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AN INVESTIGATION ON FATIGUE STRENGTH FOR TRANSVERSE CHORD OF STIFFENING TRUSS

By Kenji SAKAMOTO, Masahiko YASUDA*, Makoto FUKAZAWA** and Chitoshi MIKI****

Iwagurojima Bridge, which comes under the Honshu-Shikoku Bridge project, is a cable-stayed bridge with a main span of 420 m. In this bridge, designed to be of a highway and railway combination type, fatigue behavior due to train load will pose an important problem. In order to prove the appropriateness of the fabrication procedure for this bridge, a specimen with dimensions almost equal to the transverse chord of stiffening truss, was trially fabricated. This specimen was then subjected to a static torsional loading test and a bending fatigue test. The objectives of these tests were to investigate the fatigue behavior of different weld joint details. These results reflected on the practical design and construction.

1. INTRODUCTION

Iwagurojima Bridge, which comes under Honshu-Shikoku Bridge project, is a cable-stayed bridge with a main span of 420 m as shown in **Fig. 1**. In this bridge, designed to be of a highway and railway combination type, fatigue due to the train load will pose a serious problem. Fatigue testing on the full-size truss member made of high strength steels [SM58Q] has already been done[1] and the results reflected on the design and fabrication.

For the transverse chord of stiffening truss made of SM50Y, in order to prove the appropriateness of its structural details and fabrication procedure, a specimen with dimensions are almost equal to the actual member was trially fabricated, and then tested on its fatigue strength.

The transverse chord member supports the stringers for the railway which are designed in a simple girder, and is itself supported elastically by the vertical members, as shown in **Fig. 2**. To this chord are applied, not only axial

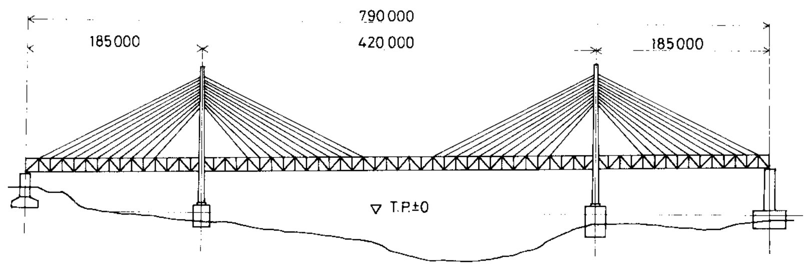


Fig. 1 Iwagurojima Bridge.

* Member of JSCE Honshu-Shikoku Bridge Authority (Mori Bld. No.22, Toranomon 4-3-20, Minato-ku, Tokyo)
** Member of JSCE Yokogawa Bridge Works (88 Shinminato, Chiba-shi, Chiba)
*** Member of JSCE Dr. of Eng., Tokyo Institute of Technology (2-12-1, Ookayama, Meguro-ku, Tokyo)

force of the truss member and bending moment of the floor member but also torsional moment due to unsymmetrical support reaction of the stringer.

Then two types of tests were carried out. The first was the static unsymmetrical loading test to examine the influence of the torsion on the web plate at the section supporting the stringer. The second was the bending fatigue test to investigate the fatigue strength of various structural details in this chord.

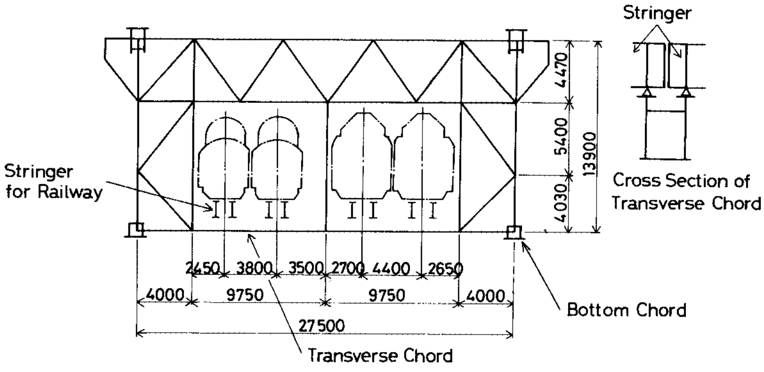


Fig. 2 Section of stiffening truss.

2. OUTLINE OF TESTS

Details of the section supporting the stringer are characteristic as shown in Fig. 3. In the fatigue design code for Honshu-Shikoku Bridge[2], details are grouped in 4 categories from A to D according to the fatigue strengths of details, where Category A is the highest. In the original design of this transverse chord, various welding details of top flange [compression-side] were all Category C and these of bottom flange [tension-side] were Category A. The diaphragm jointed to top flange and both side webs by fillet welding. But the joint between diaphragm and bottom flange was bearing connection. Moreover, because bending moment and torsional moment are applied to the transverse chord, the fillet weld is done from the inside of member together with the partially penetrated groove weld from outside for the corner joints. The size of the scallop of the diaphragm is larger than usual to allow for continuous MIG welding with a self-driven welding machine.

