Applicability of Repair Method Using CFRP Strips for Fatigue Cracks in Out-of-Plane Welded Gusset Joint

Hitoshi Nakamura*, Suzuki Hiroyuki**, Maeda Ken-ichi*** and Irube Takao****

* M. of Eng., Research Associate, Dept. of Civil and Environment Eng., Tokyo Metropolitan University, 1-1, Minami-Osawa, Hachioji-shi, Tokyo 192-0397

** Dr. of Eng., Professor, Dept. of Architecture, Meisei University, 2-1-1, Hodokubo, Hino-shi, Tokyo 191-8506

*** Dr. of Eng., Professor, Dept. of Civil and Environment Eng., Tokyo Metropolitan University, 1-1, Minami-Osawa, Hachioji-shi, Tokyo 192-0397

**** M. of Eng., Manager, Eng. Dept., TTK-Corporation, 4-18-32, Minato-ku, Tokyo 108-0023

In this paper, the method used to repair fatigue cracks in the out-of-plane welded gusset joint using CFRP strips is investigated experimentally and analytically. Fatigue tests are carried out varying the attaching method and the number of CFRP strip laminations. Consequently, drastic improvement in the fatigue life is apparent, as the number of layers of laminated CFRP strips increases and a sufficient repair effect obtained in the laminated CFRP strips of 5 layers is detectable. Moreover, it is confirmed that CFRP strip lamination is effective in preventing peeling and sharing axial force.

Key Words: Carbon Fiber Reinforced Polymer Strips, Repair, Fatigue Crack, Welded Joint, Lamination

1. Introduction

Recently, many steel bridges have been suffering from fatigue problems[1]. The fatigue cracks are often initiated at welded joints, and in such locations, there is poor repair workability, hence the desire for a convenient and efficient construction technique in the fieldwork.

In such problems, a Carbon Fiber Reinforced Polymer strip (it is hereafter called a CFRP strip) is expected to become a new material used to repair and strengthen infrastructures. This is because the CFRP strip is lightweight (with a unit weight about 1/5 of the steel), has high strength (a tensile strength about 6 times that of steel) and high-corrosion resistance. The joint system of the CFRP strips involves a very simple method for bonding, using epoxy resin adhesive and with no specifically required high technology. Subsequently, a construction method using CFRP strips is considered to be utilized as a first aid form of repair when fatigue cracks are detected.

In this study, based on a former basic study[2], the effect of conducting repairs by bonding CFRP strips is examined experimentally for fatigue cracks initiated in out-of-plane welded gusset joints. The effect of the bonding method and the number of layers of CFRP strips on the fatigue life is clarified.

2. Testing Procedure

2.1 Test Specimens

As shown in Fig. 1, the out-of-plane welded gusset joint specimens were fabricated. Table 1 shows the mechanical properties of the steel plate, CFRP strip and epoxy resin adhesive. The used CFRP strips, in which a carbon fiber is placed only longitudinally, are made from a unidirectional reinforced material of 1.2 mm thickness.

2.2 Loading Condition

Four-point bending fatigue tests were carried out under constant amplitude loading, as shown in Figs. 2 and 3. The specimen was connected to the loading system using high strength bolts. The uniform nominal tensile stress occurred in the specimen. The load waveform was sinusoidal, and the frequency 2Hz. The minimum stress was almost 20MPa, and the maximum stress varied according to the nominal stress range.

