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Fatigue of Cross-Beam Connections in Plate-Girder Highway Bridges

Fatigue dans les attaches des entretoises de ponts-routes à section ouverte

Ermüdung der Querträger-Anschlüsse in Strassenbrücken mit offenen Querschnitten

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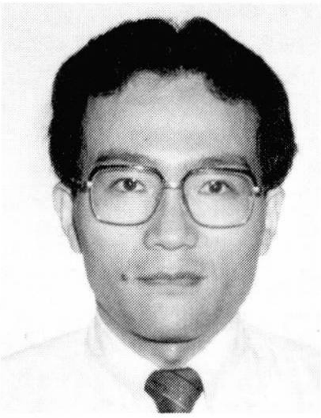

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SUMMARY

Fatigue cracks often grow from connections of cross beams to main girders in plate-girder highway bridges. The structural parameters which govern cracking at cross-beam connections are examined based on the overall behaviour of the bridges. Cracking patterns at cross-beam connections are determined from fatigue tests. A recommendation is given for connection details between concrete slabs and main girder flanges.

RÉSUMÉ

Les fissures de fatigue prennent souvent naissance à la liaison entre les entretoises et les poutres maîtresses des ponts-routes à section ouverte. Les paramètres structuraux qui régissent la fissuration aux liaisons avec les entretoises sont examinés en se basant sur le comportement global des ponts. Des modèles de fissuration des liaisons avec les entretoises sont déterminés à partir d'essais de fatigue. Une recommandation est donnée pour des détails de liaison entre la dalle de béton et les ailes des poutres maîtresses.

ZUSAMMENFASSUNG

Ermüdungsrisse in Strassenbrücken mit offenen Querschnitten gehen oft von den Verbindungen zwischen Quer- und Hauptträgern aus. Die Einflussfaktoren, die den Rissverlauf an den Verbindungsstellen bestimmen, werden unter Berücksichtigung des Gesamtverhaltens der Brücke untersucht. Das Rissverhalten an den Verbindungsstellen wird anhand von Ermüdungsversuchen betrachtet. Es werden Empfehlungen gemacht zur Gestaltung der Konstruktionsdetails bei der Verbindung zwischen Betonfahrbahnplatte und Hauptträgerflansch.

1. INTRODUCTION

In many plate girder highway bridges in the urban area of Japan, fatigue cracks are often observed at the connections of main girders with secondary members such as cross beams, sway bracings and lateral bracings. At the connections of cross beams to main girders in the plate girder bridges of the Hanshin Expressway in Osaka, four types of fatigue cracks are detected, as shown in Fig.1.

-Type 1 crack is initiated either on the bead or at the toe at the end of the fillet weld between the connection plate and the top flange of the main girder.
-Type 2 crack is initiated at the upper scallop of the connection plate, and grows diagonally through the connection plate itself.
-Type 3 crack is initiated at the toe at the end of the fillet weld connecting the connection plate to the main girder web, and grows downward along the toe on the connection plate side.
-Type 4 crack is initiated and grows along the toe on the web side of the fillet weld between the top flange and the web of the main girder.

Investigation of the causes of the crack initiation and the development of repair methods have been under way at various research institutions. However satisfactory results are not yet available.

In 1985 the authors carried out the field stress measurement of an existing plate girder bridge of the Hanshin Expressway to make clear the local stresses causing the cracking at the cross-beam connections[1,2]. They then formulated the relationship between the local stresses and the three-dimensional behavior of the bridge under traffic loading[3].

The objectives of this paper are:

-to present the parameters introduced from the structural behavior of a plate girder bridge, which govern the cracking at the cross-beam connections,
-to show the patterns of the cracking at the cross-beam connections from fatigue tests, and
-to give a recommendation to the connection details between concrete slab and main girder flange.

