Parametric Study of Skew Bridge Decks

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Abstract: The impact of major parameters on the structural behavior of skew bridges is investigated. The main parameters included in this research are: 1- The rigidity of supports, 2- The type of the bridge deck, and 3- The angle of skew. The changes in the structural behavior of the bridges are presented through the change in the reactions and the bending moments of the bridges.

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Introduction

The bridge engineer sometimes has to use skew bridges due to the complicated geometrical alignment of surface roads, rail roads and water ways. Some earlier trials were made to facilitate the design of simple types of skew bridges before the development of computer methods, [1]. Unfortunately these trials were very limited and did not reflect the actual behavior of skew bridges.

In this paper, a general study of the effect of the following parameters is presented to address the impact of each of them on the behavior of skew bridges:

A. The angle of skew.

B. The flexibility of the deck itself, i.e. the type of the construction of the deck whether it is concrete slab or slab-concrete girders, or composite concrete slab on steel deck.

C. The flexibility of the supports under the deck, i.e. the type of the supports' material.

Figure 1 shows a plan of the hypothetical bridge deck considered in this study. The locations of the bearings are shown in this figure with the bearing number Ri considered in this study. The angle of skew (***AS***) is also shown in this figure.

The three types of construction used in this study are:

- **CONS1**, reinforced concrete slab type bridge deck, with 700mm slab depth as shown in figure 2.a.
- **CONS2,** reinforced concrete slab and concrete girders as shown in figure 2.b.
- **CONS3**, concrete slab on steel girders as shown in figure 2.c.

Moreover, in order to study the effect of the flexibility of supports, two types of supports were used in this study:

- **SUPP1**, vertically rigid supports, i.e. steel rollers or hinges
- **SUPP2**, flexible supports, i.e. reinforced rubber supports (neoprene bearings).

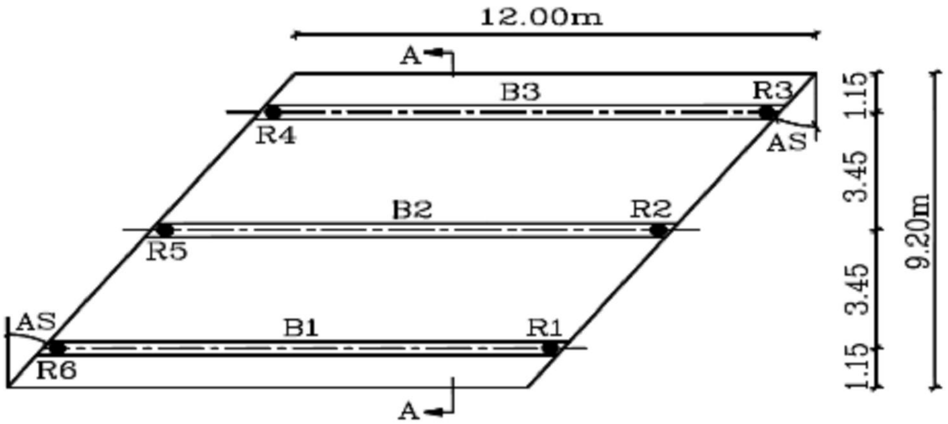

Figure 1: Plan of the bridge deck

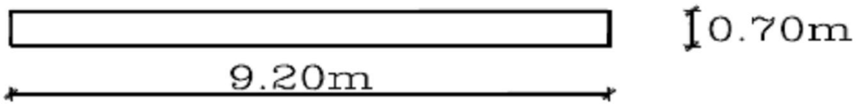

Figure 2.a: Section A-A, CONS1

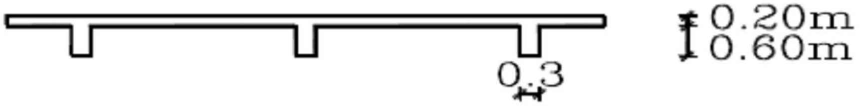

Figure 2.b: Section A-A, CONS2

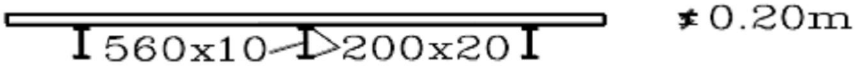

Figure 2.c: Section A-A, CONS3

Structural Modeling of the Bridge Deck

The computer program SAP2000 [2], is used in modeling the different bridge decks included in this research. An elastic analysis is used to study the effect of the above mentioned parameters on the variation of support reactions and the maximum longitudinal moments as indicators of the change of the load distribution and the behavior of the deck.

