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Fatigue Crack Repair Using Drilled Holes and Externally Bonded CFRP Strips

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ABSTRACT: Fatigue cracks in steel bridges are often repaired by constructing drilled holes at the crack tips, because these drilled holes can stop or delay crack propagation. Repair methods using drilled holes have been actively investigated, with techniques such as the tightening of high-strength bolts in the drilled holes used to enhance the repair effect. However, it may be difficult to tighten high-strength bolts in narrow locations. On the other hand, the results of some studies have demonstrated that Carbon-Fiber-Reinforced Plastic (CFRP) strips, which are lightweight, have high strength, display excellent corrosion resistance, and are easy to use, are useful for the repair of fatigue cracks. Therefore, an improvement in the effect of fatigue-crack repair by combining drilled holes with externally bonded CFRP strips is expected. In this study, a repair method combining drilled holes with externally bonded CFRP strips is proposed, and tensile tests and fatigue tests are carried out to verify the effects of the fatigue-crack repair using specimens with welded web gusset plates. As shown by the results of the tensile tests, the strain concentration of the drilled holes is greatly reduced by the externally bonded CFRP strips. The results of the fatigue tests also show that the fatigue life is improved significantly.

1 INTRODUCTION

Historically, fatigue damage often occurred at the weld joints of structures, because a weld joint is a structural discontinuity, and is subjected to stress concentration at the weld toe, welded residual stresses, and so on. In recent years, fatigue damage at welded web gusset joints, which are used to connect lateral bracing members, has been reported frequently. Fatigue crack at a welded web gusset cannot be neglected, because the fatigue crack might actually propagate and finally cause the brittle fracture of the main girder.

Fatigue cracks in steel bridges are usually repaired by forming drilled holes at the crack tips, because these drilled holes stop or delay crack propagation. There have been active investigations on such repair methods using drilled holes, such as the tightening of high-strength bolts in drilled holes to enhance the repair effect (Fisher 1984). However, it may be difficult to tighten high-strength bolts in narrow locations.

On the other hand, the results of some studies have demonstrated that a Carbon-Fiber-Reinforced Plastic (CFRP) strip is useful for the repair of fatigue cracks. A CFRP strip is lightweight, and has high strength and excellent corrosion resistance. In addition, it is a very simple structure and is easy to use.

Therefore, we proposed to improve the repair effects of drilled holes by combining this method with the use of externally bonded CFRP strips (Nakamura et al. 2009). In past studies (Nakamura et al. 2009), after the fatigue cracks initiated, they were repaired using only the CFRP strips. The fatigue-test results showed that the fatigue limit was not reached, and the proposed method was positioned as a first-aid repair for prolonging the fatigue life. Hence, a repair method combining drilled holes with externally bonded CFRP strips is expected to provide a permanent countermeasure.

Although the improvement in fatigue strength using the repair method of drilling holes at the crack tips and tightening high-strength bolts in the holes has been clarified experimentally (Mori et al. 2001), there were not sufficient data available on the repair effect achieved by combining drilled holes with externally bonded CFRP strips. For example, it has been proved that in comparison with drilled holes, the fatigue strength is greatly increased when using both drilled holes and CFRP strips on small coupon specimens of flat steel plate (Suzuki et al. 2003). Therefore, examinations such as modeling of full-scale drilled holes and fatigue-crack initiation at weld joints are necessary for the practical use of this method.

In this study, the effect of repair using both drilled holes and externally bonded CFRP strips is examined experimentally using a cracked specimen with welded web gusset plates.

In the experimental procedure, first, the effect of the lamination number of CFRP strips on the reduction in strain concentration is investigated through tensile tests. Second, the improvement in fatigue life is investigated by fatigue tests with varying stress ranges.

2 TEST PROCEDURES

2.1 Test specimen and material properties

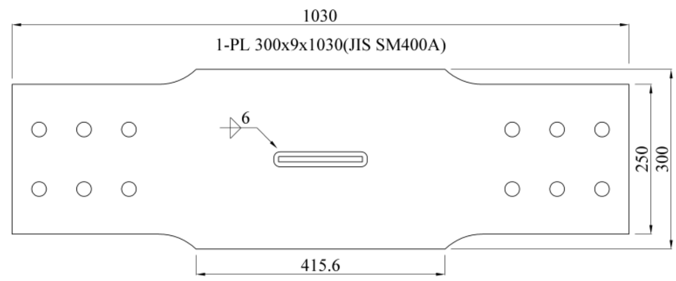
As shown in Figure 1, the specimens were fabricated with two gusset plates (100×9×140 mm) welded to both sides of the central part of the base steel plate (300×9×1030 mm). The mechanical properties of the steel plate, the CFRP strip, and the epoxy resin adhesive are shown in Table 1. The CFRP strip is 1.2 mm in thickness, and the carbon fiber is arranged unidirectionally.