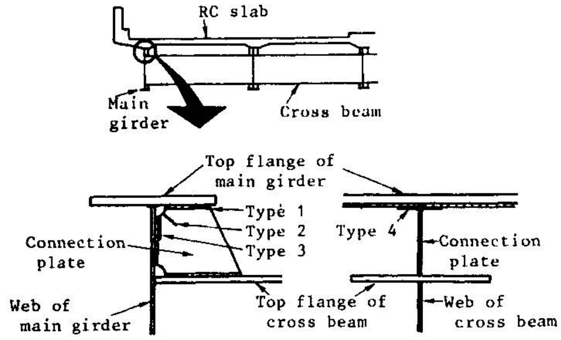


Fig.1 Fatigue cracks at cross-beam connections of plate girder bridge

2. STRUCTURAL PARAMETERS AFFECTING CRACK INITIATION

2.1 Relationship between Local Stresses and Rotations of Concrete Slab and of Cross Beam

As shown in Fig.2, the membrane stress σ_{my} in the vertical direction in the connection plate and the plate-bending stress σ_{by} in the main girder web are main factors to cause Types 1 and 4 fatigue cracks, respectively[1,2]. The relationship between those local stresses and the rotations of concrete slab and of cross beam is given by[3]

$$\begin{bmatrix}\sigma_{my}\\ \sigma_{by}\end{bmatrix} = \begin{bmatrix}k_{m1} & k_{m3}(\gamma-k_{m123})\\ k_{b1} & k_{b3}(\gamma-k_{b123})\end{bmatrix}\begin{bmatrix}\theta_{s0}\\ \theta_g\end{bmatrix} \quad (1)$$

where θ_{s0}=rotation of concrete slab due to the slab-deformation caused by wheel loads(see Fig.3), θ_g=rotation of cross beam due to the vertical displacements of main girders(see Fig.3), γ=coefficient depending on the position of a vehicle in the direction of the roadway width, and k_{m1}, k_{m3}, k_{m123}, k_{b1}, k_{b3} and k_{b123}=constants which relate the local stresses to the rotations of concrete slab and of cross beam.

2.2 Structural Parameter for Concrete-Slab Rotation

Referring to Fig.4, the rotation θ_{s0} of concrete slab at the position (a, 0) where a main girder is located, is expressed by[3]

$$\theta_{s0} = (a/D_c)\{P/(2\pi^2)\}\varphi_p(x/a)\,\varphi(x/a)\Big[\sum_{m=1}^{\infty}\{(-1)^m/m^2\}\sin(m\pi x/a)$$
$$(1+m\pi|y|/a)\exp(-m\pi|y|/a)\Big] \quad (2)$$

where a=spacing between main girders, D_c=flexural rigidity of concrete slab, P=a concentrated load, $\varphi_p(x/a)$=correction factor for the wall parapets on both sides of the roadway, and $\varphi(x/a)$=correction factor to treat the concrete slab as a continuous plate.

Equation(2) implies that the concrete-slab rotation θ_{s0} varies with values of a/D_c. The values of a/D_c are determined by the dimensions of concrete slab. Hence the reciprocal of a/D_c, namely, D_c/a is chosen as a structural parameter for θ_{s0}. The bridges with smaller values for D_c/a are more susceptible to cracking, since the decrease of D_c/a increases θ_{s0} and then results in the