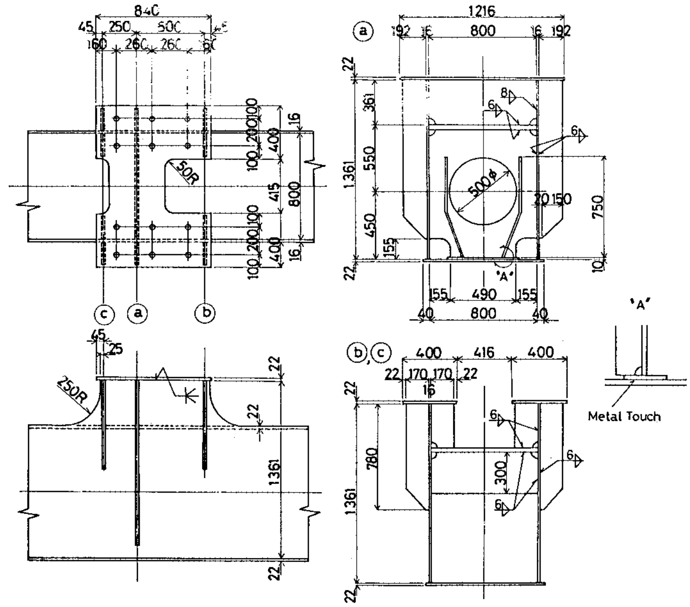


Fig. 3 Details of section supporting stringer.

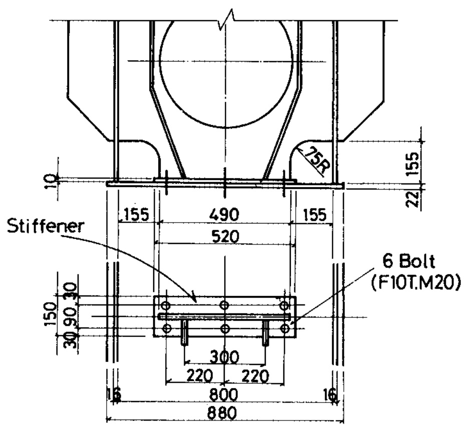


Fig. 4 Connection of diaphragm to bottom flange.

With these details it is expected that the torsion, due to the support reaction at the stringer, induces out-of-plane distortion of the web plate at the scallop of the diaphragm. This out-of-plane distortion may cause cracks at the terminating of the fillet welds of the transverse stiffener and the scallop of the diaphragm. In order to obtain the detail which prevents the out-of-plane distortion of the web plate, two details were examined. In the original detail, the diaphragm was attached to the bottom flange and in the improved detail, the diaphragm was connected to the bottom flange with six high strength bolts as shown in Fig. 4.

Furthermore, the transverse chord is the box section member to which many diaphragms are welded with stiffeners, especially the stringer support section is complex. To investigate the fatigue behavior of these particular structural details, a bending fatigue test was carried out after the static torsional loading test.

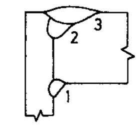
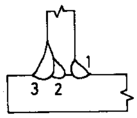
3. SPECIMEN

The configuration and dimensions of the specimen are shown in Fig. 5 To aid the bending fatigue test, the thickness of the top flanege and location of the stringer support were partially different from those of the actual member. In order to obtain the same stress conditions of the flange of the specimen under bending test, as these of the transverse chord in actual structure, the top flange plate was thickened from 22mm to 42mm. The specimen was constructed with structural steel of JIS G 3106, the flange and web plates of SM50Y and the other plates of SM41. Mechanical properties of main steels are shown in Table 1. Welding conditions for typical joints are shown in Table 2.

Table 1 Mechanical properties of steels.

	Yield Point MPa	Tensile Strength MPa	Elongation %	Remark
SM50YC t=42mm	380	540	32	Top Flange
SM50YB t=22mm	420	550	25	Bottom Flange
SM50YB t=16mm	430	540	27	Web
SM41B t=22mm	310	430	33	Bedplate for Sidewalk

Table 2 Welding conditions.

Joint	Welding Sequence	Pass	Welding Process	Welding Materials
Corner Joint Top Flange		1	MAW	LT52
		2, 3	SAW with two electrode	US36 x MF38
Corner Joint Bottom Flange		1	MIG welding	MIX50S $Ar80\%\times CO_2 20\%$
		2	SAW with two electrode	US36 x MF38
		3	SAW with one electrode	US36 x MF38
Fillet Joint Bedplate		1	MAW	LBF52A