For comparison of the repair effects, two series of repair methods were investigated experimentally. One was the repair method using only drilled holes (hereafter called DH), and the other was the repair method using both drilled holes and externally bonded CFRP strips (hereafter called DHC).

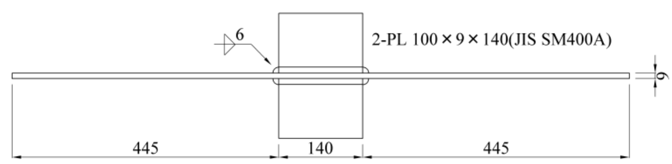
2.2 Repair method using drilled holes (DH series)

The drilled holes of the DH series are shown in Figure 2 (a). Assuming that fatigue cracks are initiated at the weld toe and then propagate, first, two circular holes of 25 mm in diameter were installed on the predicated crack path. The outer-edge distance between the two drilled holes, *c*, was set to 80 mm, considering the workability of the portable drilling machine and hand grinder. Second, the base plate between two drilled holes was penetrated using a saber saw. Finally, in order to prevent crack initiation at the other side of the weld toe, this part was smoothly treated using the hand grinder.

The strain gages were installed as shown in Figure 2 (a). The numbers refer to the distance from the center of the specimen (left side is "-" and right side is "+"). First, as shown in Figure 2 (a), strain gages were installed on the chamfer of the hole edge; these had a gage length of 1 mm and interval of 2 mm (named ±40S*a*, *m*, *b*). The strain gages of ±40S*m* were located at the center of the plate thickness. In addition, near the hole edges, strain gages (±41.5S*a*, *b*) were installed on side *a* and side *b* of the specimen.



(a)Plan view



(b)Side view

Figure 1. Specimen with welded web gusset plates

Table 1. Material properties

(a) Steel plate and CFRP strip

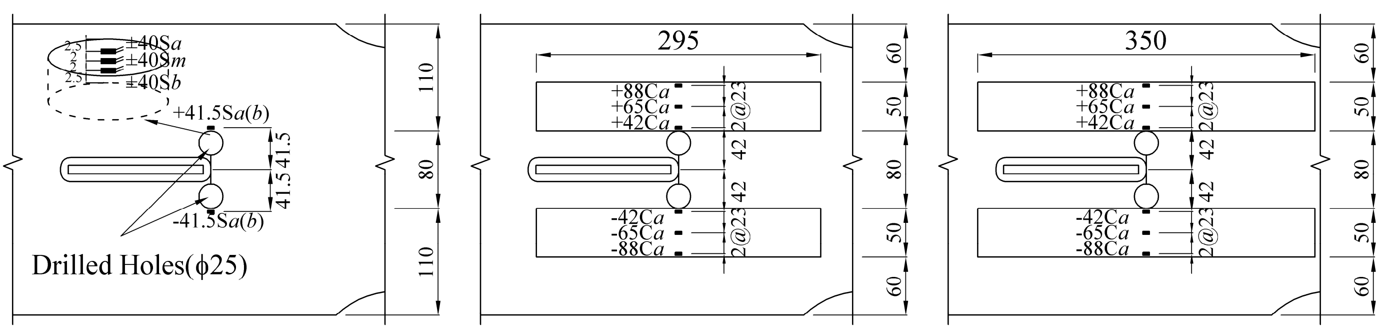
	Steel plate (JIS SM400A)	CFRP strip
Yield point σ_Y (MPa)	293	-
Tensile strength σ_{tu} (MPa)	453	2680
Breaking elongation (%)	29	-
Elastic modulus *E* (GPa)	204.5	153

(b) Epoxy resin adhesive

Compressive elastic modulus *E* (GPa)	1.5
Tensile strength σ_{tu} (MPa)	30
Bending strength σ_{bu} (MPa)	48.7

2.3 Repair method using both drilled holes and externally bonded CFRP strips (DHC series)

As shown in Figures 2 (b) and (c), the drilled holes of the DHC series are similar to those of the DH se-



(a) DH series (b) DH5C series (c) DH7C series

Figure 2. Repair method and strain gage location

ries. Five (DH5C) or seven (DH7C) layers of CFRP strips (50 mm in width) were bonded to the steel plate. In order to prevent debonding of the CFRP strips from the ends, the total and lap lengths of the CFRP strips were designed as multiple-stepped laminations on the basis of finite element analysis (FEA) considering the shear lag (Ishikawa et al. 2010).

Before bonding, the surfaces of the steel plate and the CFRP strips were roughly treated with the hand grinder.

