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On the Model Tests of Skew Girder Bridges

Essais sur modèles réduits de ponts biais à poutres multiples

Modellversuche an schiefen Trägerrostbrücken

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Introduction

The author has proposed the numerical method of analysis of orthotropic parallelogram plates which are simply supported on the two opposite sides and free or supported by the flexible edge girders on the other two sides [1], and has made model tests in order to verify the effectiveness of the proposed method [2]. The results of the model tests show that the author's method is useful to the analysis of skew girder bridge, and that it is important to take the skew angle into consideration. However, these researches were limited to the model tests on the right grillage-skew girder or right grillage-skew girder bridge of comparatively small numbers of main girders, and the characteristic values of main and cross girders were not necessarily proportional to those of the existing skew girder bridge. Recently, the Tezukayama Bridge and Utajima Bridge were constructed as a live load composite-skew girder bridge and a live load composite, right grillage-skew girder bridge, respectively, in Osaka City, Japan. The authors planed the tests on model bridges, of which the characteristic values were very close to those of the existing bridges, in order to obtain the more accurate information on the skew girder bridge and thus to complete the research work on the analysis of skew girder bridges which has been carried on since 1956. This is the report of the model tests and will give a more useful information on skew girder bridges.

Part. 1. Model Test on a Composite Skew, Girder Bridge

1. Description of Model Bridge

This model skew bridge represents the Tezukayama Bridge (skew, composite girder bridge), Osaka City. The general plan and section of the model skew girder bridge are shown in Fig. 1. The details of the model are as follows:

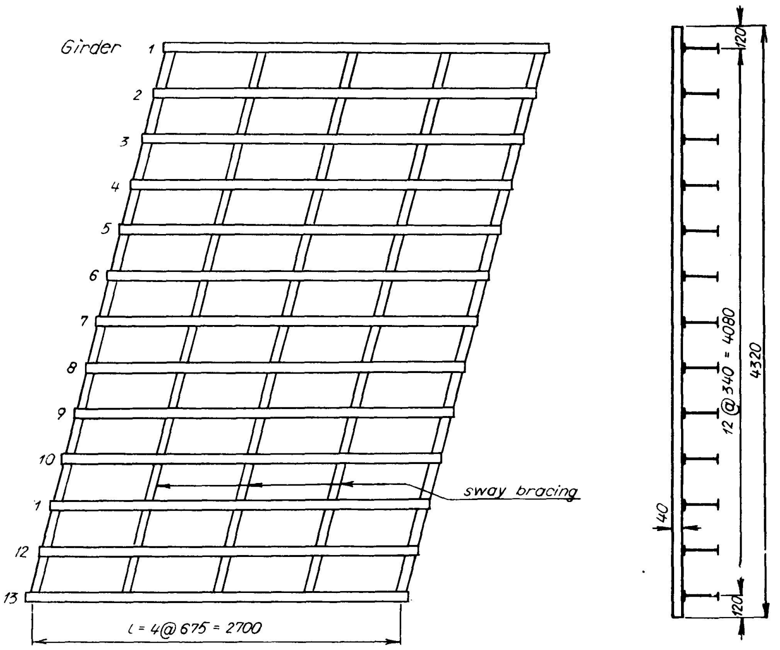

Fig. 1. General Plan and Section of the Model Bridge.

a) skew angle: 20 degrees, b) number of main girders: 13, c) span length: 270 cm, d) spacing of main girders: 34 cm, e) width: 432 cm, f) slab: 4 cm thick mortar slab connected by shear connectors recommended by G. WÄSTLUND, g) section of main girder: 1 flange plate 50×8, 1 web plate 125×6, 1 flange plate 72×8; that of edge girder: 1 flange plate 50×8, 1 web plate

Table 1. Characteristic Values of Bridges

	Existing Bridge	Model Bridge	Existing/Model
span (m)	13.50	2.70	1/5
width (m)	21.60	4.32	1/5
skew angle ($\tan \varphi$)	0.36397	0.36397	1
B_x (t·cm/cm)	17050 E_c	266.6 E_c	1/63
B_y (t·cm/cm)	341.4 E_c (without sway bracing)	5.33 E_c	1/64
B_x/B_y	49.9	50.0	1

125×6, 1 flange plate 72×12, h) sway bracing: at quarter- and mid-span sections.

The ratio of the modulus of elasticity of steel to that of mortar is assumed as 7. The characteristic values of the existing and model bridges are shown in Table 1, and the stiffness ratio is almost same for both bridges.

2. Loading and Measurement

A concentrated load of 6 tons was applied at each of 21 points shown in Fig. 2, these points corresponding to the 2/6, 3/6 and 4/6 span points of the

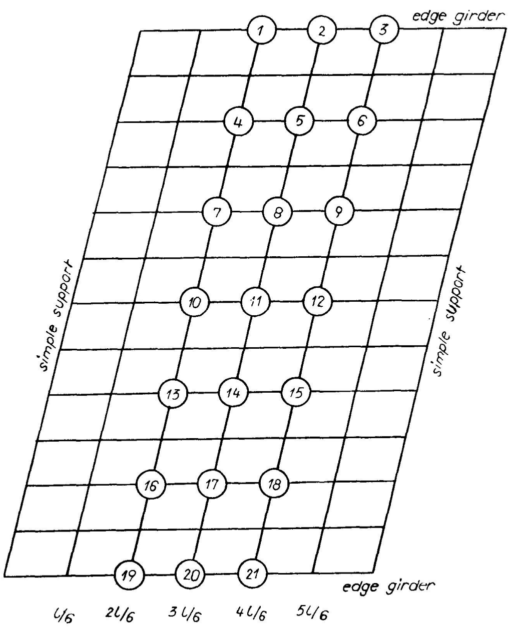

Fig. 2. Point of Loading.

girders. The strain was measured by the electrical resistance wire strain gage and "Maihak Saite" with the strain indicator and Maihak remote control extensometer respectively. The deflection was measured by the dial gage.

3. Numerical Analysis of Skew Girder Bridge by the Theory of Orthotropic Parallelogram Plates and Comparison of Measured Values with the Theoretical Values

We assume that the model skew composite girder bridge without sway bracing is an orthotropic parallelogram plate which is simply supported at the two opposite skew sides and is supported by the flexible edge girders at the other two sides, and have used the skew network finite difference equation for the numerical analysis.

Let us divide the orthotropic parallelogram plate into finite difference network and denote each network point as shown in Fig. 3. The characteristic

Table 2. Comparison of Measured Values of Deflection with Theoretical Ones at Sections in the Direction of the Loaded Span (unit: 0.01 mm)

Load		Section									
		$L/6$		$2L/6$		$3L/6$		$4L/6$		$5L/6$	
		κ									
		0	1	0	1	0	1	0	1	0	1
2	*M*	55		92		106		105		54	
	A	31	25	56	44	67	52	56	44	31	24
	B	36	27	64	47	77	57	65	47	36	26
	C	47	31	84	56	100	67	84	56	47	31
5	*M*	32		52		61		46		27	
	A	30	20	54	36	64	44	54	36	30	20
	B	30	20	55	37	67	45	55	37	30	20
	C	28	19	52	35	63	44	51	35	28	19
8	*M*	30		50		60		49		28	
	A	30	20	53	36	63	43	53	36	29	20
	B	29	20	53	36	66	45	53	36	29	20
	C	27	19	49	34	61	42	49	34	27	19
11	*M*	25		49		60					
	A	29	20	52	36	63	43				
	B	29	20	53	36	65	45				
	C	27	19	50	34	61	42				

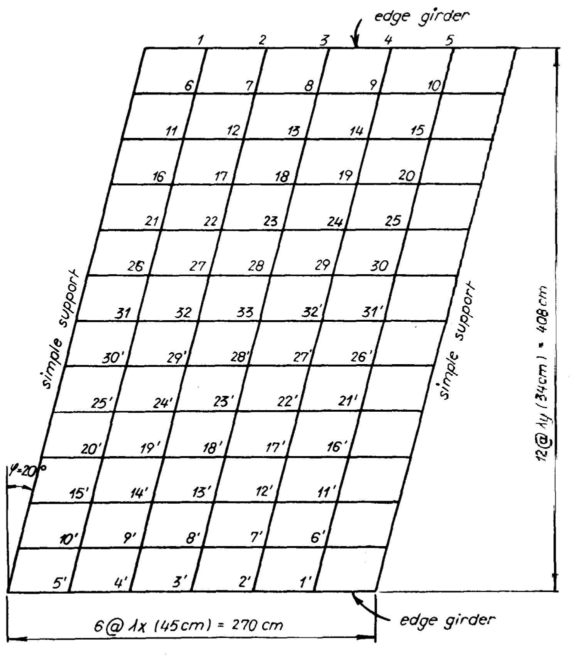

Fig. 3. Skew Network for Model Bridge.

