IABSE-JSCE Joint Conference on Advances in Bridge Engineering-III, August 21-22, 2015, Dhaka, Bangladesh. ISBN: 978-984-33-9313-5
Amin, Okui, Bhuiyan, Ueda (eds.) www.iabse-bd.org

Effect of stop-hole on fatigue at vertical stiffener welds of orthotropic steel deck

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ABSTRACT: A lot of fatigue cracks have been observed in welded joints between steel deck plates and vertical stiffeners of orthotropic steel deck under severe traffic load. Stop-hole method for preventing the extension of fatigue cracks by drilling circular holes at the tips of the cracks is often used as a countermeasure against these fatigue cracks. However, its effect has not been so clear. In this study, for the purpose of making clear the effect of stop-hole Method against fatigue crack in welded joints between vertical stiffener and deck plate of orthotropic deck, fatigue tests and finite element stress analyses are performed on small size specimens modeling the welded joints between deck plate and vertical stiffener. In addition, fatigue strength curve is proposed for performing the fatigue durability evaluation for the portion repaired by stop-hole method.

1 INTRODUCTION

A orthotropic steel deck is a structure that stiffens the deck plate by placing ribs in the directions parallel and perpendicular to the bridge axis on its underside. In the orthotropic steel deck, there have been a number of reported cases where fatigue cracks occurred near the position of loading wheel loads on which a deformation of the deck plate increases, since the wheel load is loaded directly on the orthotropic steel deck through the pavement. Among them, the frequencies of cracks initiated in the welded parts of the deck plate and the vertical stiffener shown in Figure 1 are high, and it is reported that about 30 % of the fatigue cracks confirmed in orthotropic steel deck having closed cross-section ribs are the cracks in those parts in urban expressways in Japan (JSCE. 2010). These cracks are said to occur because of the following reasons. The wheel load on the deck plate causes out-of –plane deformation of the plate, but the deformation is restrained by the vertical stiffener, therefore the high stress concentration occurs at the weld toe on the deck plate side at the upper end of the vertical stiffener, as shown in Figure 2. Therefore, it is highly likely that many fatigue cracks occur in the vertical stiffener on the same line in a bridge where a lane mark position to the bridge section is constant and wheel loads are always driven in the vicinity to the position just above the vertical stiffener.

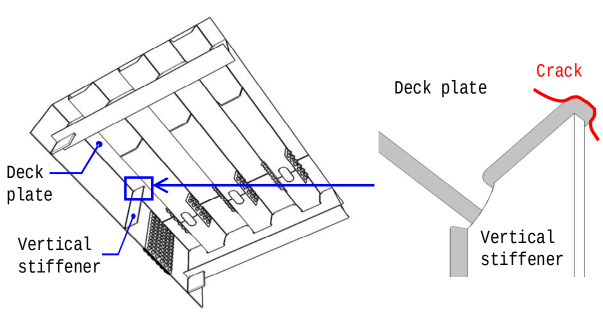


Figure 1. Fatigue crack in the welded part of the vertical stiffener of the orthotropic steel deck.

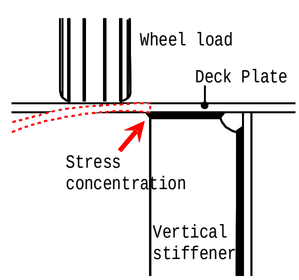


Figure 2. Cause of occurrence of a fatigue crack.

The authors investigated properties of the initiation and propagation of such cracks by conducting fatigue tests of small specimens simulating the attachment part of the vertical stiffener (Mori,T et al. 2011,Mori,T et al.2014). Then it has been verified that the main fatigue crack occurs at the weld toe on the deck plate side at the upper end of the vertical stiffener, propagates to the base material of the deck plate, and then it tends to stop after propagating to some extent. The reason for this is the fact that the deformation mode of the crack changes from Mode I to Mode III after it passes through the deck plate or that the influence of the tensile welding residual stress decreases, but its details have not yet been clear up to now.

In general, repair or reinforcement for cracks is performed by selecting or combining the methods of repairing cracks through cutting (removal of cracks) or the stop-hole method (removal of crack tips), relaxing the stress concentration through improving shape of stiffener and structural details, and/or improving the fatigue strength through finishing weld toes, peening, etc. Various investigations and construction examples have been reported for these locations, including the reinforcement of stiffening plates(Mori,T et al.2011,Yamada,K.2007), the detailed improvements by making semi-circular holes on the top part of the vertical stiffener(Yamada,K et al.2007,Takada,Y et al.2009), and the improvement of the fatigue strength by peening(Tominaga,T et al.2010). However, considering that this crack tends to stop after developed to some extent, as described above, its countermeasure is often considered to be completed by applying a stop hole to the crack tip. However, effects of the repair with the stop-hole method have not yet been clarified.

