Structural Eng./Earthquake Eng. Vol. 4. No. 2, 331s-340s. October 1987
Japan Society of Civil Engineers (Proc. of JSCE No. 386/I-8)

ANALYSES OF SWAY BRACING MEMBERS IN COMPOSITE-GIRDER BRIDGES

By Nobutoshi MASUDA, Chitoshi MIKI**, Hiroyuki KASHIWAGI****
*and Hiroshi KAIDOH*****

A simple analysis method is presented for calculation of forces in sway bracing members of composite-girder bridges. The purpose of development of this method is its application to evaluation of effects of structural types and loading conditions on fatigue crack growth in the region of welds at tops of transverse stiffeners for main girders.

Reinforced concrete floor slabs and main girders are modeled by three-dimensional plate elements, and originally introduced offset beam elements with six degrees of freedom per node, respectively. Sway bracings are considered as plane frames, and stiffness matrices of plane frames are contracted to make sway bracing elements whose nodal points are set only on the planes of floor slabs. Thus, an entire bridge is modeled as a stiffened plate.

Calculated results show that maximum axial forces in sway bracing members coincide well with those obtained by measurements on a bridge in service. The differences between the calculated and measured values are less than 20 percent.

Keywords : stiffened plate analysis, offset beam element, sway bracing element, transverse stiffner web gap.

1. INTRODUCTION

It has been frequently reported in recent years$^{1)\sim5)}$ that various types of cracks as shown in Fig. 1 have occurred at and near welds at the top ends of transverse stiffeners for main girders with floor beams or sway bracing members in composite girder bridges. In Japan, occurrences of such cracks have been reported for parts adopted as standard forms of attaching floor beams and sway bracing members for highway bridges up to the early 1970 s. Accordingly, explanations of the occurrence mechanisms of cracks, prevention of crack occurrence, and measures for reinforcement after occurrence are considered as problems requiring solutions$^{6)\sim10)}$.

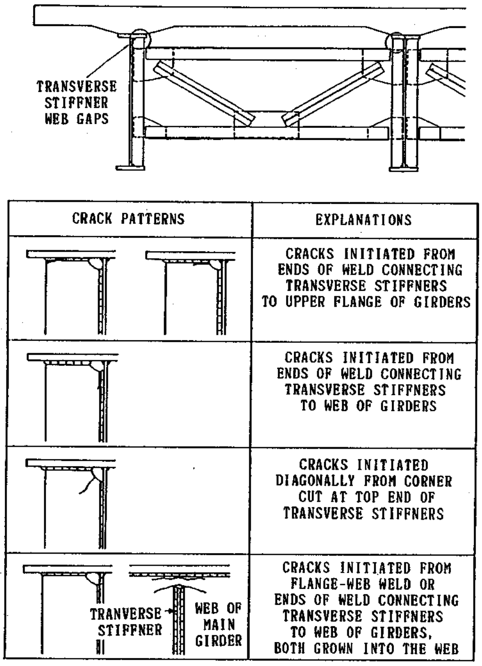
The causes of cracking are thought to be local stresses due to differences in deflections of main girders with floor beams or sway bracing members and due to deformations of reinforced concrete floor slabs$^{1),3),11),12)}$. The properties of these local stresses can be estimated to vary depending on factors such as the number of main girders, spacing of main girders, thickness of reinforced concrete floor slabs, structures of floor beams and sway bracing members, and locations of vehicle lanes. Consequently, evaluations of the influences of the various factors concerned with the occurrence and properties of these local stresses are important for explaining the occurrence mechanisms and for studying methods of reinforcement.

For evaluating the influences of various factors concerning the occurrence of local stresses and their

---

* Member of JSCE, Dr. Eng., Associate Professor, Dept. of Civil Eng., Musashi Inst. of Tech. (Setagaya-ku, Tokyo)
** Member of JSCE, Dr. Eng., Associate Professor, Dept. of Civil Eng., Tokyo Inst. of Tech. (Meguro-ku, Tokyo)
*** Member of JSCE, M. Eng., The Tokyo Electric Power Company, Inc., (Formerly Graduate Student of Tokyo Inst. of Tech.) (Futaba-gun, Fukushima)
**** Member of JSCE, M. Eng., Kawada Industries, Inc., (Formerly Graduate Student of Musashi Inst. of Tech.) (Kita-ku, Tokyo)

properties, the methods conceivable are evaluation upon measurements of bridges in service and evaluation made analytically. Of these, the method of evaluation by only measurements on bridges in service has difficult aspects because cracks occur with multiple factors intertwined, and is not advantageous from the aspect of expense. Consequently, it becomes necessary for evaluation to be made analytically, and methods of performing detailed analyses of partial structures using measured values[13),14)] have been considered. As purely analytical methods of evaluation, those used in the past have been to carry out analysis on substituting a grillage structure for the entire bridge[1),8)], and to perform three-dimenstional finite element analysis on modeling the entire bridge as a three-dimensional structure composed of thin plates[1),9)]. However, with the method of analyzing on substituting a grillage structure, although it is possible to determine the influence of differences in deflections of main girders, the deformation of reinforced concrete slabs cannot be directly evaluated, while problems remain concerning evaluation of effective width and the influence of vehicle lane location. On the other hand, the method of three-dimensional finite element analysis requires enormous amounts of data and calculations and is not necessarily desirable from the aspect of its economics. Therefore, it cannot be said under present circumstances that an effective method of evaluating local stresses in a purely analytical manner has been established.