Table 3. Comparison of Measured Values of Bending Moment with Theoretical Ones at the Sections in the Direction of the Loaded Span (unit: kg-cm)

Load		Section									
		$L/6$		$2\,L/6$		$3\,L/6$		$4\,L/6$		$5\,L/6$	
		κ									
		0	1	0	1	0	1	0	1	0	1
2	M	132		303		465		281		133	
	A	121	95	244	190	369	300	244	185	121	85
	B	133	97	276	201	432	332	279	197	137	89
	C	170	112	356	235	569	403	363	229	178	99
5	M	42		129		255		125		42	
	A	85	53	178	116	285	203	178	116	86	52
	B	67	42	166	107	338	236	166	107	66	42
	C	69	46	171	114	344	244	171	113	68	44
8	M	47		131		253		120		42	
	A	83	51	173	114	277	200	173	114	83	51
	B	63	41	160	106	331	234	160	106	63	41
	C	64	43	162	109	334	239	161	109	63	42
11	M	42		122		254					
	A	83	51	173	113	277	200				
	B	63	41	159	106	330	234				
	C	65	42	164	108	336	239				

values of this network are as follows, according to the notations used in the author's previous paper;

$$B_x = 266.6\,E_c(A,B), 290.9\,E_c(C), \qquad B_y = 5.33\,E_c,$$

$$\alpha = \left(\frac{B_y}{B_x}\right)^{1/2} = 0.141\,(A,B), 0.135\,(C), \qquad K = \frac{\lambda_y}{\lambda_x} = 1.511\,(A), 0.756\,(B,C),$$

$$A = \frac{K^2}{\alpha} = 16.149\,(A), 4.037\,(B), 4.213\,(C),$$

$$B = K\tan\varphi = 0.550\,(A), 0.275\,(B,C),$$

$$J = \frac{1}{\alpha^2}\frac{K^4}{\lambda_y}\left(\frac{E\,I_r}{B_x} - f\right) = 169.471\,(A), 21.162\,(B), 12.280\,(C).$$

The unknowns to be determined are the deflections at 65 ($= 13\times 5$) points; however, observing the symmetrical and antisymmetrical loading states, we may reduce the number of unknown terms to 33 for the symmetrical loading and to 32 for the antisymmetrical loading. The problem has now been reduced to the solution of a 33×33 or 32×32 stiffness matrix for one of these two

Table 4. Comparison of Measured Values of Deflection with Theoretical Ones at Mis-span Sections (unit: 0.01 mm)

Load		Girder													
		1		3		5		7		9		11		13	
		κ													
		0	1	0	1	0	1	0	1	0	1	0	1	0	1
2	*M*	106		20		0		-1		-1		-1		-1	
	A	67	52	5	14	-2	3	-1	1	0	0	0	0	0	0
	B	76	57	3	14	-3	3	0	1	0	0	0	0	0	0
	C	100	67	4	16	-3	3	0	1	0	0	0	0	0	0
5	*M*	17		61		17		2		0		0		-1	
	A	5	14	64	44	10	13	-1	3	-1	1	0	0	0	0
	B	3	14	67	45	13	14	-2	3	-1	1	0	0	0	0
	C	4	16	63	44	12	13	-2	3	-1	1	0	0	0	0
8	*M*	-2		15		60		16		2		0		-1	
	A	-2	3	10	13	63	43	10	13	-1	3	-1	1	0	0
	B	-3	3	13	14	66	45	13	14	-1	3	-1	1	0	0
	C	-4	3	12	13	61	42	11	13	-1	3	-1	1	0	0
11	*M*	-1		2		16		60							
	A	-1	1	-1	3	10	13	63	43						
	B	0	1	-2	3	13	14	65	45						
	C	0	1	-2	3	11	13	61	42						

cases. We calculated the inverse matrices (flexibility matrices) of the above stiffness matrices by ILLIAC, the University of Illinois automatic digital computer. From these inverse matrices, we can obtain the influence coefficients for the deflection of the above 33 points, and with these deflections thus known, can calculate the influence coefficients for the bending moment at each point.

The results of the comparison of measured values with the theoretical ones are shown in Tables 2, 3, 4 and 5 and Figs. 4 and 5 for model bridge without sway bracing. The theoretical values A, B and C are as follows:

Theoretical values A represent the values which were obtained using the skew network finite difference equation for the orthotropic parallelogram plate divided into six equidistant intervals in the direction of the span and width, with the aid of relay automatic computer FACOM 128-B (Japan home made digital computer). Theoretical values B are those for the skew network shown in Fig. 3 and were calculated by ILLIAC. The theoretical values C are obtained in the same manner as B, but the rigidity of the flexible edge girders was dealt with in the same way as that in the paper by W. Cornelius [3]. That is, theoretical values A, B and C were calculated by rough and fine skew net-

Table 5. Comparison of Measured Values of Bending Moment with Theoretical Values at Mid-span Sections (unit: kg-cm)

Load		Girder 1		Girder 3		Girder 5		Girder 7		Girder 9		Girder 11		Girder 13	
	κ	0	1	0	1	0	1	0	1	0	1	0	1	0	1
2	*M*	464		36		-8		-4		0		0		0	
	A	369	300	19	52	- 6	11	-2	2	0	0	0	0	0	0
	B	432	332	11	51	-11	10	-1	2	0	0	0	0	0	0
	C	569	403	13	64	-14	12	-2	2	0	0	0	0	0	0
5	*M*	32		255		38		-4		-2		0		0	
	A	25	68	283	203	36	50	-3	11	-2	2	0	0	0	0
	B	14	66	338	236	47	53	-6	11	-3	2	0	0	0	0
	C	16	76	344	244	45	53	-6	10	-2	2	0	0	0	0
8	*M*	-8		35		253		38		-3		-1		0	
	A	- 7	14	36	50	278	200	35	49	-3	11	-2	2	0	0
	B	-14	13	42	53	331	234	45	53	-6	11	-3	2	0	0
	C	-17	14	45	53	334	239	43	41	-3	10	-2	2	0	0
11	*M*	-5		3		33		254							
	A	-2	3	-3	11	35	49	277	200						
	B	-2	2	-6	11	45	53	330	234						
	C	-2	2	-6	10	43	52	336	239						

works respectively, and for the values A and B we neglect the term f in the formula for coefficient J.

In Figs. 4 and 5 the measured values of the model bridge with sway bracing are shown for comparison.

We may observe from Tables 2, 3, 4 and 5 that the measured values agree considerably well with the theoretical ones, and the all measured values are close to the values C. Thus, the theory of orthotropic parallelogram plates can be applied to the analysis of the skew girder bridge with considerable accuracy, and it seems better to calculate the rigidity of the flexible edge girder by the method shown by W. CORNELIUS.

This model, however, has many weak points from the view point of model analysis, and it seems better to use the plastics model than to use the composite model for the detailed research works. Let us show the other model test in next chapter.

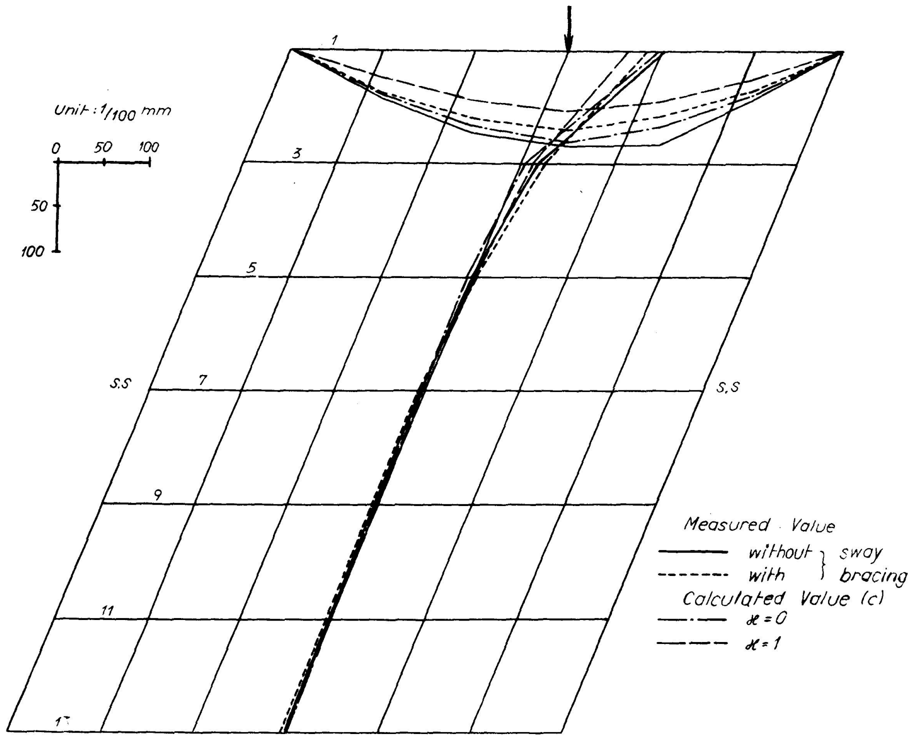
Unit : 1/100 mm
0 50 100
50
100
1
3
5
S.S
7
S.S
9
11
Measured Value
without } sway
with bracing
Calculated Value (c)
ϰ = 0
ϰ = 1

Fig. 4a.

