

REPAIRING FATIGUE CRACKS IN A STEEL DECK PLATE GIRDER BRIDGE OF UNUSUAL STRUCTURE

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Abstract

Morinomiya section of the Hanshin Expressway Higashi Osaka Route (#13) was opened to traffic in 1978. In October 2010 significant fatigue cracks were found in some main girder support areas of a three-span continuous steel deck plate girder bridge in this section. These cracks were found to have initiated in weld beads on the sole plate or around the bearing set bolts and propagated partly into the webs in only four years. This paper identifies damage cause through structural analysis and field measurement and presents an emergency repair measure which takes into account ease of operation and fatigue durability.

Introduction

A three-span continuous plate girder bridge with steel decks (spans: 9.8 m + 10.0 m + 9.8 m; total width: 16.0 m) on the Hanshin Expressway Higashi Osaka Route (#13) was found to have fatigue cracks in some main girder support areas in 1993 after 15 years of service. They were repaired by patching, and old steel bearings were replaced with rubber ones. However, fatigue cracks were again found in the main girder support areas in October 2010. Cracks originating at weld beads on the sole plate or around the bearing set bolts were found penetrating through the bottom flange of the main girder or end cross beam and propagating partly further into the webs. Since no cracks were found during the latest inspection in 2006, these fatigue cracks were thought to have initiated and propagated in about four years. It was decided to take immediate measures to prevent possible rapid growth of these cracks.

Structural overview

The bridge with the fatigue cracks is a part of a bridge system consisting of simple or continuous plate girder steel deck bridges. The steel deck plate girder type was selected for its light weight because this section passing over the ruins of the ancient NANIWA PALACE SITE needed to be designed to protect architectural remains of the palace.

The Higashi Osaka Route is a heavy traffic road connecting Osaka City area and its eastern suburb of Higashi Osaka, travelled by about 85,000 vehicles per day on average, including 17,800 heavy vehicles which account for about 20%.

The superstructure of this bridge is larger in width (16 m) than in span length (10 m) and, therefore, has a very limited girder height of 700 mm. The bottom flanges of main girders and those of end cross beams are on the same plane and connected to

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each other by welding, which inevitably results in a low fatigue strength.

This bridge has an unusual structure in which only three of seven main girders are supported by bearings.

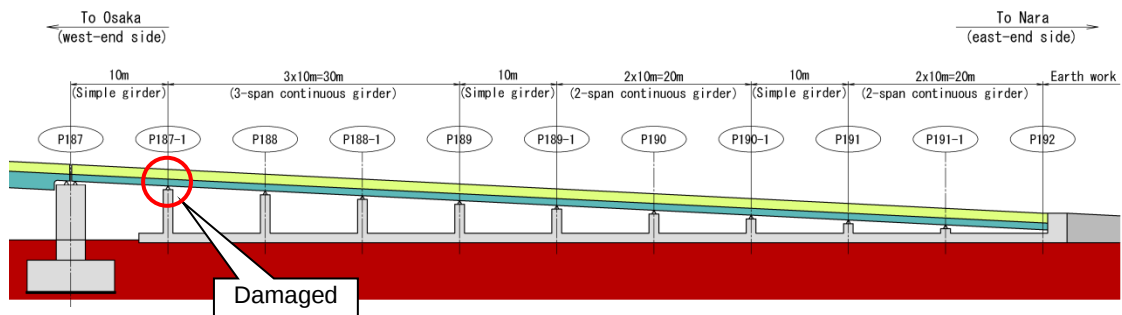


FIGURE 1 SIDE VIEW OF THE WHOLE BRIDGE SYSTEM

The fatigue cracks were found in girders G1 and G7 at the end support (P187-1) of the three-span continuous steel deck plate girder bridge which was located on the west-end side of this section.