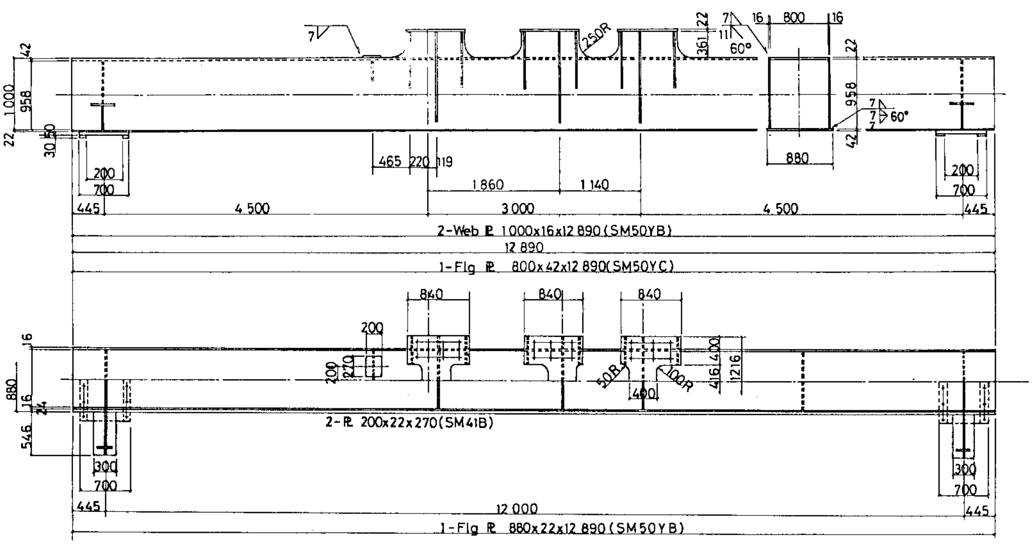


Fig. 5 Configuration and dimensions of specimen.

4. TORSIONAL LOADING TEST

(1) Test Method

Maximum torsional moment was applied to the transverse chord to receive the reaction of the stringer on only one web. Here, the train load plus impact was supposed to cause the torsional moment (R_{l+i}=42.16 tf). The specimen was tested on a 12m span under unsymmetrical four-point loading, as shown in Fig. 6. Each load at the stringer suport section was 40tf. The distance between two loading points is equal to the interval of rails.

Test set-up is shown in Photo. 1.

(2) Test Result

Typical out-of-plane bending stresses of the web and the flange near the loading point section (ⓐin Fig. 6) were measured by strain gauges. Strains near the terminating of the fillet welds were measured at a distance of 10mm from the weld toe. Fig. 7 shows the distribution of out-of-plane bending stresses.

In the original detail, out-of-plane bending stresses are large in the direction of both the specimen axis and it's right angle. Bending stress at the unloaded side web is converse to that of

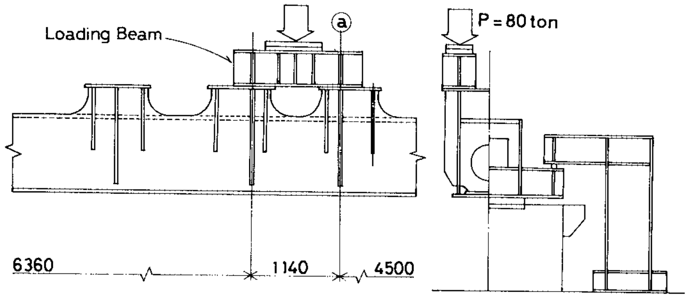


Fig. 6 Loading method in torsional loading test.

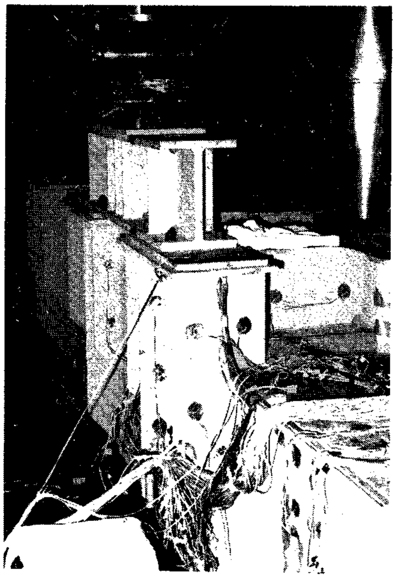


Photo. 1 Test set-up.

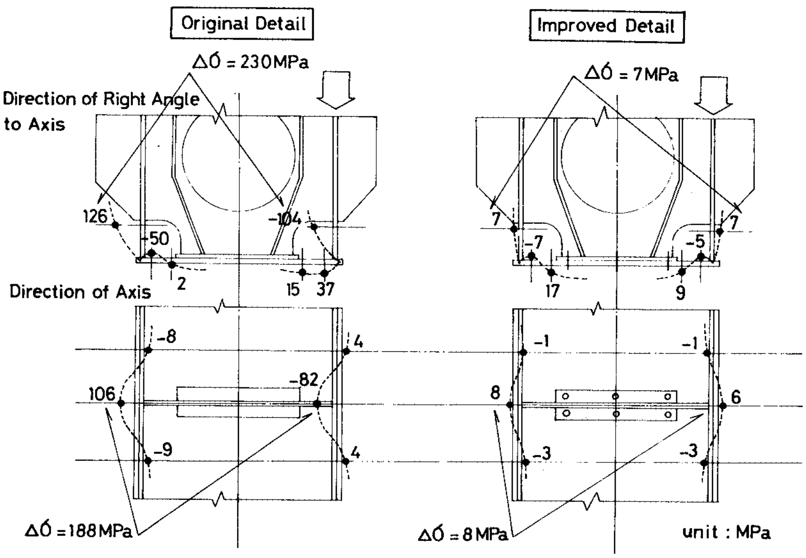


Fig. 7 Distribution of out-of-plane bending stresses.

the loaded side web. Stringer reaction is alternately applied to each web to simulate the passage of a train. Thus, the bending stress range at one particular point is considered to be the sum of the stress at these two points. So, bending stress range at the terminating of the fillet weld at the scallop is expected to be $\Delta\sigma$=230 MPa, and $\Delta\sigma$=188 MPa.