CRACK PATTERNS	EXPLANATIONS
	CRACKS INITIATED FROM ENDS OF WELD CONNECTING TRANSVERSE STIFFNERS TO UPPER FLANGE OF GIRDERS
	CRACKS INITIATED FROM ENDS OF WELD CONNECTING TRANSVERSE STIFFNERS TO WEB OF GIRDERS
	CRACKS INITIATED DIAGONALLY FROM CORNER CUT AT TOP END OF TRANSVERSE STIFFNERS
	CRACKS INITIATED FROM FLANGE-WEB WELD OR ENDS OF WELD CONNECTING TRANSVERSE STIFFNERS TO WEB OF GIRDERS, BOTH GROWN INTO THE WEB

Fig. 1 Crack patterns[5)]

Upon returning to the original standpoint of explaining the mechanism of crack occurrence which is the objective of local stress analysis, what draw attention are the investigation results from actual bridges in service[15)] that transverse stiffeners at which cracks are seen all have sway bracing members attached, while occurrences of cracks have not been observed at transverse stiffeners with no sway bracing members. In essence, whichever is the principal cause of local stresses, difference in deflections of main girders or deformations of reinforced concrete floor slabs, it can be conjectured that forces transmitted from sway bracing members cause the cracking.

Therefore, in this paper, a simple analysis method for sway bracing members in which the influences of factors such as the previously-mentioned vehicle lanes can be easily incorporated is proposed with the purpose of examining fatigue at and near top-end weld portions of transverse stiffeners by means of forces in sway bracing members taking into consideration the present situation where, as mentioned previously, effective methods of analyzing local stresses have not been established. With regard to analyses of forces in sway bracing members, there was a case in the past in which analysis was performed as three-dimensional structures with reinforced concrete slabs and main girders modeled as thin plates and sway bracing members as beam elements[9)], but in spite of detailed finite element method analyses, results of good precision have not necessarily been obtained. The analysis method described in this paper is similar to the method proposed by Oshita and Kaneko[16)] for analysis of composite girder bridges, in the sense that offset beam elements are introduced and the plate element of Ref. 17) is used. However, what they had focused on was pointing out the problematic points of grillage analysis in designing main girders, to differ from the objective of this paper. This analysis method had been reported in Ref. 18) before the paper of Oshita and Kaneko was presented, and the points that offset beams of six degrees of freedom per node were newly introduced and sway bracing members were modeled as plane frame structures differ from the method of Oshita and Kaneko. Oshita and Kaneko substituted thin straight beams of seven degrees of freedom per node for main girders and floor-beams, truss structures for lateral bracings, and made connections with the thin-plate elements of Ref. 17) through conventional offset beam elements.

In existing composite-girder bridges, stringers have been added along with which sway bracing members have been strengthened (hereafter this total procedure is called "reinforcing" or "reinforcement") to reduce deflection of reinforced concrete floor slabs aiming to prevent occurrence of cracking of slabs or to prevent growth of cracks. The depths of stringers and cross sectional areas of sway bracing members to be added have shown trends of increase year by year. At present, studies are being made by various agencies concerned regarding measures to prevent occurrence of cracks at the attachment locations of transverse stiffeners. It can also be seen that a secondary effect of preventing occurrence of cracks at the top ends of the transverse stiffeners is hoped to be obtained by the abovementioned reinforcement of reinforced concrete floor slabs. However, quantitative considerations have not been given to what kind of influence such reinforcing of slabs will have, and this is a matter that should be examined in future reinforcing of floor slabs.

In this paper, along with examining the precision of the analysis method through comparisons with measured values, calculations are made of how forces in sway bracing members will change through addition of stringers, reinforcing of sway bracing diagonals and lower struts, or increase in slab thickness which have conventionally been carried out as part of cracking damage repairing or preventing measures of reinforced concrete floor slabs and it is shown that this analysis method is applicable in evaluation of the influences of these on forces in sway bracing members.

2. ANALISIS METHOD PROPOSED

The entire bridge under consideration is modeled as shown in Fig. 2 with reinforced concrete floor slabs as thin plate elements, main girders as offset beam elements, and sway bracings as sway bracing elements described later in this paper. In effect, analysis is performed with the entire bridge modeled as a stiffened plate since the main girders and sway bracings are considered as stiffeners with offsets. The results are used to obtain member forces occurring in sway bracings[18]. In modeling, the nodes of offset beam elements and sway bracing elements are directly positioned at nodal points of thin plate elements representing reinforced concrete floor slabs, the offsets being included in calculations at the stage of evaluating stiffnesses of elements.