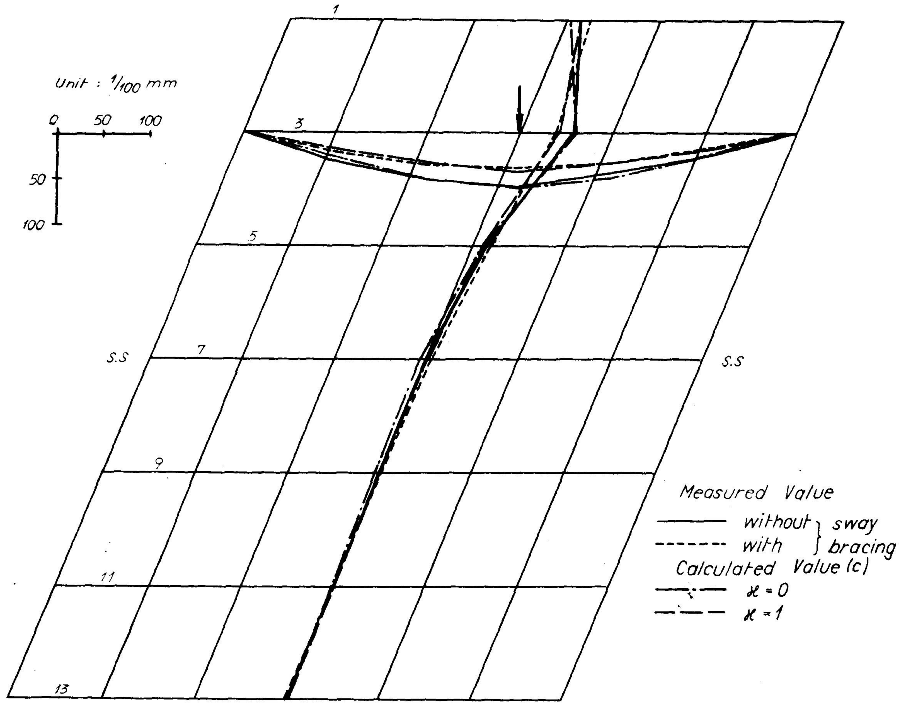
Unit : 1/100 mm
0 50 100
50
100
1
3
5
S.S
7
S.S
9
11
13
Measured Value
without } sway
with bracing
Calculated Value (c)
ϰ = 0
ϰ = 1

Fig. 4b.

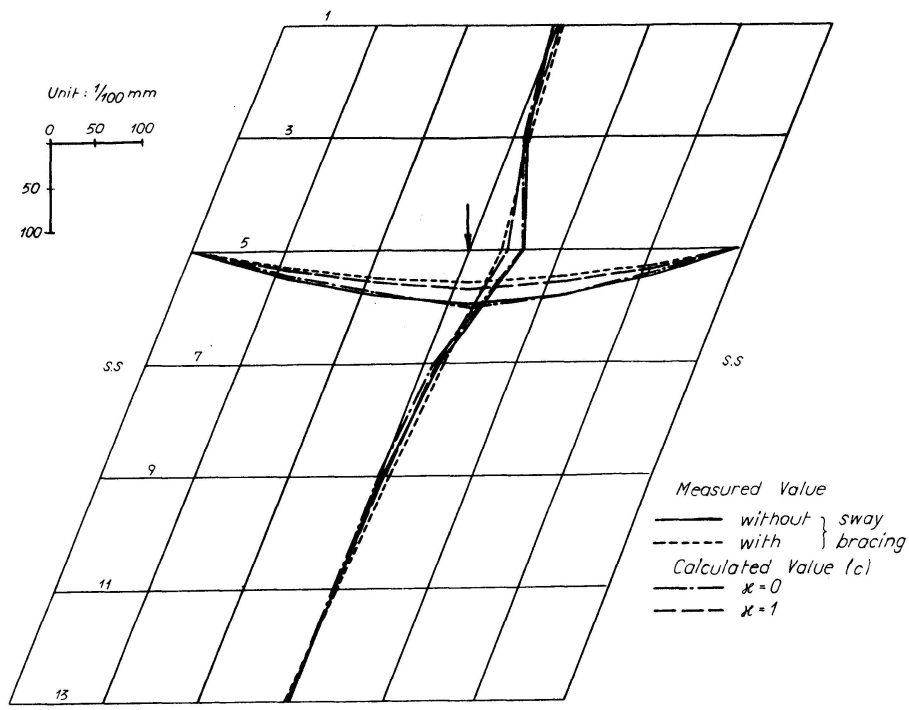

Fig. 4c.

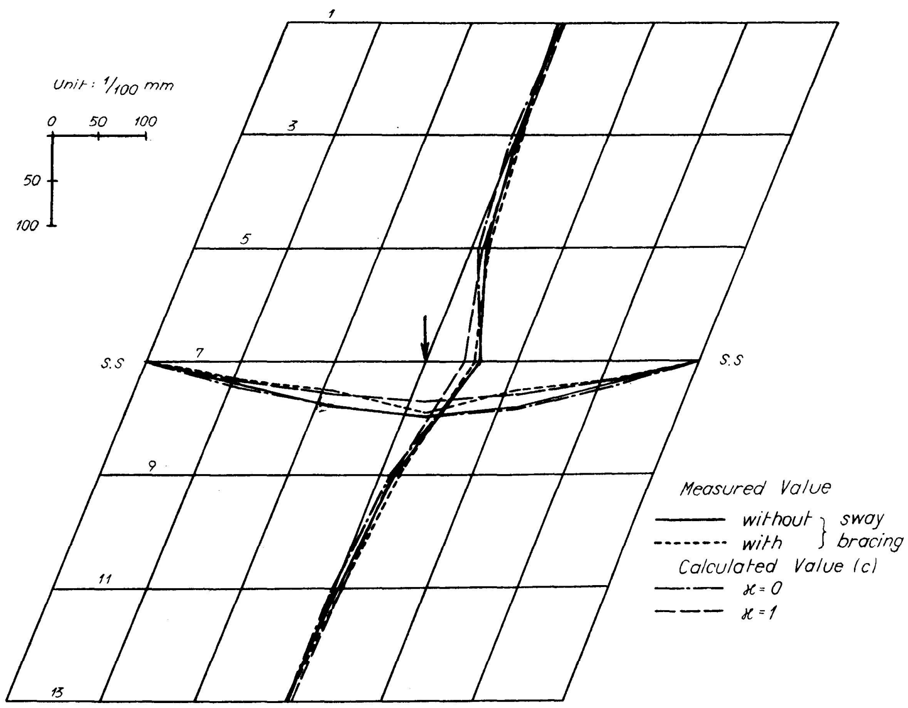

Fig. 4d.

Fig. 4a–d. Measured Values of Deflection and their Comparison with Calculated Values (Method C).

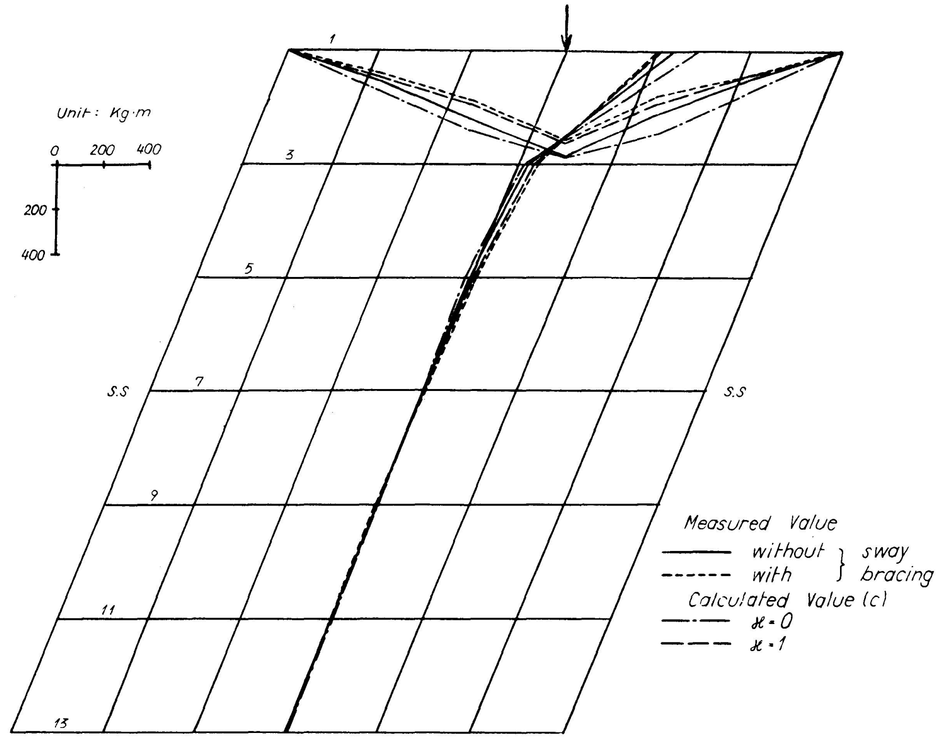
Unit: Kg·m
0 200 400
200
400
1
3
5
7
9
11
13
S.S
S.S
Measured Value
without } sway
with } bracing
Calculated Value (c)
ϰ = 0
ϰ = 1