This study aims to perform fatigue tests and stress analyses of small specimens for the purpose of clarifying effects of the stop-hole method for fatigue cracks initiated on the side toe end of the deck plate in the vertical stiffener welds of the orthotropic steel deck. It is also to examine the fatigue strength curve for performing the fatigue durability assessment when cracks are repaired with a stop hole.

2 FATIGUE TEST

2.1 *Specimen*

Specimens are the same as those used in previous studies as shown in Figure 3(Mori,T et al.2011,Mori,T et al.2014). The steel used for the specimens is SM400A with a plate thickness of 12 mm and 10 mm. The deck plates and vertical stiffeners of the specimens are welded by applying the manual arc welding and other welded joints are connected by CO_2 arc welding.

The number of specimens is five (No.1 to No.5 specimen) as shown in Table 1. No.1 to No.3 specimens have no root gap between deck plates and vertical stiffeners. No. 4 and No.5 specimens have root gaps of 1 mm. Because there are two welded joints in the deck plate and the vertical stiffener for a specimen, they are distinguished with L and R.

Before conducting fatigue tests, measurements were made for the weld leg length of the boxing weld section and the radius of curvature of the weld toe for all of the test specimens. Measurements were made by making molds of the welded parts with hydrophilic vinyl silicon impression materials, cutting out four sheets about 2 mm thick out of the molds from the center of the plate thickness of the vertical stiffener, and magnifying them by 10 or 20 times with a projector. Table 2 shows the averages of measured values in each welded part.

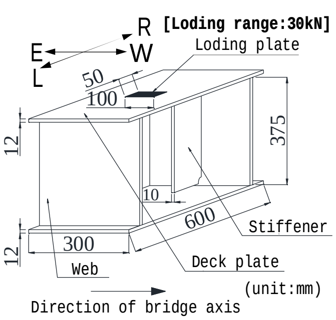


Figure 3. Shape and dimension of a specimen.

Table 1. List of specimens

Specimen	Deck-VS Root gap mm
No.1	0
No.2	0
No.3	0
No.4	1
No.5	1

Table 2. Welding shape of the specimen.

Specimen	Leg length		Radius of weld toe	
	Deck side	Stiff side	Deck side	Stiff side
	mm	mm	mm	mm
No.1L	8.8	6.6	1.3	1.3
No.1R	9.0	6.3	1.3	1.3
No.2L	8.3	5.8	1.6	1.4
No.2R	8.9	6.0	1.3	1.1
No.3L	8.9	6.3	1.3	1.3
No.3R	9.1	6.3	1.3	1.4
No.4L	10.8	7.9	2.8	3.3
No.4R	10.4	7.5	0.9	1.9
No.5L	9.6	7.5	1.2	1.2
No.5R	10.2	7.5	1.6	2.0

2.2 *Method of the Fatigue Test*

Fatigue tests were conducted for 5 specimens using a hydraulic servo type material testing machine. Their loading positions were determined to be within the range of the central part on the upper surface of the deck plate: 50 × 100 mm as shown in Figure 3, and the specimens was constrained by the pin support for installing the steel round bar below the web. Their load range was set to 30 kN (0.3 kN - 30.3 kN), and their load cycles rate was 0.5 Hz.

2.3 *Procedure of the Fatigue Test*

The procedure of the fatigue test is described below. Firstly, the fatigue test was conducted for generating fatigue cracks in a specimen. During the fatigue test, a single-axis strain gauge with the gauge length of 2 mm was attached to the underside of the deck plate 5 mm away from the toe of the boxing weld of the deck plate and the vertical stiffener as shown in Figure 4, and changes in the range of strain associated with the number of load cycles were measured with a dynamic strain gauge in order to investigate the properties of initiation and propagation of fatigue cracks. A magnetic particle examination was also carried out to measure the fatigue cracks after a large decrease in the strain range was found. Once it was confirmed that fatigue cracks were propagating to the base material of the deck plate, the fatigue test was interrupted and then resumed after stop holes were made at the tip of the fatigue cracks.

