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Stud Arrangement to Reduce Fatigue Cracks and Application of Drilled Holes

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Summary

This paper presents the arrangement of stud shear connectors to reduce the fatigue cracks at the connections of cross beams to main girders and at the top of intermediate vertical stiffeners in highway bridges. Fatigue tests are carried out on the specimens consisting of a concrete slab and two main girders. Finite element models for the transfer of load between a concrete slab and a top flange of a main girder are developed. Drilled holes are shown to be effective to stop the propagation of the cracks in main girder webs.

1. Introduction

In many plate girder highway bridges in the urban areas of Japan, such fatigue cracks as shown in Fig.1 are detected at the connections of cross beams to main girders [1]. In some bridges, they are also observed at the top of intermediate vertical stiffeners to which cross beams are not connected. This paper presents the arrangement of stud shear connectors to reduce those cracks. Fatigue tests are carried out on the specimens consisting of a concrete slab and two main girders. Finite element models for the transfer of load between a concrete slab and a top flange of a main girder are developed. Drilled holes are shown to be effective to stop the propagation of the cracks in main girder webs.

2. Fatigue Tests

The specimens of the fatigue tests are shown in Fig.2 [2]. A cross beam is provided in the specimens B, while it is not in the specimens A. The interval between the main girders is 2 m. The concrete slab 16 cm thick and 168 cm wide in the bridge-axis direction is made from lightweight-aggregate concrete. Two pieces were prepared for each of the specimens A and B. Fig.3 shows the stud arrangement on the main girders of the specimens. Studs are put just on the vertical stiffener of the main girder A1-G1 and on the connection plate of the main girder B1-G1.

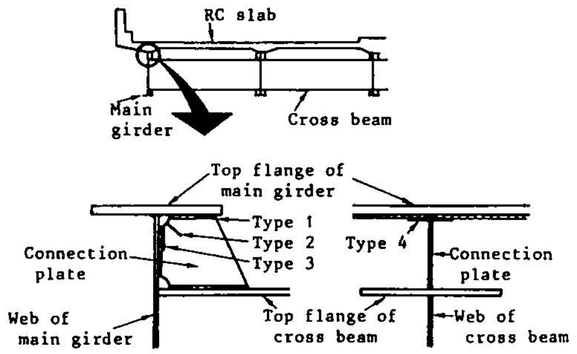
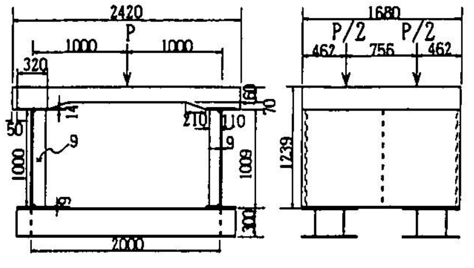
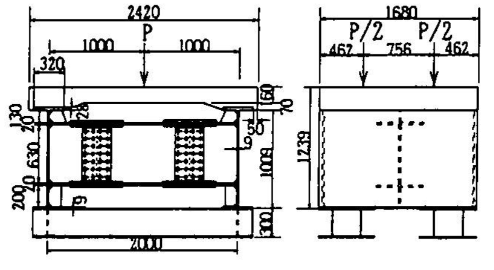