Fig. 5a,

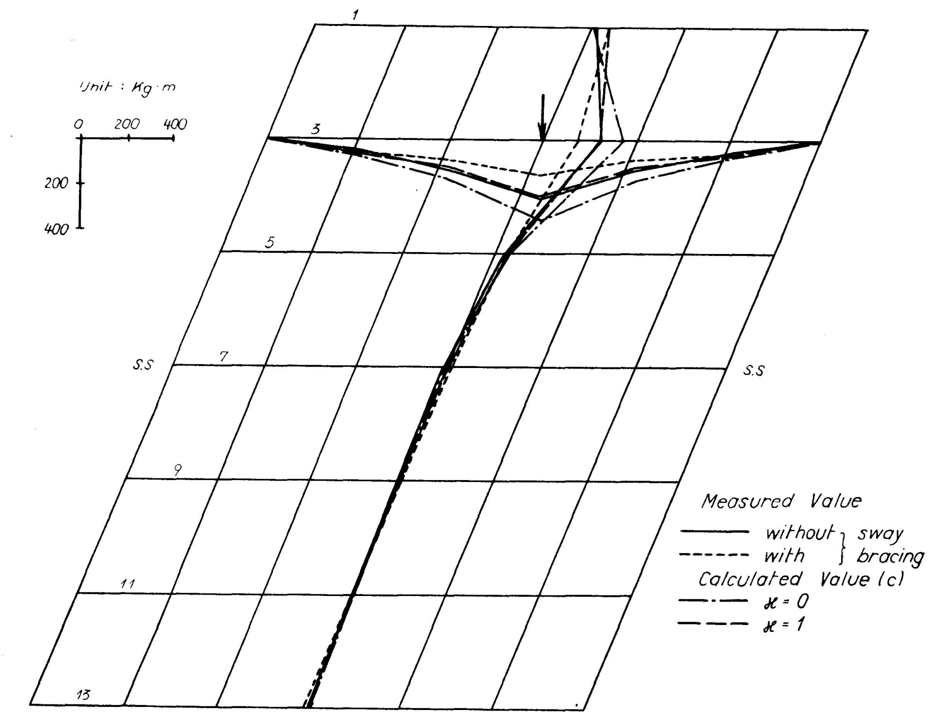
Unit: Kg·m
0 200 400
200
400
1
3
5
7
9
11
13
S.S
S.S
Measured Value
without } sway
with } bracing
Calculated Value (c)
ϰ = 0
ϰ = 1

Fig. 5b.

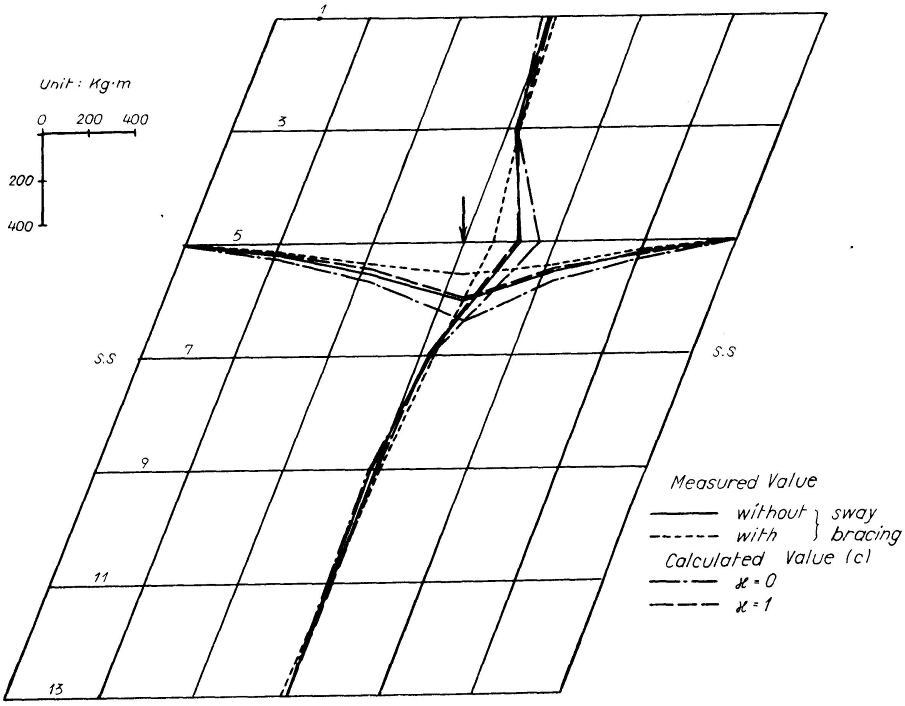

Fig. 5c.

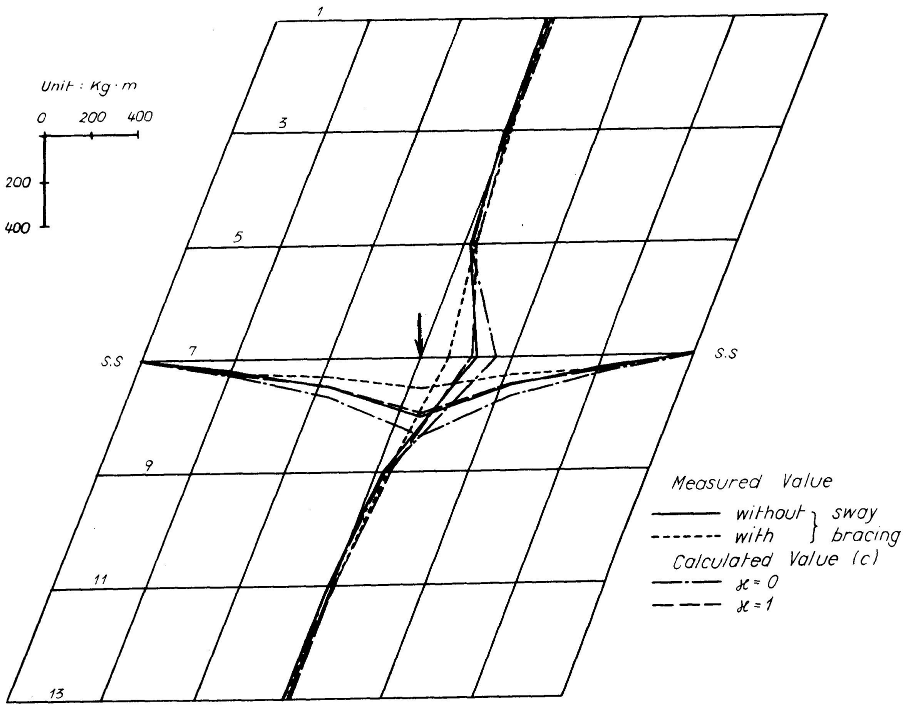

Fig. 5d.

Fig. 5a–d. Measured Values of Bending Moment and their Comparison with Calculated Values (Method C).

Part 2. Model Test on a Composite, Right Grillage-Skew Girder Bridge

1. Description of Existing and Model Bridges

The Utajima Bridge shown in Fig. 6 has the following principal features:

a) type: simply supported, live load composite, right grillage, skew girder bridge;
b) span length: 22.84 m, total width: 20.70 m (effective width of roadway 16 m, that of sidewalk 2 m);
c) number of girder: 11 for main girder, 3 for cross girder;
d) skew angle: 48 degrees and 57 minutes.

Fig. 7 shows the general plan and cross section of the model bridge. See Figs. 8 and 9. The model material is a polymethachrilmethyl, and the span length and distance of girder of the model are 1/20 of those of the existing bridge, and the moment of inertia of the main girders, the intermediate and end cross girders are about 1/40,000 of those of the existing bridge. The details are as follows:

		Existing Bridge	Model Bridge	Model/Existing
moment of inertia of grillage girder	$I_{s,A}$	726,700 cm^4	18.445 cm^4	1/39,398
	$I_{s,B-F}$	397,700	10.166	1/39,144
	I_{s,C_1}	346,600	8.719	1/39,751
	I_{s,C_2}	329,400	8.181	1/40,265
	I_{s,C_3}	123,900	3.160	1/39,210
moment of inertia of grillage girder bridge	$I_{v,A}$	1,740,000	43.480	1/40,018
	$I_{v,B-F}$	1,227,000	31.160	1/39,377

Besides the model skew girder bridge, the model right girder bridge which has the same dimension and stiffness as those of the skew model girder bridge was made for the comparison of observed values for both bridges.