There are many modeling techniques that are frequently used in the analysis of the specified bridge decks. Medhat K. [3] includes a detailed comparison between these techniques. In this research, the grillage modeling technique was chosen to analyze the decks of the different specified construction types mentioned above.

The grillage analysis is an effective modeling technique that guarantees high accuracy in modeling the behavior of the bridge decks. In this technique, the deck is divided into longitudinal grillage beams representing the main girders and transversal imaginary grillage beams representing the slab and the cross girders [3, 4 and 5].

Figure 3 shows a plan of the bridge deck with the center lines of both the longitudinal and transversal grillage elements used for the three construction systems.

Figure 4 shows a cross section through the longitudinal elements of the different systems; section A-A of figure 3, where three longitudinal elements are used for each system with the properties and spacing shown in this figure.

Figure 5 shows a cross section through the transversal elements of the different systems; section B-B of figure 3.

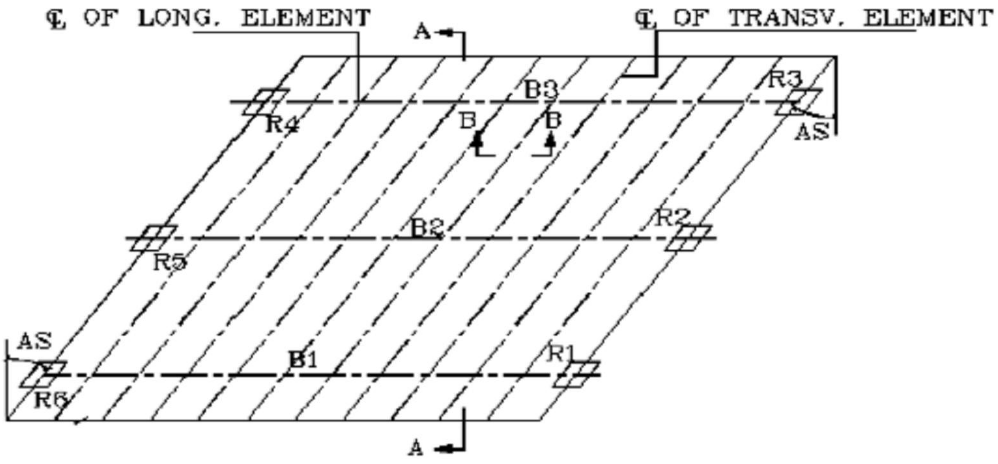

Figure 3: Plan of the grillage system used in the analytical model

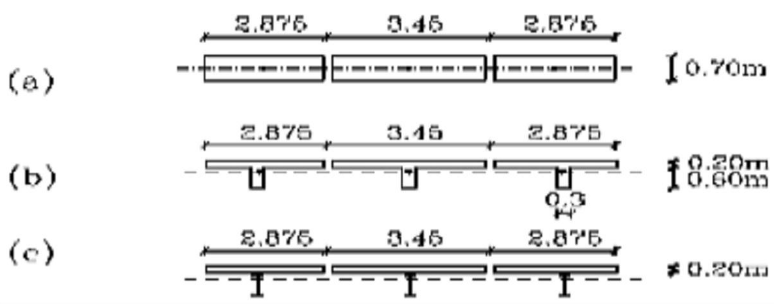

Figure 4: SEC. A – A through Longl. element
a- CONS1 b- CONS2 C- CONS3

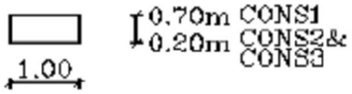

Figure 5: SEC. B - B through Transvl. element

The characteristic strength of the concrete elements used in this study Fcu_{28} is 400 Kg/cm^2 and the steel type of the steel beams is ST (52/36) with yield strength of 3600 Kg/ cm^2.

Neoprene bearings 200mm x 400mm are used for SUPP2. The total depth of rubber layers is 40mm and the total depth of the bearing including the steel plates is 82mm. The young's modulus of the bearings, $E_{b,}$ is 2.3x10^3 Kg/cm^2 and the shear modulus, $G_{b,}$ is 10 Kg/cm^2. These values are mentioned in the manufacturer's catalogs according to DIN4141 and they were used to model the bearings of SUPP2 as elastic spring. On the other hand, SUPP1 was considered as regular infinitely rigid steel rollers or hinges.