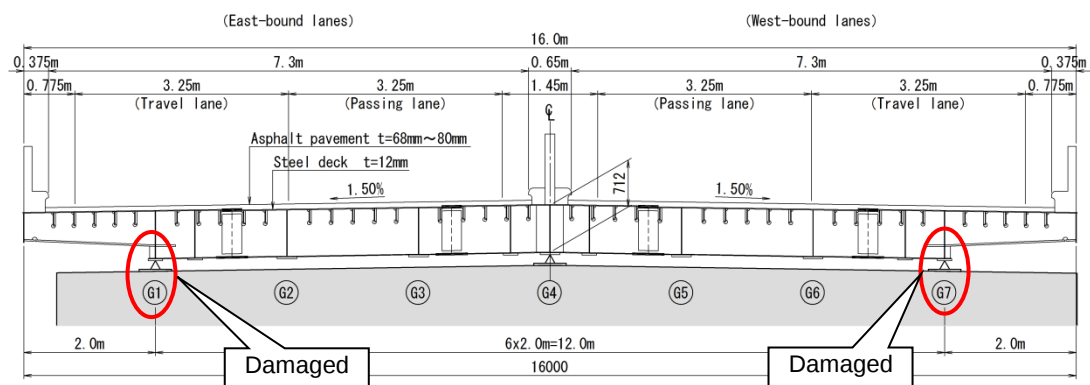


FIGURE 2 SECTIONAL VIEW OF THE SUPERSTRUCTURE

Inspection and repair histories

Every route of the Hanshin Expressway is inspected routinely and periodically for proper maintenance. Periodic inspection is primarily a visual examination from a close distance and is conducted every five to eight years. Routine inspection is conducted six times a year by primarily observing the structure at a distance from the ground using a binocular.

The first periodic inspection on the bridge in this report was performed in 1987 after nine years of service. The bridge then underwent five more periodic inspections by the end of 2006 and was found to have some damage at every close-up examination.

Table 1 shows a list of years of periodic inspections and damage found during each inspection.

TABLE 1 PERIODIC INSPECTION AND DAMAGE HISTORIES

Year of periodic inspection	Years in service	Damage in girder G1 and repairs	Damage in girder G7
1978	--	Opened to traffic.	No damage was found.
1987	9 years	No damage was found.	
1991	13 years	Cracks in welds between the sole plate and the main girder bottom flange Cracks in the main girder and end cross beam bottom flanges These cracks were repaired and bearing replacement was implemented in 1993.	
1996	18 years	Movements of the bearings Gap between the top shoe and the rubber	
2004	26 years	Same as above.	
2006	28 years	Movements of the bearings Gap between the top shoe and the sole plate	

Damage was first found in 1991 after 13 years of service when fatigue cracks were detected in girder G1 in a support area. Cracks originating at weld beads between the sole plate and main girder bottom flange or around the bearing set bolts were found propagating toward the edge of the main girder bottom flange. These fatigue cracks were welded and patched for repair, and the existing bearings were replaced with new ones.

Main girder damage was found only in 1991, and other defects detected during periodic inspections included movements of the bearings.

No damage has been detected in Girder G7 which was found in healthy state during periodic inspection in 2006.

Field investigation

Damage in girders G1 and G7 at the supports

Field investigation was carried out by close-up visual examination. Magnetic particle testing was also performed to obtain accurate locations of the cracks.

Cracks in girder G1 initiated in weld beads between the sole plate and the end cross beam bottom flange and grew penetrating through the flange and partly propagating further into the weld between the flange and the web of the end cross beam. Cracks were also found in the main girder bottom flange, originating at around the bearing set bolt. None of them was propagating into the main girder web which had a patch plate on it.

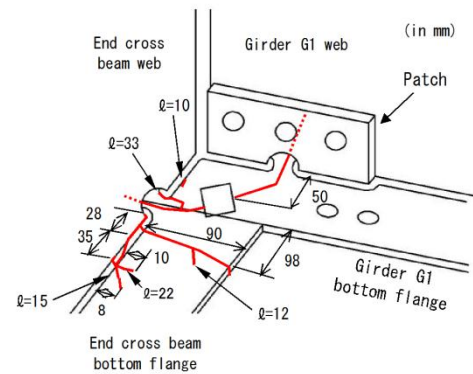
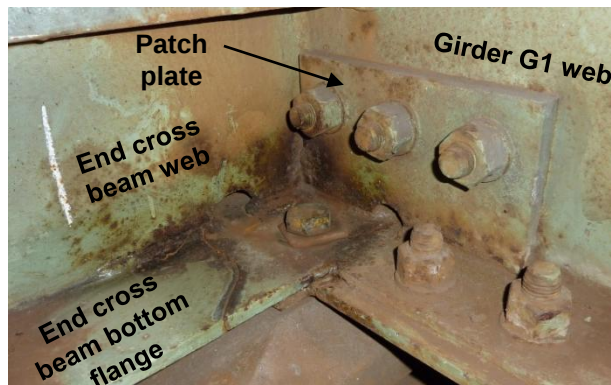


PHOTO 1 CRACKS IN GIRDER G1

Cracks in girder G7 initiated in weld beads between the sole plate and the main girder bottom flange and penetrated through the flange. They propagated into the weld between the flange and the web of the main girder, and partly further into the web.

Gap was found between the sole plate and the top shoe in both girders G1 and G7. The girders were found to move in the vertical direction with every passage of vehicle, generating metal sound.