The bonding procedure was as follows: First, the CFRP strips were multiple-stepped and laminated, and cured for one day at room temperature (approx. 25°C). Second, as shown in Figures 2 (b) and (c), the multiple-stepped CFRP strips were externally bonded at the drilled hole, and cured for seven days at room temperature (approx. 25°C). The results of the previous study (Nakamura et al. 2009) showed that the CFRP strips debonded earlier when the drilled holes were covered with the CFRP strips because the opening displacements of the drilled holes were considered to be rather large. Therefore, in this study, the bonding method of the CFRP strips shown in Figures 2 (b) and (c) and Figure 3 was adopted.

The strain gages were installed as shown in Figures 2 (b) and (c). The strain gages on the chamfer of the hole edge were similar to those of the DH series. Moreover, the strain gages were only installed on the CFRP strips of side *a* (±42C*a*, ±65C*a*, ±88C*a*).

Figure 3. Repair method of DHC series

2.4 Experimental conditions

The experimental conditions are shown in Table 2. In the first column of this table, the first mark indicates the kind of repair method, the number in the middle is the stress range, and the last number gives the specimen number of the same repair method and the same stress range.

Under fatigue-test conditions, the minimum nominal stress of the steel plate, σ_{sn}, was 20 MPa, and the nominal stress range of the steel plate, $\Delta\sigma_{sn}$, was set to 80, 100, 120, or 140 MPa by changing the maximum nominal stress. In this study, the fatigue limit was set as 10,000,000 cycles. If fatigue crack

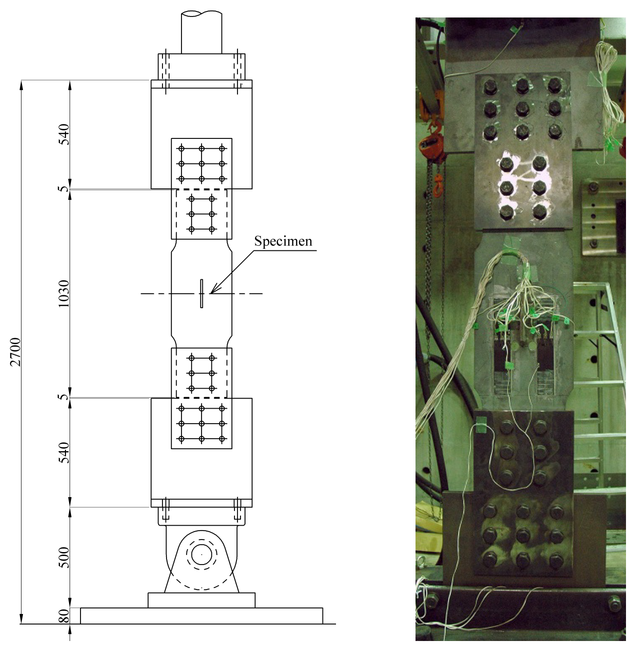


Figure 4. Test setup

Table 2. Experimental conditions

Experimental series	Repair method	Max. stress σ_{max} (MPa)	Min. stress σ_{min} (MPa)	Stress range $\Delta\sigma_{sn}$ (MPa)	Loading speed f (Hz)
DH-080	Drilled holes	100	20	80	5
DH-100-1	Drilled holes	120	20	100	5
DH-100-2	Drilled holes	120	20	100	4
DH-120-1	Drilled holes	140	20	120	4
DH-120-2	Drilled holes	140	20	120	4
DH-140-1	Drilled holes	160	20	140	3
DH-140-2	Drilled holes	160	20	140	3
DH5C-080	Drilled holes+CFRP	100	20	80	6
DH5C-100	Drilled holes+CFRP	120	20	100	5
DH5C-120-1	Drilled holes+CFRP	140	20	120	5
DH5C-120-2	Drilled holes+CFRP	140	20	120	4
DH5C-120-3	Drilled holes+CFRP	140	20	120	4
DH5C-140-1	Drilled holes+CFRP	160	20	140	3
DH5C-140-2	Drilled holes+CFRP	160	20	140	3
DH7C-080	Drilled holes+CFRP	100	20	80	-
DH7C-100	Drilled holes+CFRP	120	20	100	-
DH7C-120	Drilled holes+CFRP	140	20	120	-
DH7C-140	Drilled holes+CFRP	160	20	140	-

was not initiated, the repaired specimen could reach the fatigue limit, and the fatigue test was carried out again, increasing the stress range by 20 MPa until fatigue-crack initiation. The loading speed f was dependent on the limit of the testing machine. This was set slower when the stress range was higher. Before the fatigue test, the tensile test was carried out, but only the tensile test was carried out for the DH7C series. Figure 4 shows the test setup.