The states of a fatigue crack before and after repair with a stop hole are shown in Figure 5 and 6, respectively. The position of installing two stop holes sandwiching the crack was built with the diameter of 22mm so that the interval between the outer portions of a porous wall could be 80mm and that they could be positioned symmetrically across the vertical stiffener. The chamfering of about 2 mm to the edges of stop hole was performed. In addition, the finishing of porous walls of stop holes was performed so that there were no scratches in porous walls that could occur during the preparation of stop holes and in order to surely verify situations of removing the crack tip after installing the stop holes. Their finishing was made through polishing by using a bar grinder with a vitrified grinding stone (# 36) and then with a rubber grinding stone (# 80 or 120). After the stop holes were installed, the development and recurrence of fatigue cracks were examined by measurements of strain range by using strain gauges putting on the upper and lower surfaces of the deck located 3 mm each from porous holes on the upper surface of the deck above the edge face of the vertical stiffener and on the outer part of the stop hole as shown in Figure 4. In addition, since there are four stop holes in a specimen, they are distinguished with L/R and E/W, as shown in Figure 3.

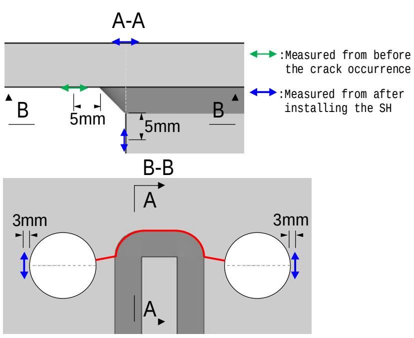


Figure 4. Position of strain gauge.

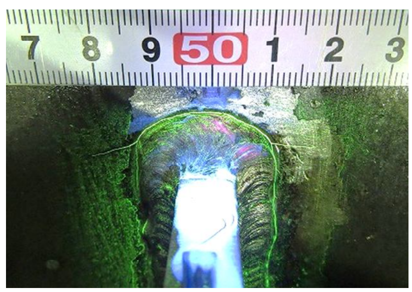


Figure 5. Before the repair (No. 3R).

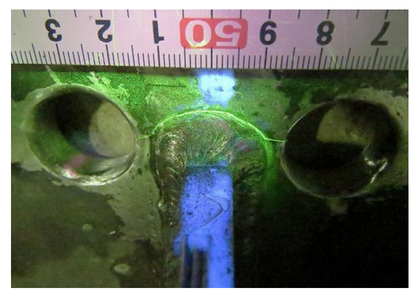


Figure 6. After the repair (No. 3R).

2.4 *Results of the Fatigue Tests*

(1) *Fatigue test for generating the fatigue crack*

Table 3 shows results of a fatigue test. The fatigue test (before installing stop holes) was conducted to generate fatigue cracks, in which cracks were generated with the length of 42 – 59 mm by applying 500 – 900 thousand repetitive loads to specimens No. 1 to 3 without root gaps on the deck plate and the vertical stiffener and cracks with the length of 27 – 48 mm by applying 2.0 to 3.6 million repetitive loads to specimens No. 4 and 5 having root gaps of 1 mm. Note that there were no places where cracks occurred on the upper surface of the deck plate at this moment. The tendency for slower development of cracks in the specimens having root gaps

Table 3. Results of the fatigue test.

Specimen		Before installing SH		After installing SH		
		Frequency of load cycles	Crack length	Frequency of deck plate crack penetration	Presence/absence of recurrent crack on SH	
					Frequency of load cycles	Presence/absence
		$\times 10^6$	mm	$\times 10^6$	$\times 10^6$	
No.1	L	0.70	58	0.00～0.80※	5.80	absence
	R	0.70	48	0.00～0.80※	5.80	absence
No.2	L	0.90	51	0.10	6.60	absence
	R	0.90	59	0.10	6.60	absence
No.3	L	0.50	42	0.10	6.20	absence
	R	0.50	43	0.15	6.20	absence
No.4	L	2.00	27	Cut in installing SH	12.07	absence
	R	2.00	49	0.20	12.07	absence
No.5	L	3.60	48	Not penetrating	9.45	absence
	R	3.60	30	Not penetrating	9.45	absence

※Not identifiable due to the lack of data was observed, and this might happen because the weld size was somewhat large in specimens No.4 - 5 compared with those of specimens No. 1 – 3, as shown in Table 2. In addition, there is a possibility that the existence of a root gap may have affected it, but its details are unknown at the present.

(2) *Installation of a stop hole*

Crack tips could be removed by installing stop holes at certain positions at eight locations with the exception of No. 4L and No. 5R, but cracks did not propagate the given position of installing stop holes in No. 4L with the crack length of 27mm and No. 5R with the crack length of 30 mm, and thus a crack was simulated by saw-cutting a deck plate between stop holes for No. 4L, and a stop hole was installed at a given position on the extended line in the direction of crack progress for No. 5R.