Loading System

The results are shown for both the dead load of the deck and a truck load of 90 ton as shown in figure 6. The maximum live load reactions were obtained for the internal bearing under beam B2. The corresponding reactions for the other bearings are presented.

The truck was located at the mid-span of each to obtain the maximum bending moment at this beam (BM), and the values of the corresponding bending moment at the other beams were recorded.

Analysis of the Results

1. Change of reactions:

Table 1 presents the effect of the skew angle on the change of the reactions for both types of supports, SUPP1 and SUPP2, for CONS1, CONS2 and CONS3 due to dead load (DL). Figures 7 to 9 present these results for the rigid supports only, SUPP1.

Table 2 presents the effect of the skew angle on the change of the reactions for both types of supports, SUPP1 and SUPP2, for CONS1, CONS2 and CONS3 due to moving truck load (LL) on the internal beam B2 to obtain the maximum reaction on R2. The corresponding reactions at other bearings are presented in the same table. Figures 10 to 12 present these results for the rigid supports only, SUPP1.

From these tables and figures the following observations may be concluded:

- The effect of the support type on the vertical dead load reactions is marginal for the three types of decks CONST1, CONST2 and CONST3. A change close to 2% was noticed in the presented case.
- On the other hand, this effect increases for the live load reaction especially in the slab type, CONST1, where the reaction for SUPP1 is 13% higher than SUPP2.
- The angle of skew ***AS*** has a great impact on the values of the reactions for both the dead and live loads at the edge bearings. The reaction at the bearings close to the acute angle, R3, decreases by increasing ***AS*** while the reaction of the bearings close to the obtuse angle, R1, increases by increasing ***AS***. In the case of live load, the increase in ***AS*** resulted in uplift at the acute corner (i.e. negative values for R3).
- The results also indicate greater impact of the skew angle, ***AS***, in the case of slab type deck, than the R/C girder type or composite type decks. This result may be attributed to the higher transversal rigidity of the slab deck than the other types.
- The design of the bearings should accommodate the changes mentioned above for skew decks; a unified bearing size may lead to uplift and instability of the deck.

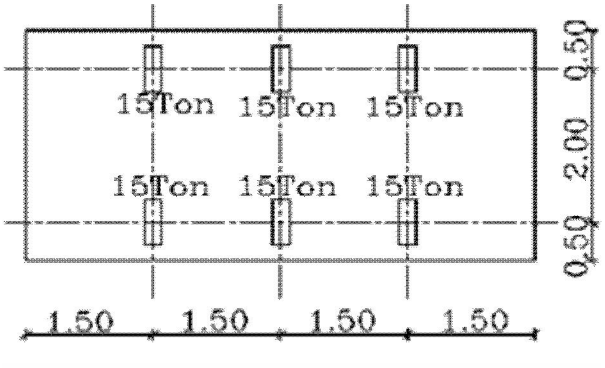

Figure 6: details of truck loads

TABLE 1: Dead load reaction vs. the angle of skew (*AS*),

	AS (Deg.)	0		20		30		50	
		SUPP1	**SUPP2**	**SUPP1**	**SUPP2**	**SUPP1**	**SUPP2**	**SUPP1**	**SUPP2**
CONS1	**R1**	30.19	30.7	42.62	41.87	46.64	45.48	46.28	45.55
	R2	36.23	35.2	33.66	33.36	32.36	32.86	32.83	33.34
	R3	30.19	30.7	20.33	21.3	17.71	18.32	17.5	17.7
CONS2	**R1**	11.42	11.4	12.09	12.5	12.5	12.61	13.33	13.31
	R2	12.87	12.8	12.7	12.61	12.64	12.51	12.15	12.15
	R3	11.42	11.4	10.86	10.8	10.6	10.61	10.24	10.24
CONS3	**R1**	9.3	9.3	10.1	10.1	10.6	10.57	12.04	12.03
	R2	10.94	10.9	11.26	11.25	11	10.98	10.19	10.14
	R3	9.3	9.3	8.93	8.93	8.72	8.75	8.16	8.15