3 DISCUSSION OF REDUCTION IN STRAIN CONCENTRATION IN DRILLED HOLES

The tensile test was carried out before the fatigue test. In order to eliminate the influence of in-plane and out-of-plane bending on the measured strains, the average value from six strain gages on the chamfer of the hole edge (hereafter called the strain in the drilled hole) is used for the discussion in this section.

The stress- or strain-concentration factor of drilled holes in a finite plate is given by Mori et al. (2001) as follows:

$$\alpha_s = \sqrt{\sec\left(\frac{\pi \cdot c/2}{w}\right)} \cdot \left\{0.166(c/M) + 1.64\sqrt{c/M} + 1.19\right\} \quad (1)$$

where α_s is the stress- or strain-concentration factor, M is the diameter of the drilled hole, w is the width of the steel plate, and c is the outer-edge distance between two drilled holes. Here, α_s is calculated to be 4.87.

As an example of the tensile test results, Figure 5 shows a comparison between the DH and DH5C series for $\Delta\sigma_{sn}$ = 120 MPa. This figure includes the tensile test results from the first to the fourth time, as well as the results calculated from Eq. (1). As shown in this figure, in the first tensile test, because of the effect of stress concentration, although the tensile stress of the steel plate σ_{sn} was under the yield point, the strain in the drilled hole became large and plastic strain was generated, and after unloading, residual strain remained both in the DH and DH5C series. In the second and subsequent tensile tests, the strain in the drilled hole was smaller than that of the first time, and after unloading, a slight residual strain remained in both series, but that of the DH5C series was smaller than that of the DH series. The residual strain after unloading decreased with an increasing number of cycles. Before the plastic strain was generated, the strain in the drilled holes was equivalent to the theoretical value calculated from Eq. (1). The other series showed similar results (not shown).

As mentioned above, the strain variations in the drilled holes became stable after several tensile tests. In Figure 6, the results after several tensile tests in each stress range are shown for all the series. It was found that the relationships between the tensile nominal stress and the strain in the drilled holes did not show elastic behaviors, and were hysteresis loops. However, residual strain was not generated so much after unloading. It was considered that the yield point of the steel plate used (JIS SM400A) was low, and the edges of the drilled holes seemed to be strongly influenced by the welding residual strain and stress concentration. It has also been shown that the stress-strain relationships in steel plates with higher yield points showed almost elastic behaviors (Uchida 2007).

In the DH5C and DH7C series, although slight hysteresis behaviors were observed compared with that of the DH series, and the stress-strain relationships in the drilled holes showed almost elastic behaviors with an increase in the number of layers of CFRP strips, it was found that the tensile stiffness near the drilled holes by the bonded CFRP strips became higher, and that the strain concentration was

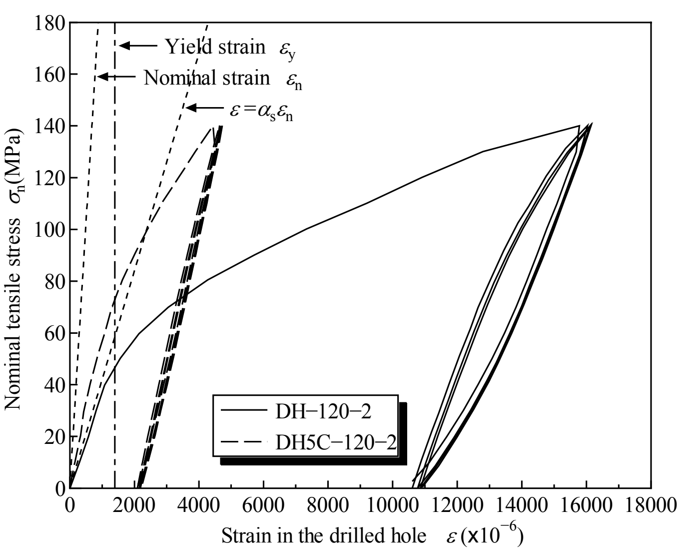


Figure 5. Relationships between tensile nominal stress and strain in drilled holes during several tensile tests

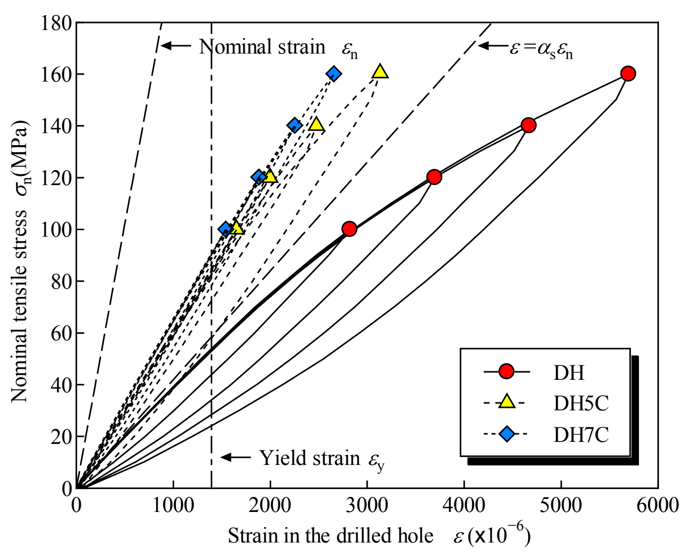


Figure 6. Relationships between tensile nominal stress and strain in drilled holes after several tensile tests

drastically reduced.