From previous studies on the transverse fillet weld[3),4)], it is known that the bending fatigue strength is almost equal to axial fatigue strength in nominal stress, and stress concentration at a distance of 10mm from the fillet weld toe is nearly 1.0. Measured bending stress ranges in this specimen are sufficiently high to result in the origination of the fatigue crack. On the other hand, in the case of improved detail, the out-of-plane bending stresses are small in both directions. It is clear that when the diaphragm is bolted to bottom flange, there is no significant out-of-plane web bending stress.

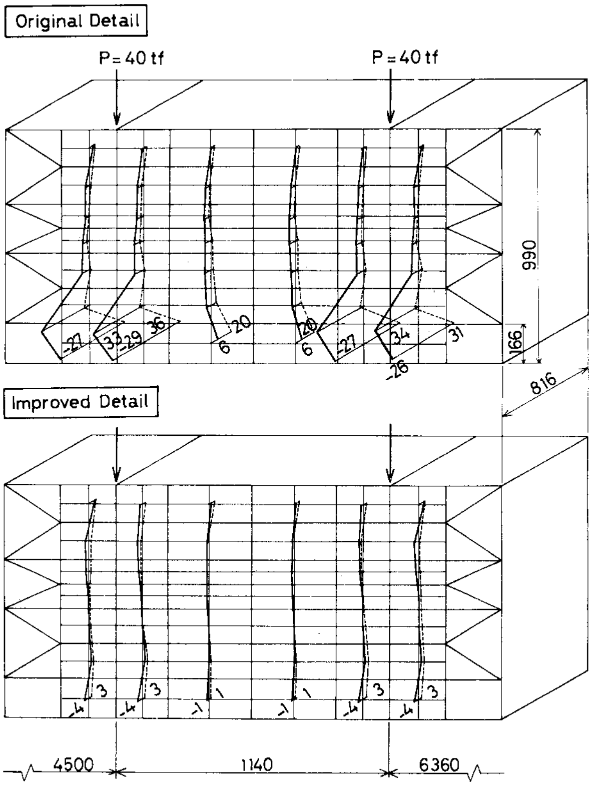


Fig. 8 Result of finite element analysis.

(3) Finite Element Analysis

In order to examine the test results, a finite element analysis using shell elements was carried out. Fig. 8 shows the distribution of the principal bending stresses of the loading side web plate. Bending stress at the scallop in the improved detail is about one-seventh of that in the original detail. This shows the same result as given in the test result.

(4) Practical Design

The result of a torsional loading test, disclosed that the diaphragm should be connected with the bottom flange. In practical fabrication, connection by the fillet weld was applied for the purpose of doing it water-tight. Consequently, allowable fatigue strength at the side of the tention bottom flange was reduced by two degrees from category A to C.

Accordingly, to reduce the applied maximum bending stress, the bottom flange plate was thickened from 22mm to 28mm, or a cover plate 16mm thick and 450mm wide was added almost the full length of the lower stress region.

5. FATIGUE TEST

(1) Test Method

The specimen was subjected to four-point bending. The test was carried out in a 4MN testing machine at a frequency of 0.55Hz. Loading method and test set-up are shown in Fig. 9 and Photo. 2.

Table 3 shows the test conditions. Under these conditions, the fiber stress ranges of 165MPa [0-tension] in the bottom flange, and 119MPa [0-compression] in the top flange, were chosen in the region of pure bending in consideration of the design allowable stresses and actual stresses. The stress range was halved every 500 000 cycles so that beach marks would remain on the fracture surface. After about

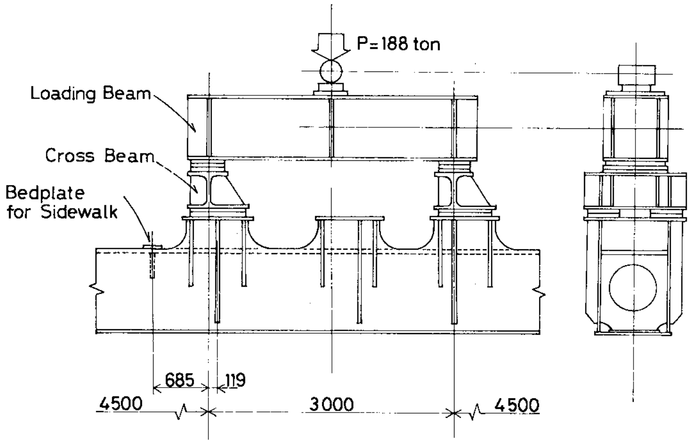


Fig. 9 Loading method in fatigue test.

1 900 000 cycles, two types of fatigue cracks were found. One was on the corner joint of the bottom flange and the other was at the transverse fillet weld of the bedplate for the sidewalk. The test was then continued to 2 000 000 cycles.