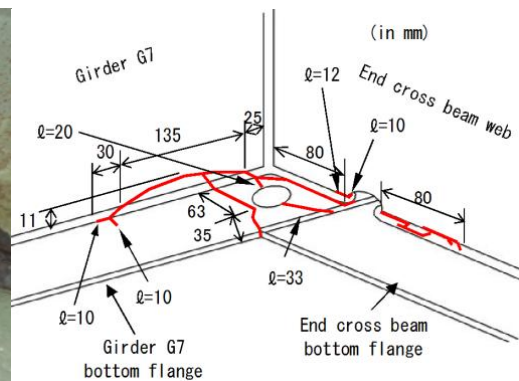
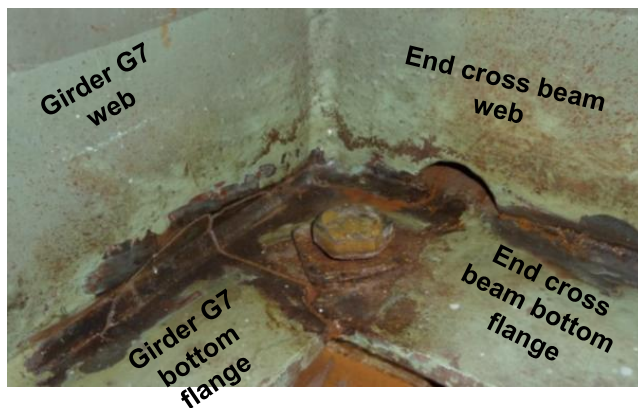


PHOTO 2 CRACKS IN GIRDER G7

Other damage

Beside fatigue cracks, shoe base mortar was found damaged on girders G1 and G4. There was corrosion in the main girders due to leakage of water from the expansion joints, but without any reduction in cross-section. No cracks were found in the longitudinal ribs or deck plates of the steel decks.

Checking surface height differences at expansion joints

The vertical movements of girders G1 and G7 with the passage of vehicles suggested the presence of surface height differences at the expansion joints between the longitudinally adjacent girders. Road surface was investigated at the expansion joints, and it was found that there were surface differences of 12 mm and 8 mm,

respectively, in the west-bound lanes (in the side of girder G7) and in the east-bound lanes (in the side of girder G1).

Heights of girders G1 and G7 were adjusted in an attempt to eliminate surface height differences. However, jacking up girder G1 made girder G7 lower, and jacking up girder G7 made girder G1 lower. Such behavior like a balancing toy suggested that the superstructure was in an unstable state balancing on a fulcrum at girder G4.

Damage cause estimation

Process from damage cause estimation to emergency repair decision

Figure 3 shows the process how emergency repair was decided based on the inspection and repair histories and field investigation results.