The effect of the externally bonded CFRP strips on the nominal stress and strain reduction of the steel plate was calculated on the basis of the tensile stiffness ratio S_R, as in the following equation (Liu et al. 2009):

$$S_R = E_s A_s / \left(E_s A_s + E_c A_c\right) \qquad (2)$$

where E and A are the elastic modulus and cross-sectional area, and the subscripts s and c refer to the steel plate and the CFRP strips, respectively. The value of S_R was 0.50 for DH5C and 0.42 for DH7C.

The strains in the drilled holes ε_{DHmax} for the maximum nominal tensile stress σ_{max} of all the series are shown in Table 3. The strains of ε_{DHmax} are the averaged values in the drilled holes after several tensile tests. The strain concentration factor of the tensile test was calculated by $\alpha_s = \varepsilon_{DHmax}/\varepsilon_{max}$, where ε_{max} is the maximum nominal strain. Compared to the DH series, the strain concentration factor of the DHC series was greatly reduced, and the reduction of the strain concentration increased with an increasing number of laminate layers. It was also found that the strain concentration factor α_s increased with increasing nominal tensile stress. It is considered that the reason for this was that a large plastic strain ε_{DHmax} was generated at the hole edges under the elastic nominal strain ε_{max}, and thus, the strain concentration factor $\alpha_s = \varepsilon_{DHmax}/\varepsilon_{max}$ increased naturally.

The repair effects are also shown in Table 3. These were calculated by comparing the strains in the drilled holes ε_{DHmax} with the maximum nominal strain ε_{max} for the DH and DHC series. First, the experimental results did not agree with the values obtained from Eq. (2) because Eq. (2) considered elastic behavior. However, a large plastic strain was generated near the drilled holes because of the stress concentration, residual strain, and so on. This also shows that the repair effect increased with increasing tensile stress, because the plastic strain was reduced by the externally bonded CFRP strips. As mentioned above, inelastic behavior was observed in the DH series, and almost elastic behavior in the DHC series.

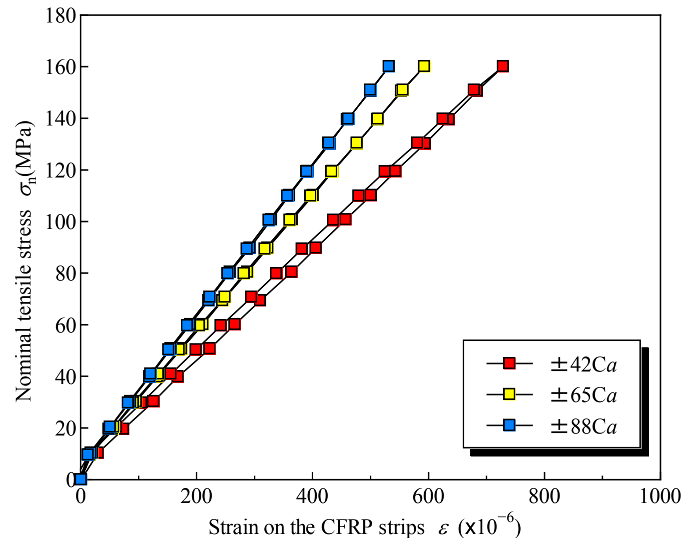


Figure 7. Strain variation in the CFRP strips (DH5C-140-2)

Figure 7 shows the tensile test results for DH5C-140-2. The strains on the CFRP strips are plotted under the nominal tensile stress. In order to eliminate the influence of in-plane bending, the average values of the left and right sides are used here. As shown in this figure, the strain of ±42Ca, which was close to the drilled holes, was the highest. It was found that the CFRP strips close to the drilled holes were also subjected to the influence of the stress concentration. Therefore, the externally bonded CFRP strips bore a part of the stress concentration of the edges of the drilled holes, and as a result, the strain concentrations of the hole edges were reduced.