(2) Test Results

After fatigue test, cracks on the surface of the specimen were observed by the magnaflux inspection method. Furthermore, in order to detect concealed cracks which originated at the roots of the fillet welds and the partially penetrated groove welds of corner joints, the roots of these welds were exposed along the weld line. Several cracks were found throughout this specimen. The location of the cracks are summarized in Fig. 10.

a) Corner Joint

A fatigue crack was discovered at 1 948 000 cycles in the partially penetrated groove weld of the bottom flange. This crack penetrated the web plate at 2 000 000 cycles (Crack A). Photo. 3 shows the appearance of this crack.

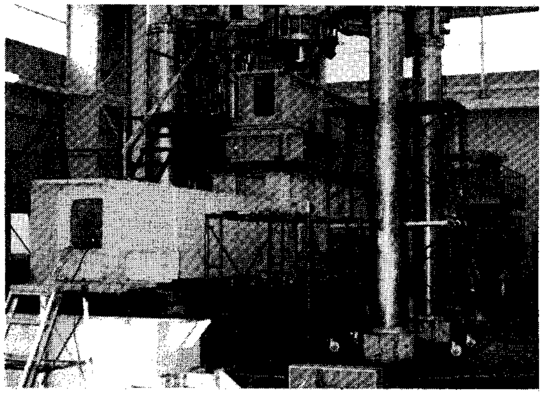


Photo. 2 Test set-up.

Table 3 Testing condition.

Load tf			Maximum Fiber Stress Range, MPa		Cycles per min.
Max.	Min.	Range	Top Flange	Bottom Flange	cpm
5	193	188	119	165	33

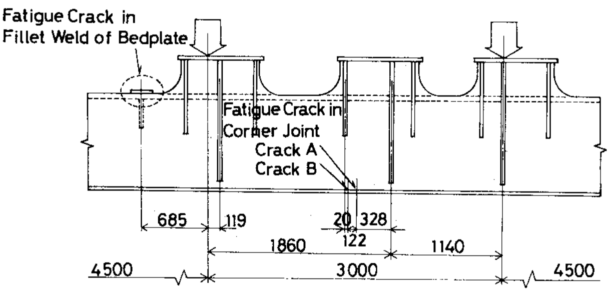


Fig. 10 Fatigue cracks in specimen.

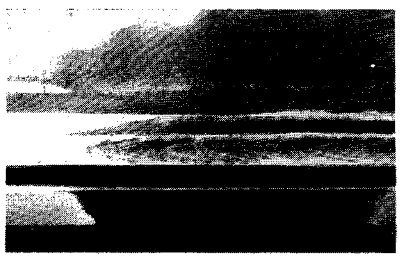


Photo. 3 Fatigue crack at corner joint (Crack A).

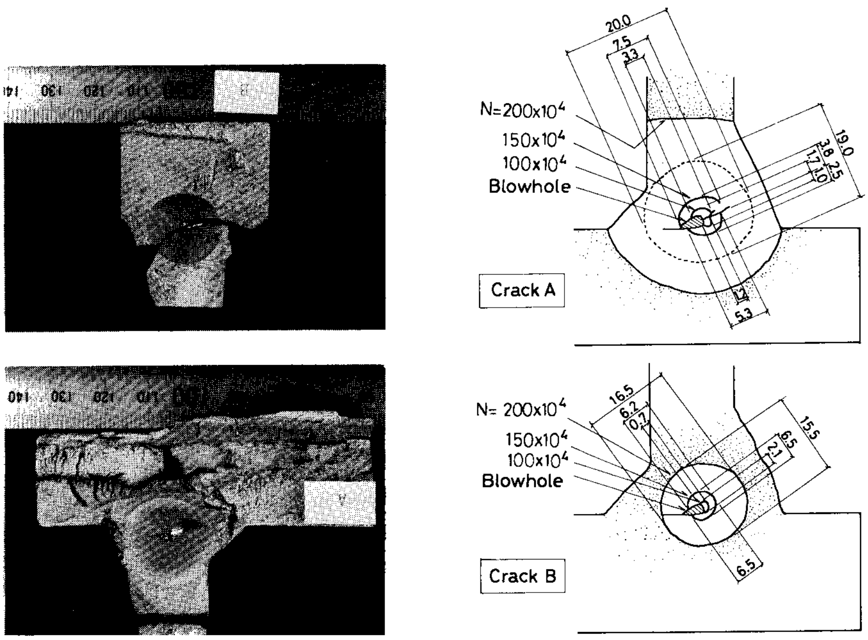


Photo. 4 Fatigue crack surfaces.

In order to observe weld defects and fatigue cracks which originated at the root of the corner joint, the root of outside welds were exposed along the weld line. This examination was conducted on areas where weld defects were indicated by ultrasonic inspection. The inside fillet weld was not examined because no defects were indicated by the ultrasonic inspection. As a result of this examination, in the region of maximum bending stress, two fatigue cracks originated from blowholes of 2mm wide×4mm high (Crack A), and 1.5mm×4.5mm (Crack B). Both blowholes are over the tolerable size of 1.5mm wide and 4mm high[5], regulated for a class A truss chord member made of quench and tempering type high strength steel. Photo. 4 shows these fracture planes. Beach marks at 1 000 000 cycles and 1 500 000 cycles were left on the fracture surfaces.

