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Life Extension of Steel-Girder Bridges on the Tomei Expressway

Prolongation de la durée de vie de ponts en acier de l'autoroute Tomei

Lebensdauerverlängerung von Stahlbrücken der Tomei-Schnellstrasse

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SUMMARY

Some steel bridges on Tomei Expressway have experienced distortion-induced fatigue cracking. Fatigue cracking, stress measurement, retro-fitting methods and structural improvements, performed for life extension of this highway, are described in this paper.

RÉSUMÉ

Quelques ponts en acier de l'autoroute Tomei (Japon) ont montré des fissures de fatigue dues à la torsion. Cet article présente les caractéristiques de ces fissures de fatigue, les mesures des contraintes, les procédés de réparation ainsi que les améliorations structurales réalisées dans le but de prolonger la durée de vie de cette autoroute.

ZUSAMMENFASSUNG

Einige Stahlbrücken der Tomei-Schnellstrasse erlitten verformungsinduzierte Ermüdungsrisse. In dieser Abhandlung werden die Eigenheiten solcher Risse, Spannungsmessungen, Reparaturmethoden sowie strukturelle Verbesserungen beschrieben, wie sie im Hinblick auf eine Lebensdauerverlängerung dieser Schnellstrasse durchgeführt wurden.

1. INTRODUCTION

The Tomei Expressway [National Expressway No. 1] is a vital arterial road running through the center of the economic activity belt of Japan extending from Tokyo to Nagoya to Osaka [Fig. 1]. The full length of this road was completed and opened to traffic in February 1969 and it has been in service now for approximately 20 years. From around 1980, fatigue damage began to be discovered in steel girders.

This report is on typical fatigue damage which have occurred on steel plate-girder bridges of the Tomei Expressway. The results of field investigations made concerning fatigue cracks produced in the cross bracing connection, studies of the causes of occurrence, and examination of retrofitting methods are reported. The facts that retrofitting work must be done while open to traffic as much as practicable because of the importance of this expressway with no alternative expressway availables, and that the places requiring retrofitting comprise a huge number are features of this rehabilitation project.

2. OUTLINE OF BRIDGE STRUCTURES ON TOMEI EXPRESSWAY

There are 112 plate-girder bridges (composite and non-composite) on the part of the Tomei Expressway under the authority of the Tokyo First Operating Bureau of the Japan Highway Public Corporation. Of these, approximately 58 percent are quadruple-main-girder bridges, 37 percent are triple-main-girder bridges, and the remainder small numbers of quintuple-main-girder and sextuple-main-girder bridges. The spacings of main girders are 3400 mm for approximately 70 percent of the quadruple-main-girder bridges and 4000 mm for approximately 80 percent of the triple-main-girder bridges. These plate-girder bridges all have reinforced concrete deck slabs, the thicknesses of which are 180 to 200 mm for triple-main-girder bridges with 190 mm in the majority of cases, while for quadruple-main-girder bridges they are 170 to 190 mm with 170 mm making up the greater part. In all of the bridges damage began to occur in the reinforced concrete deck slabs four to five years after being put into service, and stringers for supporting deck slabs are being added starting in order from bridges in the poorest conditions.

Fig. 2 shows the transitions in the volume of traffic on the Tomei Expressway.