4 DISCUSSION OF REPAIR EFFECTS BASED ON FATIGUE TEST

During the fatigue tests, the dynamic strains were

Table 3. Comparison of the maximum strain in drilled holes

Experimental series		Maximum nominal stress σ_{max} (MPa)	Maximum nominal strain ε_{max} ($\times 10^{-6}$)	Maximum strain in drilled holes (ave.) ε_{DHmax} ($\times 10^{-6}$)	Strain concentration factor α_s ($=\varepsilon_{DHmax}/\varepsilon_{max}$)	Tensile stiffness ratio S_R	Maximum strain ratio to DH
DH	DH-080	100	489	2870	5.87	-	-
	DH-100	120	587	3723	6.34		-
	DH-120	140	684	4887	7.14		-
	DH-140	160	783	5822	7.43		-
DH5C	DH5C-080	100	489	1651	3.37	0.50	0.57
	DH5C-100	120	587	1995	3.40		0.54
	DH5C-120	140	684	2518	3.68		0.52
	DH5C-140	160	783	2992	3.82		0.51
DH7C	DH7C-080	100	489	1541	3.09	0.42	0.53
	DH7C-100	120	587	1882	3.21		0.51
	DH7C-120	140	684	2252	3.29		0.46
	DH7C-140	160	783	2655	3.40		0.46

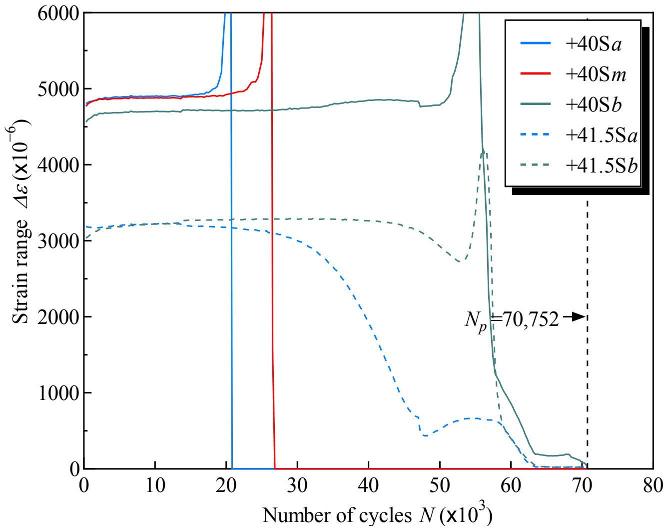


Figure 8. Relationships between measured strain range and number of cycles (DH-140-2)

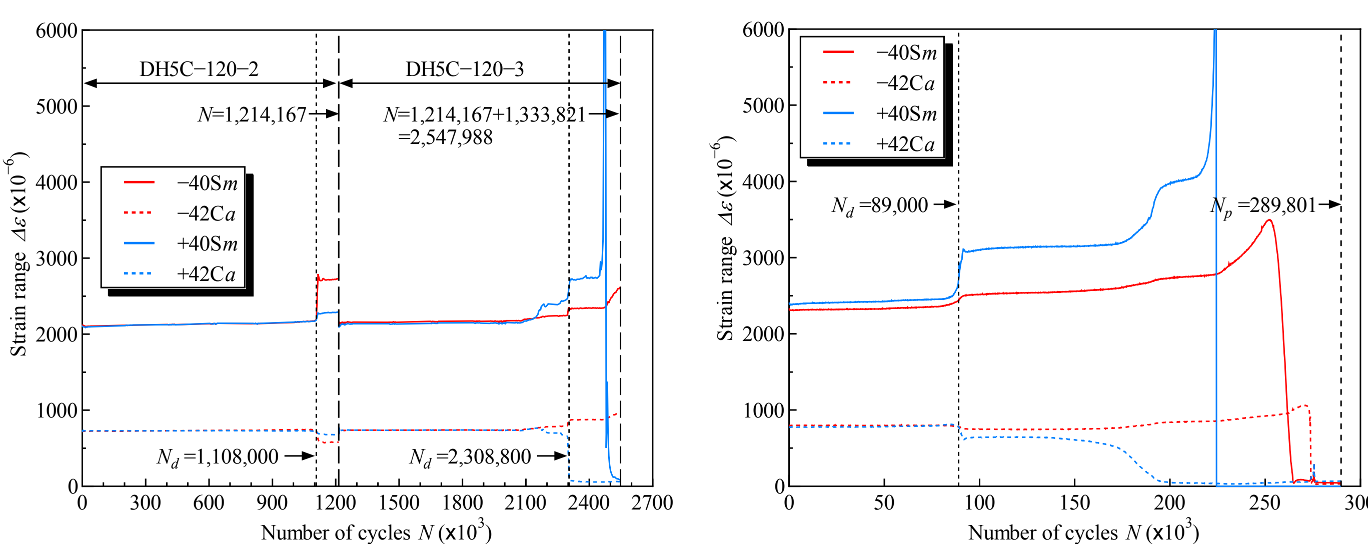
recorded at a sampling frequency of 100 Hz. The strain difference is defined as the difference between the maximum and minimum strain (hereafter called $\Delta\varepsilon$).

