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Fatigue strength and improvement effect of the center stay rod

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ABSTRACT: Center stay is installed to control a relative displacement between a girder and a cable, to restrict the inclination of short suspenders around the center of a span, and to prevent bending fatigue of the suspender. A center stay was designed so that the rod section breaks with 60% (equivalent of an earthquake whose return period is 25 years) of tension force during an earthquake. However, two rods under force lower than the designed tension broke at a mounting screw section, not at the section with the minimum cross sectional area of the rod, which is the assumed failure point. This paper discusses the detailed survey of a fracture surface observation to confirm damage factors, estimation of the level of fatigue damage by measuring a stress frequency on a real bridge, a method to improve fatigue durability, and the result of a fatigue test of improved rod with which improved fatigue durability is expected.

1. INTRODUCTION

The Honshu-Shikoku Bridges, which connect Honshu and Shikoku with three routes, consist of ten suspension bridges including the Akashi-Kaikyo Bridge, the world's longest suspension bridge, five cable-stayed bridges, one truss bridge, and one arch bridge. Among these long-span bridges, center stays are installed on suspension bridges to control a relative displacement between a girder and a cable.

Fig.1 Japan and Honshu-Shikoku Bridges

A damage that differs from the one expected during the design phase occurred to a bridge. This study estimated the causes of the damage, and examined an improvement method. This paper reports the result of this study.

(1) Target bridge

The bridge, which is the subject of this study, is a three span, two hinge suspension bridge with the main span of 600 m. It has an asymmetric geometry with the main towers of varying heights (Fig. 2). Flat hexagonal shaped box girders are used and, as for the form of the bridge in service, the number of lanes changes from the four to two (south side) on the bridge. As a result, the live load is deviated to the south side (Photo1).

(2) Structure of the center stay

The center stay of this bridge is installed to prevent additional stress, such as bending, from occurring on a suspender rope by controlling a relative

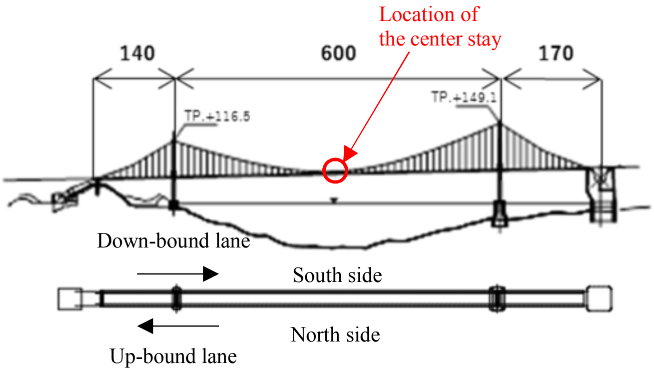


Fig.2 General view of the target bridge

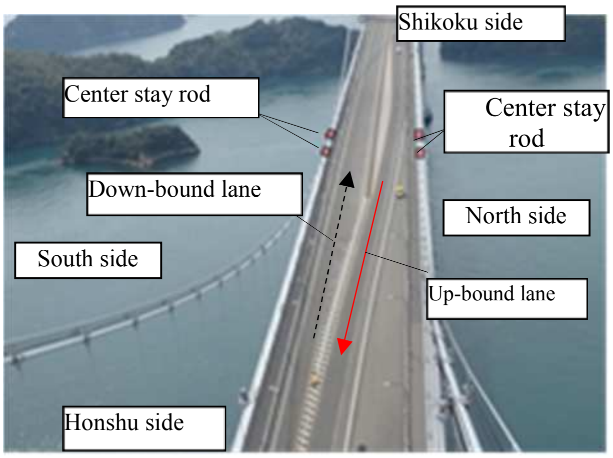


Photo.1 Lanes of the bridge

displacement between the girder and the main cable in longitudinal direction during a small-scale earthquake.

The center stay is positioned in the center of the main span. It consists of stay band, a stay rod (hereinafter called "rod"), and anchorages as shown in Fig.3 and Photo.2. The total of four center stays are installed on the bridge, two for the up-bound lane side and two for the down-bound lane side. The rod was designed to be broken at the section with the minimum cross sectional area in the center during a large-scale earthquake. These rods was actually broken almost as designed load when the Geiyo earthquake (M 6.7) occurred in March 24, 2001 as shown in Photo3.[1)]

Since the rod was designed to break with 60% tension force of the earthquake load, it can be dismounted as it is joined to the socket on the rope side and the anchor pin with screws to facilitate replacing a rod. As for the rod, Tr60 is used for screws, and its length is 695 mm. The material of the rod is SNCM625 (nickel-chrome-molybdenum steel).