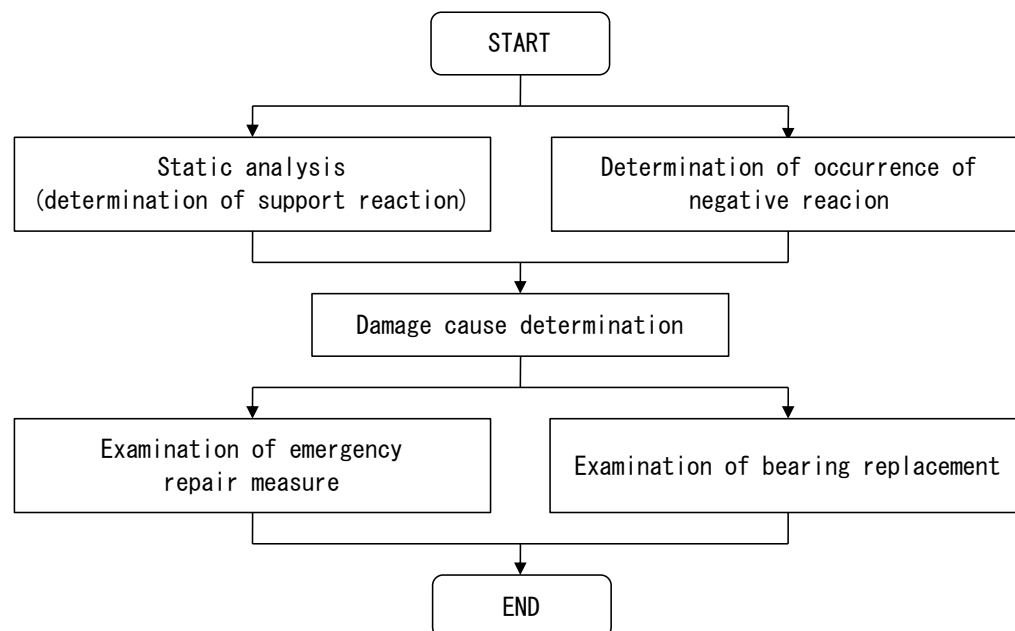


FIGURE 3 PROCESS TO EMERGENCY REPAIR DECISION

Static analysis

Static analysis was carried out first in order to understand support reactions. Using a plane frame model of the superstructure, lattice analysis was made to obtain support reaction values. Design live load of this bridge at construction was TL-20. In order to evaluate reactions under current standards, the analysis was also made for L and T loads of B live load. T load was included in addition to L load because the effects of T load were considered to be significant in this superstructure where the width, 16 m, was larger than the span length, 10 m (JRA, 2002).

Table 2 shows a list of reaction values obtained by the lattice analysis.

TABLE 2 REACTION VALUES

(in kN)

		End supports (P187-1, P189)				
		Dead load (D)	Maximum live load (L_{max})	Minimum live load (L_{min})	D + L_{max}	D + L_{min}
TL-20	Girder G1	101.9	389.1	-40.5	491.0	61.4
	Girder G4	128.7	526.0	-63.3	654.8	65.5
	Girder G7	101.9	389.1	-40.5	491.0	61.4
	Total	332.5	--	--	--	--
B live load (T load)	Girder G1	101.9	541.8	-43.3	643.7	58.6
	Girder G4	128.7	683.0	-50.0	811.8	78.8
	Girder G7	101.9	541.8	-43.3	643.7	58.6
	Total	332.5	--	--	--	--

The static analysis results showed no negative reactions at either support under normal conditions (dead load reaction + live load reaction). However, dead load reaction was found to be about 100 kN and live load reaction was about 540 kN, which made a ratio of 1:5. This large ratio of live load reaction suggested that stress from live load fluctuations was significant in this superstructure.

Determination of occurrence of negative reaction

Although no occurrence of negative reaction was indicated by the static analysis, the analysis values were based on the assumption that the superstructure was correctly manufactured and erected as designed. The vertical movements of the damaged main girders observed with every passage of vehicle during the field investigation suggested occurrence of negative reaction. In order to determine whether negative reaction actually occurred at supports or not, vertical strain under vehicle traffic was measured, using strain gauges attached to some members in a support area. It was expected that fluctuations in support reaction might be estimated from dynamic measurement of strain response to vehicle traffic in the main girder web, end cross beam web and support stiffener in the support area. Any strain occurring in the tensile direction should indicate occurrence of negative reaction overwhelming dead load reaction.

Members and points for vertical strain measurement in the support area

Because accurate stress measurement was impossible with the damaged members, the authors selected girder G7 on P189 which had the same detail but no damage for the vertical strain measurement. Figure 4 shows the measurement points: three on the main girder web, one on the support stiffener and three on the end cross beam web in the support area. Continuous measurement was carried out for 72 consecutive hours on weekdays to represent typical vehicle traffic conditions.

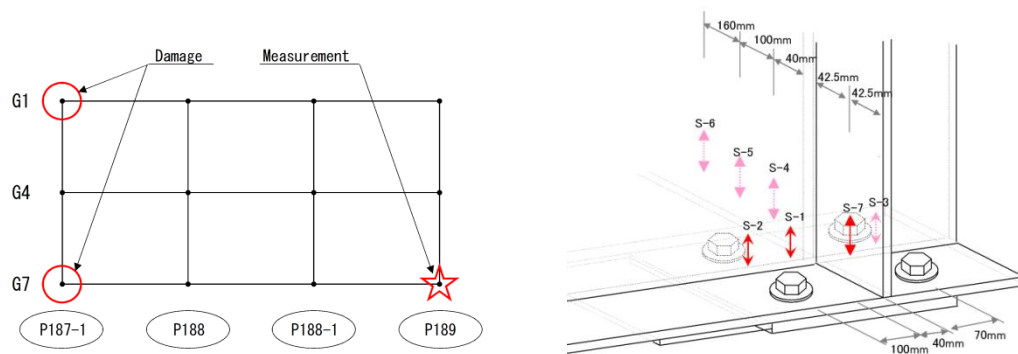


FIGURE 4: STRAIN MEASUREMENT LOCATIONS AND POINTS

Results on occurrence of reaction

Figure 5 shows stress waveforms under vehicle traffic obtained from the vertical strain measurements in the support area. As shown here, no negative reaction occurred with the passage of vehicle. There was a slight stress in the tensile direction at point S-6 on the end cross beam, which was attributed to the wheel load on the overhang causing the backup plate of bracket to uplift.