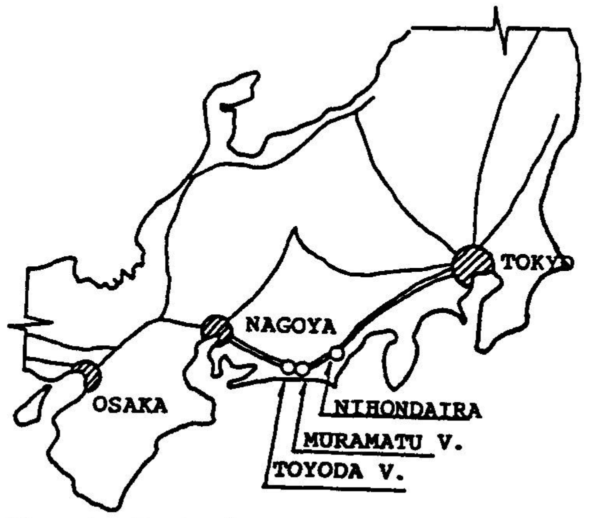


Fig. 1 Central Japan and Tomei Expressway

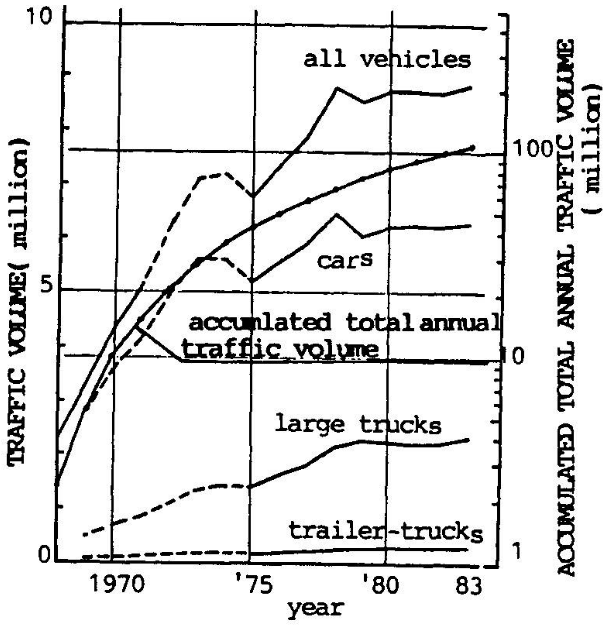


Fig. 2 Traffic Volume on Tomei Expressway

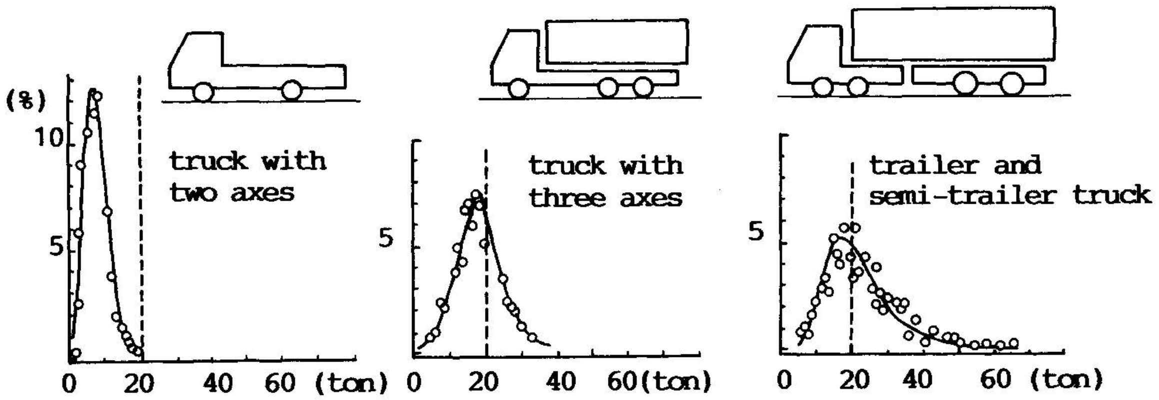


Fig. 3 Weight distributions of trucks measured at Nihondaira

The daily volume in one direction is approximately 50,000 vehicles, with about 30 percent being of large size. Scales are installed in the main traffic lanes at Nihon Daira of the Tomei Expressway. Fig.3 shows the truck weight distribution measured by these scales and it can be seen that substantial numbers of large-sized vehicles in overloaded condition are traveling on the expressway [1].

3. FATIGUE DAMAGE

Various investigations were made on two viaducts (Toyoda Viaduct and Muramatsu Viaduct) on the Tomei Expressway. The reasons for selecting these two viaducts were that they are a triple-main-girder bridge (Toyoda Viaduct) and a quadruple-main-girder bridge (Muramatsu Viaduct) which are types existing in large numbers on this expressway, they are bridges on which stringer additions were made at an early stage for strengthening the deck slab (Toyoda Viaduct) and on which additions are to be made hereafter (Muramatsu Viaduct), and they are comparatively close to Nihon Daira where vehicle weight measurements are being periodically made.

Fig. 4 shows the modes of fatigue cracks occurring at these parts and the respective identification marks given them. Vertical stiffeners are joined to top flanges and webs by fillet welds, and fatigue cracks have formed at various parts of these welds. Fatigue cracks have also formed at riveted joints for attaching cross bracing to vertical stiffeners and at cut-away portions of top flanges of top members of cross bracing.

Fig. 5 shows a part of the results of inspections on Toyoda Viaduct carried out in 1985, expressed as sums of the lengths of all fatigue cracks at various locations. The features of fatigue damage on this bridge are listed below.

- Cracks were formed at 200 locations out of the 240 locations in all excluding locations on bearing points.
- Type A cracks occurred at 198 out of the 200 locations and Type B cracks at 2 locations.
- Type C and Type D cracks occurred along with Type A and Type B cracks.
- Damage was more prominent the closer to the middle of a span and did not occur on a bearing.
- Of the three main girders damage was prominent at outer girders.

Approximately the same results were seen on Muramatsu Viaduct, but the following were tendencies differing from Toyoda Viaduct.

- Crack dimensions were comparatively small.
  Numerous Type A cracks were thought to have been initiated from the roots of fillet welds.

- Damage was prominent at inner girders (G3-G6 in Fig. 13) excluding outer girders on the traffic lane sides.