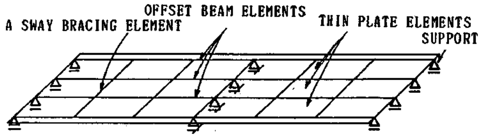


Fig. 2 Modeling of the whole structure

(1) Modeling of bridge

a) Modeling of Reinforced Concrete Floor Slabs by Thin Plate Elements

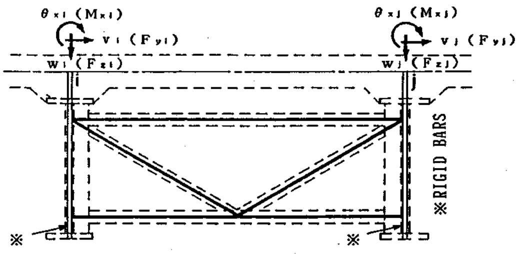
Floor slabs are modeled by triangular thin plate elements having six degrees of freedom per node, a total of 18 degrees of freedom, derived by the assumed stress hybrid method shown in Ref. 17).

b) Modeling of Main Girder by Offset Beam Element

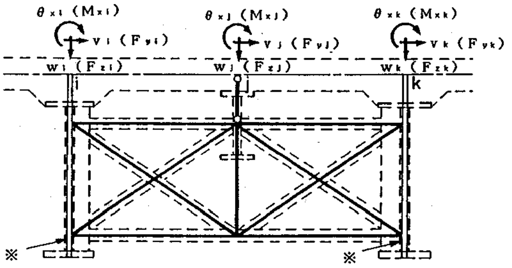
The influences of offsets on beam elements are often considered[16] by coordinate transformation[19] of their nodal displacements, where nodes are set on the neutral axes, to nodal displacements of plate elements connected with these beam elements. When offsets are considered by this method, errors are included except in case of pure bending[20]. In this paper, therefore, main girders are modeled by offset beam elements[20] whose stiffness matrices are derived by the conventional method, but directly representing displacement fields conforming with the elementary beam theory using the nodal displacements of offset beam elements provided on the neutral planes of floor slabs. An offset beam element of this kind has six degrees of freedom to a node. For evaluating influences of phenomena such as turning of web gaps (the parts between top flanges of main girders and locations of upper strut member attachment), it is thought necessary for a degree of out-of-plane deformation to be given in modeling of a main girder, but elements of six degrees of freedom per node are used here with the primary object simplicity of the analysis method.

c) Modeling of Sway Bracing by Sway Bracing Element

In correspondence with main girders having been modeled by offset beam elements that do not represent cross-sectional deformation, sway bracings are modeled by plane frame structures having rigid bars of the kind shown in Fig. 3(a), (b) at their both sides. Nodes of sway bracing elements (points *i*, *j*, or *i*, *j*, *k* in the figure) are made to coincide with the nodes on the sway bracing planes of the offset beam elements representing main girders. The stiffness matrix of the plane frame is contracted into a stiffness matrix of two nodes totaling six degrees of freedom (or, three nodes totaling nine degrees of freedom) in the floor slab plane leaving only the degrees of freedom of nodes *i*, *j* (or nodes *i*, *j*, *k*) of the stiffness matrix of the plane frame. The stiffness matrix obtained in this manner is taken as the sway bracing element stiffness matrix.



(a) MODEL OF A SWAY BRACING BEFORE REINFORCEMENTS



(b) MODEL OF A SWAY BRACING AFTER REINFORCEMENTS

Fig. 3 Modelization of sway bracings

In the sway bracing element after the reinforcement, the stringers are modeled by offset beam elements similarly to main girders.

(2) Sway bracing member force

The displacement of the floor slab is obtained modeling the entire bridge using these component elements and by performing analysis under the restraint conditions shown in Fig. 2 and the loading conditions given. By giving the displacement of the floor slab at the nodes *i* and *j* (*i*, *j*, and *k* in case of sway bracing element after reinforcing) as forced displacement to perform frame structure analysis, it is possible to obtain the member forces of the various members composing the sway bracing.

3. NUMERICAL CALCULATIONS AND MEASUREMENTS ON ACTUAL BRIDGE

Analyses were performed on an actual bridge in service on which measurements had been made of reinforced concrete floor slab deflections and sway bracing member forces before and after reinforcing such as by increasing stringers as a part of repair measures for cracking damage of floor slabs, and the accuracy of the analysis method was examined through comparisons of measured values[15] and analytical values. The measured values were forces in members obtained attaching strain gauges to sway bracing members located at the middle of the center span and reading the strain when a truck having the specified weight was made to travel over the vehicle lane. Regarding deflections, those of the main girders and stringers to which the subject sway bracings were provided (in measurements before addition of stringers, the floor slabs at locations where addition of stringers were planned) were measured.