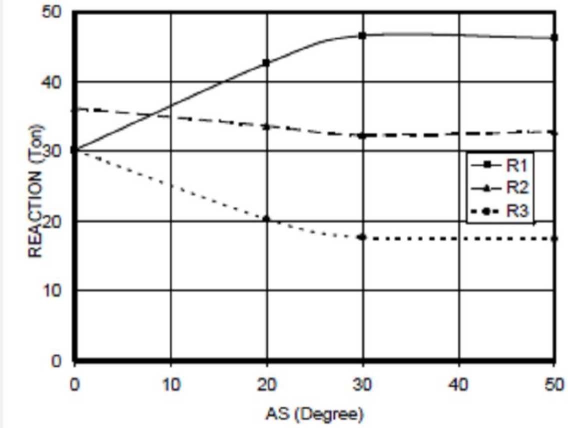

Figure 7: DL reaction on CONS1, SUPP1vs. *AS*

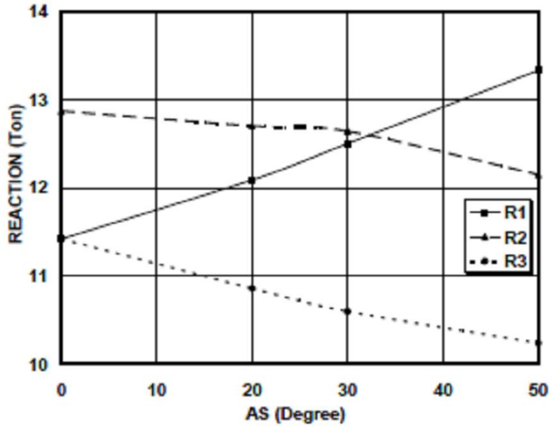

Figure 8: DL reaction on CONS2, SUPP1 vs. *AS*

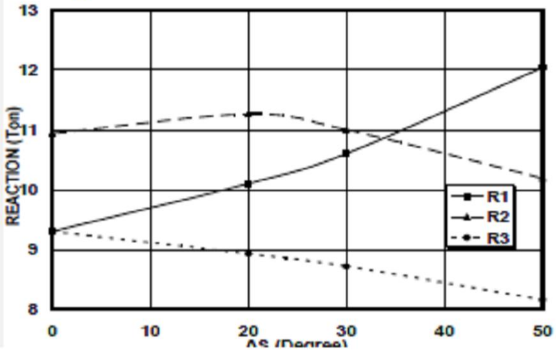

Figure 9: DL reaction on CONS3, SUPP1 vs AS

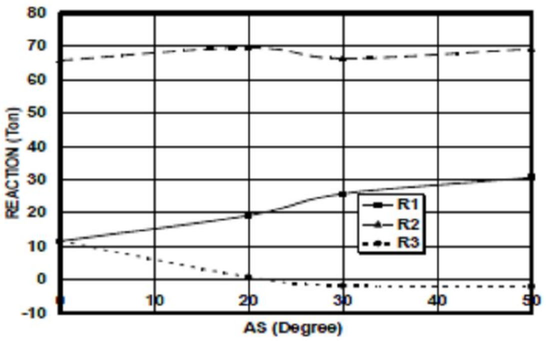

Figure 10: LL reaction on CONS1, SUPP1 vs. AS

TABLE 2: Live load reaction vs. the angle of skew (AS)

	AS (Deg.)	0		20		30		50	
		SUPP1	**SUPP2**	**SUPP1**	**SUPP2**	**SUPP1**	**SUPP2**	**SUPP1**	**SUPP2**
CONS1	**R1**	11.53	13.87	19.2	20.3	25.71	25.95	30.6	29.92
	R2	65.79	55.09	69.6	60.49	66.36	56.15	69.17	61.32
	R3	11.53	13.87	0.75	4.21	-1.86	5.75	-2.1	-2.24
CONS2	**R1**	4.95	5.11	7.16	7.39	9.07	9.15	12.2	12.34
	R2	74.16	73.47	74.25	73.48	74.08	73.43	74.04	73.54
	R3	4.95	5.11	2.69	2.86	1.63	1.85	-0.94	-0.92
CONS3	**R1**	5.25	5.23	7.31	7.3	9.09	9.1	12.42	12.5
	R2	74.04	74.5	74.09	74.2	73.88	74	73.75	73.85
	R3	5.25	5.23	3.25	3.3	2.23	2.25	0.42	0.44