During the inspection in 2014, breakage of the rods which were installed to down-bound lane, was found out even no large-scale earthquake occurred.

2. CONDITIONS OF DAMAGE

The position of the breakage is the thread root at the first screw thread where the rod is engaged with the socket coupler on the rope side. (Photo.4)

The existing rods were replaced because they were broken when the Geiyo earthquake occurred in March 2001. It is relatively new rod as it is about 13 years old. The assumed position of the breakage is the minimum cross sectional area in the center of the rod as shown in Fig. 3, which is a different position of the broken rods this time.

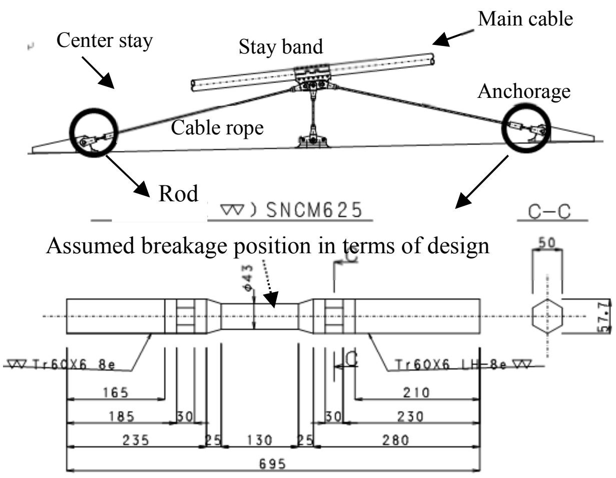


Fig.3 Outline of center stay

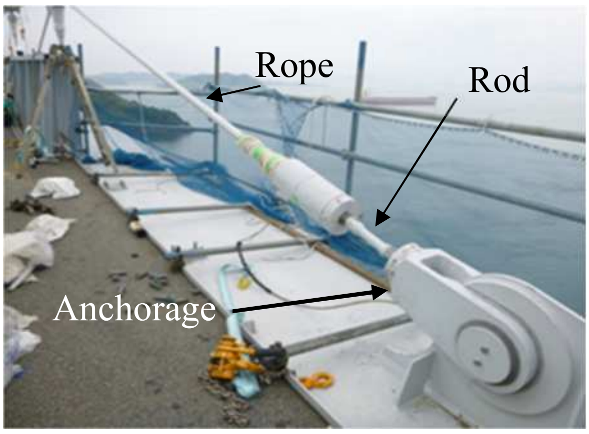


Photo.2 Center stay

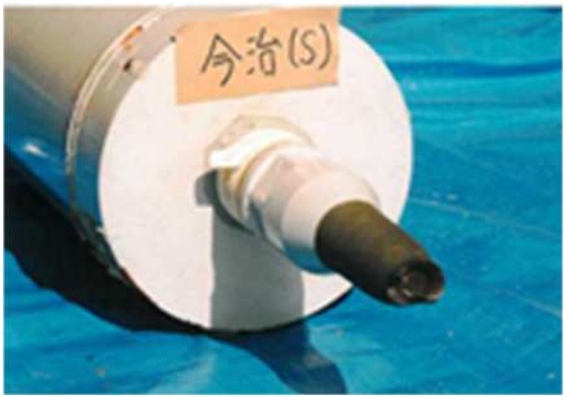


Photo.3 Breakage of the center stay rod caused by the Geiyo earthquake in 2001

3. INSPECTION OF CAUSE OF DAMAGE

In order to identify the causes of this damage, material characteristics were verified by a chemical composition analysis to conduct a macro-observation of the breakage surface, a micro-observation by SEM (Scanning Electron Microscope), and to investigate the presence of defects of the material. To confirm the condition of the occurrence of live-load stress on the rod, 72 hours continuous stress measurement was conducted on the target bridge. The chemical