Figure 8 shows an example of the DH series (DH-140-2). First, the strain ranges of all gages maintained constant values up to approximately 18,000 cycles. The strain ranges of +40S*a* and +40S*m* suddenly increased at around 18,000 and 26,000 cycles, respectively, and their values immediately became zero and the strain gages failed. Then, only the strain range of +41.5S*a* gradually decreased with an increase in the number of cycles. At about 47,000 cycles, a fatigue crack was detected by visual observation in the right drilled hole of side *a* (located near +40S*a*). Moreover, we observed visually that this crack propagated to side *b* and in the width direction when the strain ranges of +40S*b* and +41.5S*b* moved up and down. Finally, the specimen failed when these values became zero. Therefore, it was found that the strain range became almost zero when the fatigue crack penetrated near the target strain gage.

(a) Debonding from the end (b) After removing CFRP strips
Figure 10. Debonding of CFRP strips (DH5C-120-2)

The experimental results of the DH5C series, that is, the relationships between the measured strain range and number of cycles of DH5C-120-2, DH5C-120-3, and DH5C-140-1, are shown in Figures 9 (a) and (b), respectively.

First, in DH5C-120-2, during the fatigue test, one of the CFRP strips, located on the left side and side *b*, was debonded from the end after approximately 880,000 cycles. The debonding progressed to the center, and approached the drilled holes at around 1,108,000 cycles, as shown in Figure 10 (a). Then, the fatigue test was stopped after 1,214,167 cycles, and the CFRP strips were removed, as shown in Figure 10 (b). After removal of the CFRP strips, no fatigue crack in the drilled holes was observed. As shown in Figure 9 (a), the strain ranges of all gages maintained constant values even at approximately 880,000 cycles, when one of the CFRP strips was debonded from the end. Moreover, when the debonding approached the drilled hole after about 1,108,000 cycles, the strain range in the drilled hole (-40S*m*) suddenly increased and maintained a higher



(a) DH5C-120-2 and DH5C-120-3 (b) DHC5C-140-1
Figure 9. Measured strain range vs. number of cycles

constant value. The strain range in the other drilled hole (+40S*m*), where the CFRP strips were not debonded, also increased. However, its value was lower than that of the other drilled holes on the debonding side. Therefore, it can be considered that the strain ranges of both drilled holes increased and maintained higher constant values when the CFRP strips debonded near the drilled holes.

In addition, the CFRP strips were bonded again in DH5C-120-2, which was newly named as DH5C-120-3, and a retest was carried out under the same loading conditions. As a result, the other CFRP strips, which were located on the right side and side *a*, debonded 1,094,633 cycles after the restart, and the total life until debonding was approximately 2,308,800 cycles, as shown in Figure 9 (a) and Table 4.

Table 4. Debonding life and failure life from fatigue tests

Experimental series	Debonding life N_d (cycles)	Failure life N_p (cycles)
DH-080*	-	>10,000,000
DH-100-1*	-	419,019
DH-100-2	-	275,612
DH-120-1	-	94,646
DH-120-2	-	130,030
DH-140-1	-	49,529
DH-140-2	-	70,752
DH5C-080**	-	>10,000,000
DH5C-100**	-	>10,000,000
DH5C-120-1**	5,500,000	6,105,127
DH5C-120-2***	1,108,000	-
DH5C-120-3***	2,308,800	-
DH5C-140-1	89,000	289,801
DH5C-140-2	402,000	504,719

The same number of asterisks indicates the same specimen used (retest)

Figure 9 (b) shows the results for DH5C-140-1. The CFRP strips debonded near the drilled hole after about 89,000 cycles, then the fatigue cracks initiated from around 220,000 to 270,000 cycles. Finally, the specimen failed after 289,901 cycles.

On the other hand, in the DH5C series, fatigue tests under the stress ranges $\Delta\sigma_{sn}$ of 80 and 100 MPa reached the fatigue limit. The specimens failed under the stress ranges $\Delta\sigma_{sn}$ of 120 and 140 MPa. However, in all the series, the fatigue cracks initiated after debonding of the CFRP strips.

As mentioned above, two kinds of failure mode, namely the debonding of the CFRP strips and the fatigue failure of the specimen, were observed in this study. The number of cycles until the debonding of the CFRP strips near the drilled holes was defined as the debonding life, N_d, and the number of cycles until the specimen failed was defined as the failure life, N_p.

