Repair of Fatigue-Cracked Plate Girders in Highway Bridges

Réparation de poutres métalliques de ponts ayant des fissures de fatigue

Reparatur von Blechträgern mit Ermüdungsrissen in Brücken

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SUMMARY

Recent investigations showed the existence of many small cracks at the intersections between main girder and cross beam or bracing of highway bridges in Japan. The bridges comprise reinforced concrete slab and I-shaped plate girders and floor beams. Failure analysis and Finite Element Analysis were performed, then repairing method was studied and executed. The result was incorporated into the new design specification. Vulnerability of the new design specification to fatigue defects was also checked and confirmed to be appropriate.

RÉSUMÉ

Au Japon, dans de nombreux ponts à poutres en acier en I comportant des dalles en béton armé, des fissures ont été remarquées au raccordement entre la poutre principale et la traverse ou l'entretoise. Les causes de ce défaut et les réparations à faire ont été analysés par éléments finis et par des essais de fatigue. Les résultats sont inclus dans une nouvelle norme, qui tient compte des effets de la fatigue.

ZUSAMMENFASSUNG

In vielen japanischen Doppel-T-Träger-Brücken mit Stahlbetonplatten sind Risse am Verbindungsteil zwischen Hauptträgern und Querträgern bzw. Verbänden gefunden worden. Analysen des Schadenzustandes, Berechnungen nach der Methode der finiten Elemente, Ermüdungsprüfungen mit grossformatigen Modellen und Schweissprüfungen wurden durchgeführt. Die Ursachen für das Auftreten der Schäden wurden analysiert, und Reparaturmassnahmen wurden untersucht. Weiter sind auch Untersuchungen nach den gleichen Methoden in bezug auf die Möglichkeit des Auftretens solcher Schäden bei neuen Brückenträgern durchgeführt worden.

1. PREFACE

Plate girder bridges have been of predominant use in the construction of urban highway system in Japan. These are comprised of main girders, cross beams and sway and lateral bracings. And reinforced concrete deck is placed on the top of girders. Recent investigation reveals that small fatigue cracks are apt to be found at welding around connection plate at the intersection between the main girder and the cross beam, or the bracing. Some propagate through web of the girder.
Detail investigation was made to analyze the causes of the fatigue cracks, hence to devise the repairing or strengthening techniques. It was also expected that the results could be applied for revision of the contemporary design specifications.

2. INSPECTION

Hanshin Expressway Public Corporation in Osaka, Japan now provides 138.5 km of urban highway system with elevated type structures, most of them comprises of steel plate girders. 80% of the plate girder bridges were thoroughly inspected, and consequently 20% of them revealed a defects of the above-mentioned type of crack. Failure analysis concluded as follows:

(1) Defects are limited to bridges with reinforced concrete deck served more than 14 years. There is a tendency that the cracks are found for bridges,
- -1) designed according to the specification edited in 1964 [1],
- -2) with RC slab of span length more than 2.5 m long, and
- -3) with relatively shallow slab depth.

(2) Defects can be found for bridges with rigid cross beam, which was intended to secure good load distribution.

(3) Most cracks are classified into Type 1 shown in Fig. 1. Type 2 cracks follows.

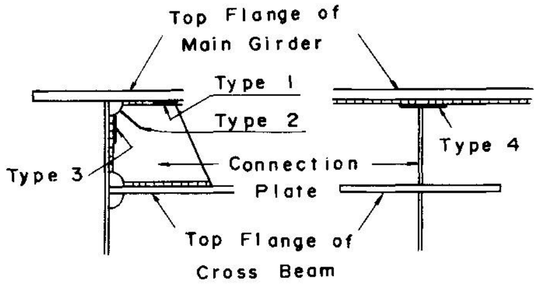
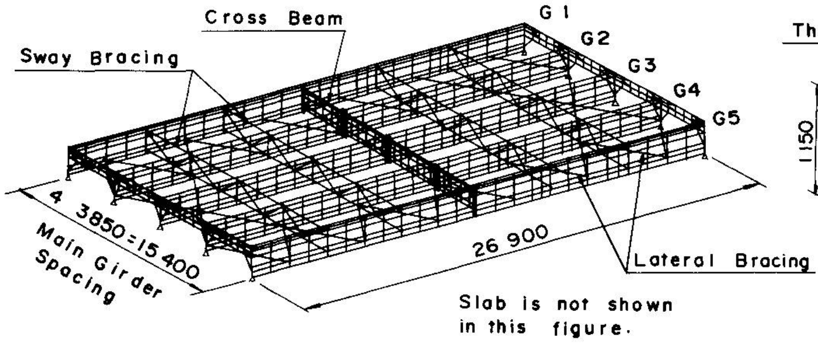