(3) *Fatigue test after making stop holes*

As shown in Table 3, 5.8 to 12.07 million load cycles were applied in a fatigue test after making stop holes. Stop-hole walls were observed in detail by the magnetic particle testing after this testing, and high repair effects of stop holes were verified as no recurrence of fatigue cracks was observed in any of the specimens. An example of observing porous walls is shown in Figure 7.

In specimens No.1 - No.4, cracks occurred on the upper surface of the deck plate in a relatively early stage after making stop holes. Examples of a crack occurring on the upper surface of the deck plate and a change in the strain range of the upper surface of the deck plate after making stop holes are shown in Figure 8 and Figure 9, respectively. The strain range has increased with the load cycles but rapidly decreased when the number of load cycles reached 200,000 times after the fatigue testing was resumed in No.4R. This is considered to be because the crack from the underside of the deck plate penetrated it or cracks occurred from the upper surface of the deck plate. Figure 10 shows an example of the fatigue failure surface. It is believed that the penetration resulted from new cracks from the upper surface of the deck plate and their coalescing with those from the underside, rather than the penetration of the crack occurring from the underside of the deck plate into the upper surface.

Figure 7. An example of observing a porous wall (No.2RW).

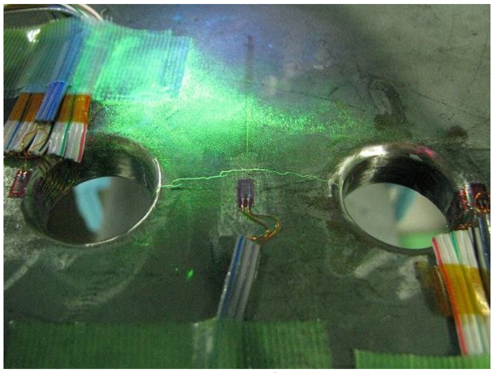


Figure 8. An example of a crack penetrating the deck (No.4R).

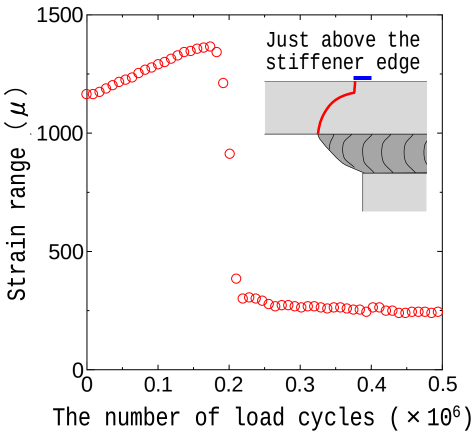


Figure 9. The relationship between the strain range and the number of load cycles (No.4R)

Figure 10. An example of the fatigue failure surface (No.4R)

As for the No.5 specimen, no cracks occurred on the upper surface of the deck plate, whereas it was confirmed that a crack occurred in the weld bead surface at the time of applying repeated loads of 2.5 million times after installing the stop holes. Figure 11 shows an example of the occurrence of the crack. Also, an example of the change in the strain range after the stop hole installation works is shown in Figure 12. While the strain range was almost constant on the upper and lower surfaces of the deck plate, that of the weld toe of the vertical stiffener decreased to 1.4 million times, and thus the crack of the weld bead surface is considered to have occurred at 1.4 million times. The authors(Mori,T et al.2014) have already investigated starting points of initiation of concerned cracks from fatigue tests with the weld leg length, the leg length ratio and the root gap as parameters and the stress analysis with the three-dimensional finite element method, confirming that the reduced throat thickness resulted in an increase in the stresses of the root portion and the weld toe of the vertical stiffener. It is believed that cracks occurred from the root part or the weld toe part of the vertical stiffener due to the smaller throat thickness in specimen No. 5 having a root gap. No cracks extended even with repeated loads after the occurrence of cracks on the weld bead surface.