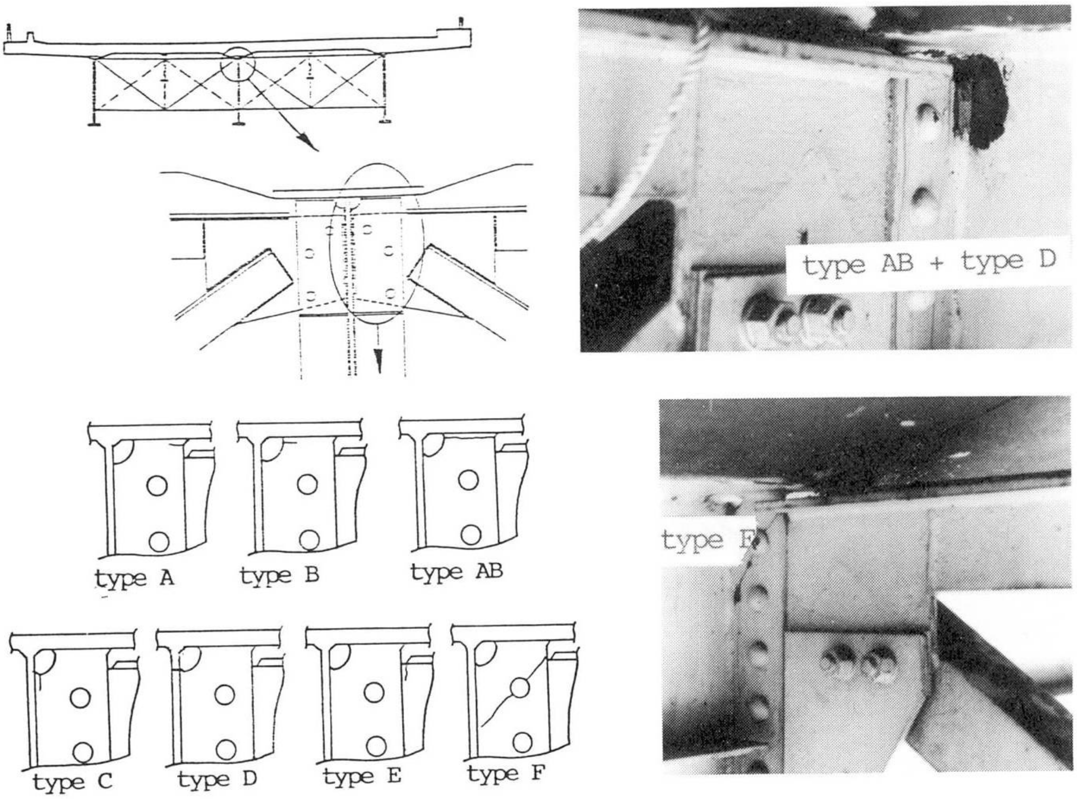


Fig. 4 Modes of fatigue crack

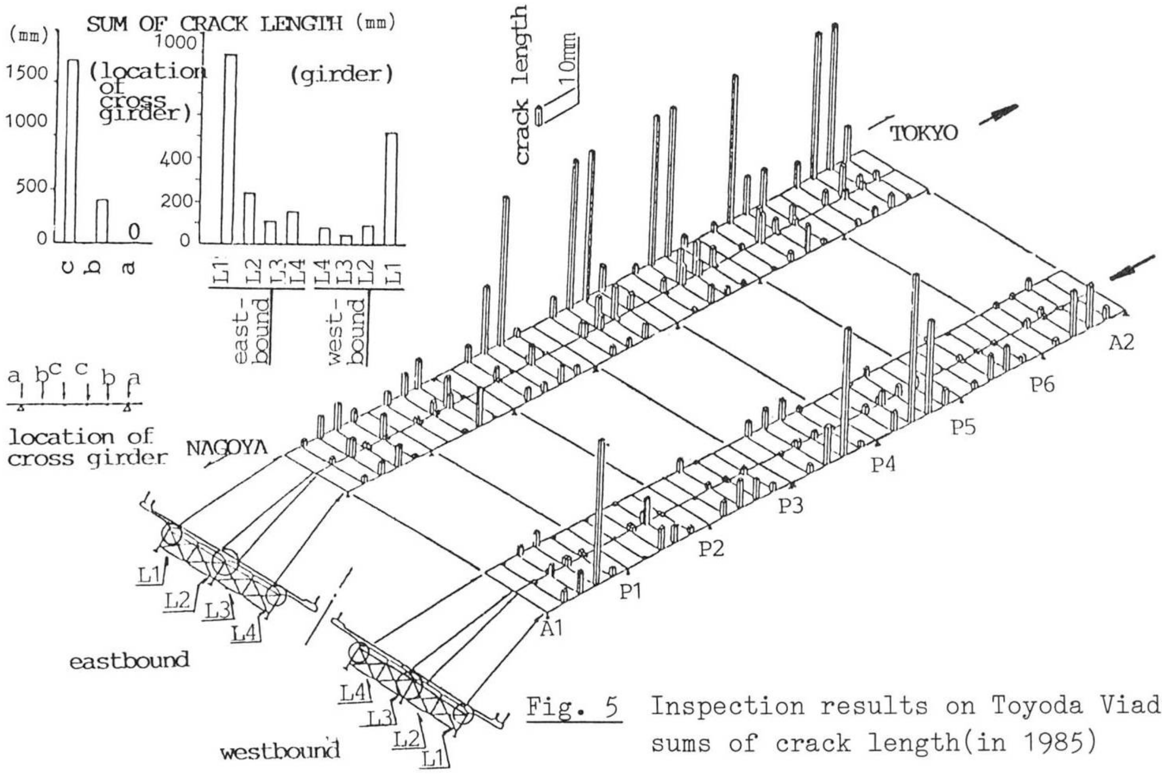


Fig. 5 Inspection results on Toyoda Viaduct, sums of crack length(in 1985)

4. STRESS MEASUREMENT OF DAMAGED BRIDGES UNDER ACTUAL TRAFFIC LOAD

A series of field measurements on stress and deflection of actual bridges was carried out.