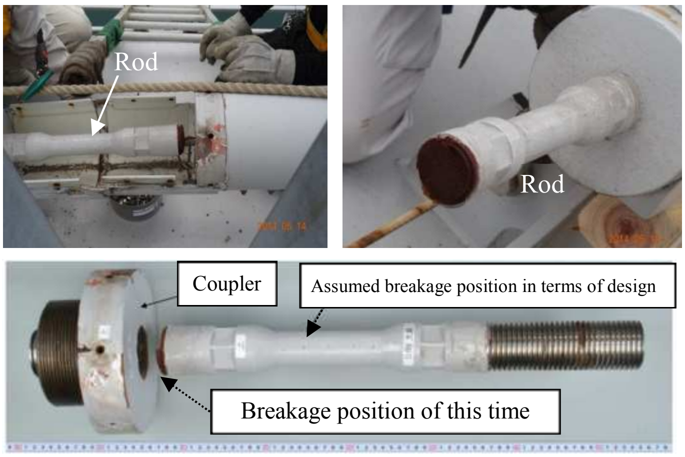


Photo.4 Condition of break in the rod

composition analysis included the rods of the up-bound lane where no damage was found.

(1) Observation of the breakage surface

a) Result of the macro-observation of the fracture

The result of the macro-observation of the fracture after descaling is shown in Fig.4(a).

Distinctive beachmark was found on the fatigue fracture of the two broken rods; therefore, it is assumed that fracture developed due to a repetitive stress.

The final breakage part is identified on the top of any section. When the transmission direction was assumed from the pattern of the beachmark, the starting point of the breakage was believed to be on the lower side.

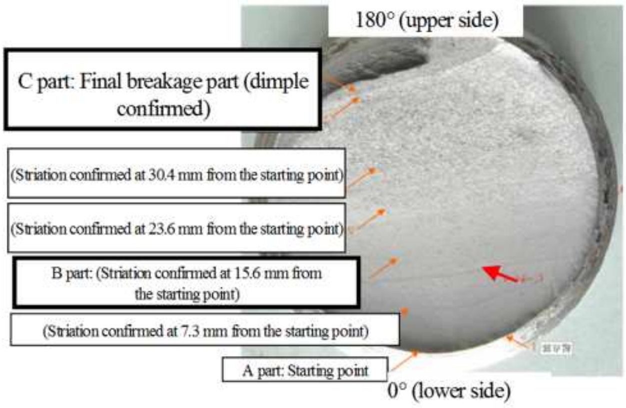
b) The result of micro-observation of fracture by SEM

The trace of occurrence of crack caused by defects and the corrosion was not found from the condition of the fracture in the neighborhood of the starting point. Distinctive striation (a striped pattern) was identified on the fatigue fracture as shown in Fig. 4 (b). And, on the top side that is assumed to be the final breakage part, a significant dimple (a hallow pattern) was identified on the ductile fracture as shown in Fig. 4 (c).

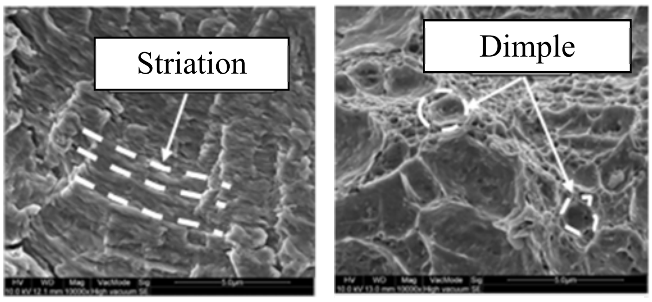
According to the results of the macro-observation and the cross-sectional observation with micro-observation by SEM, no defects including corrosion and fine cracks were identified.

(2) Chemical composition analysis of material

When the result of chemical component analysis was compared with specification values of SNCM625 listed in JIS G 4053 Low-alloyed steels for machine structural use, the all components were satisfied the criteria. In addition, the result matches with the test result during manufacturing, no significant deterioration is found. As a result, it was determined that the material had no problem.