3 ANALYSIS OF THE STRESS OF THE TEST SPECIMEN

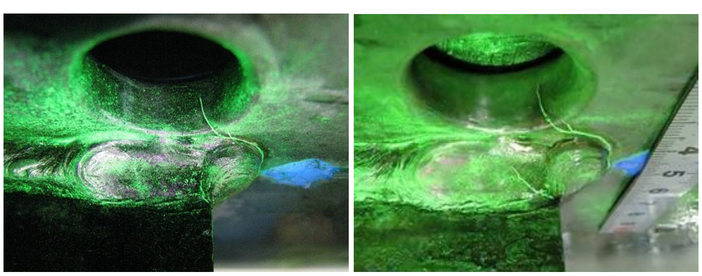
3.1 *Effects of Installing Stop Holes on The Initiation and Propagation of Cracks*

Since it was considered likely that the installation of stop holes would accelerate the propagation of cracks from the underside of the deck plate and their occurrence from the upper surface of the deck plate, an analytical model with a crack not yet penetrating the deck was prepare d for the states before and after installing stop holes to determine the stress intensity factor (K value) at the tip of the direction of the crack depth and the stress on the upper surface of the deck plate. The element diagram of the analytical model is shown in Figure 13. The analytical model was determined to be the 1/4 model of the specimen in consideration of its symmetry as in References(Mori,T et al.2011,Mori,T et al.2014). The size of the crack was 8.5 mm deep and 58 mm long (aspect ratio: 0.29), simulated on the plane to the position of the weld toe of the deck plate on the part of the boxing weld center. The element size of the crack tip is 0.25 mm. Stop holes were set to a diameter of 22 mm and the chamfering depth of 2 mm as in the case of the fatigue test. The load was set to 30kN, the elastic modulus to 2.0×10^5 N/mm^2, and the Poisson's ratio to 0.3. MidasNastranFX and NEiNastran were used for the pre- and post- program and its solver, respectively.

The K value of the crack tip was determined by making calculations from displacements obtained through the analyses of the three points: 0.25 mm, 0.50 mm, and 0.75 mm away from the crack tip with the displacement method and extrapolating them. The K values of the crack tip before and after installing stop holes were 594 kN/mm$^{3/2}$ and 830 kN/mm$^{3/2}$, respectively. In addition, the stresses in the direction perpendicular to the bridge axis on the upper surface of the deck plate before and after installing stop holes were 554 kN/mm^2 and 728 N/mm^2, respectively. Therefore, it is suggested that the installation of stop holes would accelerate the extension of fatigue cracks originated from the underside of the deck plate and the initiation of cracks from the top surface of the deck plate.

3.2 *Effects of the Chamfering Size and the Diameter of a Stop Hole on the Stress on the Wall of a Stop Hole*

To determine influences of the chamfering size and the diameter of a stop hole on the stress on the wall of a stop hole, an analysis was performed with them as parameters. As shown in Figure 14, a crack was simulated along the weld toe of the deck place in the boxing weld and linear in the direction to the bridge axis in other cases. It was also assumed that the crack penetrated linearly in the vertical direction.



(a)Immediately after installing a stop hole (b)At 2.5 million cycles after installing a stop hole

Figure 11. An example of crack in the specimen not yet penetrating the deck (No.5R).

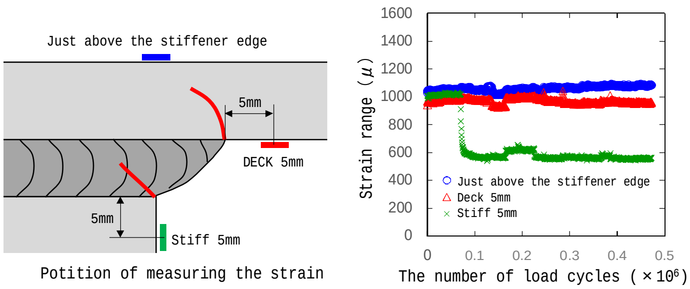


Figure 12. The relationship between the strain range and the number of load cycles (No.5R)..