(1) Actual bridge in service and modeling thereof

a) Bridge Analyzed and Element Division

The object of analysis was the composite bridge with four main girders and three-continuous-spans as shown in Fig. 4. The bridge had additions of stringers possessing moments of inertia about one-tenth of main girders and accompanying reinforcements of diagonals and lower struts of sway bracings for the purpose of reinforcing floor slabs. The number of main girders, spacing of main girders, length of top-end gap of transverse stiffener, and type of reinforcing as a measure against cracking of floor slabs were those used frequently in typical highways in Japan.

The element mesh division diagram for this object of analysis is shown in Fig. 5. The bold lines indicate the locations where main girder and sway bracing elements were arranged. The A_i in the diagram indicates the number of the main girder, the numerals the numbers of sway bracings, P 24, P 25 and P 26 the numbers of piers, and A'2 the number of the abutment.

b) Loading conditions

The loads applied were rear wheels of T-20 load as specified in the Highway Bridge Specifications[21] (each 8 tf (78.4 kN)) totaling 16 tf (156.8 kN) at the sway bracing location at the center of the middle span (the location indicated by ○ marks in the diagram ; hereafter called" center section") and front wheels (each 2 tf (19.6 kN)) totaling 4 tf (39.2 kN) at locations of the ● marks in the diagram. Because of the dimensions of the floor slab elements as mentioned previouusly, calculations were performed with the loading conditions of spacing between front and rear wheels of 3.75 m, 6 percent shorter than the 4 m of T-20 load, and 1.70 m spacing between right and left wheels, 3 percent shorter than the 1.75 m of T-20.

c) Restraint Conditions

To correspond with the actual bridge, displacements were restrained in the Y and Z directions for the support locations of piers P 24 and P 26 and abutment A'2, and in the X, Y, and Z directions at the support location of pier P 25.

(2) Results of analysis of entire structure before reinforcing

a) Deflection of Reinforced Concrete Floor Slab

The measured and analytical values of floor slab deflection at the center section are shown in Fig. 6 (a). The difference between the two at maximum deflections is 0.2 mm (approximately 6 percent) and the two are in very good agreement.

b) Axial Forces of Sway Bracing

The measured and analytical values of sway bracing axial force at the center section are shown in Fig. 6 (b). Regarding the upper strut axial forces of the right and left panels, there is a discrepancy in the analytical and measured values that the former indicate tensile forces while the latter compressive, however the analytical values are close to measured

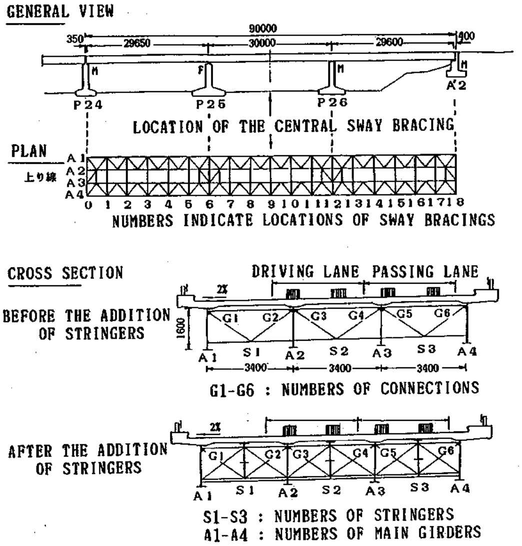


Fig. 4 The three-span continuous composite girder bridge with four-main-girders to be analized

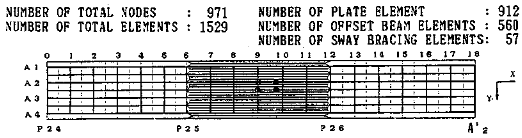
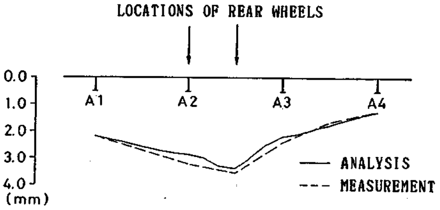
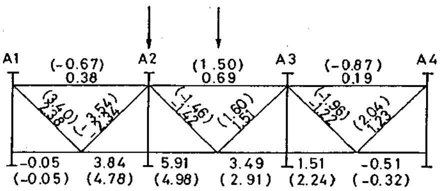


Fig. 5 Element division for the analysis object



(a) COMPARISON OF CONCRETE SLAB DEFLECTIONS



NUMERALS IN PARENTHSES INDICATE MEASURED VALUES
TENSILE FORCES ARE TREAED AS POSITIVE

(b) COMPARISON OF FORCES IN SWAY BRACINGS (tf)