(a) Result of macro-observation



(b) SEM image of B part (c) SEM image of C part

Fig.4 Appearance of breakage surface and the result of SEM observation

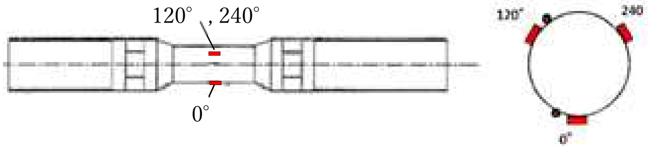


Fig.5 Positions to mount a strain gauge

(3) Other investigations

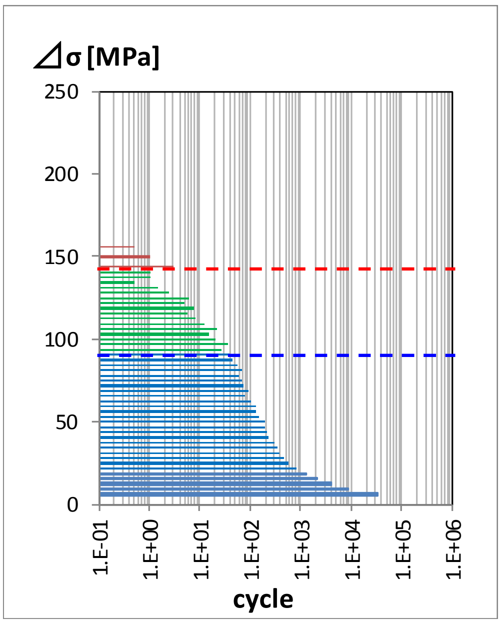
Apart from (1) and (2), although a structure observation, a Vickers hardness test, a liquid penetrant test of the rod screw, and a magnetic-particle test were carried out after etching, neither confirmed abnormality.

From the above mentioned results, it was confirmed that the assumed damage was led to following reason the assumed damage. A crack by repetitive stress gradually developed starting from the thread root so that the decreased cross section cannot bear with a pulling force. As a result, the breakage become large gradually.

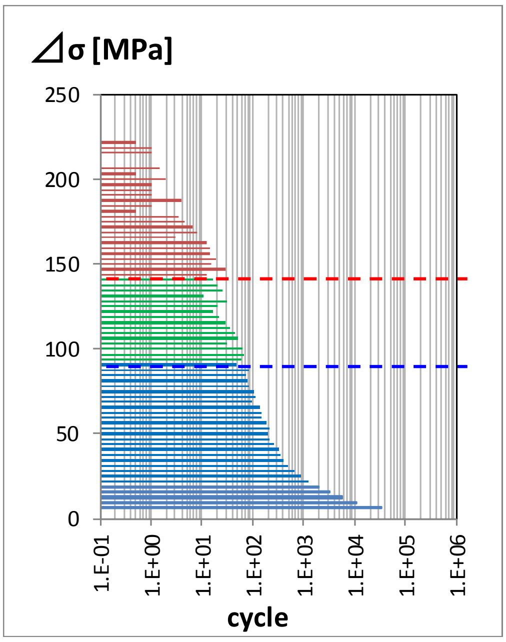
(4) Stress frequency measurement

To confirm the condition of the occurrence of live-load stress on the rod, 72 hours continuous stress measurement was conducted on the target bridge.

All four rods on the up-bound and down-bound lanes were measured. Fig.5 shows the positions to put a strain gauge. The gauges were installed at



(a)Up-bound lane
(end point side)
Unbroken rod



(b)Down-bound lane
(end point side)
Broken rod

Fig.6 Result of analysis of frequency

three locations (0° (the lower side), 120°, 240°) of the small diameter part of the center of the rod after recovering since it cannot be directly installed on the thread part on the breakage position.

Fig.6 shows the result of the stress frequency analysis of the measurement result which was converted from strain gauge of 0° to cross section area of thread root by FEM result as described next section. The strength ranges of 0° was larger than 120°, 240°. In addition, the strength ranges of down bound lane was larger than up bound lane.

4. FEM ANALYSIS

(1) Identification of stress concentration

FEM analysis was conducted to identify the stress concentration of the thread root.

a) Modelling

Fig.7 shows a model diagram. The rod and coupler were modelled by using two-dimensionally axisymmetric models to conduct the FEM analysis using ABAQUS, a general-purpose analysis code.

When making the model, the number of remaining screw threads of the coupler was set to three in order to similar the actual structure to reproduce the condition of damaged rod. The thread root R, where crack occurred, was set to 0.3 mm that was measured from a macro photograph of the cross section of the broken rod.

b) Result of the analysis

Fig.8 shows the maximum principal stress contour when tensile load to the axis direction was applied. The stress concentration was identified from the thread root R located in the first raw from the engaged part that is assumed as the starting point of the fatigue crack.