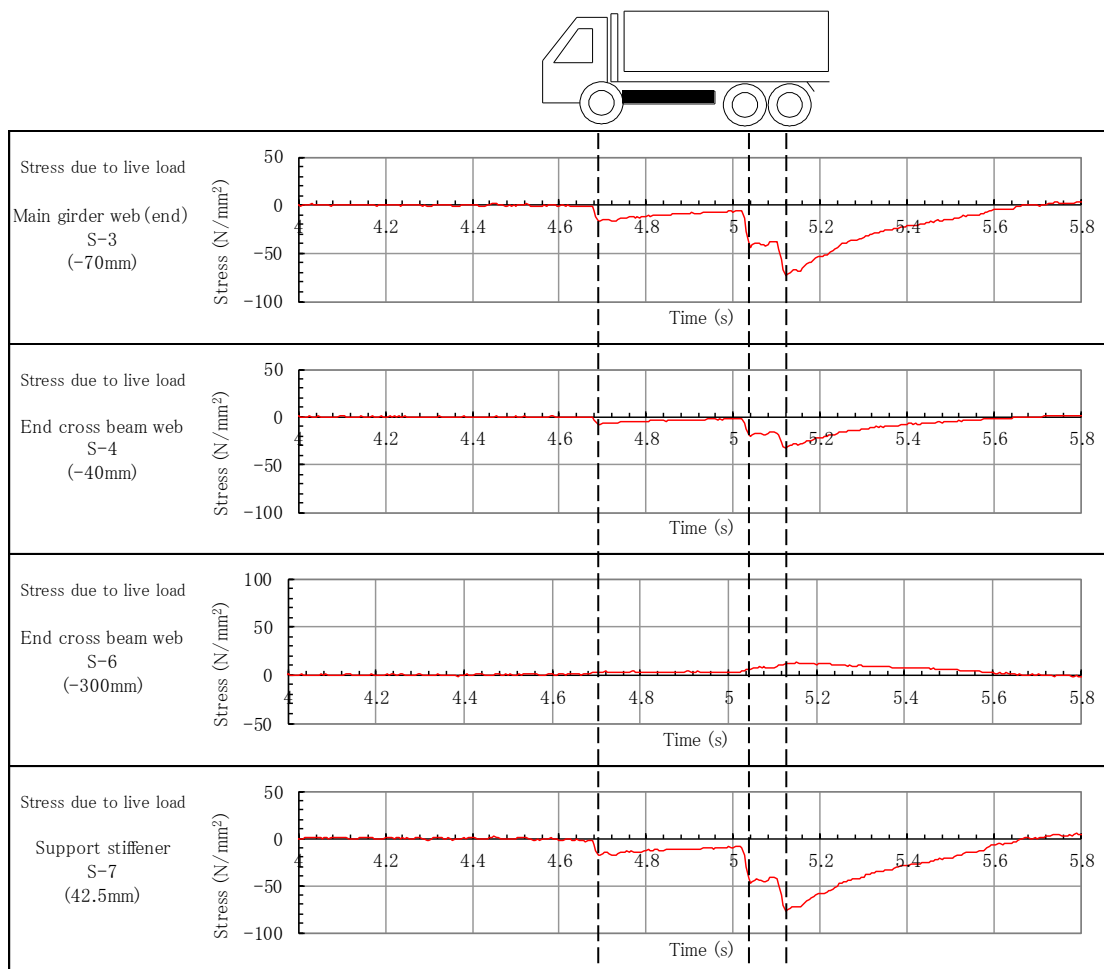


FIGURE 5 STRESS WAVEFORMS UNDER VEHICLE TRAFFIC

Damage cause estimation

The static analysis and stress measurement revealed no occurrence of negative reaction in the support areas. Therefore, it was concluded that what caused the damage was not an uplift of the girders due to negative reaction.

The focus was then moved to the damage to the shoe base mortar on girders G1 and G4. The assumption was that deterioration of the shoe base mortar with time caused settlement of the bearings, which resulted in vertical movements of the main girders, giving impacts to the damaged parts (Figure 6).