Fig. 6 Comparisons of analytical results with those obtained by measurements for the structure before the reinforcement of concrete slab values for axial forces of other members. The difference between the two in axial forces of members where absolute values of axial forces are maximum is 0.93 tf (9.1 kN : approximately 16 percent of measured value). The differences between analytical and measured values of axial forces of right and left upper struts are thought to be due to it being impossible to express the out-of-plane deformation of main girders, because to correspond with the analysis model in which the main girders are expressed by offset beam elements, the main girder portions of the sway bracing elements are handled as rigid bars. However, in case of Fig. 6, the upper strut axial forces of the right and left panels are fairly small compared with the axial forces of other members and it is thought the influences on local stresses of upper strut axial forces are comparatively small.

(3) Analysis results of entire structure after reinforcing

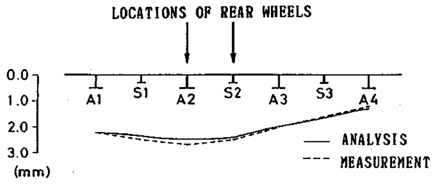
a) Deflection of Reinforced Concrete Floor Deck

The measured and analytical values of floor slab deflections at the center section are shown in Fig. 7 (a). As a whole, the analytical values are in good agreement with measured values, and the difference between the two with regard to maximum deflections was about 0.2 mm (approximately 9 percent of measured value).

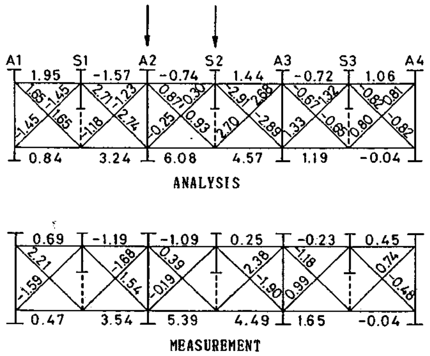
b) Axial Force of Sway Bracing

The measured and analytical values of sway bracing axial forces at the center section is shown in Fig. 7 (b). The overall trends of the two are similar, and the difference between them regarding the maximum axial forces produced at the lower struts between main girder A 2 and stringer S 2 is 0.69 tf (6.8 kN : approximately 10 percent of measured value).

As described in the foregoing, the analytical values obtained by the previously-described analysis method and the measured values of the structure before and after reinforcing coincide well. According to the results of a study in the past where detailed analyses were performed with the entire structure of the bridge modeled three-diemnsionally using thin plate elements, the differences between measured and analytical values were about 34 percent in terms of maximum deflection of floor slab and about 100 percent in terms of axial force of diagonal of sway bracing. Since the structure taken up in that study is not the same as that analyzed in the present paper, it may not be necessarily appropriate for the previously-mentioned values to be compared, but it can be seen that the analysis method proposed here provides a technique by which deflections of floor slab and forces in sway bracing members can be evaluated with good precision in spite of it being a comparatively simple analysis method.



(a) COMPARISON OF CONCRETE SLAB DEFLECTIONS



TENSILE FORCES ARE TREAED AS POSITIVE
(b) COMPARISON OF FORCES IN SWAY BRACINGS (tf)

Fig. 7 Comparisons of analytical results with those obtained by measurements for the structure after the reinforcement of concrete slab

4. INFLUENCE OF FLOOR SLAB DAMAGE REPAIR AND REINFORCING WORKS ON FORCES IN SWAY BRACING MENBERS

(1) Influence of addition of stringer and accompanying sway bracing reinforcement

An example of calculations of the influences of reinforcement work on forces in sway bracing members based on the results of analyses before and after reinforcing made in the preceding section is discussed here.

The floor slab deflections and axial forces of diagonals in sway bracings at the center section before and after reinforcing are ginen in the columns A to D in **Tables 1** and 2, respectively. **Table 2** also gives measured values. Since the ratios of axial forces of sway bracing members before and after reinforcing show measured and analytical values to be close to each other, it is thought that the results of this analysis are reasonable. Floor slab deflection has been reduced on the whole by reinforcement, and it can be seen that the original purpose of this reinforcement is being achieved. However, although the axial forces of diagonals of sway bracings are reduced 30 to 50 percent in almost all diagonals, at the diagonal G 4 the axial force increases by about 80 percent and an axial force (2. 68 tf (2. 63 kN)) greater than the maximum axial force before reinforcing (2. 38 tf (23. 3 kN)) is produced. In measurements also, the maximum value after reinforcing occurred at the diagonal G 4 (2. 38 tf (23. 3 kN)) for an increase of approximately 50 percent compared with before reinforcing (1. 60 tf (15. 7 kN)), and further detailed examinations are needed regarding the relation of reinforcing work on floor slabs with the occurrence of cracking in transverse stiffeners.