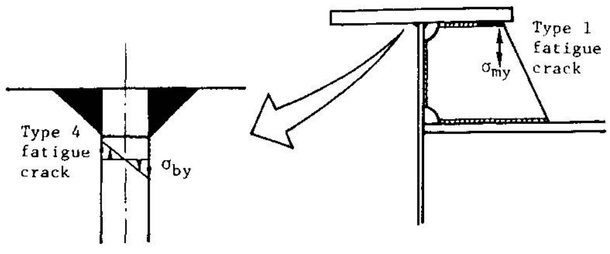


Fig.2 Local stresses σ_{my} and σ_{by}

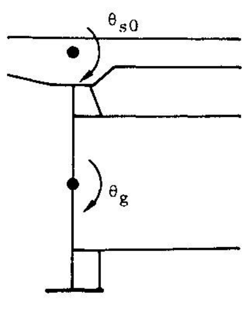


Fig.3 Rotations θ_{s0} and θ_g

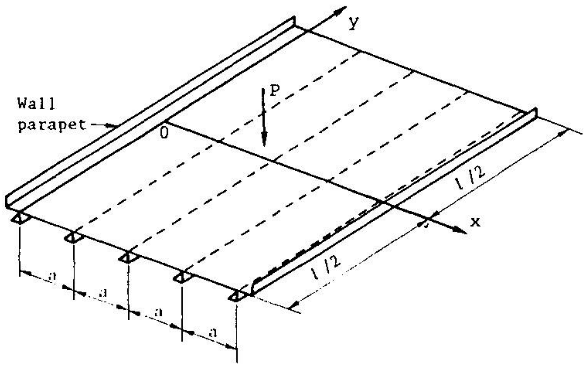


Fig.4 Concrete slab under concentrated load P

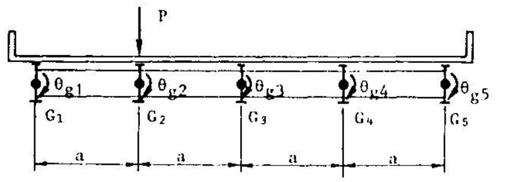


Fig.5 Cross-beam rotation θ_{gi}

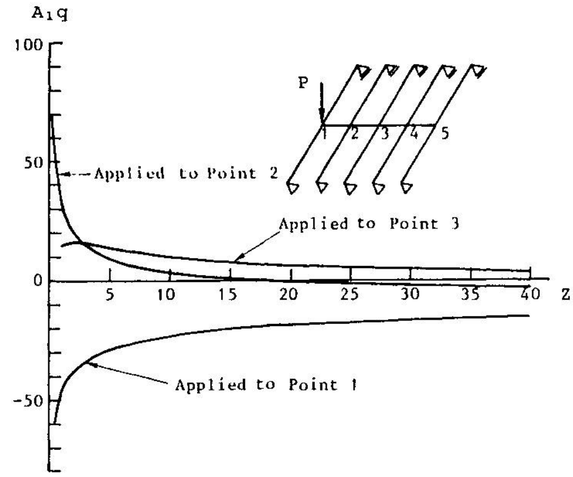


Fig.6 Relationship between $\mathbf{A_1 q}$ and z

increase of the local stresses of σ_{my} and σ_{by}.

2.3 Structural Parameters for Cross-Beam Rotation

In a plate girder bridge with five main girders as shown in Fig.5, the rotation θ_{gi} of the cross beam at the main girder G_i is given by[3]:

$$\theta_{gi} = \mathbf{A_i v}/(56a) \tag{3}$$

where $\mathbf{v}=(v_1,v_2,v_3,v_4,v_5)^T$, v_i=vertical displacement of the girder G_i at the cross-beam connection, T=symbol representing transpose, and $\mathbf{A_i}$=row vector consisting of constants which correspond to θ_{gi}. When a concentrated load P is applied to the girder G_j, the vertical displacement v_i of the girder G_i is provided with

$$v_i = Pq_{ij}l^3/(48E_s r_i I_g) \tag{4}$$

where q_{ij}=load-distribution-coefficient from the girder G_j to G_i, l=span length of main girders, E_s=Young's modulus of steel, $r_i=I_{gi}/I_g$, I_{gi}=moment-of-inertia of the main girder G_i, and I_g=moment-of-inertia of any girder arbitrarily selected among the five main girders. The load-distribution-coefficient q_{ij} is expressed by a function of r_i and Z defined by

$$Z = (I_Q/I_g)\{l/(2a)\}^3 \tag{5}$$

where I_Q=moment-of-inertia of a cross beam. Substitution of Eq.(4) into Eq.(3) provides

$$\theta_{gi} = \{P/(2688E_s)\}\{l^3/(aI_g)\}\mathbf{A_i q} \tag{6}$$

where $\mathbf{q}=(q_{1j}/r_1,q_{2j}/r_2,q_{3j}/r_3,q_{4j}/r_4,q_{5j}/r_5)^T$.

Figure 6 shows the relationship between $\mathbf{A_1 q}$ which corresponds to the cross-beam rotation θ_{g1}, and Z. The calculation of $\mathbf{A_1q}$ is carried out for all $r_i=1$. Except for the case of a concentrated load P applied to the girder G_3 above which a center divider exists on the roadway, $\mathbf{A_1q}$ is approximately inversely-proportional to Z for Z≤10. Accordingly, when Z≤10, the term $\{l^3/(aI_g)\}\mathbf{A_1q}$ in Eq.(6) is proportional to $\{l^3/(aI_g)\}/Z$, and then considering Eq.(5), $\{l^3/(aI_g)\}/Z$ is changed into $8a^2/I_Q$. On the other hand, when Z>10, only the term $l^3/(aI_g)$ is variable in Eq.(6), since $\mathbf{A_1q}$ takes almost constant values for Z>10.