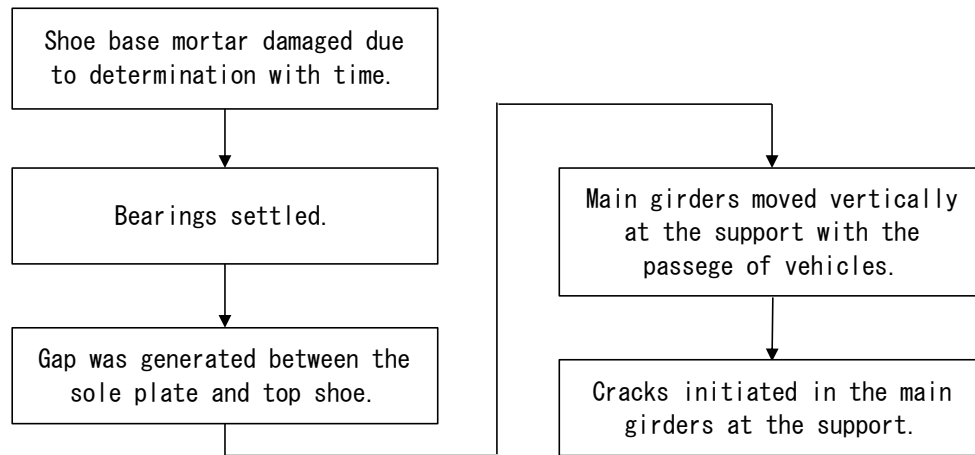


FIGURE 6: COURSE OF DAMAGE EVOLUTION

Emergency repair measure

Examination of emergency repair measure

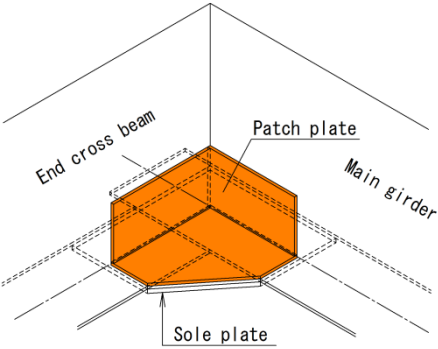
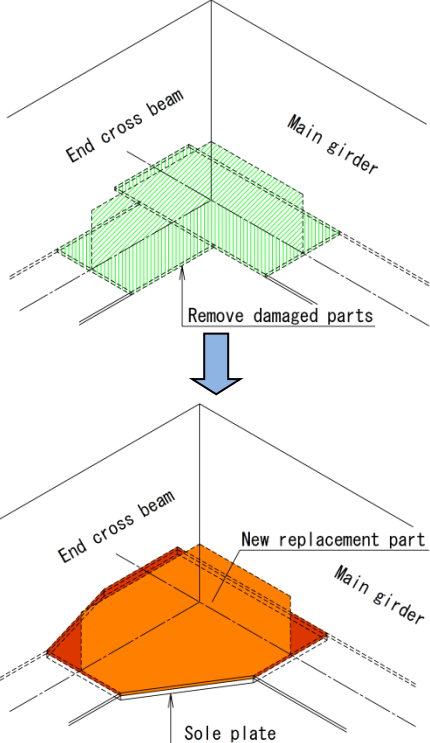
The fact that the cracks found in the main girders in the support areas grew in a very short period indicated an urgent need for some action. It was decided to carry out emergency repair as an immediate measure. There were two plans for emergency repair: (1) patching; and (2) partial replacement. Replacement of bearings was also taken into account because of the damage to the shoe base mortar of girders G1 and G4. Through a comparative examination, the partial replacement plan was selected to take advantage of complete removal of cracks which could eliminate possible future concerns and provide improved fatigue durability to the structure.

Table 3 shows a comparative table of the two plans.

High tension bolts were selected for the connection of parts, while field welding was also possible. The repair work needed to be carried out while the expressway was open to traffic, and the headway available for work space was very limited. Field welding under such conditions was considered to be difficult, especially in terms of quality control. In addition, the large stress amplitude due to live load might cause

damage to the new weld in future. In contrast, high tension bolts were considered to be easy to install even under normal traffic and capable of providing more secure connection than field welding.

TABLE 3 EMERGENCY REPAIR MEASURE COMPARATIVE TABLE

	PLAN 1: PATCHING		PLAN 2: PARTIAL REPLACEMENT	
Schematics				
Description	● Patch plates are fitted to the main girder web, end cross beam web and their bottom flanges to cover the cracks. ● Cracks remain as they are.		● Parts with cracks are removed, and new shop-manufactured parts are installed. ● Cracks are removed completely.	
Structure	● Fatigue durability does not change.	△	● Cracks are removed, leaving no concerns about their growth. ● Fatigue durability increases as the main girder and end cross beam bottom flanges are unified in the new part.	○
Ease of operation	● Work under normal traffic is possible. ● Work period is shorter than Plan 2. ● Limited headway makes the work difficult.	○	● Work under normal traffic is possible. ● Removal of the parts with cracks requires a longer work period. ● Limited headway makes the work difficult.	△
Economics	● Economic efficiency is high.	○	● Economic efficiency is low.	△
Maintenance	● Existing cracks may grow in future. ● Existing cracks cannot be monitored because a check hole cannot be made in the patch plate.	×	● Increased fatigue durability due to the replacement provides excellent maintenance properties.	○
Overall evaluation	△		○	

Features of the partial replacement plan are described below.