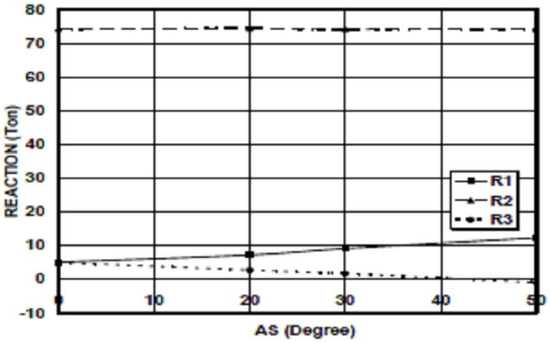

Figure 11: LL reaction on CONS2, SUPP1 vs AS

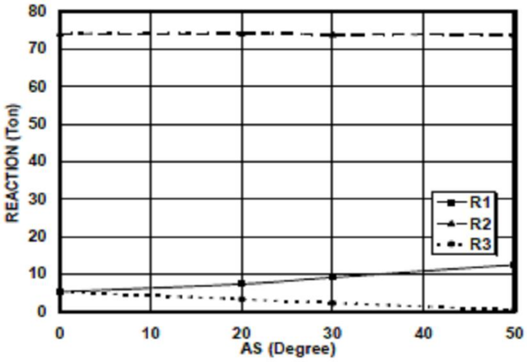

Figure 12: LL reaction on CONS3, SUPP1 vs. AS

2. Change of the bending moment (BM)

Table 3 presents the effect of the skew angle on the change of BM for both types of supports for CONS1, CONS2 and CONS3, due to the specified truck load at midpoint of beam B2. Moreover, figures 13 to 18 present these results for the case of rigid supports only, SUPP1.

The values of BM are shown for the 3 quarters points indicated by **1, 2** and **3** on these figures, and referred to hereafter by M_{ij}, where i refers to the beam number and j refers to the section number.

From these tables and figures the following observations may be concluded:

- The change in the values of BM due to the change of the type of supports is less than 6% for most of the cases shown in the table. This change is insignificant and may be ignored.
- The change in BM due to ***AS*** is significant. The value of M13, in CONS1, changes from 40.31 to 24.74 when ***AS*** changes from=0°, to 50°, with a ratio of 39%. This ratio decreases to 23% for CONS2 and 22% for CONS3. The load redistribution in both CONS2 and CONS3 is better than CONS1 due to the higher transversal rigidity of CONS1.
- The ratio M11/M13 is 100% for rectangular decks of the three construction types. But, at ***AS***= 50°, this ratio is -16%, 0.8% and 9% for CONS1, CONS2 and CONS3 respectively, indicating unsymmetrical distribution along this edge beam. Not only the change is higher in CONS1 than the other two systems but also the direction of BM changes, with tension side at the top, for this simple beam due to the higher transversal rigidity of CONS1.
- The increase in ***AS*** results in a remarkable decrease in the value of the mid-span moment of edge beams, B1 and B3. The ratio of M12 at ***AS*** =50° to M12 at ***AS*** = 0° is 18%, 29% and 33% for CONS1, CONS2 and CONS3 respectively. These ratios are 45%, 88% and 90% for the intermediate beam M22, indicating less influence of the angle of skew on the intermediate beam B2.
- Generally speaking, the effect of the angle of skew ***AS*** is higher on CONS1 than CONS2 and CONS3.

Tables 4.A and 4.B and figures 19 to 30 present the change of BM of the three longitudinal grillage members for different cases due to the specified truck load moving on B1 and B2 respectively.

The following observations may be noticed from the shown results:

- The type of supports has higher effect on the behavior of CONS1 than the other decks especially in skew bridges. At ***AS***=50°, using SUPP2 results in an increase in the values of M12 of 3%, M22 of 31% and M32 of 81% for CONS1. (Table 4. A).

This increase is not more than 6% for CONS2 and CONS3 and may be ignored.

- The change in ***AS*** results in a noticeable change in the distribution of BM for slab type deck, CONS1. When ***AS***=50^o the change of the mid-span moment M12, of the loaded beam B1, is -20% for CONS1. This change is not more than 1% for CONS2 and CONS3. Moreover, the distribution of BM is not symmetric along B1 compared to the case of ***AS***=0^o.
- The BM at the edge of the intermediate beam B2, the unloaded beam in this case, changes to negative moment by increasing ***AS*** for CONS1, CONS2 and CONS3.
- The increase of the angle of skew results in a remarkable change of BM on B3, the unloaded edge beam, in CONS1. On the other hand, the values of BM of this beam are negligible in CONS2 and CONS3. These changes may be attributed to the high flexibility of both CONS2 and CONS3 compared to CONS1 which reduces the load transferred from B1, the loaded beam, to the unloaded beams.
- In Table 4B and figures 28 to 30, the values of the BM of the edge beams at joint 1, close to the acute angle, are negative values and much less than those at joint 3, close to the obtuse angle, of the same beams. In other words, by increasing the angle of skew, the moments close to the acute angle decreases and change to hogging moments while those close to the obtuse angle increase and keep their signs as sagging moments.