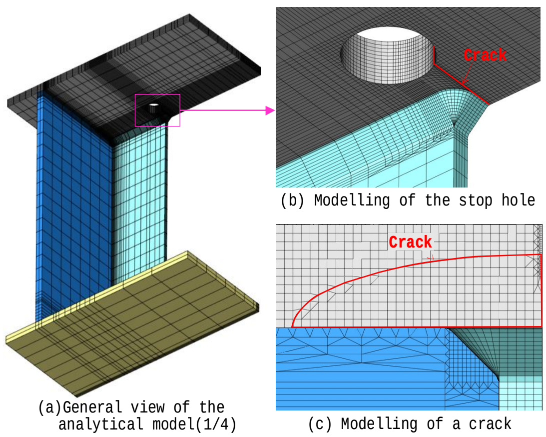


Figure 13. An analytical model to verify effects of stop

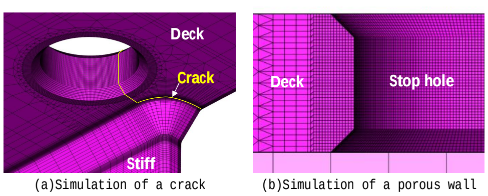


Figure 14. An analytical model to check the stress on the wall of the stop hole

The analytical and experimental stresses were compared on the upper and lower surfaces of the deck plate at the position of 3 mm away from the wall of the stop hole. Figure 15 shows their results. It should be noted that the experimental values are measurement values after the deck plate was penetrated in the specimen after stop holes were installed. Experimental values are lower than analytical values on the upper and lower surfaces of the deck plate. It is considered to be because cracks were simulated linearly in the vertical direction without considering the contact of the fatigue cracked surface in the analysis, whereas actual cracks propagated while turning in the direction of the plate thickness as shown in Figure 13 (b), and cracked surfaces contacted with each other for transmitting force when the compressive force was applied to contact surfaces.

The analysis was made by setting the diameter of the stop hole to 22 mm and changing the chamfering amount to 0, 1 mm, 2 mm, and 3 mm. In addition, the chamfered model had a structure to drop the corners of the upper and lower surfaces of the deck plate in a straight line, as shown in Figure 15 (b). Figure 16 shows the stress distribution on the outer wall of the stop holes. The bending deformation of the deck plate causes tensile stress on the upper surface of the deck plate and compressive stress on its lower surface. The stresses on the upper and lower parts of the deck plate are reduced by increasing the chamfering amount; the stress value on the upper surface of the deck plate with chamfering of 2 mm is 15% lower than that with chamfering of 0 mm.

The analysis was also made by setting the chamfering amount to 2mm and changing the diameter of the stop hole to 20 mm, 22 mm, and 24 mm. Figure 17 shows the stress distribution on the outer wall of the stop holes. The reduction of stresses on the upper surface of the deck plate was 8 % even though the diameter of the stop hole was changed from 20 mm to 24 mm, indicating its small effect on the stress reduction as compared to the case of chamfering amount. In the repair of a real bridge, however, it is necessary to confirm the status of removing crack tips and the presence or absence of stop wall flaws after installing stop holes, and thus it is considered to be desirable to make the diameter of the stop hole large enough for inspection.

Figure 18 shows the distribution of the maximum principal stress with the stop-hole diameter of 22 mm and chamfering amount of 2 mm that were used in this study. The maximum stress on the stop-hole wall occurred on the chamfered surface at the position of 30° to the vertical stiffener side with respect to the center of the circular hole, and its value was 330N/mm^2.

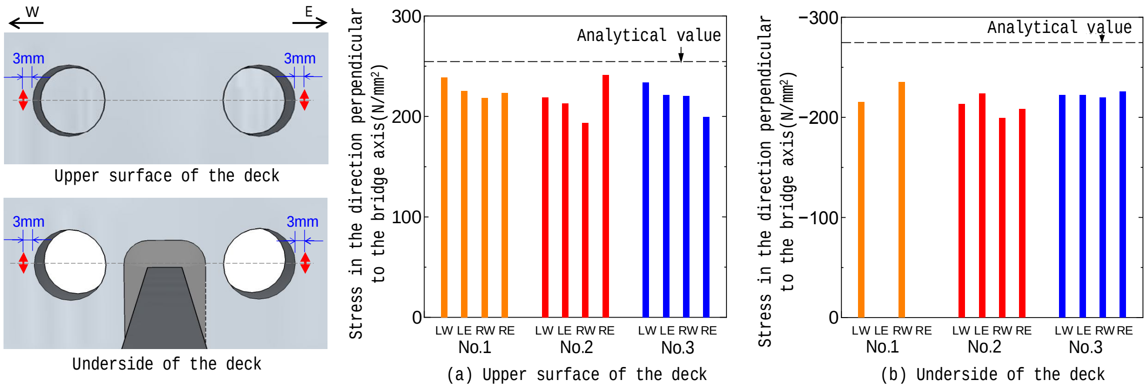


Figure 15. Comparison of experimental values and analytical values for the stresses on the deck plate near the stop hole