The relation among the initiation of crack, size of blowhole and applied stress range is shown in Fig. 11. Only two cracks are not enough to derive apparent relation. Fatigue cracking however, tends to originate from relatively large blowholes at a higher applied stress range region.

b) Fatigue Strength of Corner Joint

In the fatigue design code for Honshu-Shikoku Bridges[2], corner joints of SM50Y steel are classified as Category A. The relation between the design allowable stress range σ_r(MPa) and the number of cycles N for welded joints in Category A is expected as follows:

$$(\sigma_r)^4 \cdot N = 1.19\times10^7 \cdots\cdots (1)$$

This curve is shown in Fig. 12. Estimated fatigue life is the number of cycles at which a fatigue crack may

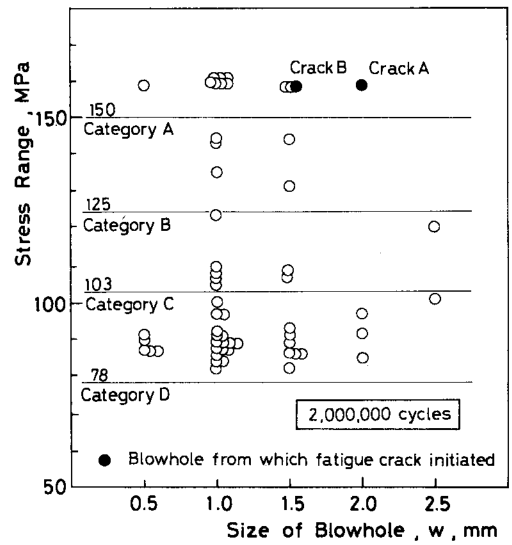


Fig. 11 Relation among initiation of crack, size of blowhole and applied stress range.

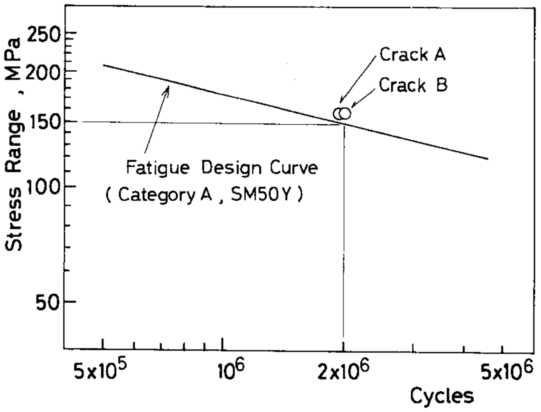


Fig. 12 Fatigue design courve and test resul.

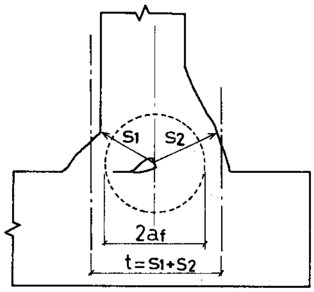


Fig. 13 Corresponding thickness.

propagate to 80% of the corresponding thickness t as shown in Fig. 13. The fatigue life of each crack is estimated on the basis of the following assumption by the fracture mechanics.

(i) The fatigue cracks are in the shape of a circle with a radius of 2a=7.5mm at 1,500,000 cycles (Crack A), and 16mm at 2 000 000 cycles (Crack B). Stress intensity factor K (MPa $\sqrt{m}$) can then be expressed as follows.

$$K=\sigma\sqrt{\pi a}\cdot\frac{2}{\pi}\cdot\sqrt{sec\frac{\pi a}{t}} \qquad (2)$$

(ii) Equation (3) is used in the calculation of the fatigue life between the relation of the fatigue crack growth rate da/dN (mm/cycle) and the stress intensity factor range ΔK

$$da/dN=C\cdot(\Delta K)^{m} \qquad (3)$$ [6]

Where $C=1.64\times10^{-14}$

$m=4$

A margin of error at less than 25% remains for the estimate fatigue life from 1 500 000 cycles to 2 000 000 cycles of Crack B. This may prove the method appropriate. Estimated fatigue lives N_f are as follows.

Crack A N_f=1 950 000 cycles

Crack B N_f=2 020 000 cycles

No difference in the fatigue lives was found between Crack A and Crack B. The estimated fatigue lives are plotted beyond the fatigue design curve toward the longer life side.