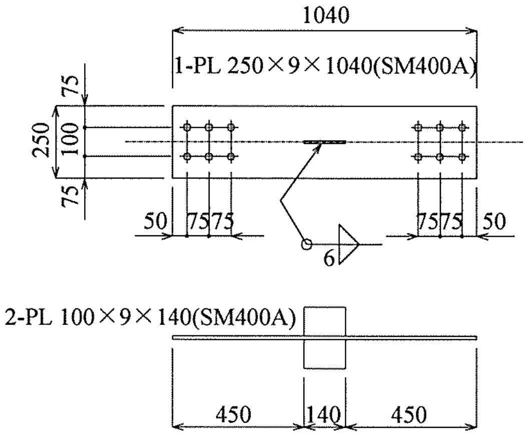


Fig. 1 Test specimen configuration

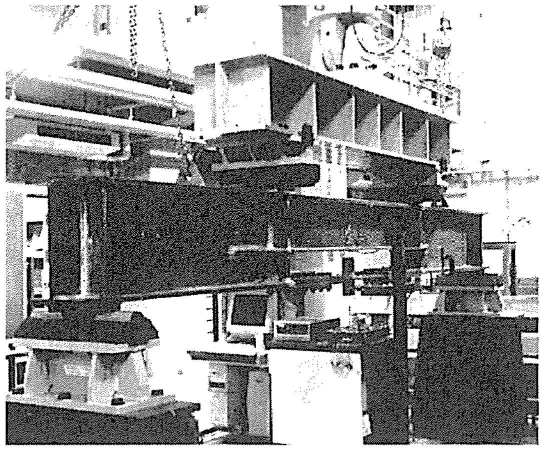


Fig. 2 Test setup

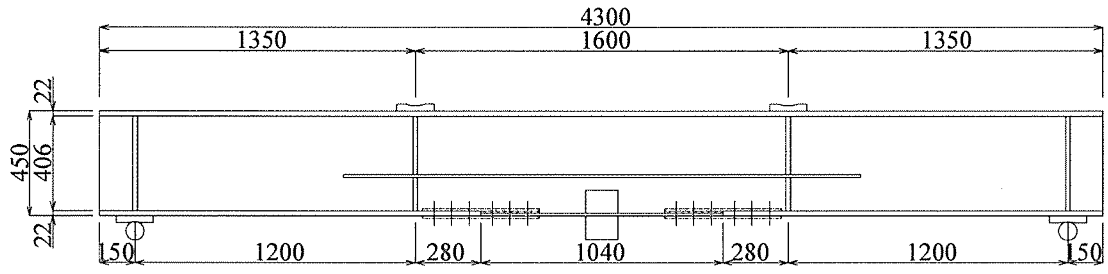


Fig. 3 Loading system

Table 1 Mechanical properties

	Steel plate (JIS SM400A)	CFRP strip	Epoxy resin adhesive
Yield point (MPa)	293	—	—
Tensile strength (MPa)	453	2664	30
Elongation (%)	23	1.9	—
Elastic modulus (GPa)	204.5	188.0	1.5

3. Repair Method Using CFRP Strips and Adhesive

First, in order to initiate a fatigue crack at the weld toe, cyclic loading was carried out. The fatigue test stopped, when the crack length a reached 15mm (a crack length of about 12% of the overall width) from the center of the specimen on one side. Next, the specimen was removed from the loading system, and repair was effected via the following methods. The bonding positions of the CFRP strips in Series S and M are shown in Fig. 4.

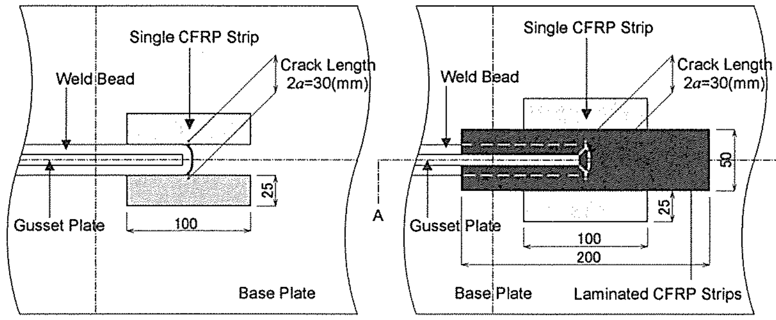
In Series S, four-single CFRP strips (25×1.2×100) were placed on both sides of the gusset plate, and the repair was carried out using the epoxy resin adhesive, as shown in Fig. 4 (a). In these series, the high stress concentration was assumed to be reduced at the crack tip, since the crack tip is covered with a CFRP strip.

In Series M, as shown in Figs. 4 (b) and 5, the repair was carried out as follows:

1) In order to improve the bonding condition, the weld bead was finished using the pencil grinder.
2) The CFRP Strips (50×1.2×200) slit in rectangles were very close, with each individual layer bonded to the weld bead using epoxy resin adhesive. The number of laminations varied between 1, 3 and 5 layers.
3) Four-single CFRP strips (25×1.2×100) were adjacently bonded to both sides.

In these series, a sufficient repair effect is expected based on the reduction in the crack opening displacement, since the crack opening is perfectly covered with laminated CFRP strips. CFRP strips are also laminated at 5 layers in order to cover around the weld bead, as shown in Fig. 5.

In addition, the used adhesive hardened at room temperature in this study, and reached the required strength within a day. In order to eliminate dispersion caused by the curing condition of the adhesive, the specimen was cured at 40 degrees Celsius for a week after repair. For the other weld toe, in order to prevent

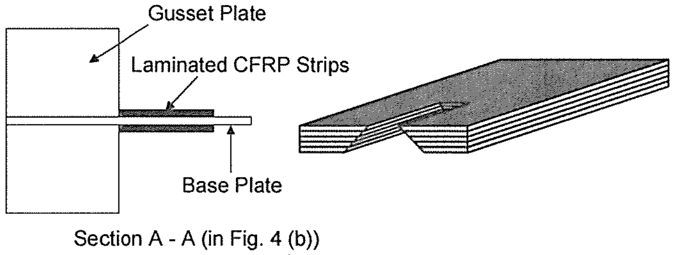


(a) Series S (b) Series M

Fig. 4 Bonding method of CFRP strips

Table 2 Experiment Series

Series	Repair method
N	No Repair
S	Fig.4 (a) Single CFRP strips
M1	Fig.4 (b) 1-layer of CFRP strips
M3	Fig.4 (b) 3-layer of CFRP strips
M5	Fig.4 (b) 5-layer of CFRP strips