The measurements were made for the following two purposes:

(1) Purpose 1: To clarify structural characteristics
Load, deflection and stress are measured simultaneously and the relations between the loading conditions and stress responses at various details of the bridge structure are analyzed. This is important for investigating the causes of fatigue damage and finding the most suitable repair methods.

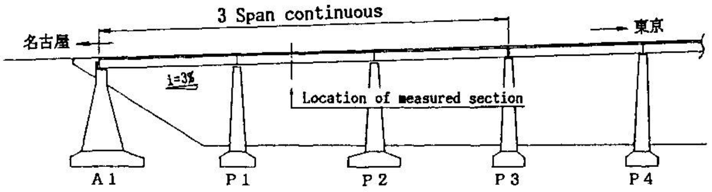
(2) Purpose 2: To obtain data for fatigue life estimation
Stress at the exact point concerned is continuously measured for certain period of time under ordinary service conditions. Direct evaluations are made on fatigue damage and remaining fatigue life by stress histogram analysis of the measured data.

One of the main features of the stress measurements in this study is that the on-site measurements of actual bridges in service were carried out without disturbing ordinary traffic flow. The measured items and locations for Toyoda Viaduct of Tomei Expressway are shown in Fig. 6.

For the Purpose 1 measurements, a newly developed automatic vehicle detector and computer controlled measuring system were utilized[2]. This system enables the simultaneous measurements of stresses and deflections in accordance with passing vehicle information such as passing time and lane, vehicle speed, length and interval.

Fig. 7 is an example of measured influence lines at various measuring points. The pattern of vehicle detector output indicates that these data were obtained when a truck passed through on the passing lane.

For the Purpose 2 measurements, an automatic stress histogram analyzer [histogram recorder] was utilized. Fig. 8 is an example of the output of stress histogram analysis. The same data were analyzed in two ways, by the level-crossing method and the rain-flow method. From the field stress measurements described here, it was found that the fatigue strengths of fillet welds between stiffeners and top flanges of cross bracing connections are not high enough for



Measured items	Location
①Stress distribution arround the cracked portions	Sway bracing connections ; G1~G4
②Member forces of sway bracing	All members at the measured section
③Deflection of main girders	Lower flanges of main girders ; A1~A3

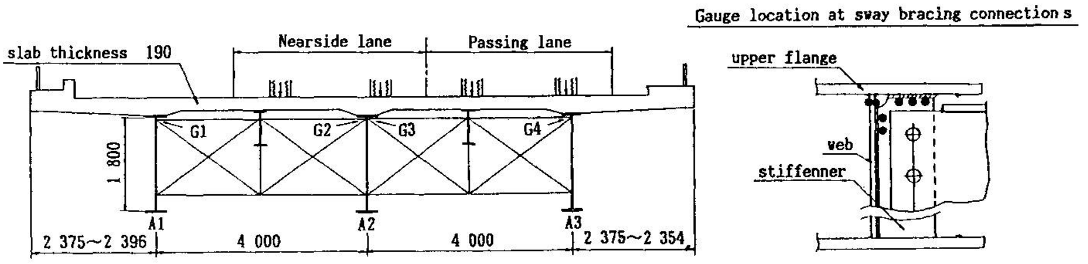


Fig. 6 Measuring plan for Toyoda Viaduct

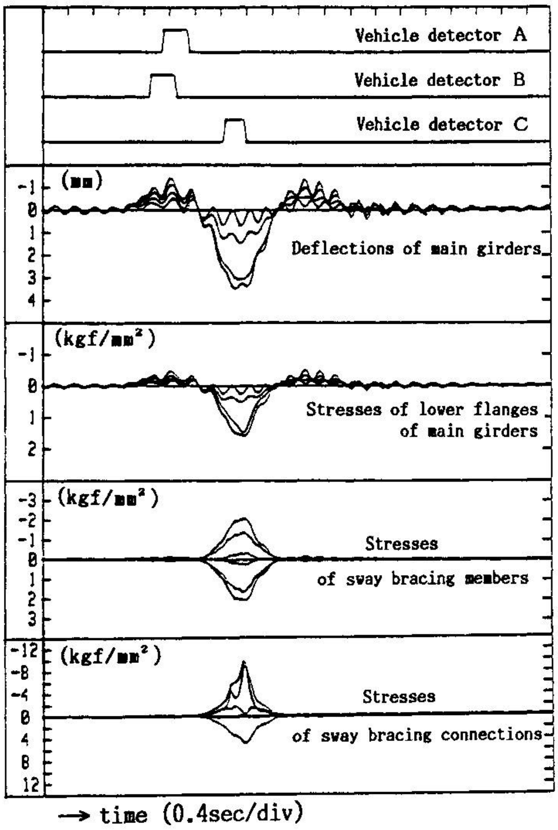
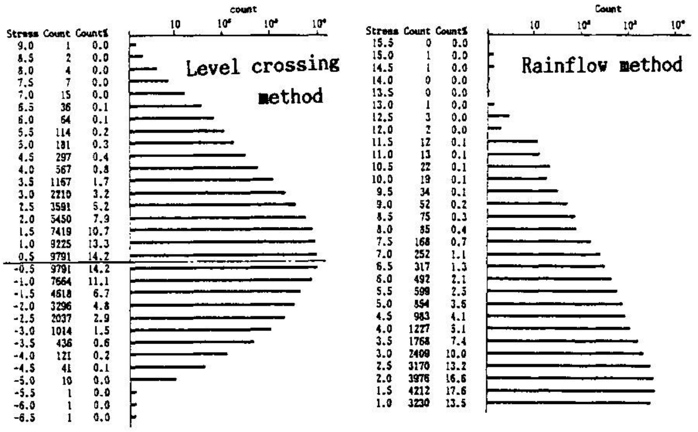