The right and skew grillage girders (without slab or deck plate) were first made. The moment of inertia of the girders of these grillage girders is also about 1/40,000 of those of the grillage girder of the existing bridge as shown in the above table. The slab or deck plate was cemented to the upper flange of the right and skew grillage girders and thus the right and skew girder bridges (with slab or deck plate) were made. The iterative trials were made in order to make the ratio of I (model) / I (existing) constant for the both cases of grillage girder and grillage girder bridge. These two models correspond to the cases of existing bridges of which the composite slab was not executed, and was executed and the composite action could be expected, respectively.

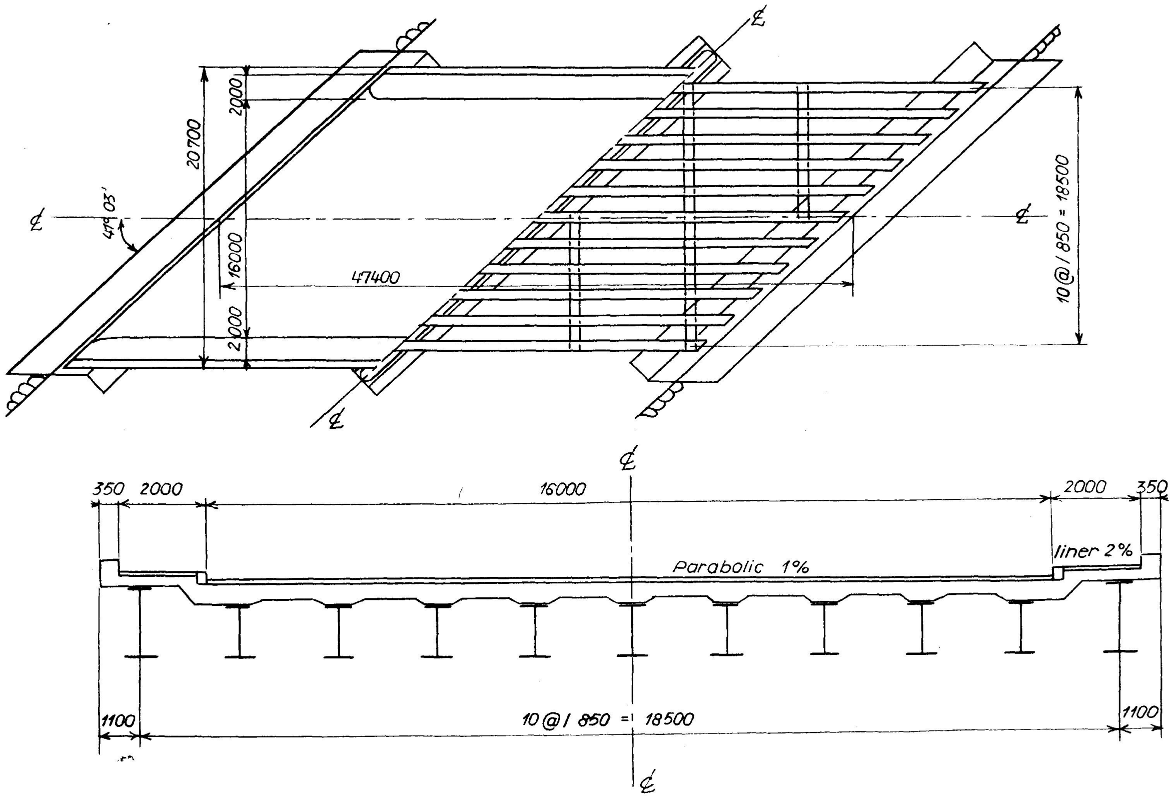

Fig. 6. General Plan and Section of the "Utajima Bridge".

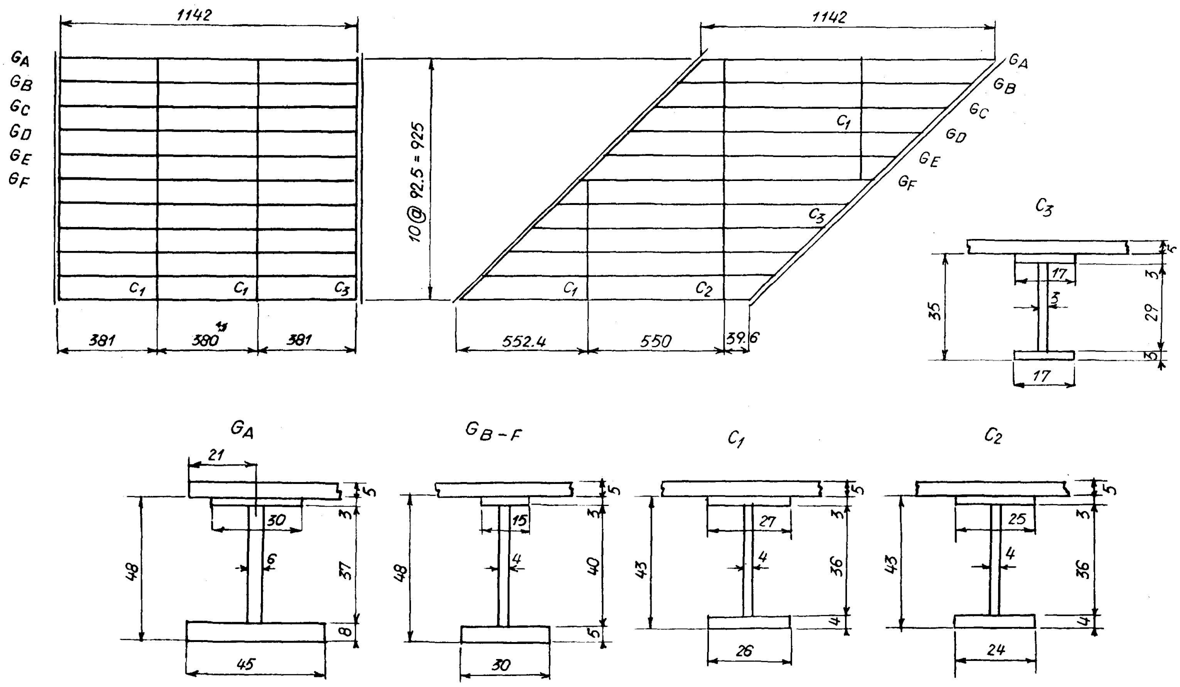

Fig. 7. General Plan and Section of the Model Bridge.

A steel angle was used as the supporting frame to which a round steel bar was welded as the supporting line. The model girders were connected to the supporting line by steel wire in order to prevent them from rising. The lower part of supporting frame was anchored to the concrete bed of 10 cm thickness.

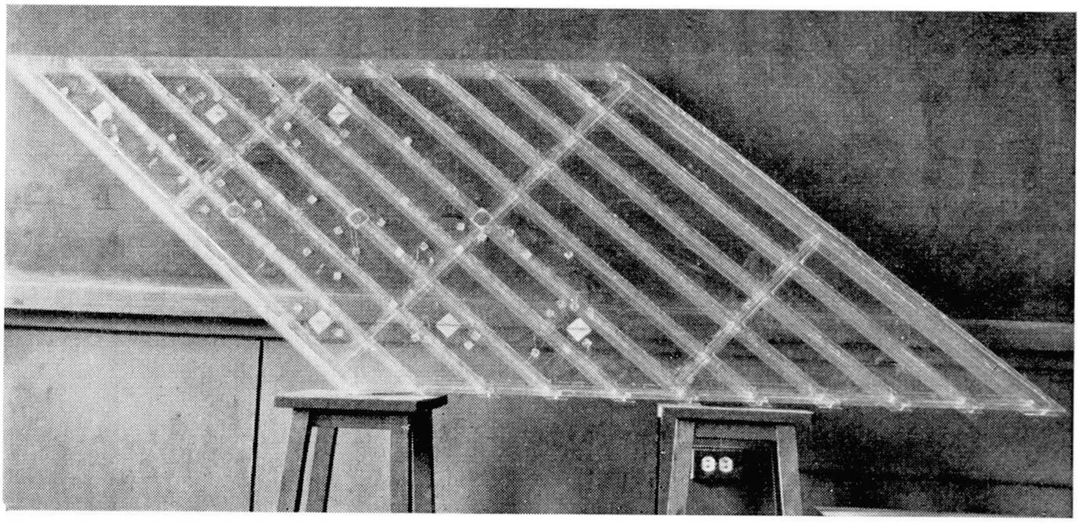

Fig. 8. Model Skew Bridge.

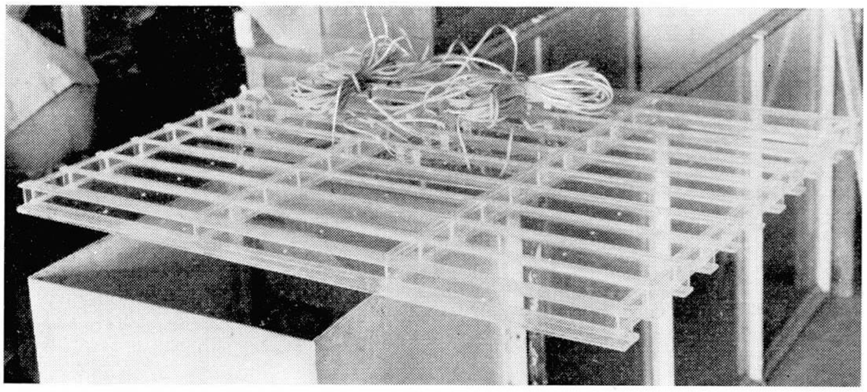

Fig. 9. Model Right Bridge.