(2) Examination on structure that takes fatigue measures

The structure of rod for the fatigue measures was examined. And, the effect of measures was confirmed by the FEM analysis.

a) Examining measures

The following methods were considered for structural measures to improve the fatigue strength:

[1] A method to reduce stress by increasing the diameter of the thread part.

[2] A method to reduce the stress concentration of the thread root R that was the starting point of the crack.

With the method [1], substantial changes in structure, such as improved socket and anchor pin coupler, were required when increasing the cross sectional area to increase the diameter of the thread part.

On the other hand, with the method [2], change in the thread root R was required. The method [2] is seemed to be comparatively easy to take as it only involves the rod; and substantial structural change is not required. Therefore, the structure of rod for the fatigue was examined with method [2].

b) Modelling

The following two cases were analyzed by FEM analysis. The thread root R of a FEM analysis model

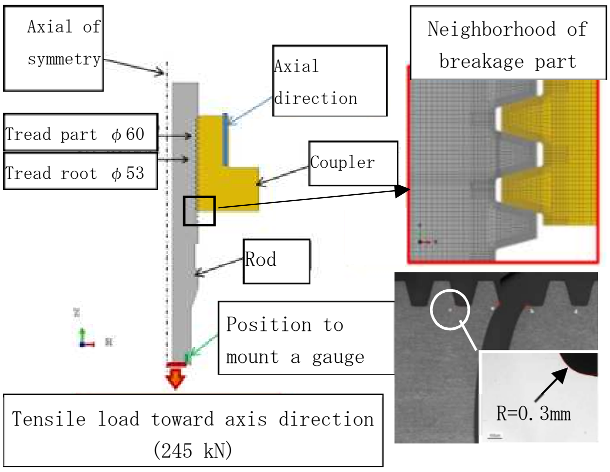


Fig.7 FEM analysis model diagram

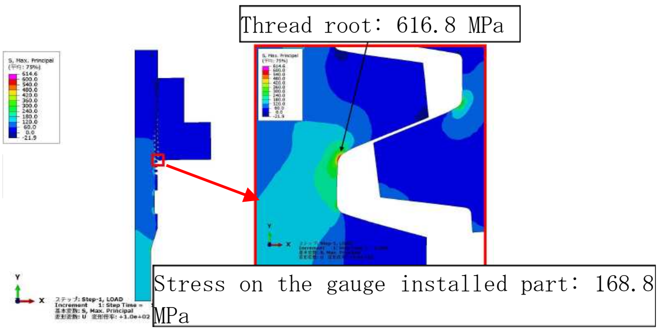


Fig.8 Result of the analysis (figure of the maximum principal stress contour)

Table1 Relation between radius and stress of the thread root R

R(mm)	Stress on the gauge mounted part (MPa)	Stress of the thread root (MPa)
0.3	168.8	616.8
0.5		521.3
0.7		464.7

for calculating stress concentration were set to 0.5 mm and 0.7 mm.

c) Result of analysis

Table 1 shows the relation between radius and stress of the thread root R. In the result of the analysis, reduction of the stress concentration by the increasing the thread root R was confirmed. As a result, the structure of the thread root R of 0.7mm that was decided the structure of rod for the fatigue measures.

5. FATIGUE TEST

With the results obtained in the previous chapters, improved fatigue durability of a rod can be expected by increasing the thread root R. The fatigue durability of rods was examined by the fatigue test using the manufactured real size test pieces.

(1) Test pieces

Fig.9 and Table 2 show the general drawing, materials, etc., of test pieces that are tested this time. There are three types of test pieces. The existing rod is an actual rod that was not broken at the time of 2014 and had been used for 13 years in the up-bound lane of the actual bridge. The two types of new rods were manufactured, one has the same shape as the existing rod with the thread root R of 0.3mm, and the other has the improved radius of 0.7mm.

The steel of existing rod is SNCM625. But the steel of the new rods are SNCM630. Since the tensile strength of steel used for the new rod is higher than that of the existing rod due to procurement reasons, as for the new rod, the tensile strength of the small diameter part was made the same as that of the existing rod by reducing the diameter of the small diameter part of the rod part.