Fig. 7 Examples of measured influence lines



Stress	Count	Count%
9.0	1	0.0
8.5	2	0.0
8.0	4	0.0
7.5	7	0.0
7.0	15	0.0
6.5	36	0.1
6.0	64	0.1
5.5	114	0.2
5.0	181	0.3
4.5	297	0.4
4.0	567	0.8
3.5	1167	1.7
3.0	2210	3.2
2.5	3591	5.2
2.0	5450	7.9
1.5	7419	10.7
1.0	9225	13.3
0.5	9791	14.2
-0.5	9791	14.2
-1.0	7664	11.1
-1.5	4618	6.7
-2.0	3296	4.8
-2.5	2037	2.9
-3.0	1014	1.5
-3.5	436	0.6
-4.0	121	0.2
-4.5	41	0.1
-5.0	10	0.0
-5.5	1	0.0
-6.0	1	0.0
-6.5	1	0.0

Stress	Count	Count%
15.5	0	0.0
15.0	1	0.0
14.5	1	0.0
14.0	0	0.0
13.5	0	0.0
13.0	1	0.0
12.5	3	0.0
12.0	2	0.0
11.5	12	0.1
11.0	13	0.1
10.5	22	0.1
10.0	19	0.1
9.5	34	0.1
9.0	52	0.2
8.5	75	0.3
8.0	85	0.4
7.5	168	0.7
7.0	252	1.1
6.5	317	1.3
6.0	492	2.1
5.5	599	2.5
5.0	854	3.6
4.5	983	4.1
4.0	1227	5.1
3.5	1768	7.4
3.0	2409	10.0
2.5	3170	13.2
2.0	3976	16.6
1.5	4212	17.6
1.0	3230	13.5

Fig. 8 Examples of Stress counting

the repeated stresses induced by relative vertical deflections between adjacent main girders and by deflections of concrete slabs.

5. RETROFITTING METHODS FOR FATIGUE CRACKS

Two kinds of retrofitting methods are conceivable for the prevention and repair of fatigue cracks:

(1) Lowering stress occurring at a crack location.
(2) Increasing fatigue strength of joint.

In this study, however, "increasing fatigue strength of joint" was taken for the first step, and increasing weld size and finishing toes with TIG dressing was proposed as one of the most suitable repair methods. The repairing effect was examined by fatigue tests and fatigue life analyses [3].

In the fatigue tests, three kinds of specimens were tested, AS-WELD, GRINDING and TIG specimens. The AS-WELD specimens were reproductions of fillet welds of the damaged portions. The GRINDING specimens are welded by full penetration welding and their weld toes were finished by grinder. The TIG specimens had an additional pass of fillet welding on top after welding in the same way as the AS-WELD specimens, and the toes were finished smooth by TIG dressing. Macro-etch-examinations of the welds are shown in Fig. 9.

Fatigue test results are shown in Fig. 10 with the design allowable S-N curves in the Design Standards for Steel Railway Bridges [4]. From Fig. 10, AS-WELD specimens results can be classified as Class D and it can be improved to be Class A by one pass of reinforcement welding and TIG dressing, or to be Class B by grinding. An approximate evaluation of the fatigue life remaining after repairs was made based on the fatigue test result and the actual load condition.

Considering the make-up ratio of vehicles, approximately 30 million large vehicles had passed in each direction during the 16 years from the time of opening in 1968 to 1983, when the damage was found. And 2.5 million large vehicles had passed in each direction annually during 1978 to 1983.