It is confirmed that Category A is applicable to the corner joint made of SM50Y, and with blowholes up to aobut 1.5mm the category is upgraded comparing with that to the high strength steels.

c) Fillet Weld of Bedplate for Sidewalk

Fatigue cracks were discovered along the fillet welds of the bedplate on the top flange for the sidewalk at 1 938 000 cycles. The location of these cracks is shown in Fig. 14. The cracks appeared in three of the four front fillet welds. Appearance of a typical crack is shown in Photo. 5. A crack was found in the root of the fillet weld

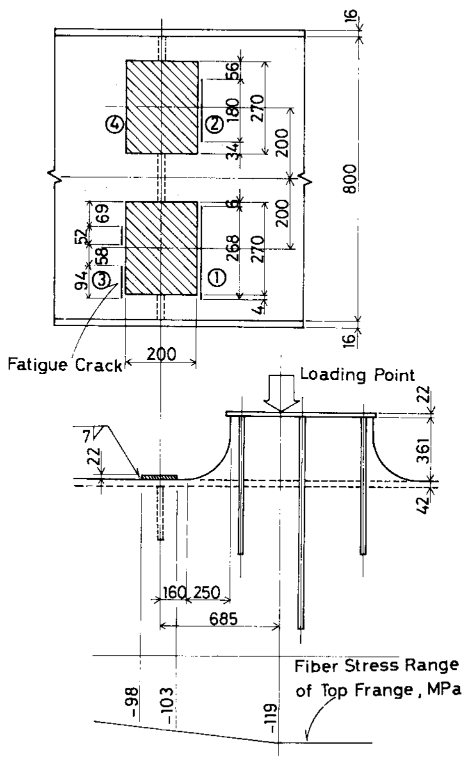


Fig. 14 Fatigue cracks in fillet welds of bedplates.

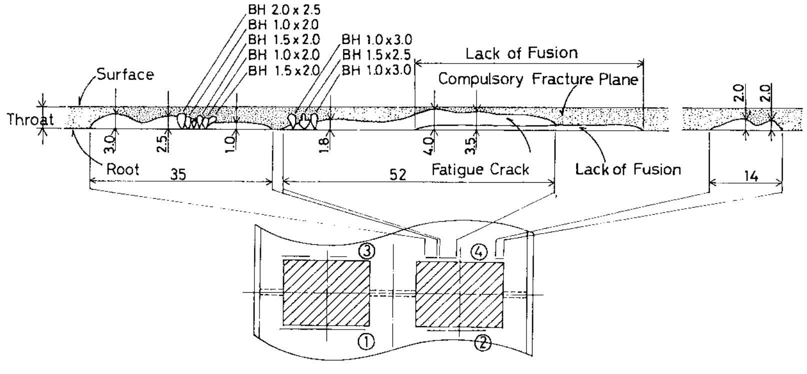


Fig. 15 Sketch of fatigue crack at root.

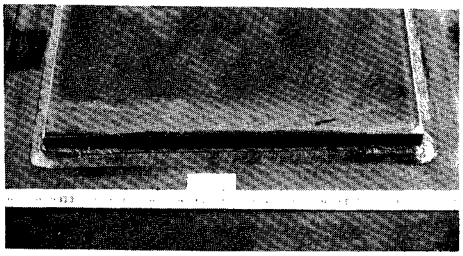


Photo. 5 Appearance of crack.

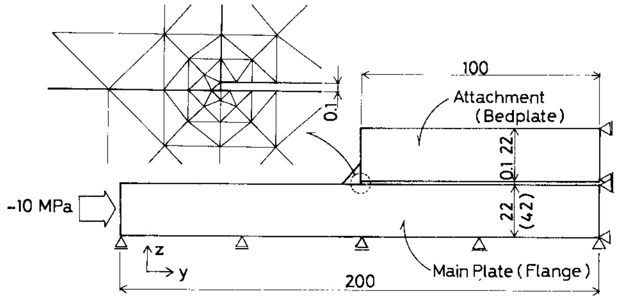


Fig. 16 Model calculated by finite element method.

with no surface crack, as skeched in Fig. 15. However, no relation is apparent between crack origination and weld defects, such as blowholes and slag-inclusions at the root. The exposure of every crack surface confirmed that the cracks propagated through the weld throat from the root.

The bedplate for the sidewalk were on the top compression flange where a bending fiber stress range of 0 ~103MPa was applied. Allowable design stress range of this weld joint, which is classified in Category C, is 134MPa. This suggests that the transverse fillet weld of the attachment cause a substantial reduction in fatigue strength. There are many reports about fatigue strength of the plate with welded attachment[7]. However, the crack initiation at the root, and especially the crack on the compression side, have received little attention.

d) Finite Element Analysis of Transverse Fillet Weld

Stress characteristics at the root of the transverse fillet weld under compression are examined by the finite element method. The finite element model in this analysis is shown in Fig. 16. Displacements in z-direction of the main plate were restricted according to the constraint of the web plate and the transverse stiffener. Three cases were conducted in order to calculate the effect of the fillet weld size, and to examine the difference between the flange plate thickness of the specimen (42 mm thick), and the actual member (22 mm thick). Case-1 dealt with the 42mm thick flange, case-2 with the 22 mm thick flange, and case-3 with the larger size fillet weld.