Fig.1 Fatigue cracks at cross-beam connections

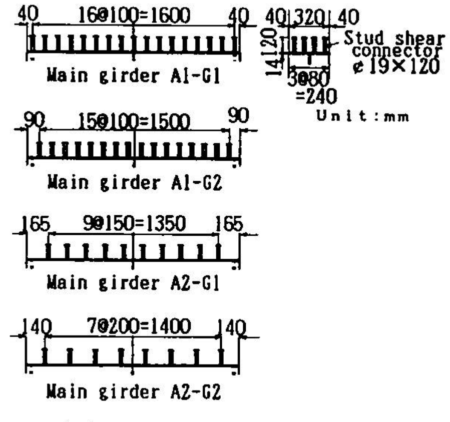


(a) Specimens A

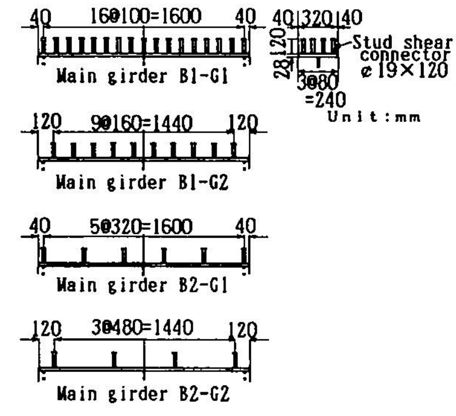


(b) Specimens B

Fig.2 Fatigue test specimens



(a) Specimens A

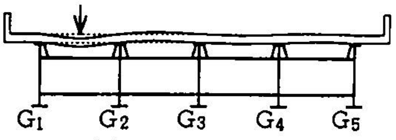


(b) Specimens B

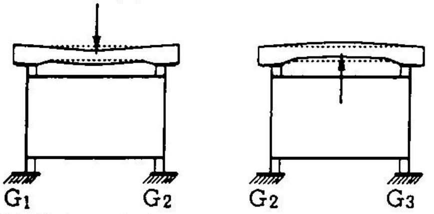
Fig.3 Stud arrangement

In other main girders, studs are not located on the connection plate or the vertical stiffener. The studs used are 19 mm in diameter and 120 mm in height.

Static loading tests were conducted before fatigue tests. To examine the relations between the slab deformation and the local stresses influential for the cracks, equal loads were applied downward at two points 75.6 cm apart in the bridge-axis direction on the top surface of the slab, in the middle between the main girders. Next, the loads were applied upward at the same locations on the bottom surface of the slab. As schematically shown in Fig.4(a), for a load between the main girders G_1 and G_2 in an actual bridge, the slab is deformed in a downward convex form between the main girders G_1 and G_2 and in an upward convex form between the main girders G_2 and G_3. In the static loading tests, the downward and upward convex forms of the slab deformation are given by such loading conditions as shown in Figs.4(b) and (c), respectively. Here, the slab deformations in Figs.4(b) and (c) are named slab-positive deformation and slab-negative deformation, respectively.

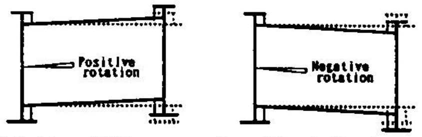


(a)Slab deformation

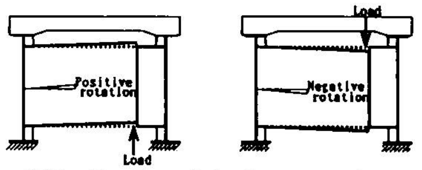


(b)Slab-positive deformation
(c)Slab-negative deformation

Fig.4 Positive and negative deformations of slab



(a)Relative difference of vertical displacements of adjacent main girders



(b)Application of load to cross beam

Fig.5 Positive and negative rotations of cross beam

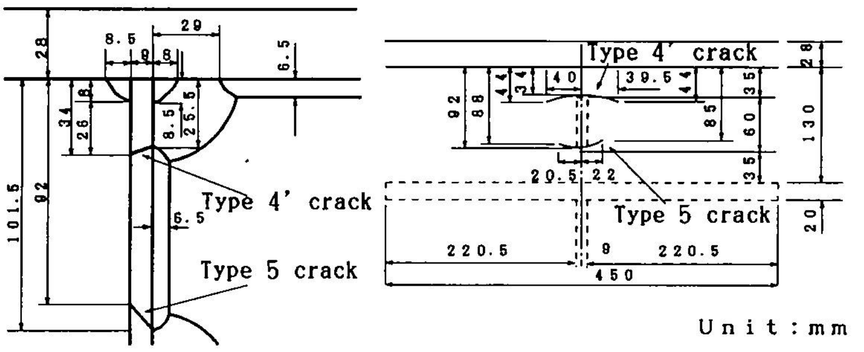


Fig.6 Types 4' and 5 fatigue cracks at 5.1 × 10^6 cycles [Main girder B2-G1]