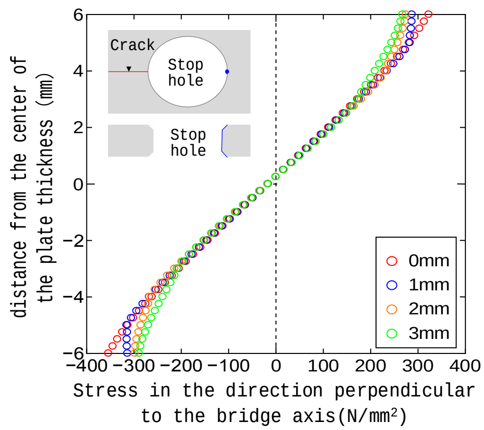


Figure 16. Stress on the porous wall by the chamfering size

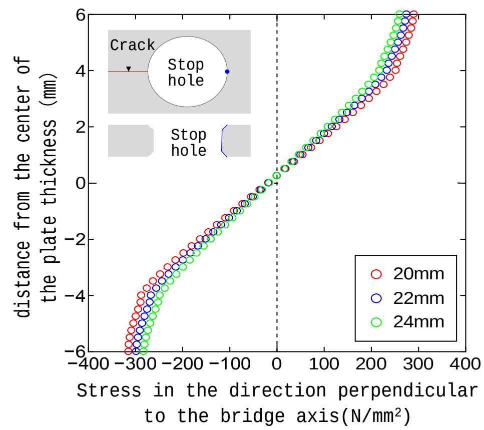


Figure 17. Stress on the porous wall by the diameter of a stop hole.

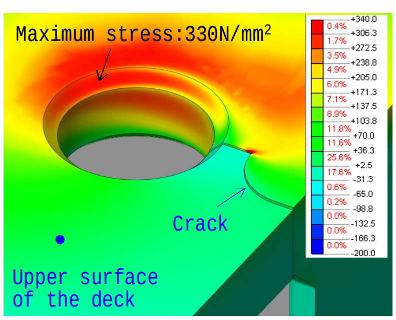


Figure 18. Contour of the maximum principal stress

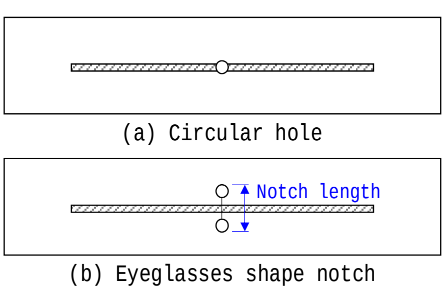


Figure 19. Shapes of specimens.

Table 4. List of the exiting specimens for fatigue testing.

(a) Specimen #NF

Specimen	Material quality	Plate thickness	Hole diameter	Notch length	Number of specimens
		mm	mm	mm	piece
①	SM400	12	18	70	6
②	SM490A	9	24.5	-	9
③	SM490	12	18	70	6
④	SM490Y	12	18	70	17
⑤	SM490Y	25	18	70	6
⑥	SM490Y	12	18	100	5
⑦	SM570	12	18	70	6
⑧	WEL・TEN780	12	18	70	6

※Plate width: 150 mm

(b) Specimen #80

Specimen	Material quality	Plate thickness	Hole diameter	Notch length	Number of specimens
		mm	mm	mm	piece
①	SM400A	6	18	70	6
②	SM490A	9	24.5	-	9

※Plate width: 150 mm

4 EVALUATION OF THE FATIGUE DURABILITY

4.1 *Method of Investigation*

The fatigue strength curve for evaluating the fatigue durability of the members repaired with stop holes was investigated on the basis of the existing fatigue test data(Mori,T et al.2002,Mori,T et al.2010,Hiroto,K et al.2002) .

Table 4 indicates the list of specimens that were used in the existing fatigue tests, and Figure 19 shows the shapes of those specimens. Note that the portions where the notch length is shown in Table 4 refer to the eyeglasses shape notch specimen as shown in Figure 19 (b). The specimens shown in Table 4 (a) are those where circular holes are left open with a saw cut, which are called specimens NF. In addition, those finished with a rubber grindstone of # 80 to #220 as shown in Table 4 (b) are referred to as Specimens #80. It was already confirmed that the fatigue strength of the steel with stop holes finished with rubber grindstones # 80 and # 220 was approximately the same(Hiroto,K et al.2002). Because the number of Specimens #80 is small, the fatigue strength curve in consideration of strength improvements by finishing is proposed here in arranging the fatigue test data for Specimens #NF having a larger number.