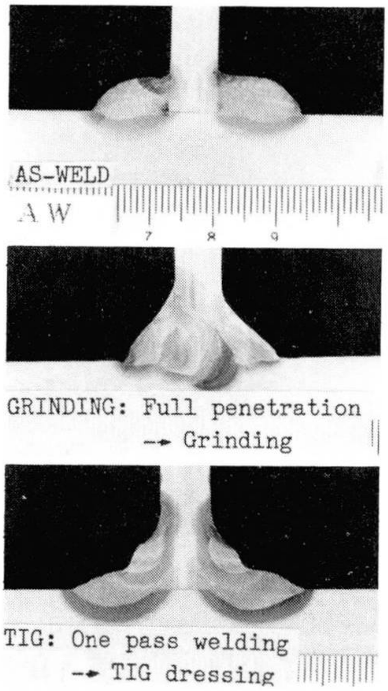


Fig. 9 Macro-Etch results of specimen

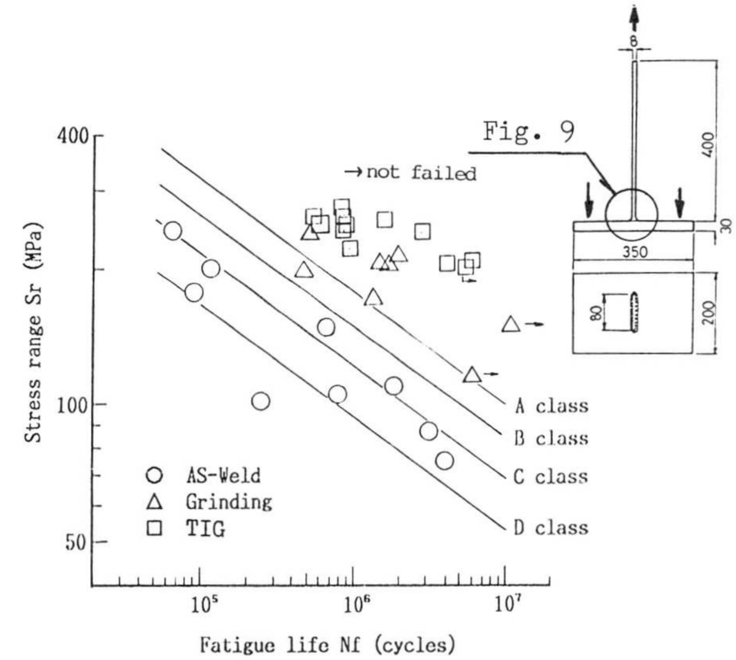


Fig. 10 Fatigue test results

When improvement has been done from Class D up to Class A, the remaining fatigue life will be

$$\left(\frac{15.3}{8.05}\right)^4 \times \frac{3 \times 10^7}{2.5 \times 10^6} = 157 \text{ years}$$

When improvement has been done from Class D up to Class B, the remaining fatigue life will be

$$\left(\frac{12.75}{8.05}\right)^4 \times \frac{3 \times 10^7}{2.5 \times 10^6} = 76 \text{ years}$$

where 15.3 kgf/mm^2, 12.75 kgf/mm^2, and 8.05 kgf/mm^2 are allowable stress range for Cass A, B and D respectively.

The abovementioned evaluation shows that ample remaining fatigue life can be obtained by the repair method proposed here.

6. ANALYTICAL INVESTIGATIONS ON THE EFFECTS OF STRUCTURAL CHANGES AND CONSIDERATIONS FOR STRUCTURAL IMPROVEMENTS

The influences of structural changes aiming to prevent occurrence or growth of slab cracking on fatigue damage of transverse stiffeners are studied through numerical analyses.

The following countermeasures for the fatigue damage of transverse stiffeners may also be considered such as: introduction of floor beams with high stiffness at span centers in order to achieve more effective transverse load distribution together with the elimination of all or a part of cross bracing members, which are considered to be the sources of the fatigue damage; or conversely, addition of cross bracings between existing ones in order to reduce maximum member forces in cross bracings. The effects of these measures are also analytically examined.

6.1 Analytical Model [5]

The entire bridge under consideration is modeled as a stiffened plate, as shown in Fig. 11, where reinforced concrete floor slabs are modeled by thin plate elements, main girders by offset beam elements, and cross bracings by cross bracing elements, which can be obtained through the contraction of stiffness matrices describing the cross bracings as plane frame structures. In cases where lateral bracings exist, lateral bracing elements are similarly introduced.

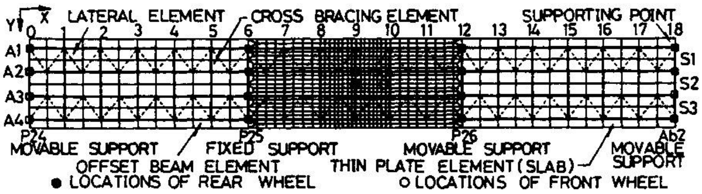


Fig. 11 Modelling of the whole bridge superstructure

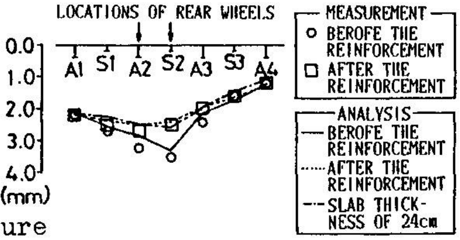


Fig. 12 Comparison of concrete slab deflections

6.2 Influences of Additional Stringers with Cross Bracing Reinforcement

Here, the object of analysis is the Muramatsu Viaduct with four main girders. The moments of inertia of supplemented stringers are about one-tenth of main girders. Additional diagonals and reinforcement of lower struts are provided for cross bracings. The element mesh division diagram for this object of analysis is illustrated in Fig. 11. The Ai in the diagram indicates the number of the main girder, the numerals the numbers of cross bracings, Pij and Ab2 the numbers of piers and abutment, respectively.