Table 3: Bending moment due to truck load at midpoint of B2

AS ***(degree)***			**0**		**20**		**30**		**50**	
			SUPP1	**SUPP2**	**SUPP1**	**SUPP2**	**SUPP1**	**SUPP2**	**SUPP1**	**SUPP2**
B1	**CONS1**	**M11**	40.31	40.94	23.25	24.74	11.33	12.5	-3.99	-3.76
		M12	61.14	64.49	53.83	54.65	40.83	42.1	10.97	9.91
		M13	40.31	40.94	45.74	46.1	43.71	41.4	24.74	26.22
	CONS2	**M11**	25.77	25.99	19.5	19.75	13.59	13.9	0.15	0.16
		M12	41.66	41.94	38.94	39.23	33.19	33.5	11.79	11.97
		M13	25.77	25.99	31.14	31.33	31.54	31.7	19.92	20.02
	CONS3	**M11**	26.5	26.7	20.63	20.41	15.18	15.2	1.96	2.09
		M12	42.45	42.72	39.83	44.33	34.48	34.5	13.91	14.06
		M13	26.5	26.7	31.69	31.87	32.2	32.2	20.74	20.83
B2	**CONS1**	**M21**	54.39	53.11	52.23	52.13	33.47	34.5	14.3	16.68
		M22	96.72	96.02	86.25	81.53	74.57	75.6	43.57	46.34
		M23	54.39	53.11	44.51	45.99	32.82	33.8	14.3	16.55
	CONS2	**M21**	83.47	83.03	77.53	77.11	78.43	77.9	72.09	71.87
		M22	141.69	141.1	138.1	137.5	135.7	135	125.4	125.14
		M23	83.47	83.03	81.5	81.08	77.39	76.7	69.21	68.99
	CONS3	**M21**	82	81.59	76.66	76.27	77.95	77.8	72.62	72.41
		M22	140.11	139.6	137.2	136.7	135.3	135	126.6	126.36
		M23	82	81.59	80.47	80.08	76.81	76.5	69.57	69.39

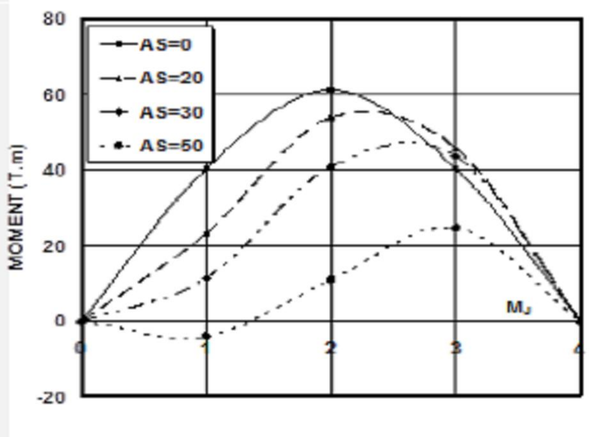

Figure 13: Distribution of B.M, on B1, CONS1.

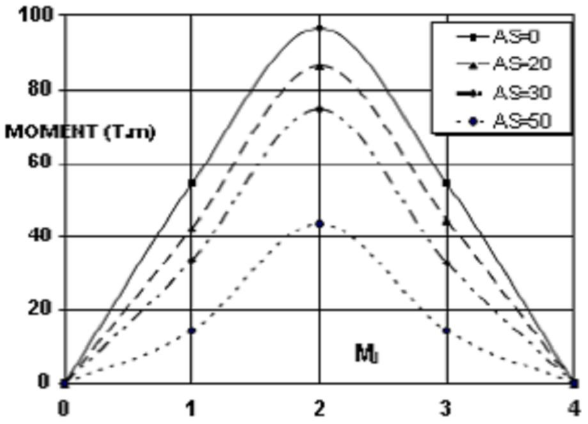

Figure 14: Distribution of B.M on B2, CONS1.