From the above, the following structural parameters are chosen for the cross-beam rotation θ_{gi}:

I_Q/a^2 for Z≤10 (7)

aI_g/l^3 for Z>10 (8)

The bridges with smaller values for these structural parameters suffer more chances of cracking, since the decrease of the parameters increases θ_g, which leads to the increase of the local stresses of σ_{my} and σ_{by}.

2.4 Relationship between Structural Parameters and Cracking

The relationship between I_Q/a^2 and initiation of Types 1 and 4 cracks is investigated for 158 plate girder bridges on a route of the Hanshin Expressway[4]. The structural parameter D_c/a is found to be almost invariable on this route.

Figure 7 shows the relationship between I_Q/a^2 and the number of bridges in which Type 1 cracks were detected. As shown in Ref.[4], the influence of θ_g on the local stress σ_{my} which causes Type 1 cracks is very small in the bridge with $I_Q/a^2=3.1$ cm^2. In Fig.7, however, Type 1 cracks occur in the bridges for $I_Q/a^2>3.0$ cm^2. This indicates that Type 1 cracks can be initiated by the

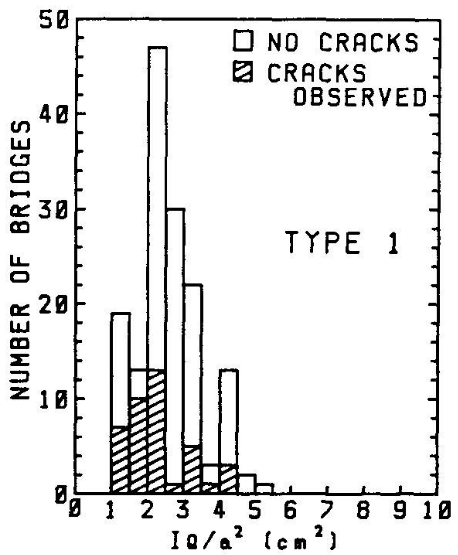


Fig.7 Relationship between I_Q/a^2 and the number of bridges in which Type 1 cracks were observed

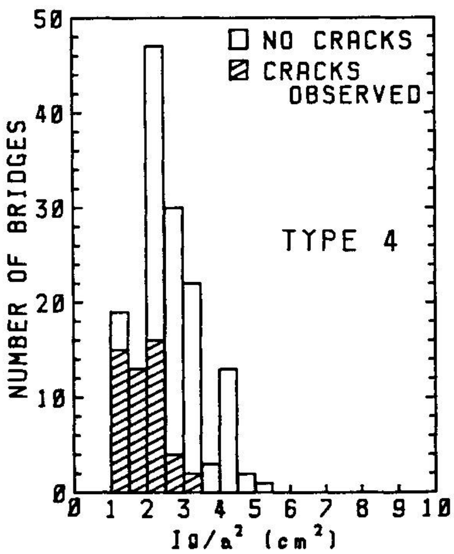


Fig.8 Relationship between I_Q/a^2 and the number of bridges in which Type 4 cracks were observed

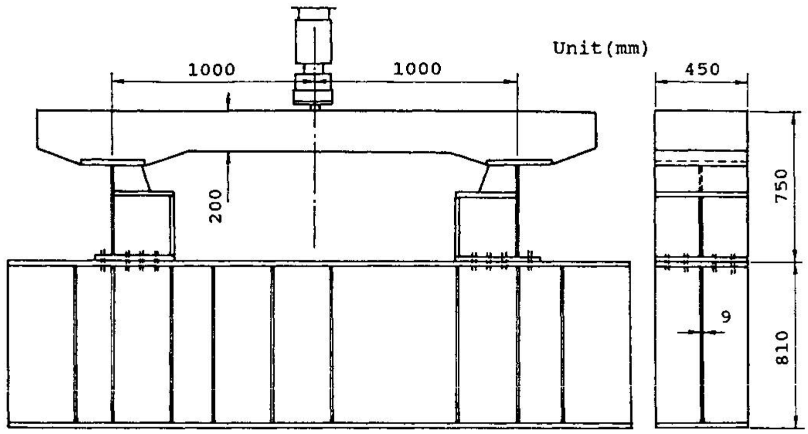
concrete-slab rotation only.