Fig. 1 Types of Fatigue Crack

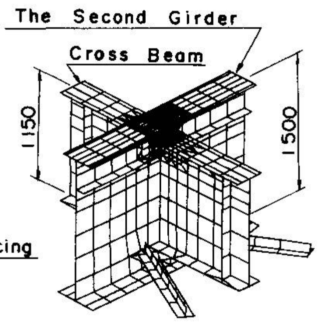
3. FAILURE ANALYSIS

3.1 Analysis of Stress Distribution

Finite Element Method was used to analyze stress distribution and its value. Phase-1 analysis was made on coarse three dimensional model shown in Fig. 2(a) to asses the global stress flow. A 20-ton-truck load, designated as T-20 loading in design specification [1](Fig. 3), was placed in the longitudinal



(a) Global Model



(b) Local Model

Fig. 2 Analysis Model

direction, two in the transverse direction so that those cause the most severe stress distribution at the place of concern. To make a detail investigation of stress distribution, Phase-2 analysis was made on a partial three dimensional model shown in Fig. 2(b) by applying the sectional force given by the Phase-1 analysis.

From Phase-1 analysis, it was concluded there is a close correlation between the equivalent stress at the connection plate and the rotational difference between the slab and the cross beam as shown in Fig. 4.

From Phase-2 analysis it was concluded,

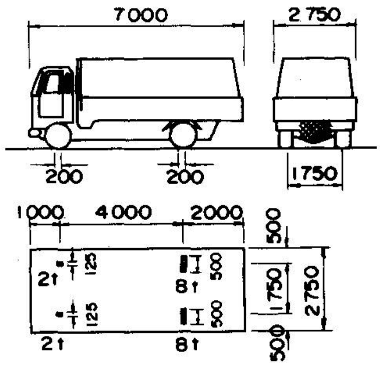


Fig. 3 T-20 Truck Load

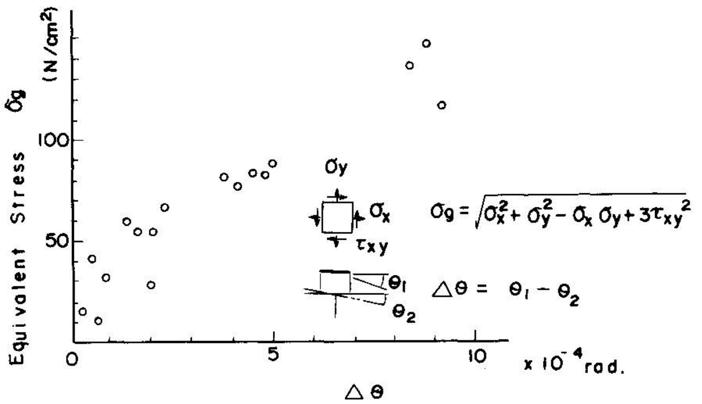


Fig. 4 Relation between σg and Δθ

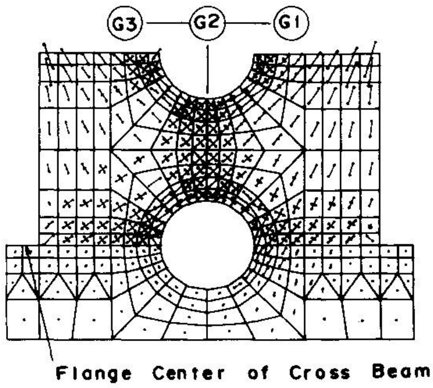


Fig. 5 Principal Stress Diagram

-1) The Principal stress over 200 N/cm^2 is detected on the connection plate adjacent to the free edge of the top flange of the main girder. Due to shearing stress, the principal stress direction vary significantly as it comes closer to the web as shown in Fig. 5.