2. Loading and Measurement

The deflection of the girders was measured by dial gage and the strain by electrical resistance wire strain gage of polyester base. The dial gages were arranged at the points of six equi-distant intervals for the girder $A \sim F$. The strain gages were cemented on upper and lower flanges of the main and cross girders.

The concentrated loads of 5 kg and 15 kg were applied to the points of six equi-distant intervals of the main girders (total 55 points) for the case of the grillage girder and of the grillage girder bridge, respectively. For the tests on cross girder and slab, representative loads were applied additionally.

3. *Numerical Analysis of Skew Girder Bridge by the Theory of Orthotropic Plates*

The skew network shown in Fig. 10 was used to cover the orthotropic parallelogram plate. The span was divided into six equi-distant intervals and the width between the edge girders into ten equi-distant intervals. The network lines in the longitudinal direction coincide with the axis of each main girder, the total number of network points was 55.

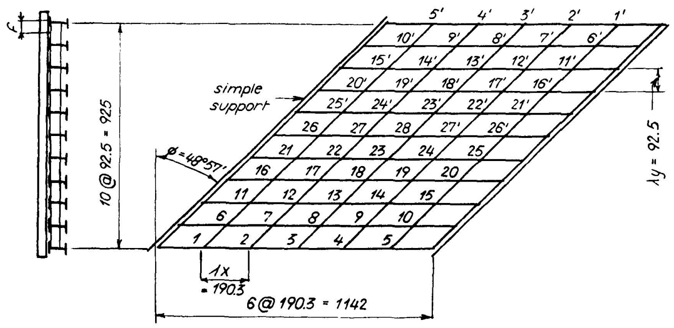

Fig. 10. Skew Network for Model Bridge.

The characteristic values of this skew network are as follows, according to the notations used in the author's paper:

$$\alpha = \left(\frac{B_y}{B_x}\right)^{1/2} = 0.317, \qquad K = \frac{\lambda_y}{\lambda_x} = 0.486,$$

$$A = \frac{K^2}{\alpha} = 0.745, \qquad B = K \tan\varphi = 0.558, \qquad J = \frac{1}{\alpha^2}\frac{K^4}{\lambda_y}\left(\frac{EI_r}{B_x} - f\right) = 0.496.$$

The edge condition are the same as those used by W. CORNELIUS.

The torsional parameter $\kappa = H/(B_x\, B_y)^{1/2}$ was assumed as 0.5 under the consideration that the torsional rigidity of the model bridge is larger than that of the actual bridge. The stiffness matrix, flexibility matrix and the influence coefficients of deflection and bending moment of the orthotropic plates derived by the numerical method of analysis are omitted here because of space limitation. The matrix inversion was done with the aid of ILLIAC.

4. *Results of Experiments*

For the case of right grillage-skew girder bridge, Table 6 shows the comparison of the observed values of deflection at the mid-span section of each girder under the concentrated load of 15 kg applied to the same section of the each girder with the theoretical values which were calculated by the theory of orthotropic plates and also by the right grillage-skew girder method. The latter method means the structural analysis method of statically indeterminate structure with 23 redundants (interaction forces between main girder and

Table 6. Measured Deflection at the Mid-span Sections of Each Girder and Their Comparison with Theoretical Ones (unit: 0.01 mm) (concentrated load: 15 kg)

Load		w_3	w_8	w_{13}	w_{18}	w_{23}	w_{28}	$w_{23'}$	$w_{18'}$	$w_{13'}$	$w_{8'}$	$w_{3'}$
3	*M*	114.0	72.5	41.0	22.0	14.0	7.0	3.0	3.5	2.5	1.0	2.0
	P	113.3	72.8	43.4	25.0	14.3	8.4	4.9	2.9	1.7	0.9	0.4
	G	144.6	110.0	83.8	58.1	40.3	28.9	19.5	13.3	9.9	8.4	5.3
8	*M*	70.5	67.0	39.0	22.0	15.5	5.5	4.5	3.0	1.0	1.0	1.5
	P	72.8	65.5	48.2	32.5	21.2	13.6	8.6	5.4	3.3	1.9	0.9
	G	87.2	107.5	70.0	51.2	36.8	27.2	18.8	12.9	10.1	7.9	5.5
13	*M*	39.0	39.5	49.0	26.0	18.0	6.5	4.5	2.5	1.5	1.0	2.5
	P	43.4	48.2	52.5	42.8	31.1	21.4	14.2	9.1	5.6	3.3	1.7
	G											
18	*M*	17.0	23.5	31.5	48.0	33.5	18.0	13.5	8.0	4.5	3.0	5.0
	P	25.0	32.5	42.8	50.7	42.8	31.7	21.8	14.5	9.1	5.4	2.9
	G	37.4	51.4	52.9	76.4	51.4	39.3	28.9	21.0	15.6	12.9	8.5
23	*M*	13.0	15.0	19.5	31.5	48.5	29.0	22.5	15.0	10.0	7.5	7.5
	P	14.3	21.2	31.1	42.8	51.2	43.3	32.0	21.8	14.2	8.6	4.9
	G											
28	*M*	8.5	10.5	12.5	19.5	34.5	37.0	30.0	21.5	14.0	9.5	10.0
	P	8.4	13.6	21.4	31.7	43.3	51.6	43.3	31.7	21.4	13.6	8.4
	G	14.2	24.0	31.6	42.5	53.4	58.3	53.4	42.5	31.6	24.0	14.2

Table 7. Measured Deflection Along Each Girder under the Mid-span Concentrated Load 15 kg and Their Comparison with Theoretical Ones (unit: 0.01 mm)

Load		w_1	w_2	w_3	w_4	w_5	Load		w_6	w_7	w_8	w_9	w_{10}
3	*M*	56.5	99.0	114.0	90.5	45.5	8	*M*	25.0	49.5	67.0	45.0	18.0
	P	48.1	90.6	113.3	91.3	47.8		*P*	27.5	53.0	65.5	49.7	23.3
	G	67.5	120.5	144.6	126.6	73.7		*G*	45.2	84.0	107.5	85.8	38.8
Load		w_{11}	w_{12}	w_{13}	w_{14}	w_{15}	Load		w_{16}	w_{17}	w_{18}	w_{19}	w_{20}
13	*M*	11.0	30.5	49.0	32.0	7.0	18	*M*	11.0	34.0	48.0	27.0	6.0
	P	20.3	41.6	52.5	39.8	19.6		*P*	20.2	38.6	50.7	39.2	20.0
	G							*G*	25.7	60.3	76.4	66.2	20.3
Load		w_{21}	w_{22}	w_{23}	w_{24}	w_{25}	Load		w_{26}	w_{27}	w_{28}		
23	*M*	16.0	37.5	48.5	38.5	12.0	28	*M*	11.0	28.5	37.0		
	P	20.4	39.9	51.2	40.0	20.0		*P*	20.7	40.2	51.6		
	G							*G*	28.6	49.9	58.3		

Table 8. Measured Strains at the Mid-span Sections of Each Girder and Their Comparison with Theoretical Ones (Unit: 10^{-6}) (concentrated Load: 15 kg)

Load		Strain																					
		ϵ_3		ϵ_8		ϵ_{13}		ϵ_{18}		ϵ_{23}		ϵ_{28}		$\epsilon_{23'}$		$\epsilon_{18'}$		$\epsilon_{13'}$		$\epsilon_{8'}$		$\epsilon_{3'}$	
		L	*U*	*L*	*U*	*L*	*U*	*L*	*U*	*L*	*U*	*L*	*U*	*L*	*U*	*L*	*U*	*L*	*U*	*L*	*U*	*L*	*U*
3	*M*	255	−220	190	−105	70	−70	55	−25	45	−15	50	−15	20	−15	30	−5	10	−5	5	−5	0	−15
	P	251	−306	225	−118	115	−60	57	−30	29	−15	17	−9	10	−5	6	−3	4	−2	2	−1	1	−1
	G	273	−333	321	−171			100	−53			69	−37			28	−14			16	−9	11	−13
8	*M*	185	−190	295	−170	85	−85	60	−25	35	−20	50	−15	35	−10	20	−5	15	−5	15	−0	15	−10
	P	138	−169	245	−128	153	−80	85	−44	48	−25	29	−15	18	−9	11	−6	7	−4	4	−2	2	−2
	G	163	−199	547	−291			101	−54			75	−40			29	−16			17	−9	12	−15
13	*M*	105	−125	125	−70	275	−160	130	−60	55	−30	65	−25	30	−20	20	−10	10	−5	10	−5	10	−15
	P	73	−89	157	−82	204	−107	135	−71	81	−42	49	−25	30	−16	19	−10	12	−6	7	−4	3	−4
	G	101	−123	166	−88			108	−58			89	−48			35	−19			21	−11	14	−17
18	*M*	60	−75	60	−35	140	−70	250	−130	95	−55	85	−35	40	−25	30	−15	20	−15	20	−10	15	−20
	P	40	−48	91	−48	138	−72	207	−108	134	−70	82	−43	48	−25	31	−16	20	−10	12	−6	5	−6
	G	73	−88	112	−59			535	−28			113	−60			48	−25			26	−14	19	−23
23	*M*	45	−45	35	−30	55	−40	85	−55	245	−100	110	−40	75	−30	40	−15	30	−15	30	−10	10	−20
	P	23	−27	53	−28	83	−43	134	−70	197	−103	136	−71	83	−43	49	−25	31	−16	20	−10	8	−10
	G	52	−64	76	−40			113	−60			146	−78			66	−35			38	−20	27	−33
28	*M*	30	−35	25	−20	40	−25	60	−25	90	−35	175	−50										
	P	13	−16	32	−16	50	−26	83	−43	136	−71	197	−103										
	G	39	−48	55	−29			89	−48			157	−83										