- (1) To improve fatigue durability, the main girder and end cross beam bottom flanges were unified in the new replacement part.
- (2) The planar dimensions of the sole plate were made larger to reduce stress concentration in the support area.
- (3) The ends of the sole plate were tapered to alleviate stress concentration due to drastic change in cross-section around the sole plate.
- (4) High tension bolts were used for the connection with the sole plate, main girder bottom flange and end cross beam bottom flange, to improve fatigue durability.
- (5) In order to assure stiffness in the main girders in the support areas, splice plates were installed on the main girder web to a height one half the girder height which was the effective buckling length above the support point.
- (6) Angle steels were installed where the main girder web met the end cross beam web, to ensure transmission of vertical force between the new and existing parts above the support point.
- (7) As a fatigue countermeasure for the support stiffener, stiffness of the overhang bracket was enhanced to control deflection.

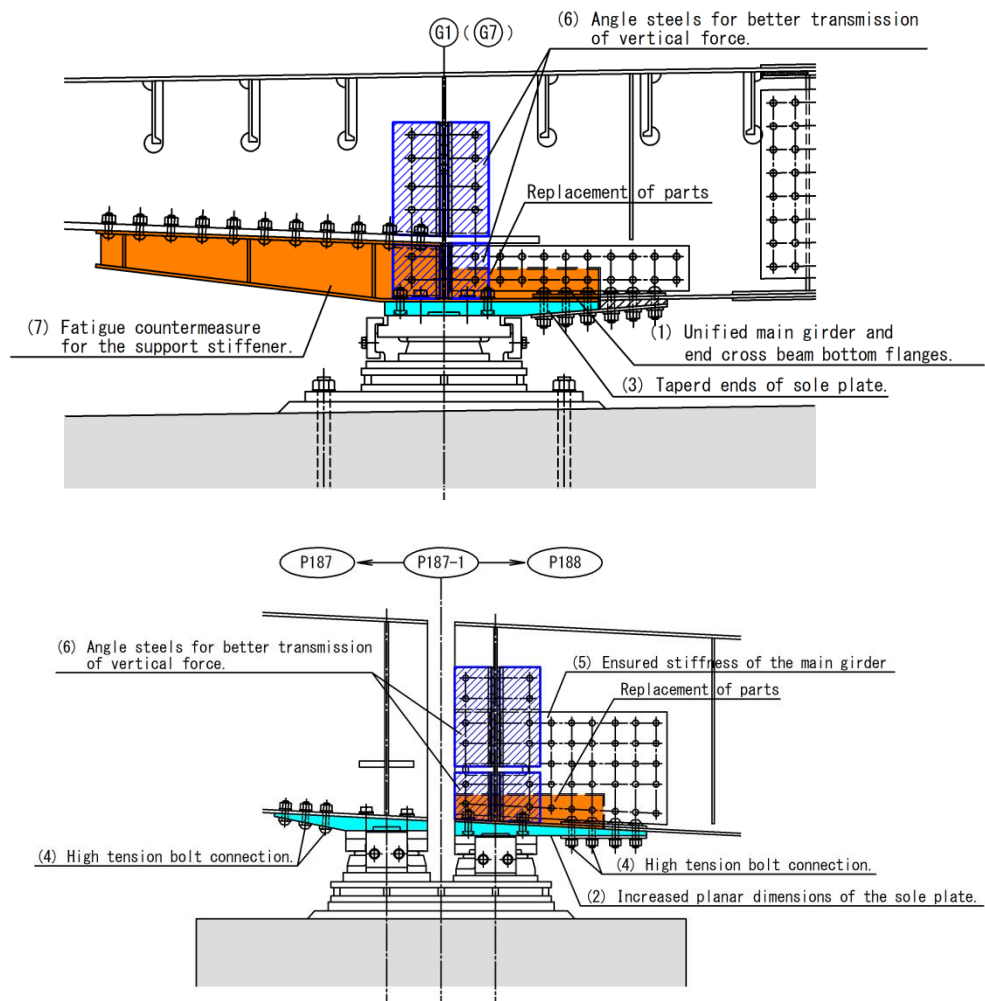


FIGURE 7 SCHEMATIC DIAGRAMS OF THE REPAIR

Figure 7 shows the schematic diagrams of the partial replacement plan. The numbers in the diagrams correspond to the numbers in the above list. The parts marked with red color are those to be replaced, and the blue-colored part is the new sole plate to be installed.