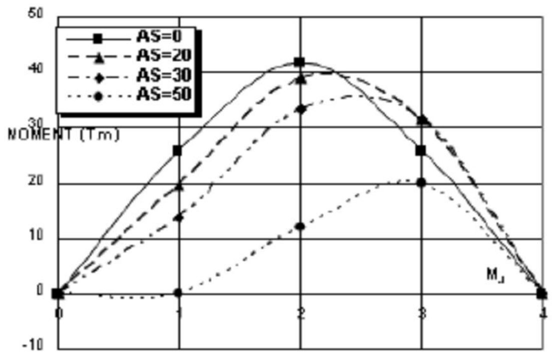

Figure 15: Distribution of B.M on B1, CONS2.

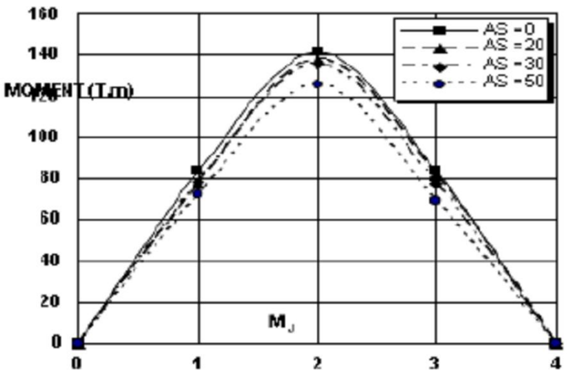

Figure 16: Distribution of B.M on B2, CONS2.

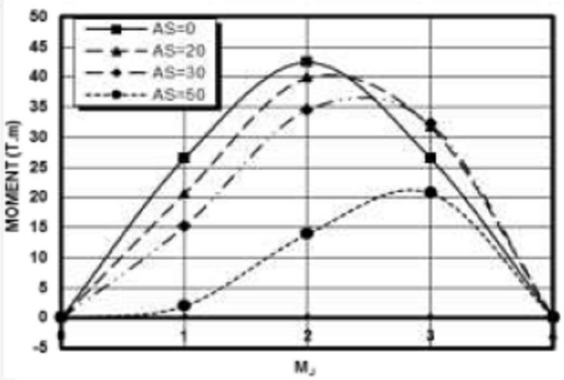

Figure 17: Distribution of B.M on B1, CONS3.

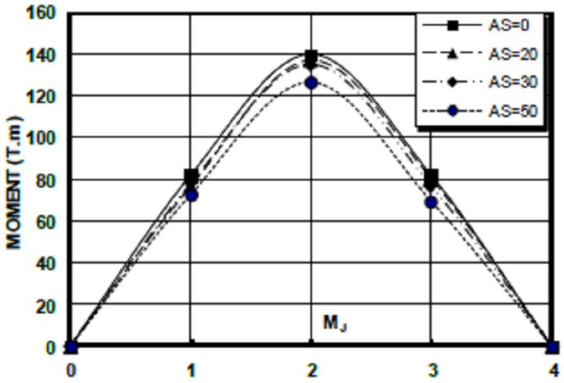

Figure 18: Distribution of B.M on B2, CONS3.

TABLE 4. A: B.M. due to moving truck on B1

AS degree		**0**		**20**		**30**		**50**	
		SUPP1	**SUPP2**	**SUPP1**	**SUPP2**	**SUPP1**	**SUPP2**	**SUPP1**	**SUPP2**
CONS1	**M11**	103.9	102.9	96.08	95.83	85.7	94.83	96.98	99.05
	M12	123.13	123.04	114.96	115.77	110.18	111.87	99	102.05
	M13	103.9	102.9	93.98	94.02	90.26	91.1	80	89.09
	M21	51.53	52.5	61.49	65.96	69.61	67.51	56.65	57.76
	M22	73.32	74.38	66.06	63.33	52.11	54.12	13.49	17.67
	M23	51.53	52.5	17.87	30.08	-6.12	9.65	-26.47	-24.55
	M31	14.15	14.11	22.17	22.37	17.72	18.1	-1.45	-2.45
	M32	27.44	27.58	21.76	21.48	11.6	10.99	-4.14	-7.49
	M33	14.15	14.11	4.25	2.41	-3.3	6.52	-2.42	-6.3
CONS2	**M11**	148.7	148.55	146.2	146.06	147.4	147.33	157.25	157.17
	M12	192.5	192.33	185.83	185.72	186.65	186.62	191.74	191.71
	M13	148.7	148.55	143.01	142.9	142.42	142.35	152.14	152.12
	M21	23.65	23.88	35.62	35.82	34.21	34.34	21.6	21.88
	M22	35.84	36.11	39.45	39.76	36.2	36.52	10.59	11.11
	M23	23.65	23.88	20.21	20.54	10.97	11.37	-4.01	-3.77
	M31	-5.1	-3.21	-3.61	-3.71	-2.98	-3.05	0.17	-0.08
	M32	-6.2	-3.43	-3.37	-3.54	-2.37	-2.55	-0.07	-0.26
	M33	-5.1	-3.12	-2.33	-2.5	-1.9	-2.09	-0.21	-0.4
CONS3	**M11**	149.17	149.32	147.39	147.26	148.66	148.49	159.34	159.26
	M12	194.1	193.95	188.27	188.16	188.89	188.74	194.27	194.23
	M13	149.17	149.32	144.39	144.25	143.64	143.53	153.37	153.35