Figure 8 shows the relationship between I_Q/a^2 and the number of bridges in which Type 4 cracks were observed. With the increase in I_Q/a^2, the number of bridges suffering from cracking gradually decreases, since the influence of θ_q on the local stress σ_{by} which causes Type 4 cracks becomes small. No cracks occur in the bridges for $I_Q/a^2>3.5\ cm^2$.

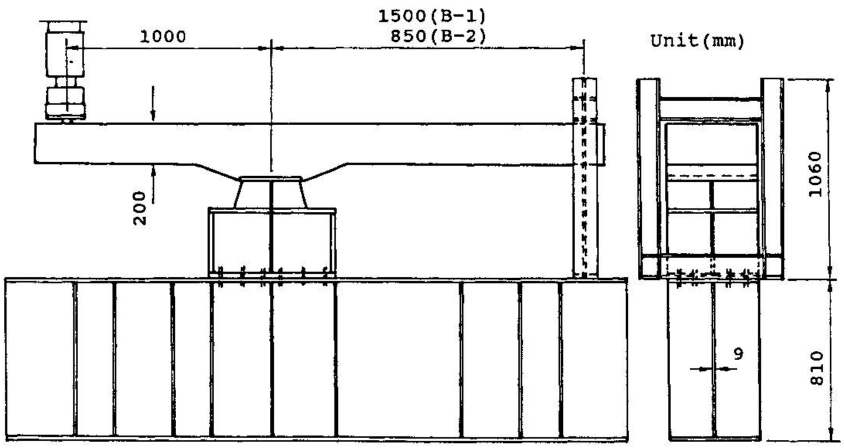
3. FATIGUE TESTS OF CROSS-BEAM CONNECTIONS

3.1 Fatigue Test Specimens

As can be seen from Eq.(1), the local stresses σ_{my} and σ_{by} are provided with the sum of stress components due to the rotations of concrete slab and of cross beam. This implies that effects of concrete-slab rotation and of cross-beam rotation on the local stresses can be divided. Then in order to clarify the influence of the concrete-slab rotation on the cracking at cross-beam connections, fatigue tests are carried out on the specimens as shown in Fig.9. The specimens consist of cross-beam connections and of



Series A



Series B

Fig.9 Fatigue test specimens

a concrete slab in a stripped form. The series A corresponds to the cross-beam connections of exterior main girders. The series B does for interior main girders. In the series B, negative moment is created in the concrete slab above the cross-beam connection.

3.2 Connection Details between Girder Flange and Concrete Slab

In order to examine the effects of connection details between girder flange and concrete slab on the cracking, the number of stud shear connectors and their arrangement are changed at each cross-beam connection, as shown in Fig.10. In the right side of Specimen A-2 and in Specimen B-2, a slab anchor is used.

3.3 Results of Fatigue Tests

The following observations are drawn from the fatigue tests:

-The similar cracks as shown in Fig.1 occur at all the cross-beam connections, not depending on the connection details between girder flange and concrete slab.
-In the series A corresponding to the cross-beam connections of exterior main girders, there exists no order in initiation of Types 1 and 4 cracks, while in the series B corresponding to the