The following results were proved by these analysis. When the main plate is under the compressive axial force, the gap between the main plate and the attachment plate is enlarged, and tensile stress acts on the root of the fillet weld. A principal stress diagram of the root is shown in Fig. 17. The load sharing ratios which were calculated by the supporting reaction in y-direction are given in this figure. In case-1, corresponding to the test specimen, the maximum principal stress at the root is 103MPa. The relationship between the direction of the actual crack, which penetrated through the throat, and that of calculated

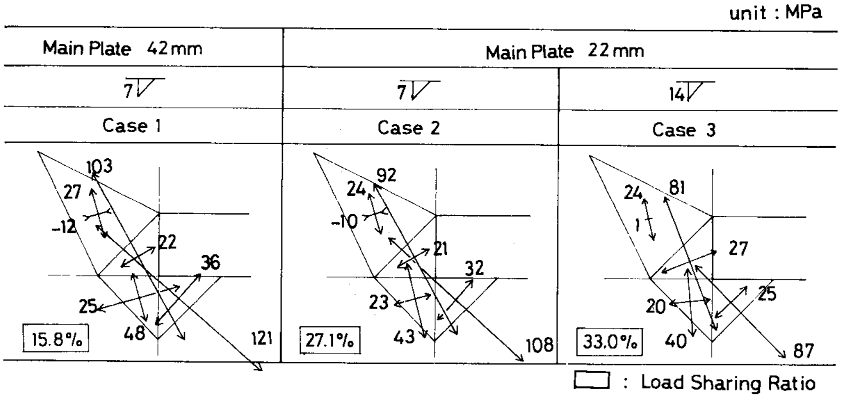


Fig. 17 Principal stress diagram about root.

principal stress can not be clearly explained. It is supposed that the direction of the principal stress could be changed by the modelling of the element at the root, and that cracks originate due to this tensile stress.

In comparison with this case, maximum principal stress decreases with the thinner main plate in case-2 and with the larger fillet weld size in case-3.

As the actual member will be under the same stress of −98MPa as the specimen, enlargement of the fillet weld size would increase fatigue strength.

f) Other Weld Joints

It was confirmed by visual inspection that no surface crack originated at the weld joints in the section supporting the stringers. The exposing survey on the typical fillet weld joints was carried out ot find concealed cracks. The survey showed that no fatigue crack originated, though there were some weld defects such as the hanging-down and blowhole.

As secondary shear stress may act on the corner joint near the region supporting the stringer, roots of the outside and inside weld were exposed. No collective crack which originated on the full-size box section specimen[1], was found.

6. CONCLUSION

The examine the fatigue behavior of the transverse chord of stiffening truss made of SM50Y, the static torsional loading test and the bending fatigue test were carried out with the full-size specimen. The results of these tests are summarized as follows.

Torsional loading test

(1) When the diaphragm was not welded to the bottom flange, out-of-plane distortion of the web plate at the scallop of the diaphragm appeared. Due to the torsion corresponding to the support reaction, out-of-plane bending stress of this point was expected to be over 200MPa during passage of a train. This stress is high enough to result in a fatigue cracking.

(2) In the diaphragm bolted to the bottom flange, no significant out-of-plane bending stress was measured. This result was confirmed by the finite element analysis.

Bending fatigue test

(3) Structural details used at the section supporting the stringer had sufficient fatigue resistance.

(4) The fatigue strength of the corner joint, made of SM50Y with blowholes up to about 1.5mm, was over the design allowable stress of Category A.

(5) On the transverse fillet weld of the bedplate for the sidewalk, cracks were initiated at the root and propagated through the weld throat at a stress below the allowable design stress of Category C.

(6) In finite element analysis, when the flange plate was under compressive stress, tensile stress was

produced to the root of the fillet weld. This tensile stress which decreased in the case that the flange plate was made thinner and the fillet weld size was larger.

In the practical fabrication of Iwagurojima Bridge, the following changes were made to improve the fatigue strength of the transverse chord.

(a) The diaphragm was welded to the bottom flange

(b) The bottom flange plate was thickened from 22mm to 28mm, or a cover plate 16mm thick and 450mm wide was added, almost over the full length of the flange.

(c) Size of fillet weld to the bedplate for the sidewalk was increased from 7mm to 12mm.

7. ACKNOWLEDGEMENT

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REFERENCES

1) Shimokawa, H., Takena, K., Fukazawa, M. and Miki, C. : A Fatigue Test on the Full-Size Truss Chord, Proc. of JSCE No.344/I-1 April 1984.

2) JSCE : Report on the Steel Superstructure of Honshu-Shikoku Bridges, 1983 (in Japanese).

3) Kashiyagi, H., Miki, C. and Mori, T. : Fatigue Strenth and Crack Growth of Fillet Weld Loaded in Bending, Proc. of the 39th Annual Conference of JSCE, 1984 (in Japanese).

4) Ushirokawa, O. and Nakayama, E. : Stress Concentration Factor at Welded Joints, Ishikawajima-Harima Engineering Review, Vol.24 No.1,1984 (in Japanese).

5) Technical Committee for the Construction of Honshu-Shikoku Bridges and Kaiyo Kakyo Chosakai : Technical Report for the Construction of Stiffening Truss, 1984 (in Japanese).

6) Okumura, T., Nishimura, T., Miki, C. and Hasegawa, K. : Fatigue Crock Growth Rates in Structural Steels, Proc. of JSCE No.322, June 1982.

7) Fisher, J.W., et al. : Detection and Repair of Fatigue Damage in Welded Highway Bridges, National Cooperative Highway Research Program Report 206, June 1979.

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