(2) Degree of reinforcing and relation with forces in sway bracing members

The depth of a stringer newly provided in the reinforcing mentioned above was approximately one-half of that of main girder, while the cross-sectional area of a diagonal of sway bracing newly added was roughly twice that of an existing diagonal, indicating that comparatively large members were being used[15]. Although it is desirable for a greater degree of reinforcing to be done from the viewpoint of aiming for reduction in local stresses as a secondary effect of reinforcing to reduce deflection of floor slabs, it is conceivable as described previously that there will be cases when forces in sway bracing members, and consequentially local stresses, will rather increase due to reinforcing.

Therefore, from the point of view of reducing forces in sway bracing members, it will be necessary to study the degree of reinforcing that would be desirable.

Table. 1 Comparison of concrete slab deflections

POSITION	MEASUREMENT (mm)		ANALYSIS (mm)			
	A:BEFORE THE REINFORCEMENT	B:AFTER THE REINFORCEMENT	C:BEFORE THE REINFORCEMENT	D:AFTER THE REINFORCEMENT	E:WEAKER REINFORCEMENT	F:SLAB THICKNESS OF 24cm
A 1	2.2	2.2	2.18	2.23	2.23	2.01
S 1	2.7	2.5	2.53	2.36	2.44	2.27
A 2	3.2	2.7	2.83	2.47	2.61	2.48
S 2	3.5	2.5	3.32	2.40	2.58	2.56
A 3	2.4	2.0	2.17	1.97	2.07	1.96
S 3	1.6	1.6	1.71	1.63	1.68	1.57
A 4	1.2	1.2	1.25	1.30	1.28	1.17

Table. 2 Comparison of axial force in diagonal member of sway bracing

POSITION OF DIAGONAL MEMBER	MEASUREMENT tf (kN)			ANALYSIS tf (kN)				
	A:BEFORE THE REINFORCEMENT	B:AFTER THE REINFORCEMENT	B／A	C:BEFORE THE REINFORCEMENT	D:AFTER THE REINFORCEMENT	D／C	E:WEAKER REINFORCEMENT	F:SLAB THICKNESS OF 24cm
G 1	3.34 (3.27)	2.21 (21.7)	0.66	2.38 (23.3)	1.65 (16.2)	0.69	1.73 (17.0)	1.60 (15.7)
G 2	-3.54 (-34.7)	-1.68 (-16.5)	0.47	-2.34 (-22.9)	-1.23 (-12.1)	0.53	-1.04 (-10.2)	-1.56 (-15.3)
G 3	-1.46 (-14.3)	0.39 (3.8)	-0.27	-1.42 (-13.9)	0.87 (8.5)	-0.61	1.36 (13.3)	-0.96 (- 9.4)
G 4	1.60 (15.7)	2.38 (23.3)	1.49	1.51 (14.8)	2.68 (26.3)	1.77	3.13 (30.7)	1.04 (10.2)
G 5	-1.96 (-19.2)	-1.18 (-11.6)	0.60	-1.22 (-12.0)	-0.67 (- 6.6)	0.55	-0.60 (- 5.9)	-0.63 (- 6.2)
G 6	2.04 (20.0)	0.74 (7.3)	0.36	1.23 (12.1)	0.81 (7.9)	0.66	0.79 (7.7)	0.64 (6.3)

In a three-main-girder, three-span composite bridge of the same size as the four-main-girder bridge analyzed here, which had been reinforced previously in the same manner as the latter, the reinforcing done was comparatively weak. In this reinforcement, the moment of inertia of a stringer was approximately one-half that of a stringer in the four-main-girder bridge, and the cross-sectional area of a diagonal newly added was about 1.5 times that of an existing diagonal in the four-main-girder bridge, while reinforcing of lower struts was not done. An example of calculations performed on the influences of the degree of reinforcing on forces in sway bracing members will be given below. Here the weaker reinforcing used for the three-main-girder bridge was applied to the four-main-girder bridge.

Comparisons of floor slab deflections at the center section for the four-main-girder bridge after actually being reinforced, and the four-main-girder bridge when reinforced to the same degree as the three-main girder bridge are given in Table 1 (Columns D, E), and comparisons of axial forces in sway bracing diagonals in Table 2 (Columns D, E). With regard to floor slab deflections, the difference of the two can be seen between main girders A 2 and A 3, the difference being about 4 to 7 percent. As for axial forces of sway bracing diagonals, they are larger for the weaker reinforcing at diagonals G 3 and G 4, with increases of 56 percent and 17 percent, respectively, compared with the actual reinforcement. Especially, with regard to the axial force of the diagonal G 4, it is more than double (3.13 tf (30.7 kN)) the axial force before reinforcing (1.51 tf (14.8 kN)), and there will be a larger stress than in case of actual reinforcement acting on the top end of the transverse stiffener to which the diagonal G 4 is connected. It can be comprehended from this that within the scope of the comparisons of the two cases made here, regarding the dimensions of stringers and sway bracings used for reinforcing floor slabs, those used actually are more desirable than those of the weaker reinforcement.