Table 9. Measured Strain Along Each Girder and Their Comparison with Theoretical Ones (unit: 10^{-6}) (concentrated load: 15 kg)

Load		Strain									
		ϵ_1		ϵ_2		ϵ_3		ϵ_4		ϵ_5	
		L	*U*	*L*	*U*	*L*	*U*	*L*	*U*	*L*	*U*
3	*M*	45	55	165	100	255	220	170	170	80	85
	P	24	30	120	146	251	306	110	134	32	39
	G	119	144	195	237	273	333	163	198	81	99
		ϵ_6		ϵ_7		ϵ_8		ϵ_9		ϵ_{10}	
		L	*U*	*L*	*U*	*L*	*U*	*L*	*U*	*L*	*U*
8	*M*	55	20	125	80	295	170	55	65	20	40
	P	28	15	94	49	245	128	113	59	17	9
	G	115	61	216	115	547	291	102	55	51	27
		ϵ_{11}		ϵ_{12}		ϵ_{13}		ϵ_{14}		ϵ_{15}	
		L	*U*	*L*	*U*	*L*	*U*	*L*	*U*	*L*	*U*
13	*M*	40	30	90	35	275	160	40	10	20	10
	P	5	3	66	34	204	107	82	43	9	5
		ϵ_{16}		ϵ_{17}		ϵ_{18}		ϵ_{19}		ϵ_{20}	
		L	*U*	*L*	*U*	*L*	*U*	*L*	*U*	*L*	*U*
18	*M*	30	0	0	55	250	130	115	45	40	25
	P	7	4	67	35	207	108	51	26	18	9
	G	71	38	65	34	535	284	155	83	113	60
		ϵ_{21}		ϵ_{22}		ϵ_{23}		ϵ_{24}		ϵ_{25}	
		L	*U*	*L*	*U*	*L*	*U*	*L*	*U*	*L*	*U*
23	*M*	5	5	20	10	245	100	115	45	0	0
	P	10	5	71	37	197	103	71	37	8	4
		ϵ_{26}		ϵ_{27}		ϵ_{28}					
		L	*U*	*L*	*U*	*L*	*U*				
28	*M*	0	10	95	35	175	50				
	P	10	5	71	37	197	103				
	G	64	34	110	59	157	83				

cross girder, 11 for the center cross girder and 2 times 6 for the side cross girders). Both methods are called briefly as the plate method (P) and grillage method (G).

For the same case, Table 7 shows the comparison of the observed values of deflection of the loaded girder with the calculated values of the loaded girder under the concentrated load applied to the mid-span section of each girder.

Tables 8 and 9 show the comparison between the observed and calculated values of strain, corresponding to both cases of Table 6 and 7 respectively.

According to these tables, the theory of orthotropic plates gives a good agreement between the observed and theoretical values. On the contrary, a considerable difference is found between the observed and theoretical values by the grillage girder theory. This difference is due to the fact that it neglects

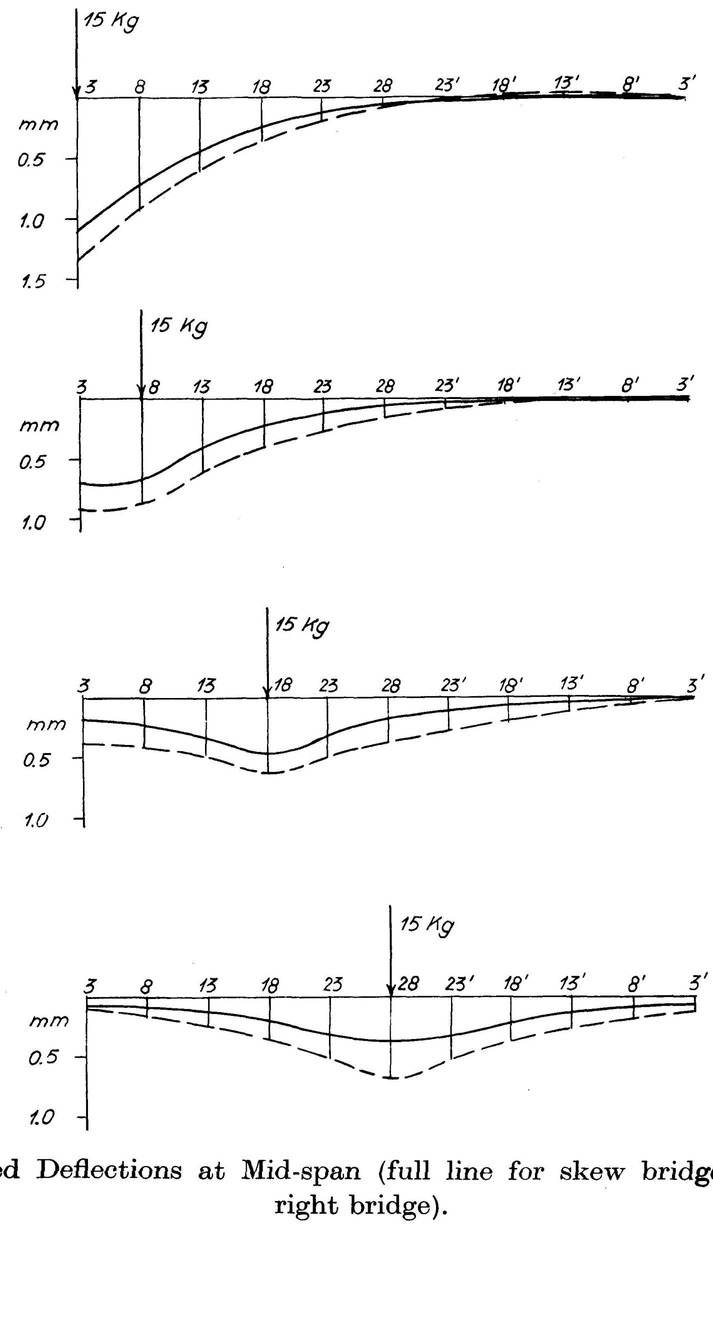

Fig. 11. Measured Deflections at Mid-span (full line for skew bridge, dotted line for right bridge).

the torsional rigidity of the girder and also the load distribution of the slab which connects many main girders and cross girders.

Fig. 11 shows the deflection measured at the mid-span section of each girder under the concentrated load of 15 kg applied to the mid-span section of each girder for the case of right grillage-right and skew girder bridges. Fig. 12 shows the measured values of deflection along each girder under the concentrated load applied to the mid-span section of the girder. Fig. 13 shows the measured values of bending moment at the mid-span section, calculated by the measured values of strain, corresponding to the loading states for Fig. 11,

These figures show that the measured values of stress and deflection of the right grillage-skew girder bridge are smaller than those of right grillage-right