To investigate the relations between the cross-beam rotation and the local stresses, the bolted connection at one end of the cross beam in the specimens B was loosened, and an upward or downward load was applied to this end. As shown in Fig.5(a), positive and negative rotations are produced at the end of a cross beam in an actual bridge, depending on the relative difference of the vertical displacements of adjacent main girders. In the static loading tests, as shown in Fig.5(b), the application of a vertical load to one end of the cross beam induces positive and negative rotations at the other end.

The fatigue tests were accomplished on the specimens A1, B1 and B2 under the slab-positive deformation shown in Fig.4(b) at $\Delta P = 93.1$ kN and 142.1 kN. Type 1 crack such as shown in Fig.1 was initiated in the connection plate or at the top of the vertical stiffener of each main girder of the three specimens. However, the crack grew very slowly, and stopped after the propagation of about 10 mm. As shown in Fig.6, the specimen B1 suffered Type 4' crack in the web of each main girder, and the specimen B2 experienced Type 4' and 5 cracks. Types 4' and 5 cracks were initiated at the toes on the web side of the upper and lower end returns of the fillet weld between the connection plate and the main girder web, respectively. Both cracks penetrated the web, and propagated horizontally in the web.

In the specimen B1, drilled holes 25 mm in diameter were provided at the tips of Type 4' crack at 10 million cycles of loading [Case(I)]. The hole edge was smoothed by sandpaper. No cracks were created at the drilled holes during 2 million cycles after the resumption of the test. In actual bridges, there are instances that connection plates are separated from the top flange and/or the web of main girders due to the propagation of Types 1, 2 and 3 cracks. Then, the connection plate was flame-cut along the fillet weld between the connection plate and the top flange of the main girder [Case(II)]. The test continued by 2 million cycles without cracks at the drilled holes. Moreover the connection plate was flame-cut along the fillet weld between the connection plate and the main girder web [Case(III)]. The test carried on by 2 million cycles with the result of no cracking at the drilled holes.

3. Finite Element Models for Test Specimens

In the static loading tests, it was observed that as shown in Fig.7, the slab rotated at the edges A and B on the top flange of the main girder for the slab-positive and -negative deformations, respectively. Likewise, as shown in Fig.8, the top flange rotated at its edges A and B for the cross-beam-positive and -negative rotations, respectively. Fig.9 shows finite element models for the transfer of load between a concrete slab and a top flange of a main girder through those observations. Fig.9(a) corresponds to the slab-positive deformation and the cross-beam-positive rotation. Fig.9(b) corresponds to the slab-negative deformation and the cross-beam-negative rotation. In the finite element analysis, rectangular and triangular plate elements with 6 degrees of freedom at each node are used [3]. In Fig.9(a) rigid beams with hinges at both ends connect the nodes on the edge A-A on the neutral plane of the top flange to those on the neutral plane of the slab, and in Fig.9(b) they do so on the edge B-B. For the studs, beam elements with the stiffness of the studs join both nodes on the neutral planes of the top flange and the slab.

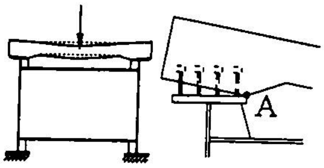
As an example, Fig.10 presents the mesh division for the specimen B1 with loads applied to the slab and drilled holes provided at the tips of Type 4' cracks. Type 4' crack and the flame cutting of the connection plate are expressed by double nodes. As shown in Fig.3, the stud arrangement is different on the right and left main girders of the specimens. Due to the limitations of calculation capacity of the computer, the quarter of the specimen is divided into finite elements. The boundary condition of symmetry was imposed on the cut sections. The bottoms of the web and the vertical stiffener of the main girder were fixed.