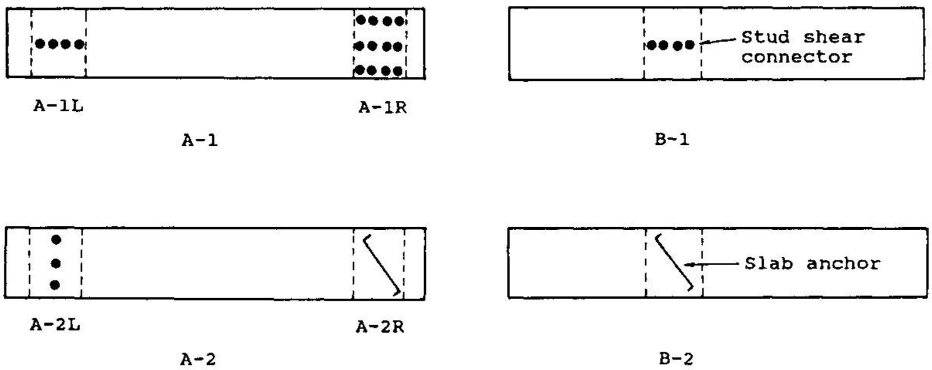


Fig.10 Connection details between girder flange and concrete slab

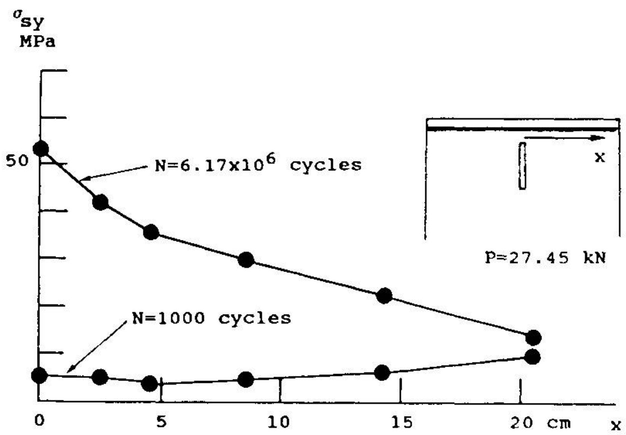


Fig.11 Distribution of web surface stress σ_{sy} along the flange-to-web fillet weld(Specimen B-1)

cross-beam connections of interior main girders, Type 4 crack follows Type 1 crack.

The distribution along the flange-to-web fillet welds of the stress σ_{sy} on the surface of the web plate is shown in Fig.11 for Specimen B-1. In the figure, at N=1000 cycles σ_{sy} is very small and Type 1 crack does not occur, while at $N=6.17\times10^6$ cycles σ_{sy} becomes large and Type 1 crack is initiated and grows. Therefore in the series B the propagation of Type 1 crack makes the local stress σ_{by} increase, and then results in Type 4 crack initiation.

3.4 Characteristics of Occurrence of Local Stresses

In order to make clear the occurrence of the local stresses σ_{my} and σ_{by}, a finite element analysis is carried out for a model as shown in Fig.12. It consists of a girder flange, girder web and connection plate, and a half of them is divided into finite elements from symmetry. The bottom edges of the girder web and connection plate are fixed. The forces which are determined by the measurements of displacement of the concrete slab and by the measurements of strain of the stud shear connectors are applied to the girder flange of the F.E.M. model, as shown in Fig.13. The vertical forces on the girder flange are produced by the pull-out action of stud shear connectors and by the contact action between concrete slab and girder flange. The horizontal forces on the girder flange are created by the shear resistance of stud shear connectors.

Comparison of F.E.M. values with the measured ones is shown in Fig.14 for σ_{my} and σ_{by}. As for σ_{my}, F.E.M. values are close to the measured ones. As for σ_{by}, the distribution of F.E.M. values shows the same tendency as that of the measured ones, though the former shifts slightly from the latter.

The local stresses σ_{my} and σ_{by} can be correlated with the forces Q and S. Here Q is, as shown in Fig.13, the total of the vertical forces on the girder flange, while S is the total of the horizontal forces on the girder flange. The stress components of σ_{my} and σ_{by} against Q and S are listed in Table 1 for the series A. The stress values in the table are obtained at the points of the strain gauges nearest to the crack initiation in the fatigue tests. Connection A-0, which is just a model for the F.E.M. analysis, corresponds to the cross-beam connections in which neither stud shear connectors nor slab anchors are used between concrete slab and girder flange. In this model, the concentrated load of 49.0 kN is applied vertically to the edge of the girder flange just above the connection plate.

The following are pointed out from Table 1:

-The local stress σ_{my} is mostly produced by the vertical force Q, while the local stress σ_{by} is produced by both Q and S.
-The stress values of Connection A-0 are much smaller than those of any other connection model.

In order to reduce the local stresses and thus to prevent cracking, it is recommended that neither stud shear connectors nor slab