The load applied are rear wheels of T-20 load as specified in the Japanese Highway Bridge Specifications [6](each 8 tf (78.4 kN)) totaling 16 tf (156.8 kN) on the cross bracing location at the center of the middle span(the location indicated by dark circle marks in the diagram; hereafter called "center section") and front wheels (each 2 tf (19.6 kN)) totaling 4 tf (39.2 kN)) at locations of the circle marks in the diagram.

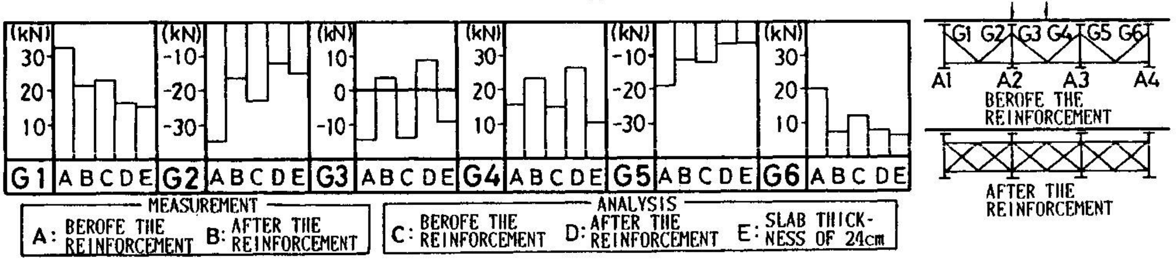


Fig. 13 Comparison of axial force in diagonal members of a cross bracing

The floor slab deflections and axial forces of diagonals in cross bracings at the center section before and after reinforcing are given in Figs. 12 and 13, respectively. Measured values are also given therein. The ratios of axial forces of cross bracing members before and after reinforcing for measured and analytical values are very close to each other. Floor slab deflection is reduced on the whole by the reinforcement, and it can be seen that the original purpose of this slab reinforcement is achieved. However, although the axial forces of diagonals of cross bracings are reduced 30 to 50 percent in almost all diagonals, at the diagonal G4 the axial force increases by about 80 percent and an axial force (2.68 tf (26.3 kN)) greater than the maximum axial force (2.38 tf (23.3 kN)) before reinforcing is produced. This tendency was observed in .lh12 measurements also.

6.3 Influence of Floor Slab Thickness on Forces in Cross Bracing Members

Since cracking damage occurred frequently in slabs of thickness 17 cm made based on the standard design up to the latter half of the 1960s, the specifications were subsequently revised and since 1978 a slab thickness of 24 cm has been adopted.

The results of analyses based on the current specification as for slab thickness are also illustrated in Figs. 12 and 13.

It may be understood from this that slab thickness of 24 cm which coincides with the current specification and aforementioned reinforcing by addition of stringers and cross bracing reinforcement as measures for reinforcing existing bridges have effects that are roughly equal from the point of view of reducing deflection of floor slabs. But it may be judged that increasing floor slab thickness is more effective in the sense that it reduces forces in cross bracing members on the whole, although this procedure may not necessarily be applicable to all existing bridges.

6.4 Effects of Introduction of Cross Beams and Additional Cross Bracings

Toyoda Viaduct with three main girders is concerned here. Calculated cases of structural changes and the results are illustrated in Table 1 and Figs. 14 and 15, respectively. Loading conditions are similar to the ones described previously, but here, the subject of the study is a side span instead of the main span.

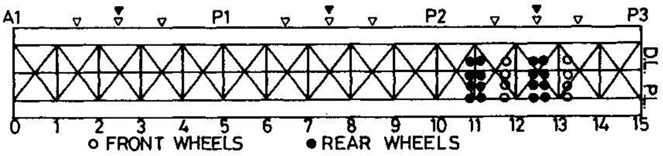
Table 1 Considered structural changes and loading conditions

CASE	LOCATION OF REAR WHEELS	SUPPLEMENTED MEMBER				REMOVAL OF CROSS-BRACING MEMBER
		FORM	NUMBER PER SPAN	BENDING STIFFNESS*	LOCATION	
F/G	11/SPAN CENTER	———	———	———	———	NONE
H/I	11/SPAN CENTER	CROSS BEAM	1	1/4	SPAN CENTER	NONE
J/K	11/SPAN CENTER	CROSS BRACING	1	1/8	SPAN CENTER	NONE
L/M	11/SPAN CENTER	CROSS BRACING	3	1/8	**	NONE
N/O	11/SPAN CENTER	CROSS BEAM	1	1/4	SPAN CENTER	***

* RATIO WITH THAT OF A MAIN GIRDER

** INDICATED BY IN THE FIGURE AT BOTTOM

*** THOSE MEMBERS AS SHOWN IN Fig.14 BY DOTTED LINE



The results can be summarized as in the following subsections:

6.4.1. Effects of additional cross beams or cross bracings on member forces of existing cross bracings

When rear wheels are placed on the center of a side span, induced member forces in the cross bracings at locations 12 and 13 adjacent to the span-center are reduced 40 to 50 percent for the case where cross beams, whose bending stiffness are about one-fourth of the main girders, are introduced at the center of each span. For the cases where one and three-per-span additional cross bracings having equivalent bending stiffness of one-eighth of main girders are introduced, reductions of member forces in the same cross bracings at locations 12 and 13 are 20 to 30 percent and 30 to 40 percent, respectively.