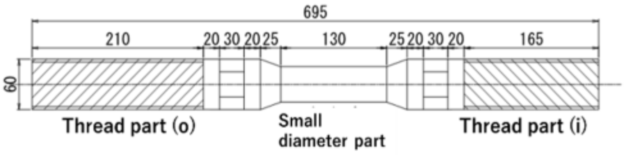
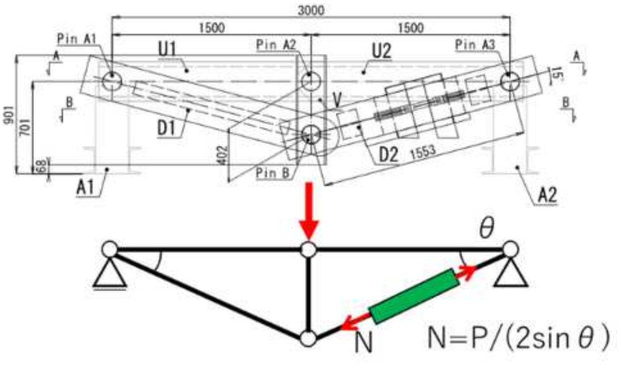


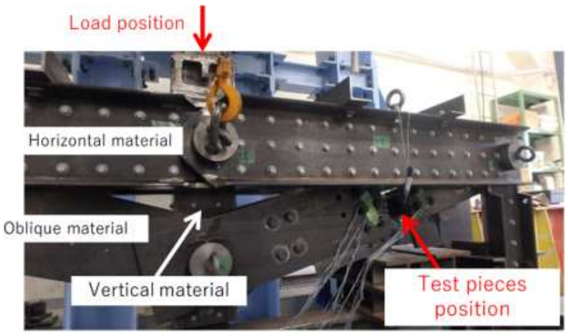
Fig.9 General drawing of test piece

Table.2 List of specifications of test pieces

Test pieces	Steel	Nunber of test pieces	Diameter(mm)	
			Small diameter part	Thread part
Existing rod	SNCM625	1	42.2	Max : 53.0 Min : 60.0
New rod(R0.3)	SNCM630	3	39.9	
New rod(R0.7)	SNCM630	3	39.9	



(a) Loading frame (general drawing)



(b) Loading frame (photo)

Fig.10 Fatigue test loading frame

There are one test piece for the existing rod and three each for the new rods. Fatigue test was conducted using the total of seven test pieces.

(2) Method of fatigue test

Fig.10 shows a loading frame. The loading frame is constructed so that loads can be transmitted to the test piece installed on a diagonal member by applying loads to vertical material. Fig.11 shows the positions to mount a strain gauge. In the small diameter part, single axis gauges with the length of 5 mm are installed at intervals of 90° for measuring nominal stress. In the neighborhood of thread part, single axis gauges with the length of 1 mm are installed at intervals of either 45° or 60° for detecting the occurrence of cracking.

For setting the applying load, the load range *ΔP* = 130 kN (P = 20-150 kN) is set according to the maximum stress range of the small diameter part obtained from the 72-hour stress frequency measurement at the actual bridge shown in Fig. 12 to allow the maximum stress range of 200 MPa to act at the small diameter part. A repetition frequency is set to 3 Hz.

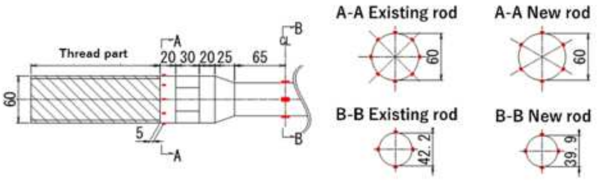


Fig.11 Positions to mount a strain gauge

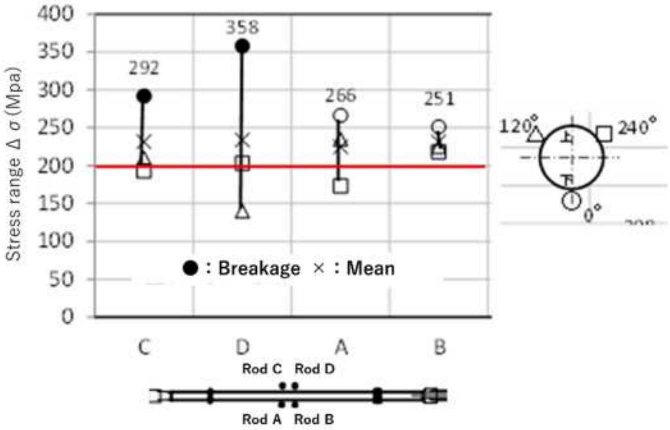


Fig.12 Stress range from 72-hour stress frequency measurement at a actual bridge

(3) Result of fatigue test

Typical results for each test piece are discussed in this section. Photo.5 shows the existing rod after the test. With the existing rod, breakage occurred at the thread part after load was applied 520,000 cycles. The position of breakage is the thread root of the first screw thread engaged with the anchoring body. And, by the breakage surface, to breakage is assumed an arc-like crack occurred in between 0 degree and 90 degrees. Therefore, fatigue breakage occurred at the actual bridge is believed to be reproduced.