Table 4 and Figure 11 show the N_d and N_p values of all the specimens. The fatigue limits were reached with stress ranges of 80 MPa for the DH series and 100 MPa for the DH5C series. In the stress range of 120 MPa or over, the debonding of the CFRP strips became dominant in the durability assessment. However, the fatigue life was drastically improved compared to the DH series.

As shown in Figure 6, the strain in the drilled holes was lower in all the repaired series (except DH5C-140) than in the DH-080 series, which reached the fatigue limit. Therefore, the fatigue limit might be achieved in the stress range of 120 MPa if the debonding of the CFRP strips can be prevented.

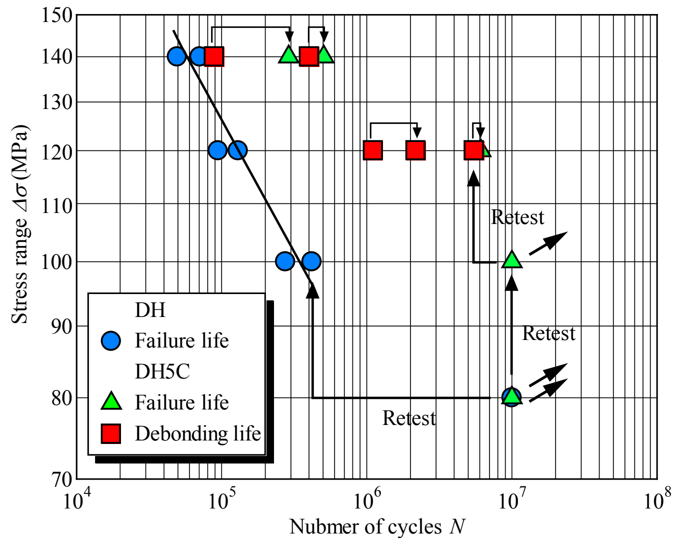


Figure 11. *S-N* curves

5 CONCLUSION

In this study, a repair method combining drilled holes with externally bonded CFRP strips was proposed, and tensile tests and fatigue tests were carried out in order to verify the effects of the fatigue-crack repair using specimens with welded web gusset plates. The following conclusions were obtained:

(1) The externally bonded CFRP strips bore a part of the stress of the edges of the drilled holes, and the strain concentration of the hole edges was reduced drastically.

(2) Since the plastic strain of the hole edges was reduced by the externally bonded CFRP strips, the repair effect increased with increasing tensile stress.

(3) In this study, the fatigue limit was achieved in the stress range of 100 MPa when using the drilled holes and five layers of externally bonded CFRP strips.

(4) In the stress range of 120 MPa and over, the debonding of the CFRP strips became dominant in the durability assessment. However,

the fatigue life was improved drastically compared to the use of drilled holes only.

(5) Fatigue cracks were not initiated before the CFRP strips debonded near the drilled holes. The repair effect would be greater if the debonding of the CFRP strips could be prevented.

Although the durability of the adhesive joint became dominant in higher stress ranges, a significant effect on the fatigue-crack repair was confirmed when combining drilled holes with the application of externally bonded CFRP strips.

REFERENCES

Fisher, J.W. 1984. *Fatigue and Fracture in Steel Bridges*. New York, USA: John Wiley & Sons.

Nakamura, H., Jiang, W., Suzuki, H., Maeda, K., Irube, T. 2009. Experimental study on repair of fatigue cracks at welded web gusset joint using CFRP strips. *Thin-Walled Structures*, 47(10): 1059-1068: Elsevier.

Mori, T. & Uchida, D. 2001. Fatigue Strength of Out-of-Plane Gusset Welded Joints Repaired by Bolting-Stop-Hole Method, *Steel Construction Engineering*, JSSC. 8(29): 15-26. (in Japanese)

Suzuki, H. & Okamoto, Y. 2003. Repair of Steel Members with a Fatigue Crack using the Carbon Fiber Reinforced Polymer Strip, *Journal of Constructional Steel*, JSSC. 11: 465-472. (in Japanese)

Ishikawa, T. & Okura, I. 2010. Required Length and Optimum Stiffness of Multiple-Stepped CFRP Strips Bonded to Steel Plate, *Journal of Japan Society of Civil Engineers, Ser. A*, JSCE. 66(2): 368-377. (in Japanese)

Uchida, D. 2007. Fatigue Strength Evaluation of Out-of-Plane Gusset Welded Joints Repaired by Bolting-Stop-Hole Method, *Mitsui Zosen Technical Review*, 190: 45-53. (in Japanese)

Liu, H., Xiao, Z., Zhao, X. L. & Al-Mahaidi, R. 2009. Prediction of Fatigue Life for CFRP-Strengthened Steel Plates, *Thin-Walled Structures*, 47(10): 1069-1077: Elsevier.