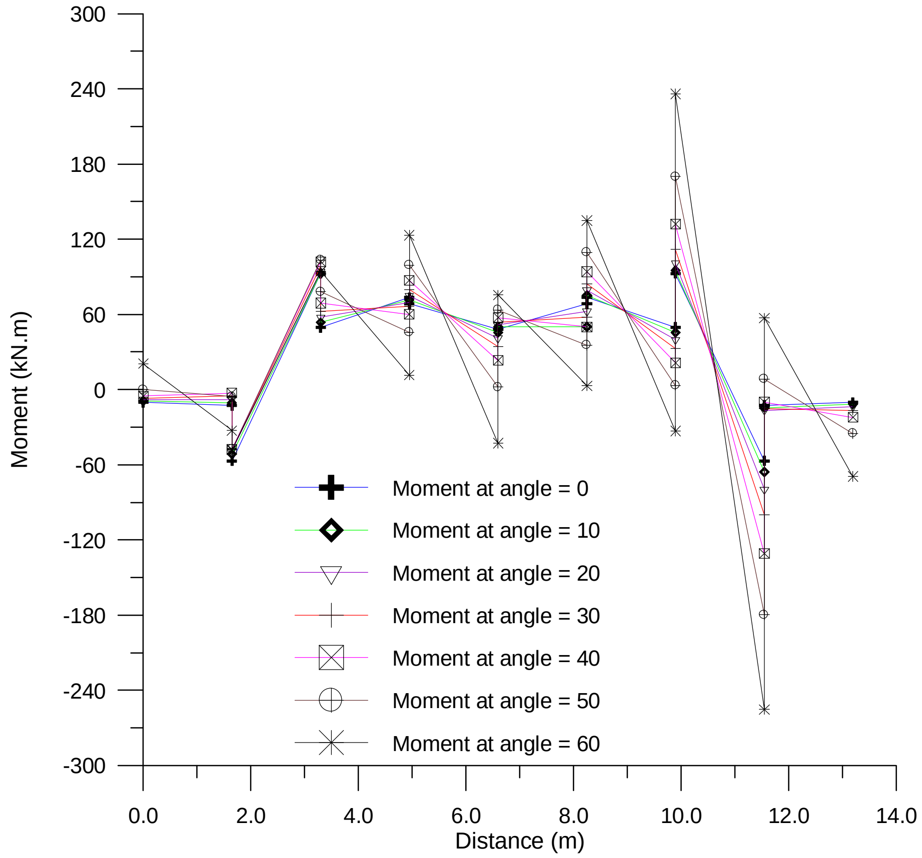



**Fig. 14, Bending moment diagrams in the diaphragm location at one-third span (skew type 2)**

## CONCLUSIONS

The grillage analogy of analysis for bridge decks is versatile, easy for engineers to visualize and prepare the data. It has been found that in skew bridges, the moments develop with the change of skew angle. Based on the results of the analysis, the following conclusions are drawn:

- In the skew type 1 which is used in the special case of highway bridges the maximum moment increases with increases of skew angle. The maximum moment is reached at angle $60^o$ to 175% than the maximum moment at right span, so, it depends on the skew angle only and this percent is increased up to 350% when the effect of increasing the dead load and the live load (due to increase of the span) are taken into consideration.
- In the skew type 2 which is more widespread in the skew highway bridges the maximum moment in the longitudinal direction decreases with increases in the skew angle. The maximum moment is reached to 86% at skew angle $60^o$, on the other hand the maximum torque increases with increases of skew angle for more than ten times that the torque in the right span at angle $60^o$. Also the maximum negative moment in the transverse direction increases as the skew angle increases this increase reaches to four times it values at right span when the skew angle reaches to $60^o$.
- According to the results obtained here, it is preferable to use the skew type 2 in the highway bridge decks more than skew type 1.

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