(3) Influence of floor slab thickness on forces in sway bracing members

Besides such measures as the addition of stringers mentioned above for repair of cracking damage of reinforced concrete floor slabs, the method of backing the entire undersides of the floor slabs has also been used. Also, since cracking damage occurred frequently in slabs of thickness 17 cm made based on the standard design up to the latter half of the 1960 s, the specifications were subsequently revised and since 1978 a slab thickness of 24 cm has been adopted.

The results of the influence of floor slab thickness on forces in sway bracing members calculated in comparison with the influence of reinforcing by addition of stringers will be shown here.

The results of analyses of floor slab deflections at the center section when the slab thickness (17 cm) of the bridge before reinforcing was increased to 24 cm are given in Column F of Table 1, and the results of analyzing the axial forces in diagonals of sway bracings in Column F of Table 2. In reinforcing by addition of stringers, the deflection of the floor slab is a maximum at the location of main girder Al (Column D in Table 1), but in reinforcing by increase in floor slab thickness, the maximum is at the location of attachment of the stringer S 2 (roughly corresponding to the location of wheel load in the driving lane). This difference is due to deflection of the floor slab becoming small at the location of attachment of the stringer S 2 because the stringer is supported by sway bracing in the method of reinforcing by stringer addition. However, the two show amounts of deflection that are roughly equal on the whole. The axial forces in the sway bracing diagonals are also decreased roughly by about 30 to 50 percent similarly to the case of stringer addition. In this case, however, axial forces of all diagonals are reduced, including G 4.

It may be understood from this that the current specifications on floor slab thickness and the degree of reinforcing by addition of stringers and sway bracing reinforcement as measures for reinforcing existing bridges have effects that are roughly equal, but it may be judged that increasing floor slab thickness is more effective in the sense that it reduces forces in sway bracing members on the whole.

5. CONCLUSIONS

A comparatively simple analysis method for evaluating forces produced in sway bracing members in composite girder bridges has been proposed in this paper, and further, the accuracy of this analysis method has been studied through comparisons with measured values. Further, as a case of application of this analysis method, the influences of adding stringers conventionally done with the purpose of reinforcing floor slabs and the accompanying reinforcement of sway bracings, or the increase of slab thickness on the forces in sway bracing members were studied to an extent. The results may be summarized as follows :

(1) The analysis method proposed does not require three-dimensional finite element analysis of the entire structure, it being sufficient to analyze the entire bridge as a plate with offset stiffeners, while it is also possible to readily evaluate the influences of the location of wheel load application to the floor slab and of the floor slab thickness on the forces in sway bracing members.

(2) As a result of comparing analytical and measured values on bridges for which measured values have been obtained, the analytical values in relation to maximum axial force of sway bracing coincide with measured values, errors being within 10 to 20 percent. Regarding the maximum deflection of the floor slab, the margins of error in relation to measured values are within 10 percent.

(3) It has been shown that analyses of forces in sway bracing based on this method are quite effective compared with conventional methods, and it has been confirmed that it is a method worth utilizing in examining and making decisions on future designing and reinforcing methods. As for local stresses themselves at the top ends of transverse stiffeners, if the forces in the sway bracing members are properly evaluated, it will be possible to obtain them by ordinary zooming techniques.

Further,

(4) Whether or not the addition of stringers done as a measure to repair damage of floor slabs and to provide reinforcement and the accompanying reinforcement of sway bracing or increase in slab thickness would be useful in preventing occurrence of cracks at and near welds at top ends of transverse stiffeners as a secondary effect was calculated by this analysis method from the point of view of seeing whether there would be a reduction in the forces in sway bracing members, and the following conclusions were obtained as a result :

a) Reinforcing by addition of stringers does not necessarily result in reduction of forces in sway bracing members, and further detailed studies are required concerning secondary effects.

b) The increase in floor slab thickness currently specified and addition of stringers have roughly the same effects from the point of view of reducing deflection of floor slabs which is the original purpose. However, with regard to the aspect of reducing forces in sway bracing members, the former is more effective when the two are compared, although increasing slab thickness may not necessarily be applicable to an existing bridge.

ACKNOWLEDGEMENT

The authors sincerely thank Prof. Takeo Nishiwaki, Department of Civil Engineering, Musashi Institute of Technology for his apposite advice in carrying out this study and Mr. Hiroyuki Takenouchi and other persons of the Japan Construction Methods and Machinery Research Institute of the Japan Construction Mechanization Association for their enormous amount of cooperation including furnishing of valuable measurement data. The study was carried out aided by a Grant-in-Aid for Scientific Research from the Japanese Ministry of Education, Science and Culture, while all calculations described in this paper were performed using the HITAC M-68 2 H/M-680 H at the Computer Centre, the University of Tokyo and the FACOM M-360 of the Musashi Institute of Technology Information Processing Center.