6.4.2 Effects of removal of cross bracing members on remaining cross bracing member forces

When the load is applied at the span center, the largest member force existing at location 13 is reduced by the removal from 2.5 tf (24.5 kN) to 1 to 2 tf (9.8 to 19.6 kN) according to the lane loaded. When the load is applied at location 11, on the other hand, the largest member force existing at location 11 is further increased by several percent, if the removals have taken place.

6.4.3 Effects of additional cross beams or cross bracings and removal of cross bracing members on floor slab deflections

For any of the previously-mentioned cases deflection of the floor slab at the loaded location does not show considerable change from the present situation.

Considering the effects both on member forces and floor slab deflections, the method of adding three-per-span cross bracings may be the best one among the methods listed here, for the purpose of countering fatigue of girder-cross bracing connections.

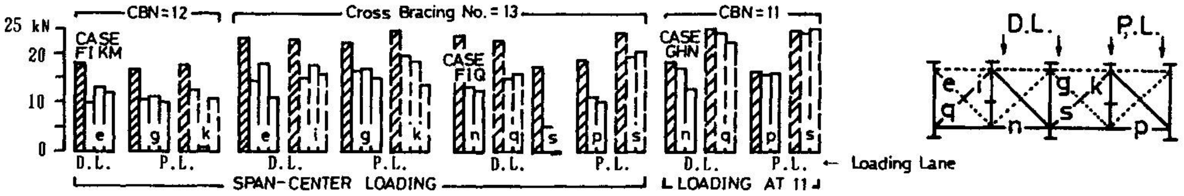
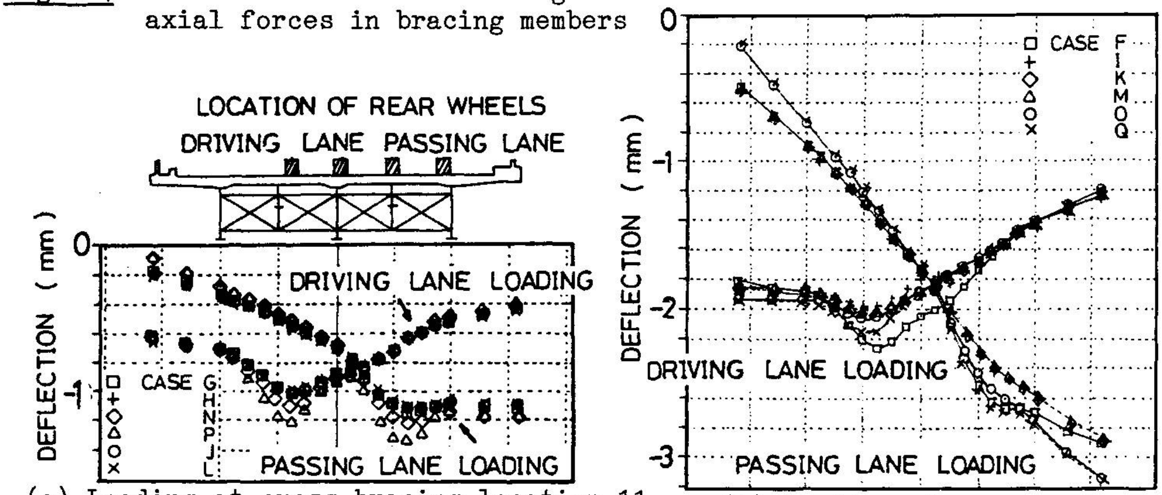


Fig. 14 Effects of structural changes on axial forces in bracing members



(a) Loading at cross bracing location 11

(b) Loading at span-center

Fig. 15 Effects of structural changes on floor slab deflections

7. CURRENT STUDY ON LIFE EXTENSION PROGRAMS

Based on the results of this study, a repair manual for the fatigue cracks in cross bracing connections has been prepared by the Japan Highway Public Corporation, and it is now beginning to be used. At the same time, the following two main items are being studied concerning the repair manual.

(1) Education and training for proper use of the repairing manual
(2) Long-term observations of repaired portions

Various studies for life extension of highway bridges are being conducted at Toyoda Viaduct, where damage were first reported and stress measurements described in this report were carried out. Presently, experimental works of thickness incrementation on top of reinforced concrete slab and adding cross bracings to the present framework are being done and stress measurements to investigate the effects of these works are being performed.

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