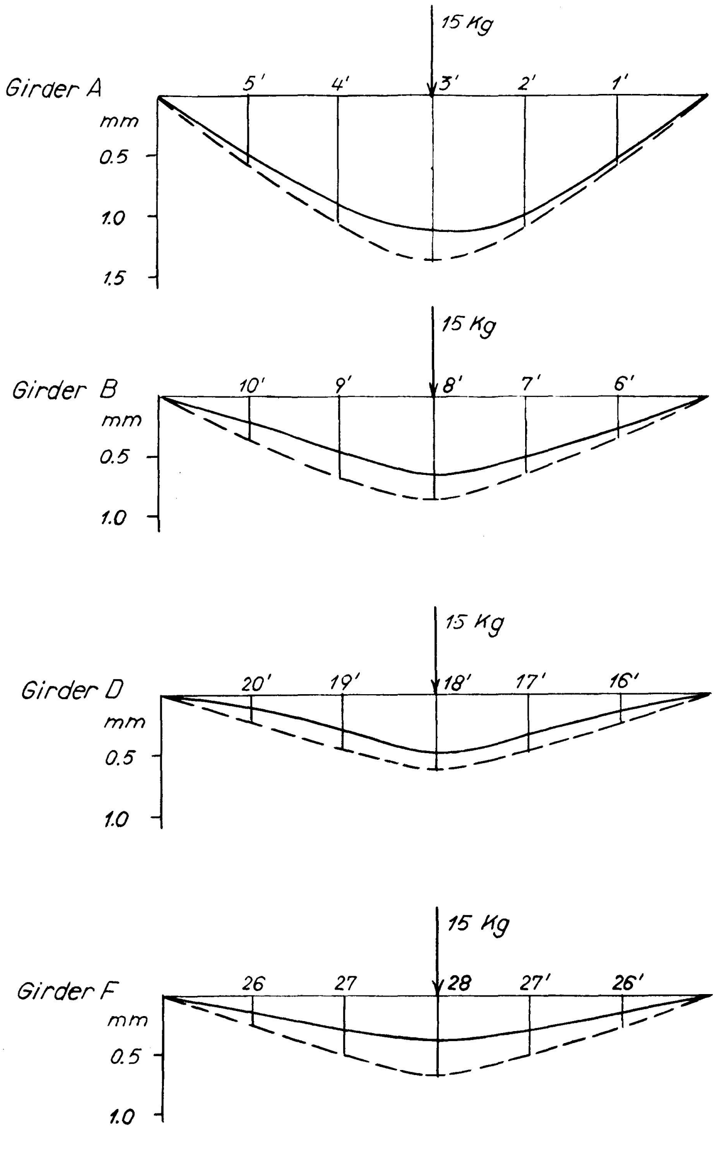

Fig. 12. Measured Deflections at Each $l/6$ Section (full line for skew bridge, dotted line for right bridge).

girder bridges with the same characteristic values, and that the former has a better load distribution than the latter. It will be made clear that there will be an important difference between the right grillage-right and skew girder bridges.

The strain in lower flange of the cross girder was measured on the mid-span section of the cross girder when the concentrated load of 15 kg was applied to the section. The results were 280×10^{-6} for the right grillage-right girder, 228×10^{-6} for the right grillage-right girder bridge, 534×10^{-6} for the right grillage-skew girder and 324×10^{-6} for the right grillage-skew girder bridge. From these values, it can be found that the composite effect is significant in the case of skew girder bridge. Also, the strain of cross girder of the right

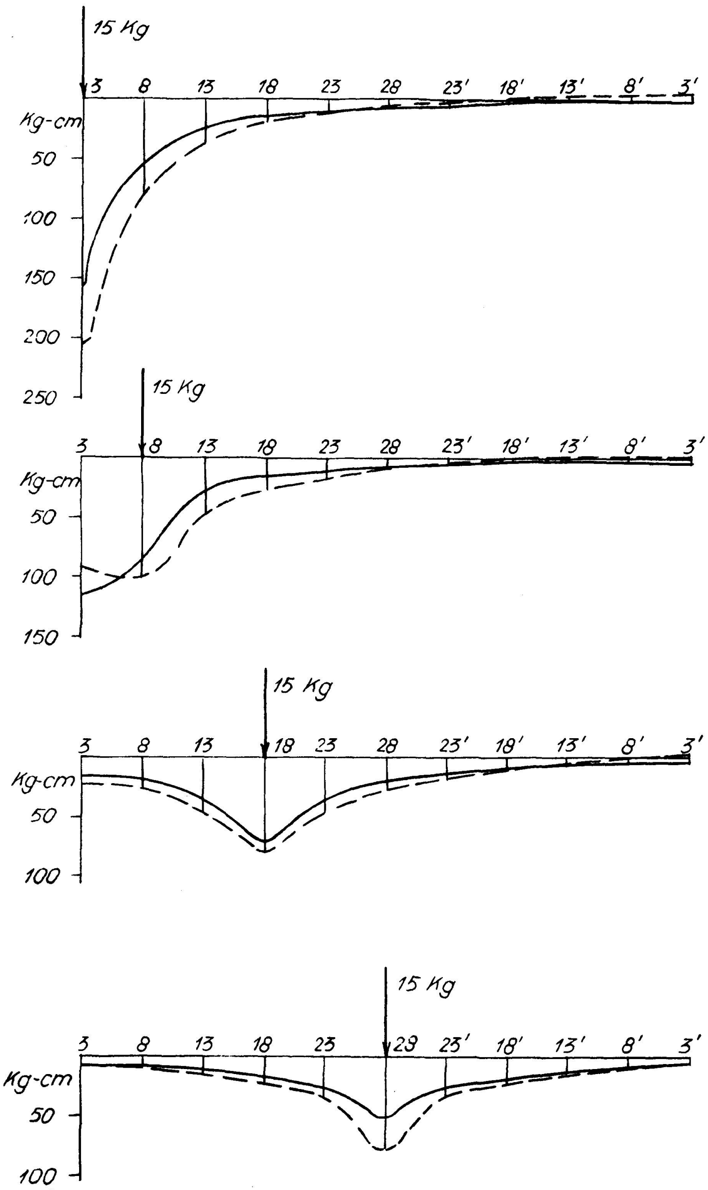

Fig. 13. Measured Bending Moments at Mid-span (full line for skew bridge, dotted line for right bridge).

grillage-skew girder bridge is larger than that of the right grillage-right girder and girder bridge. This is due to the fact that both ends of the cross girder are close to the supports of the bridge and the cross girder can be assumed as a simply supported girder, and therefore, the load carrying capacity is larger in the case of skew bridge than that in the case of right bridge.

Conclusion

The model tests on skew girder bridge and right grillage-skew girder bridge were made by the carefully prepared models of which the characteristic values are proportional to those of the prototype bridge, and the measured values of deflection and bending moment were compared with the theoretical values calculated by the authors' numerical method of analysis of the theory of orthotropic plates. Moreover, in Part 1, the comparison of measured values of deflection and bending moment was given for both skew girder bridges with and without sway bracings. In Part 2, the observations on the right grillage-right girder model bridge which has the same characteristic values as those of right grillage-skew girder model bridge except the skew angle were obtained to compare with those for the latter. These comparisons give us the more accurate and useful informations and knowledges than those obtained formerly by the authors.

As can be understood, the numerical method of analysis of the theory of orthotropic plates does not seem quite satisfactory for the accurate and exact analysis of skew girder bridge, but it gives the fairly good results in general and offers a powerful tool to the design of skew girder bridges at present when no other method has yet been proposed.

Acknowledgement

The inversion of 33×33, 32×32, 28×28 and 27×27 elements matrices was solved with the aid of ILLIAC in order to obtain the influence coefficients of deflection and bending moment of the plate. The authors wish to express their sincere thanks to staff members of the Digital Computer Laboratory of the University of Illinois for their assistance and operation.

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Summary

The tests on skew girder bridges were made on two models of which the characteristic values are proportional to those of the existing skew girder bridge and right grillage-skew girder bridge. Moreover, for the latter, the observations on the right model bridge which has the same characteristic values were made to compare them with those for the skew model bridge. The comparisons of the measured values of stress and deflection with the theoretical values for both cases and also those for the cases of skew and right bridges gave the results that the theory of orthotropic plates was a powerful tool to the design and analysis of skew girder bridges when another method has not yet been proposed.

Résumé

Les deux modèles utilisés pour ces essais sur ponts biais à poutres multiples étaient des réductions à l'échelle de deux ouvrages existants, avec des entretoises parallèles aux culées dans l'un des cas, perpendiculaires aux poutres dans l'autre. Pour ce dernier, on a de plus effectué, à titre de comparaison, des mesures sur un modèle de pont droit présentant les mêmes caractéristiques. Pour toutes les dispositions étudiées, on a comparé aux valeurs calculées les contraintes et les flèches mesurées; il s'avère que la théorie des plaques orthotropes, à défaut d'autres méthodes, est un instrument bien adapté à l'étude et au calcul des ponts biais à poutres multiples.

Zusammenfassung

Zur Untersuchung schiefer Trägerrostbrücken wurden zwei Modelle hergestellt, deren maßgebende Größen proportional sind denjenigen von zwei bestehenden schiefen Brücken. Die eine weist parallel zu den Widerlagern angeordnete Querträger auf, die andere senkrecht zu den Hauptträgern verlaufende Querträger. Für die zweite Anordnung wurde zudem ein orthogonales Modell mit identischen Abmessungen und Querschnittswerten untersucht, um einen Vergleich zwischen schiefer und gerader Modellbrücke anstellen zu können. Der Vergleich der gemessenen Spannungen und Deformationen mit den theoretisch ermittelten Werten zeigte für beide Konstruktionsarten und für schiefe wie gerade Brücke, daß die Theorie der orthotropen Platten eine nützliche und zutreffende Methode zur Untersuchung schiefer Trägerrostbrücken darstellt, solange keine besseren Lösungsmöglichkeiten vorgeschlagen werden.

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