Photo.6 shows the new rod (R0.3) after the test. With the new rod (R0.3), breakage occurred at threaded part after load was applied 1,620,000 cycles. The position of breakage is the thread root of the first screw thread engaged with the anchoring body, which is similar to that of the existing rod. And, by the breakage surface, to breakage is assumed an arc-like crack occurred in about 180 degrees.

Photo.7 shows the new rod (R0.7) after the test. With the new rod (R0.7), crack did not occur by the load range *ΔP* = 130 kN. Therefore, the load range *ΔP* = 260 kN (P = 20-280 kN) was set. In the result, breakage occurred at threaded part after load was applied 410,000 cycles. The position of breakage is the thread root of the first screw thread engaged with the anchoring body, which is similar to the other rods. And, by the breakage surface, to breakage is assumed an arc-like crack occurred in about 180 degrees.

A fatigue test is conducted on all seven test pieces. Fig.13 shows the result of fatigue test, together with fatigue design curves of cables and high-tensile bolts (K1-K5) that receive direct stress. The vertical axis indicates a stress measured at the small diameter part that is converted into the cross section of the thread root.

From Fig. 13, the existing rod has a shorter fatigue life than the new rod (R0.3). The existing rod is assumed had damage in actual bridge. And, in new rods (R0.3), it is assumed that there is a fatigue limit in 93MPa. In new rods (R0.7), it is assumed that there is a fatigue limit in 144MPa. Therefore, fatigue limit was increased to 1.5times by the changing the fatigue