4. Stud Arrangement to Reduce Fatigue Cracks

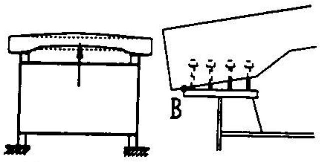
The finite element analysis was carried out for the stud spacing which was not considered in the fatigue tests [4]. Combining the relations between the stud spacing and the local stresses which are obtained from the finite element analysis and the previous researches [5-7] gives us the following conclusion on the arrangement of studs to reduce the fatigue cracks:

Keeping studs away from the locations of connection plates and vertical stiffeners has an effect on the reduction of the fatigue cracks for interior main girders. However, it does not for exterior main girders.

Usually, the stud spacing is determined by the shear force in the bridge-axis direction between a top flange of a steel girder and a concrete slab. In order to reduce the fatigue cracks in interior main girders, studs should be placed as far as possible from the locations of connection plates and vertical stiffeners, not exceeding the stud spacing determined by the shear force.

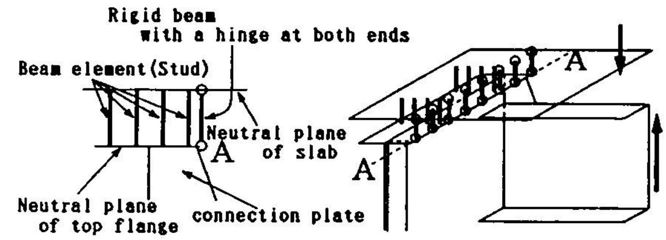


(a) Slab-positive deformation

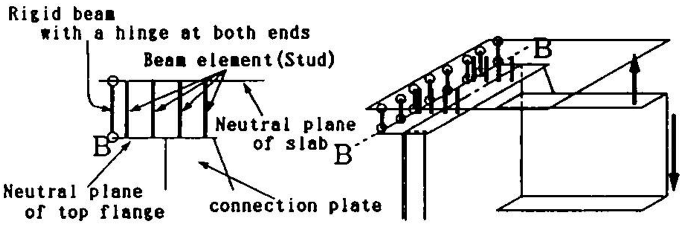


(b) Slab-negative deformation

Fig. 7 Behavior between slab and flange for slab deformation

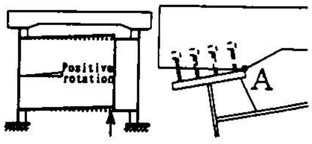


(a) Load-transfer-model for slab-positive deformation and cross-beam-positive rotation

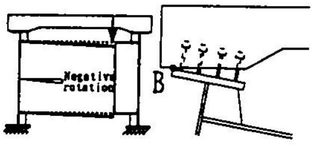


(b) Load-transfer-model for slab-negative deformation and cross-beam-negative rotation

Fig.9 Load-transfer-model between slab and flange



(a) Cross-beam-positive rotation



(b) Cross-beam-negative rotation

Fig.8 Behavior between slab and flange for cross-beam rotation

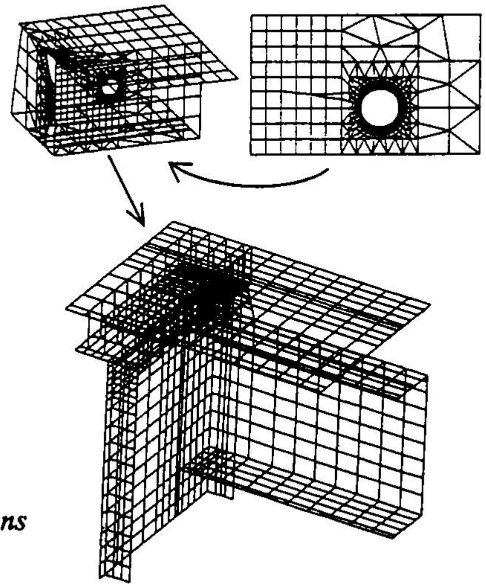


Fig.10 Mesh division for specimens

5. Effectiveness of Drilled Holes

The condition to prevent drilled holes from cracking is as follows [8]:

$$\Delta\sigma_t < 213\sqrt{\sigma_Y} \quad (1)$$

where $\Delta\sigma_t$ = stress range at the edge of drilled holes (in MPa), and σ_Y = yielding stress of steel

plates in which the drilled holes are provided (in MPa).
The stress range $\Delta\sigma_t$ at the drilled hole edge is estimated by the following equation [8]:

$$\Delta\sigma_t = 1.05\Delta\sigma_{m(FEM)} + \frac{1.766 + 3.464\,\rho/t}{1 + 3.539\,\rho/t}\Delta\sigma_{b(FEM)} \qquad (2)$$

where $\Delta\sigma_{m(FEM)}$ and $\Delta\sigma_{b(FEM)}$ = membrane and plate-bending stresses at the drilled hole edge computed by the finite element analysis with plate elements, respectively, ρ = radius of drilled holes, and t = thickness of steel plates.

Since ρ and t of the specimen are 12.5 mm and 9 mm, respectively, its stress range $\Delta\sigma_t$ is calculated by

$$\Delta\sigma_t = 1.05\Delta\sigma_{m(FEM)} + 1.11\Delta\sigma_{b(FEM)} \qquad (3)$$

The membrane and plate-bending stresses in the tangential direction at the drilled hole edge are used for $\Delta\sigma_{m(FEM)}$ and $\Delta\sigma_{b(FEM)}$, respectively. The maximum of $\Delta\sigma_t$ is 112.7 MPa in the cases (I), (II) and (III), which are defined in the fatigue tests. This value is much smaller than $21.3\sqrt{\sigma_Y} = 450.6$ MPa in Eq.(1), where the yielding stress σ_Y of the specimen is 447.6 MPa. This explains why there was no crack initiation at the drilled holes in the specimen.

6. Conclusion

The arrangement of stud shear connectors to reduce the fatigue cracks at connection plates and vertical stiffeners was presented. Drilled holes were shown to be effective to stop the propagation of the cracks in main girder webs.

References

[1] OKURA, I. *Fatigue in Steel Bridges.* (in Japanese) Toyo-shoten Publisher, Tokyo, Japan, 1994.

[2] OKURA, I.; SAKAMOTO, H.; SHIOZAKI, T.; FUKUMOTO, Y. *Local stresses and fatigue cracks at the top of vertical stiffeners of plate girders.* (in Japanese) J. Structural Eng., JSCE, Japan, Vol.40A, 1994, pp.1087-1100.

[3] ISAP (Integrated Analysis Program), NEC Corporation, FXI 52-10, Tokyo, Japan, 1989.

[4] OKURA, I.; SHIOZAKI, T.; FUKUMOTO, Y.; NANJYO, A. *Stud arrangement to reduce fatigue cracking in vertical stiffeners.* J. Structural Eng./Earthquake Eng., JSCE, Japan, Vol.13, No.1, 1996, pp.55s-66s.

[5] OKURA, I.; FUKUMOTO, Y. *Fatigue of cross beam connections in steel bridges.* Proc., IABSE 13th Congress, Helsinki, Finland, 1988, pp.741-746.

[6] OKURA, I.; FUKUMOTO, Y. *Fatigue of cross-beam connections in plate girder highway bridges.* Proc., IABSE Workshop, Lausanne, Switzerland, 1990, pp.167-176.

[7] OKURA, I.; FUKUMOTO, Y. *Fatigue tests of cross-beam connections in plate girder highway bridges.* Porc., First World Conference on Constructional Steel Design, Acapulco, Mexico, 1992, pp.466-469.

[8] OKURA, I.; SHIOZAKI, T.; NAKANISHI, Y. *Fatigue strength of drilled holes under membrane and plate-bending stresses.* (in Japanese) J. Structural Eng./Earthquake Eng., JSCE, Japan, No.537/I-35, 1996, pp.327-338.