-2) There is a stress turbulence due to scallop.

3.2 Stress Measurement at Bridge Site

Stress measurements were executed at the bridge in service to confirm the resutls obtained by the stress analysis. Stress concentration was of a primary concern on the connection plate adjacent to the free edge of the main girder. It was revealed that the tensile stress is 80 N/cm^2 at 20 mm away from the point of interest. The stress is small compared with the analyzed value, about a fourth, but is not small enough as a tensile stress to be ignored for fillet welds.

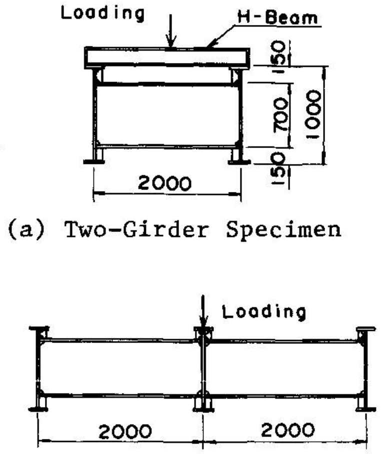
3.3 Fatigue Experiment [2]

It was assumed that the principal causes of the defects are 1) the rotational difference between the slab and cross beam, and 2) the difference of vertical displacement between the adjacent main girders, fatigue experiment was executed in this respect. Two types of the specimen shown in Fig. 6(a) and (b) were tested. The first was a two-girder type. An equivalent vehicle load was applied at the center of H-beam, each end was fixed on the top flange of the girder, with equivalent bending rigidity with RC slab. The second was a three-girder specimen. The test load was applied directly on the interior girder, and was adjusted so that the curvature of the test girder is equivalent with the actual girder when the rear axle load 16 tons of the T-20 loading is applied

on the girder.
It was revealed that the three-girder specimen, which causes only the vertical mutual difference of deflection, caused no cracks after 2 million cycles of load repetition, but on the two-girder specimen, which causes the rotational difference, cracks were induced at the cycles of about 100,000. The three-girder system caused no fatigue cracks even the test was further continued by the load amplitude 1.45 times greater.
The similar experimental results were reported by KATO and three [3].

3.4 Causes of the Crack

From the experiment, it was concluded that the rotational difference between the slab and the cross beam or the bracing is the main cause of the defects. Other inducements are to be welding defects caused by an excessive root-gap, or a notch of weld bead around a scallop.



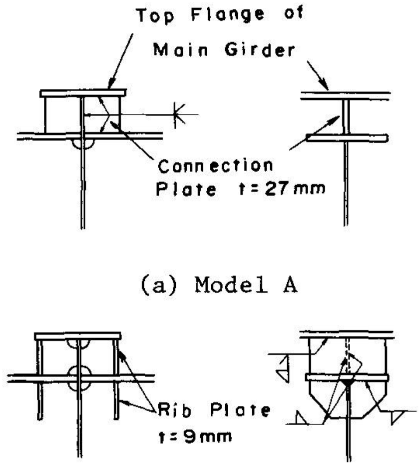
(a) Two-Girder Specimen

(b) Three-Girder Specimen

Fig. 6 Fatigue Test Specimen

4. STUDY OF REPAIRING METHOD

It is assumed that followings are effective for retrofitting the above-mentioned defects,
-1) to lessen the local stress at the welding, and
-2) to lessen the stress at the structural part as a whole.
It is available to exemplify the former one by,
-a) attaching a piece of structural member to increase the cross-section,
-b) increasing the welding size, or
-c) grinding the weld bead to alleviate the stress concentration.
It is not so practical to introduce the latter method 2) because it requires the modification of the structural system.
From the economical stand point, the simpler one 1) is preferred. Fatigue experiment on the method c) showed crack generation at about 30,000 cycles, so the method was concluded not effective at all.
Also the method b) was rejected because it causes large stress to the existing connection plate.