REFERENCES

1) Fisher, J. W., Fisher, T. A. and Kostem, C. N. : Displacement induced fatigue cracks, Eng. Struct., Vol. 1, pp. 252~257, Oct. 1979.

2) Miki, C. : Damage and maintenance of highway bridges in the United States of America, Dohro, pp. 26~30, Nov. 1982 (In Japanese).

3) Nishikawa, K. : Examples of damage and repairing in highway structures, Dohro, pp. 44~47, Nov. 1982 (In Japanese).

4) Nishikawa, K. : Some examples of fatigue damage in plate girder bridges, Dohro, pp. 58~63, July 1985 (In Japanese).

5) Subcommittee for Investigation of Fatigue Damage of Steel Structures, Committee for Steel Stuructures : Survey of fatigue damages in steel bridges, Proc. JSCE, No. 368, pp. 1~12, April 1986 (In Japanese).

6) Nishikawa, K : Fatigue problems and repairings in highway bridges, Bridge and Foundation Engineering, Vol. 17, No. 8, pp. 23, Aug. 1983 (In Japanese).

7) Miki, C. and Fisher, J. W. : Fatigue problems and repairings in oversea bridges, Bridge and Foundation Engineering, Vol. 17, No. 8, Aug. 1983 (In Japanese).

8) Saeki, S., Nishikawa, K. and Takizawa, A. : Report of Loading Test for Kyouwa Viaduct, Technical Notes of Public Works Research Institute, The Ministry of Construction, No. 2123, June 1984 (In Japanese).

9) Hanshin Highway Public Corporation and Kawasaki Heavy Industries : Report of Advanced Investigation on Floor-Beam Connection of Composite-Girder Bridges, March 1985 (In Japanese).

10) Shinohara, Y., Nishikawa, K. and Takizawa A. : Measurement of Stress Histograms of Fatigue Damaged Composite-Girder Bridges, Technical Notes of Public Works Research Institute, The Ministry of Construction, No. 2344, March 1986 (In Japanese).

11) Kato, S., Yoshikawa, O., Terada, H. and Matsumoto, Y. : Studies on fatigue damages based on strain measurements of a highway bridge, Proc. of JSCE Struct. Eng./Earthq. Eng., Vol. 2, pp. 199~208, Oct. 1985.

12) Hirano, H., Okura, I. and Maeda, Y. : Relation between overall stiffness and fatigue cracks at floor-beam connection in plate girder bridges, Proc. of JSCE Annual Meeting, pp. 523~524, Nov. 1986 (In Japanese).

13) Abe, M. and Iguchi, M. : Study on stress distribution around coped part of a floor beam by finite element method, Technical Paper for Design of Structures in Japanese National Railways, No. 47, pp. 23~26, Sep. 1976 (In Japanese).

14) Abe, H. and Abe, M. : Fatigue of floor-beams and stringers in through plate girders-Part 2-, Technical Paper for Design of Structures in Japanese National Railways, No. 61, pp. 2~5, March 1980 (In Japanese).

15) Japan Highway Public Corporation and Japan Construction Method and Machinary Research Institute : Report of Investigation on Repairings and Retrofittings of Damaged Structures, March 1986 (In Japanese).

16) Oshita, S. and Kaneko, S. : Three dimensional analysis of straight, curved or skewed composite I-girder bridges, Proc. of JSCE, No. 374, pp. 339~348, Oct. 1986 (In Japanese).

17) Yoshida, Y., Amemiya, E. and Masuda, N. : A flat finite element for thin shell analysis derived by assumed stress approach, Proc. of JSCE, No. 211, pp. 19~29, March 1973 (In Japanese).

18) Nishiwaki, T., Miki, C. and Masuda, N. : A simplified analysis method for local stresses in composite-girder bridges, Study on Fatigue Life Estimation and Maintenance of Steel Bridges, Chap. 5, Report of the Research Project supported by a Grant-in-Aid for Scientific Research from the Japanese Ministry of Education, Science and Culture in 1985-1986, pp. 167~184, March 1986 (In Japanese).

19) Kawai, T. Kawashima, K. and Sanbongi, S. : Analyses of Thin Plate Structures, Lecture Notes on Structural Engineering using Computers, Ser. II-7-A, Baifuhkan, pp. 48~52, Nov. 1973 (In Japanese).

20) Masuda, N., Nishiwaki, T., Minagawa, M. and Hayasaka, S. : A study on estimation of ultimate strength of stiffened panels by finite element method, Proc. of Symp. on Comp. Meth. in Struct. Eng. and Related Fields, Vol. 10, pp. 371~376, July 1986 (In Japanese).

21) Japan Road Association : Specification for Highway Bridges, Maruzen, pp. 8~17, Feb. 1980 (In Japanese).

(Received January 26 1986)