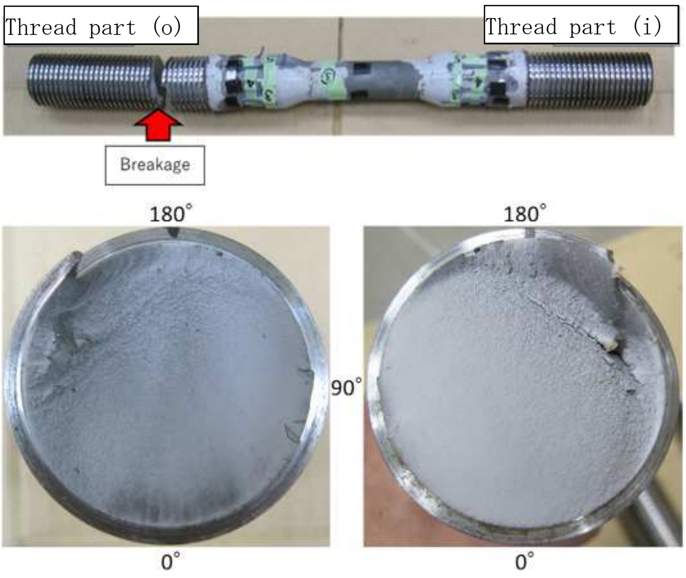


Photo.5 Existing rod after the test

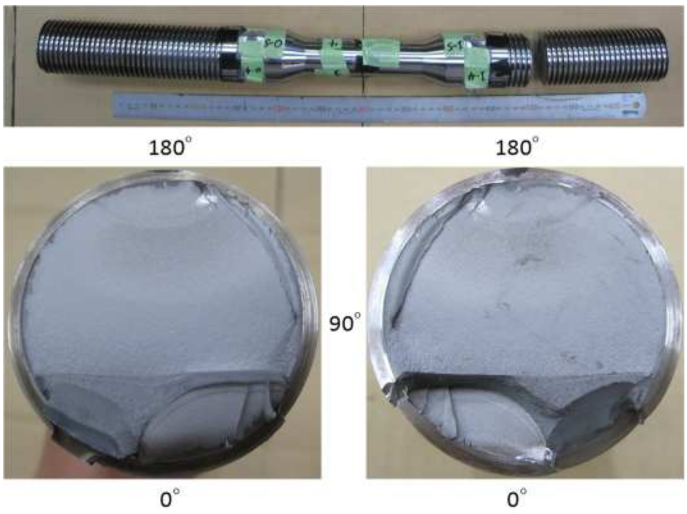


Photo.6 New rod (R0.3) after the test

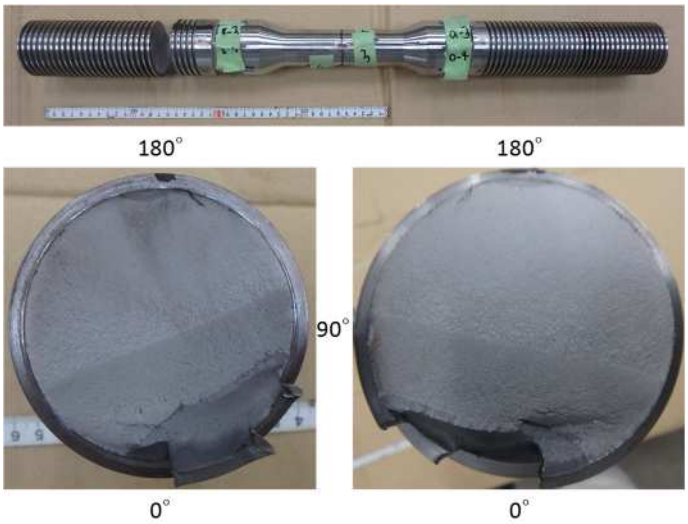


Photo.7 New rod (R0.7) after the test

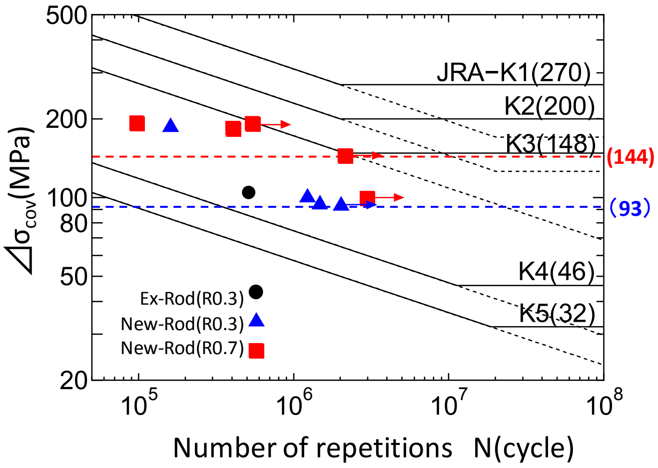


Fig.13 Summary of the result of fatigue tests

limit from 93MPa to 144MPa. Therefore, the fatigue strength is improved by changing the thread root R from 0.3mm to 0.7mm.

Meanwhile, it was confirmed that the fatigue life of one of the new rod (R0.3) and one of the new rod (R0.7) are reversed. According to the hearing investigation of the manufacturer, about ±0.1 mm of error occurs as manufacturing accuracy of the thread root R. In the future, a detailed investigation is required by measuring the thread root R of test pieces.

6. CONCLUSION

In this study, the following knowledge was obtained by conducting an investigation for the causes of breakage on the center stay rod and an actual size fatigue test:

- Inspection of cause of damage

(1)No defects, such as a problem with materials and a crack at the starting point, were found from the broken rod.

(2) In the result of observation of the breakage surface, fatigue crack occurred from lower-side.

(3)The cause of the breakage is a fatigue damage caused on the thread root of the first screw thread on the coupler side of the rod.

(4)The target bridge is in a state where vehicles lean to the down-bound lane. As a result, the stress range of the down-bound lane where the rod was broken becomes large.

(5)Fatigue damage may occur in a short time according to the 72-hour stress frequency measurement.

- Result of fatigue test

(1) Fatigue cracks were initiated at the thread root, and propagated in arc shapes, then finally broke the rod, similarly in the actual structure.

(2)The fatigue limit increased to 1.5times by changing the radius of the thread root from 0.3mm to 0.7mm.

According to the above mentioned result, the improved center stay rod was applied to the actual bridge. However, it is difficult to inspect the rod, since the rod is covered. Therefore, new inspection method that can detect a crack of the thread part without opening cover will be developed.

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