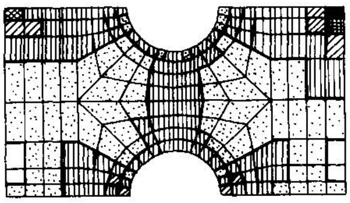
(a) Model A

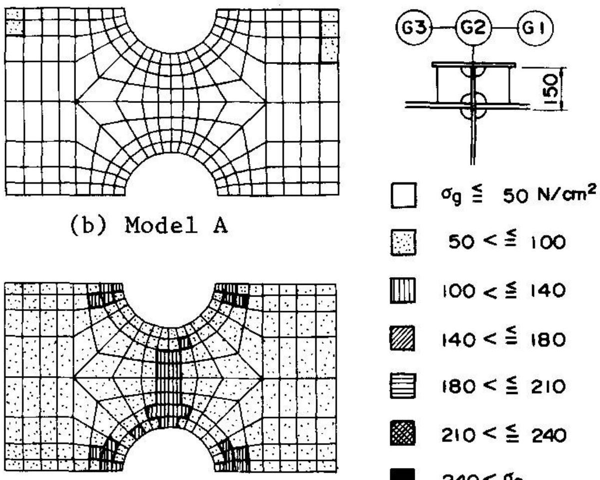
(b) Model B

Fig. 7 Prototypes

4.1 Analysis of The Repairing Prototypes

Two prototypes shown in Fig. 7 are proposed as repairing prototypes. For Model A, Fig. 7(a), the thickness of the connection plate was tripled. For Model B, Fig. 7(b), a rib plate was attached along the edge of the connection plate. Analysis was performed in accordance with the method shown in 3.1. The results are shown in Fig. 8. Model A lessens stress to one third. Model B improves the stress distribution at the free edge of the connection plate, but stress distribution around the scallop remains almost the same.
From these results, Model A was expected as an effective repairing detail and its availability was confirmed by fatigue testing on the tested two-girder type specimen by replacing cracked connection plate with tripled thickness one.


(a) Actual Detail



(b) Model A

(c) Model B

Fig. 8 Equivalent Stress Diagrams

4.2 Trial by Specimen

In the practice of repairing, the influence of heat stress caused by welding have to be taken into consideration besides the stress caused by vehicles. An experiment with one half scale model was performed to confirm the structural behavior and the working condition. An equivalent dead load is applied through the test. No harmful deformation to cause structural instability was detected. But the top flange of the main girder between the studs attached on the flange deformed so as to cause a gap between a slab and the flange. This seems due to the heat effect of full penetration welds, initially intended to secure strength at the intersection.

4.3 Decision of Repairing Method

As a result of the investigation shown above, the repairing method was decided as follows: replace the present 9 mm thick plate with 19 mm one by partial penetration welds. It is expected to secure strength and minimize the harmful influence at field welds.

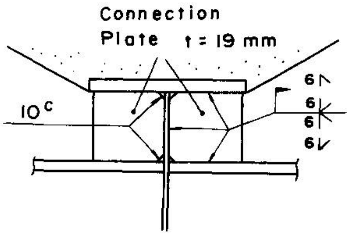


Fig. 9 Repairing Detail

5. FEEDBACK TO DESIGN CODE

Current Specification for Highway Bridges in Japan[4] revised in 1980 specifies narrower girder spacing and thicker slab thickness after the experience of several damage of RC slab. Now, it was to be tested whether the bridges designed according to the revised specification can sustain the vehicle load without showing any fatigue cracks. The same procedure as shown in chapters 3 and 4 was applied.

