STRUCTURAL PARAMETERS GOVERNING FATIGUE CRACKING IN HIGHWAY BRIDGES

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In many plate girder highway bridges, fatigue cracks occur at the connections of cross beams to main girders. In this paper, the structural parameters governing the cracking at the cross-beam connections are presented. Then, the relationship between the parameters and the cracking at the cross-beam connections is investigated for the plate girder bridges on a route of the Hanshin Expressway in Osaka, and it is shown that the deformation of a concrete slab due to running vehicles has a great influence on the cracking at the cross-beam connections.

Keywords: fatigue, plate girder bridge, connection

1. INTRODUCTION

Fatigue cracks occur at the connections of cross beams to main girders in many plate girder highway bridges in the urban area of Japan. The fatigue cracks observed in the plate girder bridges of the Hanshin Expressway in Osaka are classified as shown in Fig. 1 according to the locations of cracking. Four types of cracks are initiated at the cross-beam connections. The 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 know the local stresses influential for the cracking at the cross-beam connections^{1), 2)}. Later, they formulated the relationship between the local stresses and the three-dimensional behavior of the bridge under traffic loading³⁾.

The objective of this paper is to clarify the qualitative relationship between the parameters introduced from the structural behavior of a plate girder bridge and the cracking at the cross-beam connections. First, the structural parameters affecting the cracking at cross-beam connections are deduced from the equations presented in Ref. 3). Then, the relationship between the structural parameters and the cracking at the cross-beam connections is investigated for the plate girder bridges on a route of the Hanshin Expressway.

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

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

Fig. 3 Rotations θ_{s0} and θ_g .

2. STRUCTURAL PARAMETERS AFFECTING CRACK INITIATION

(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 on the connection plate and the plate-bending stress σ_{by} on the main girder web 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 by³⁾

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

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) 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 by³⁾

$$\theta_{s0} = \frac{1}{2\pi^2} \frac{a}{D_c} \left\{ P\phi_p\left(\frac{x}{a}\right) \phi\left(\frac{x}{a}\right) \sum_{m=1}^{\infty} \frac{(-1)^m}{m^2} \sin \frac{m\pi x}{a} \left(1 + \frac{m\pi|y|}{a}\right) \exp\left(-\frac{m\pi|y|}{a}\right) \right\} \dots\dots\dots (2)$$

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

Eq. (2) expresses that the concrete-slab rotation θ_{s0} varies with the values of a/D_c , even if the traffic conditions are the same. The values of a/D_c can be 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 plate girder bridges with the smaller values of D_c/a are more susceptible to cracking, since the decrease of D_c/a increases θ_{s0} and then results in the increase of the local stresses of σ_{my} and σ_{by} .

(3) Structural parameters for cross-beam rotation

Let us consider a plate girder bridge with five main girders shown in Fig. 5. The rotation θ_{gi} of the cross beam at the main girder G_i is given by the following equation³⁾:

$$\theta_{gi} = \frac{1}{56a} A_i v \dots\dots\dots (3)$$

where $v = (v_1, v_2, v_3, v_4, v_5)^T$, v_i =vertical displacement of the girder G_i at the cross-beam connection, T =symbol representing transpose, and A_i = i -th row vector of the following 5×5 matrix:

$$\begin{bmatrix} -71 & 90 & -24 & 6 & -1 \\ -26 & -12 & 48 & -12 & 2 \\ 7 & -42 & 0 & 42 & -7 \\ -2 & 12 & -48 & 12 & 26 \\ 1 & -6 & 24 & -90 & 71 \end{bmatrix}$$

Fig. 4 Concrete slab under concentrated load P . Fig. 5 Cross-beam rotation θ_{gi} . Fig. 6 Relationship between A_1q and Z .

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 the following equation :

$$v_i = \frac{P q_{ij} l^3}{48 E_s r_i I_g} \quad (4)$$

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 five main girders.

The load-distribution-coefficient q_{ij} is expressed by a function of r_i and Z defined by

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

where I_g =moment-of-inertia of a cross beam.

Substitution of Eq. (4) into Eq. (3) provides the following equation :

$$\theta_{gi} = P \frac{1}{2688 E_s} \frac{l^3}{a I_g} A_1 q \quad (6)$$

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

Fig. 6 shows the relationship between A_1q which corresponds to the cross-beam rotation θ_{gi} , and Z . The calculation of A_1q is carried out for $r_i=1$. The formulae of q_{ij} are given in Ref. 4). Except for the case of the concentrated load P applied to the girder G_3 , A_1q is approximately inversely-proportional to Z for $Z \leq 10$. Accordingly, when $Z \leq 10$, the term $\{ l^3/(a I_g) \} A_1 q$ in Eq. (6) is proportional to $\{ l^3/(a I_g) \} / Z$, and then considering Eq. (5), $\{ l^3/(a I_g) \} / Z$ is changed into $8 a^2 / I_g$. On the other hand, when $Z > 10$, only the term $\{ l^3/(a I_g) \}$ is variable in Eq. (6), because A_1q takes almost constant values for $Z > 10$.

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

$$I_g/a^2 \text{ for } Z \leq 10 \quad (7)$$

$$a I_g / l^3 \text{ for } Z > 10 \quad (8)$$

The plate girder bridges with the smaller values of these structural parameters are more susceptible to cracking, since the decrease of the parameters increases θ_g and then results in the increase of the local stresses of σ_{my} and σ_{by} .

3. RELATIONSHIP BETWEEN STRUCTURAL PARAMETERS AND CRACKING

The relationship between I_g/a^2 and initiation of Types 1 and 4 cracks is investigated for the plate girder

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.

bridges on a route of the Hanshin Expressway⁵⁾. The value of D_c/a is almost invariable on the route.

Fig. 7 shows the relationship between I_q/a^2 and the number of bridges in which Type 1 cracks were detected. As pointed out in Ref. 5), the influence of θ_g on the local stress σ_{my} which causes Type 1 cracks is small in the plate girder bridge with $I_q/a^2 = 3.1 \text{ cm}^2$. In Fig. 7, however, Type 1 cracks occur in the bridges for $I_q/a^2 \geq 3.0 \text{ cm}^2$. This indicates that Type 1 cracks can be initiated by the concrete-slab rotation only.

Fig. 8 shows the relationship between I_q/a^2 and the number of bridges in which Type 4 cracks were detected. With the increase of I_q/a^2 , the number of the bridges suffering from cracking gradually decreases, because the influence of θ_g on the local stress σ_{by} which causes Type 4 cracks becomes small. No cracks occur in the bridges for $I_q/a^2 \geq 3.5 \text{ cm}^2$.

4. CONCLUSIONS

The structural parameters governing the fatigue cracking at the cross-beam connections of plate girder highway bridges are specified as follows according to the rotations of bridge components, that is to say, concrete slab and cross beam under vehicle loading :

- For the concrete-slab rotation, D_c/a .
- For the cross-beam rotation, I_q/a^2 for $Z \leq 10$, and aI_g/l^3 for $Z > 10$.

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

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