	M21	23.44	23.66	34.82	35.02	33.69	34.34	22.19	22.46
	M22	35.27	35.51	38.84	39.14	36.14	36.52	12.09	12.56
	M23	23.44	23.66	20.42	20.72	11.74	11.37	-2.96	-2.73
	M31	-3.56	-3.67	-4.37	-4.58	-3.42	-3.55	1.27	1.16
	M32	-4.34	-4.46	-4.16	-4.32	-2.35	-2.56	1.33	1.14
	M33	-3.56	-3.67	-2.29	-2.45	-1.38	-1.57	0.52	0.39

TABLE 4. B: B.M. due to moving truck on B2

Angle of Skew (*AS*)		**0**		**20**		**30**		**50**	
		SUPP1	**SUPP2**	**SUPP1**	**SUPP2**	**SUPP1**	**SUPP2**	**SUPP1**	**SUPP2**
CONS1	**M11**	43.39	44.21	26.37	30.22	16.91	21.95	-5.2	-6.76
	M12	62.35	62.19	52.85	53.79	43.41	44.95	15.77	23.14
	M13	43.39	44.21	46.78	47.16	42.79	43.36	27.55	30.26
	M21	82.65	80.32	87.06	84.19	65.35	64.25	59.56	59.4
	M22	100.97	100.62	91.03	91.09	79.51	80.39	49.33	51.8
	M23	82.65	80.32	78.44	76.35	69.3	67.39	49.5	59.08
CONS2	**M11**	22.67	22.9	19.57	19.86	14.1	14.53	-1.8	-1.68
	M12	34.37	34.62	38.4	38.7	33.33	33.71	9.66	12.33
	M13	22.67	22.9	30.71	30.9	30.97	31.19	17.86	18.05
	M21	124.75	124.21	119.61	118.9	114.26	113.62	118.48	117.94
	M22	156.24	155.72	140.26	139.7	137.06	136.26	144.8	144.37
	M23	124.75	124.21	120.93	120.24	114.12	113.19	114.77	114.37
CONS3	**M11**	23.42	23.64	20.65	20.92	15.57	15.64	0.95	1.92
	M12	35.32	35.47	39.32	39.59	34.6	34.64	11.46	14
	M13	23.42	23.64	31.27	31.45	31.65	31.68	17.91	19.07
	M21	123.37	122.88	118.96	118.3	113.85	113.62	118.5	117.98
	M22	154.54	154.05	139.3	138.78	136.54	136.26	145.17	144.76
	M23	123.37	122.88	120.26	119.63	113.71	113.19	114.75	114.37

Conclusions:

In this paper the effects of the support rigidity, the type of the bridge deck and the angle of skew on the behavior of skew bridges were investigated through analytical study of a hypothetical bridge deck. Both elastic and rigid supports were included in the study. Three types of bridge decks were investigated: slab deck, reinforced concrete slab and girders deck and reinforced concrete slab on steel beams. The angle of skew was changed from 0^o to 50^o.

The main conclusions of this study may be summarized as follows:

- The slab type deck is more sensitive to the changes in both the rigidity of supports and the angle of skew. This is attributed to the higher transversal rigidity of this type of decks compared to the slab-girder type.
- The reactions at supports close to the acute angles are very low and may change to uplift while the reactions and the shearing forces at supports close to the obtuse angles are very high due to the increasing torsional rigidity of the transversal grillage elements.
- A unified design of the bearings supporting a skew bridge deck may result in instability of the deck. Each bearing should be designed separately to accommodate the reaction on its location.
- The increase in the torsional rigidity of transversal elements close to the acute angles of skew bridges results in hogging and negative bending moments at these corners even at simply supported beams. Attention should be paid in the design of skew decks to accommodate this behavior.

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