5.1 Stress Analysis

Structural analysis was made by Finite Element Method by assuming a girder as a beam element, and a cross beam as a plane stress rectangular element. It was confirmed that the stress level is about one third and a favorable behavior can be expected under the new specification.

5.2 Field Measurement of Strain

Field measurement of strains caused by vehicle loads in service was executed on a newly constructed plate girder bridge. The maximum measured stress was 25 N/

cm^2, so the stress in practice is assessed to have been improved to one third.

5.3 Fatigue Test [2]

The similar fatigue test as 3.3 was also performed for the structure designed by applying new specification. No cracks were detected.
A series of the fatigue test was summarized as S-N relation in Fig. 10. The doted line shows the S-N line given by the least square method. The slope is,

$k = 1 / m = 0.185,$

$m = 5.4,$

therefore the stress amplitude for 2,000,000 cycles is about 200 N/cm^2.
Assuming that the bridges showed the defects are estimated to have experienced stress amplitude of 80 N/cm^2 for the past 14 years, we may conclude that bridges designed by new specification can sustain more than $(80/25)^{5.4} \times 14$ years.

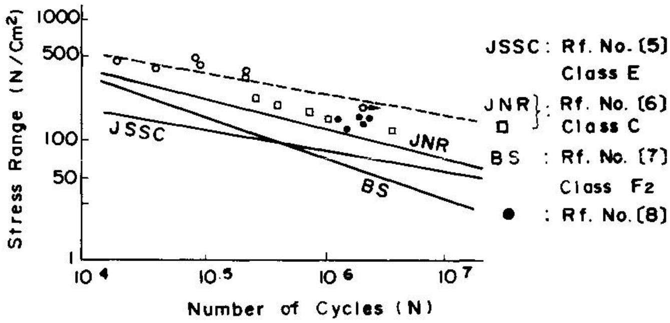


Fig. 10 Fatigue Test Result

5.4 Recommendation for Specification

Slab span and the slab thickness have been improved from the stand point of fatigue. But in view of the increase of excessive truck loads, 12 mm thick connection plate is recommended to be applied in place of 9 mm one. And, no scallops are allowed in this portion, as it can be seen in 3.1.

6. CONCLUSION

From the present investigation, it seems necessary to give more safety margin to some structural details, i.e. connection plate on cross beam, from the point of view of fatigue. The repairing method on the fatigue defected members and the revision of the current specification were recommended. It is essential that the fatigue design is to be introduced for the design of highway bridges.

References

1. Japan Road Association, Specifications for Highway Bridges, 1964 (in Japanese)
2. MATSUMOTO S., HORIKAWA K. and KITAZAWA M., Fatigue Behavior of Connection Plate between Main Girder and Cross Beam in Composite Plate Girder, Proc. of JSCE No.386/I-8, pp.247∿255, October, 1987. (in Japanese)
3. KATO S., YOSHIKAWA O., TERADA H. and MATSUMOTO Y., Studies on Fatigue Damages Based on Strain Measurements of Highway Bridge, Proc. of JSCE, Struct. Eng. /Earthq. Eng., Vol.2, No.2, pp.445s∿454s, 1985.
4. Japan Road Association, Specifications for Highway bridges, 1980 (in Japanese)
5. Japan Society of Steel Construction, Recommendation and its Commentary for Fatigue Design (Draft Version), JSSC, Vol10, No. 101, May, 1974.(in Japanese)
6. Japan Society of Civil Engineering, Design Specification and its Commentary for Railway Steel Structures, 1983. (in Japanese)
7. British Standard Institution ; Code of Practice for Fatigue, BS 5400 Part 10, 1980.
8. Public Works Research Institute, Fatigue Test on Field Welding of U-Shaped Rib Plate Attached on Steel Deck Plate, No. 25-3, Technical Note of the Public Works Research Institute, Ministry of Construction, 1983. (in Japanese)