Study on bearing replacement

The damage found in the existing shoe base mortar on girders G1 and G4 suggested influences on the capacity to carry reaction force. On the other hand, the limited headway required the existing bearings to be temporarily removed for the emergency repair work to create a sufficient work space. However, fine height adjustment was difficult with the existing bearing system in which the higher bearing on the west-end side and the lower bearing on the east-end side were mounted on the same block, sharing one base plate, one height adjustment plate and one bottom shoe (Figure 8).

Consequently, it was decided to replace the bearings at the same time with the emergency repair work. Steel bearings were employed to replace the existing rubber ones so that reaction force would be carried more properly. In order to make height adjustment in the field easy, the height adjustment plate was divided into two parts for the two bearings.

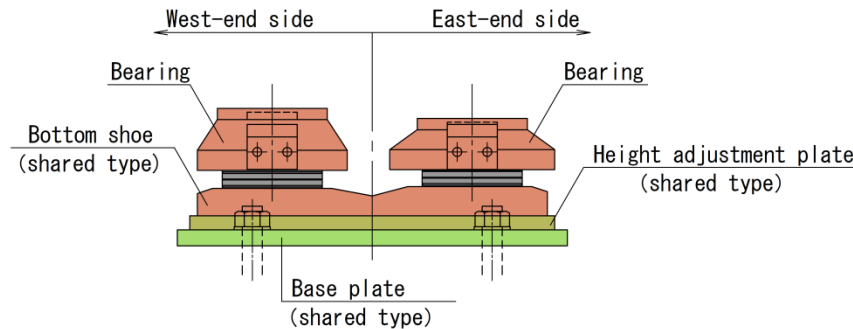


FIGURE 8 SIDE VIEW OF THE EXISTING BEARINGS

There was significant leakage of water from the expansion joints. Rainwater could have penetrated through the damage in the shoe base mortar, causing corrosion of the bearing anchor bolts. Ultrasonic measurement was carried out on the existing bearing anchor bolts, and it was found that their embedment length was about 400 mm at minimum against 610 mm in as-built drawings.

Since corrosion and possible reduction in cross-section of the existing bearing anchor bolts were suggested by the measurement results, the existing anchor bolts were discarded and replaced with new ones for the new bearings.

Conclusions

In this paper damage cause was estimated from structural analysis and field measurement results, and emergency repair measure was discussed, with fatigue durability emphasized for the prevention of possible similar problems in future. Key findings are summarized below.

- 1) Static analysis revealed that the superstructure was subject to live load effects, with a ratio of dead load reaction to live load reaction being 1:5.
- 2) The static analysis and stress measurement revealed no occurrence of negative reaction. Therefore, it was concluded that what caused the damage was not an uplift of the girders due to negative reaction.
- 3) The damage cause was assumed to be impact from vertical movements of the main girders due to settlement of the bearings caused by deterioration of shoe base mortar with time.
- 4) Partial replacement was selected for the emergency repair to take advantage of complete removal of cracks which could eliminate future concerns about growing cracks and provide improved fatigue durability to the structure.
- 5) High tension bolts were used for the connection with the sole plate, main girder bottom flange and end cross beam bottom flange to improve fatigue durability.
- 6) The bottom flange of the main girder and that of the end cross beam were unified in the new replacement part for improved fatigue durability.
- 7) Although no damage was found in the support stiffener in this study, damage was detected in other locations with the same detail in other spans. Therefore, fatigue countermeasure was taken as a preventive maintenance by improving stiffness of the overhang bracket to control deflection.
- 8) Bearings were replaced at the same time with the emergency repair work. This allowed to obtain a sufficient work space in the limited headway, improving ease of operation.
- 9) In the new bearing system the height adjustment plate was divided into two parts for the two bearings on the west- and east-end sides to make height adjustment in the field easy.

Closing remarks

The emergency repair project described in this paper has just been completed. Photo 3 shows girder G7 after removal of the damaged parts. Photo 4 shows the same girder after the partial replacement, with the bearings also replaced.

Stress measurement is planned in the vicinity of the emergency repair site to evaluate the repair effect by comparing the measurement results with those for other locations with the same detail but no damage.

This section of the expressway consists of similar structures to this bridge which is subject to live load effects. Permanent repair including in-depth modification will be conducted on this section next year.



PHOTO 3 GIRDER G7 IMMEDIATELY AFTER REMOVAL OF THE PARTS WITH CRACKS



PHOTO 4 GIRDER G7 AT THE COMPLETION OF EMERGENCY REPAIR

References

- [1] Japan Road Association (JRA): Specifications for Highway Bridges and Commentary, Part II Steel Bridges, March 2002.