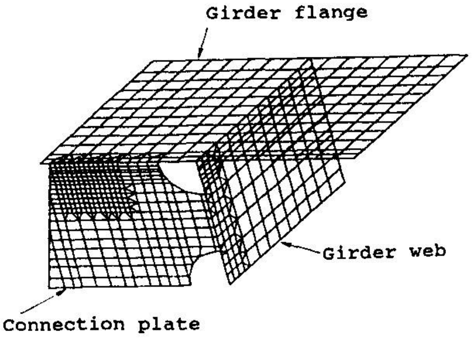


Fig.12 Mesh division

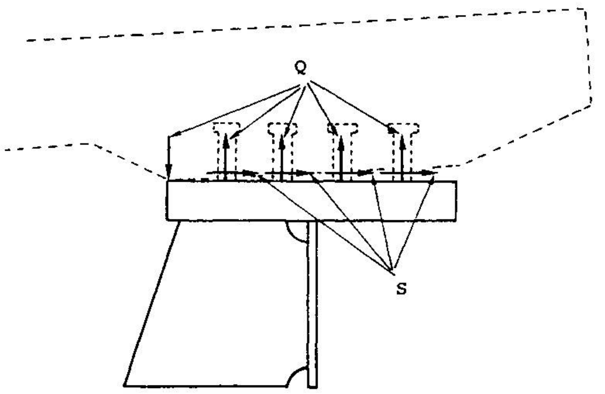
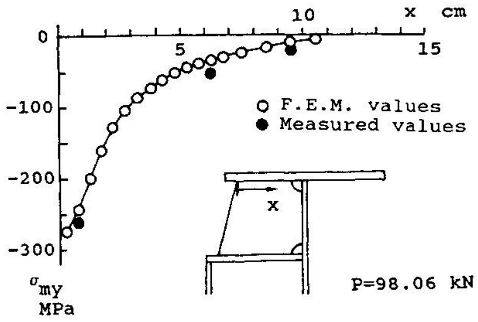
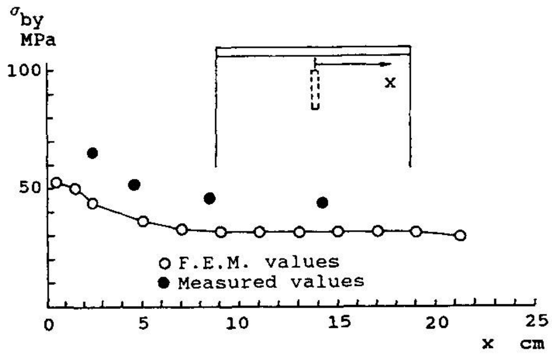


Fig.13 Forces acting on F.E.M. model



(a) σ_{my} at connection plate



(b) σ_{by} at girder web

Fig.14 Comparison of F.E.M. values with measurement values(Connection A-1L)

Table 1 Comparison of stress components against Q and S

Connection	Q (kN)	S (kN)	σ_{my} (MPa)	σ_{mQ} (MPa)	σ_{mS} (MPa)	σ_{by} (MPa)	σ_{bQ} (MPa)	σ_{bS} (MPa)
A-1L	48.88	41.45	-237.9	-240.8	2.9	43.2	8.6	34.6
A-1R	49.17	56.43	-292.3	-296.2	3.9	96.3	49.2	47.1
A-2L	56.03	66.08	-275.4	-279.8	4.4	77.1	21.1	55.9
A-2R	42.02	44.32	-295.9	-298.9	2.9	26.5	-11.9	38.5
A-0	49.03	0.0	-184.0	-184.0	0.0	-9.7	-9.7	0.0

Note: $\sigma_{my} = \sigma_{mQ} + \sigma_{mS}$
$\sigma_{by} = \sigma_{bQ} + \sigma_{bS}$
σ_{mQ} = membrane stress component produced by Q
σ_{mS} = membrane stress component produced by S
σ_{bQ} = plate-bending stress component produced by Q
σ_{bS} = plate-bending stress component produced by S

anchors be placed above the connections of cross beams to main girders.

4. CONCLUSIONS

(1)The structural parameters governing the fatigue cracking at the connections of cross beams to main girders in plate girder highway bridges were specified as follows according to the rotations of concrete slab and of cross beam:

a) For the concrete-slab rotation, D_c/a.
b) For the cross-beam rotation, I_Q/a^2 when $Z \le 10$, and aI_g/l^3 when $Z>10$. Here $Z=(I_Q/I_g)\{l/(2a)\}^3$.

The bridges with smaller values of the above structural parameters become more susceptible to cracking. Type 1 cracks at the connection plates can be initiated by the concrete-slab rotation only.

(2) From the fatigue tests to investigate the influence of the concrete-slab rotation on the cracking, it was revealed that cracks are initiated at the cross-beam connections with stud shear connectors regardless of the number of them and their arrangement, and that they are also initiated at the cross-beam connections with slab anchors.

(3) To reduce the local stresses and thus to prevent cracking, it was recommended from a F.E.M. analysis that neither stud shear connectors nor slab anchors be placed above the connections of cross beams to main girders.

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