4.2 *Proposal of the Fatigue Strength Curve for the Fatigue Durability Evaluation*

The total number of Specimens #NF is 61. According to previous studies(Mori,T et al.2002), the fatigue strength of the member repaired with a stop hole can be arranged with the stress range at the stop hole wall $\Delta\sigma_s$ including stress concentration, regardless of the notch shape, steel type, and the plate thickness. The $\Delta\sigma_s$-N (N: fatigue life) relationship in which results of the fatigue test for specimens #NF shown in Table 4 (a) were are shown in Figure 20. The solid line in the figure shows the regression line of $\Delta\sigma_s$ for the fatigue life N determined using the least squares method, and the dotted line is the $\Delta\sigma_s$ -N relationship of the positions away from there by two standard deviations. In addition, the fatigue limit was determined to be the fatigue strength at two million cycles in view of the stress range of data without failure. Figure 21 shows the $\Delta\sigma_s$ -N relationship of Specimens # 80 with finishing stop-hole walls. As the number of test data is small for Specimen #80, the slope and the standard deviation of its $\Delta\sigma_s$ -N relationship were assumed to be the same as those of Specimen #NF. It is proposed that the fatigue durability evaluation should be carried out using the $\Delta\sigma_s$ -N relationship for evaluation of fatigue durability of the members repaired with stop holes with finished porous walls.

Figure 21 also shows results of the fatigue tests for 5 small specimens indicated in Chapter 2. Note that the stress ranges on the circular porous walls of these specimens are determined on the basis of the finite element stress analysis results explained in Chapter 3. Experimental results are located below the $\Delta\sigma_s$ -N curve away from the mean value of Specimens #80 by two standard deviations, and these results correspond to the fact that no cracks recurred from porous walls in the experiment of small test specimens.

On the basis of the above results, fatigue strength curves for the members repaired with stop holes with or without porous walls finished are proposed below. The fatigue strength at 2 million stress cycles obtained from these regression lines is 366 N/mm^2 for no finishing and 432 N /mm^2 for the #80 finishing.

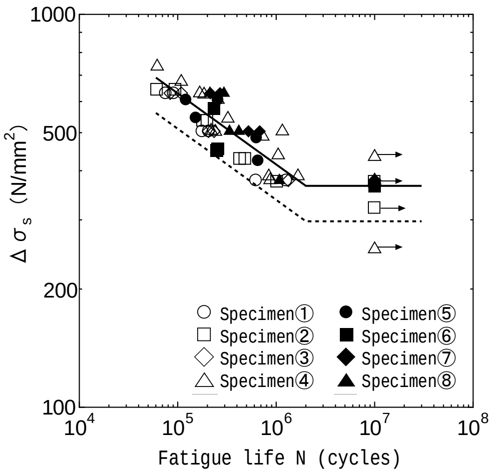


Figure 20. $\Delta\sigma_S$-N relationship (with no finishing).

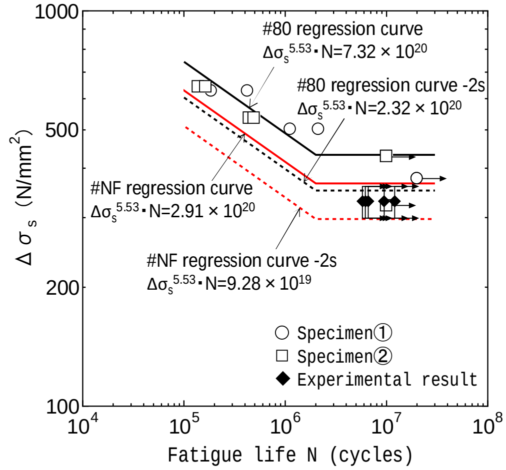


Figure 21. $\Delta\sigma_S$-N relationship (with finishing).

No finishing : $\Delta\sigma_s^{5.53} * N = 2.91 \times 10^{20}$ (Fatigue strength at 2×10^6 stress cycles: 366 N/mm^2)
Finishing : $\Delta\sigma_s^{5.53} * N = 7.32 \times 10^{20}$ (Fatigue strength at 2×10^6 stress cycles: 432 N/mm^2)

5 CONCLUSIONS

In this study, the fatigue tests and the stress analyses on small specimens were conducted for the purpose of revealing the effects of the stop-hole method on fatigue cracks in the welded parts of the vertical stiffener of orthotropic steel deck. The fatigue strength curve was also studied for performing a fatigue durability evaluation when members are repaired with the stop-hole method. The results obtained here are as follows:

i. As a result of conducting the fatigue tests for small specimens repaired with stop holes after fatigue cracks in them, it was verified that the stop-hole method has a high repair effect.
ii. A stop-hole repair for cracks not yet penetrating the deck plate accelerates the development of fatigue cracks initiating from the underside of the deck plate and the occurrence of cracks from the upper surface of the deck plate.
iii. The stress on the stop-hole wall on the upper surface side of the deck plate can be reduced by about 15 % by chamfering stop holes.
iv. A fatigue strength curve was proposed for evaluation of fatigue durability of the members repaired with stop holes with or without finished by arranging existing fatigue test data. Its validity was also confirmed by comparing it with the experimental data obtained here.

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