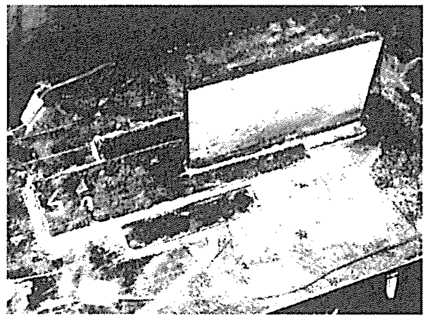


Fig. 5 Bonding method of laminated CFRP strips in Series M5

fatigue cracks from initiating, it was smoothly finished using the pencil grinder.

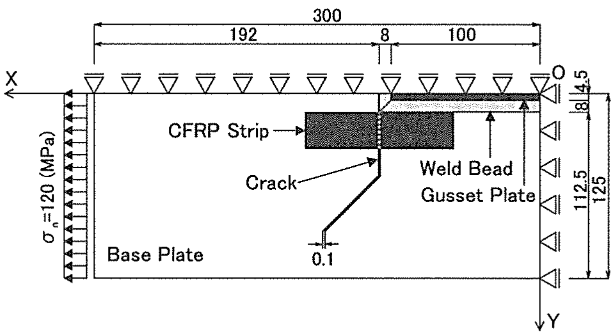
Table 2 shows an experiment series involving the bonding method of CFRP strips. Including no repair, fatigue tests were carried out on the five series listed in Table 2.

4. Results of Static Loading Test

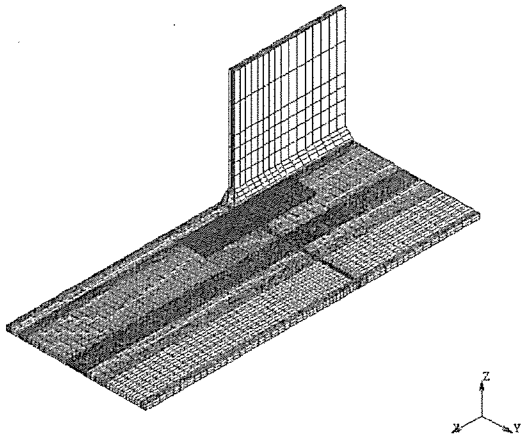
To begin with, the result of examining the repair effect under the static loading is described. The cracks were initiated by fatigue test ($\Delta\sigma_n$=84MPa), and the repair of Series S was carried out, when the crack length a reached 55.7mm (a crack length of about 45% of overall width). The static loading test was carried out before and after repair. The distribution of the longitudinal stress and crack opening displacement in the steel plate were investigated. They were measured using strain gauges and clip-type displacement transducers.

In addition, in order to evaluate the validity of experimental results, elasto-plastic finite displacement analysis was carried out with 3D FEA code, MSC. Marc 2001. The analytical model attached CFRP strip is shown in Fig. 6. Using symmetry and boundary condition, whole 1/4 was modeled. On the same conditions as the experiment, the uniform stress of 120MPa was loaded.

The distribution of the longitudinal stress and crack opening displacement are shown in Figs. 7 and 8. There is the plastic zone by high stress concentration around the crack tip after repair. But the distribution of the longitudinal stress totally lowered. In this study, the detailed figure is omitted, and it was found that the plastic zone decreased after repair in the analytical result. The distribution of the crack opening displacement also totally lowered, and the crack opening displacement



(a) Modeling and boundary conditions



(b) Element divisions

Fig. 6 Analytical model attached single CFRP strip

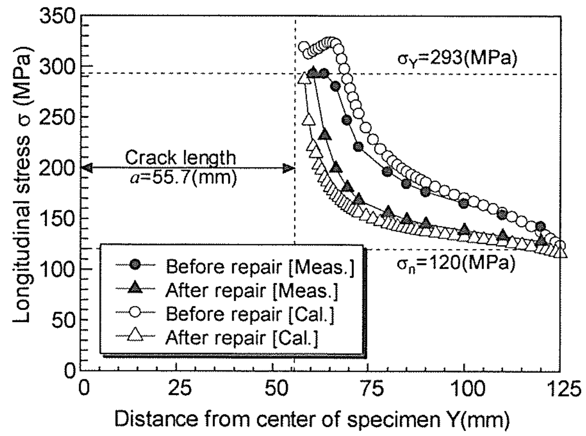


Fig. 7 Distribution of longitudinal stress

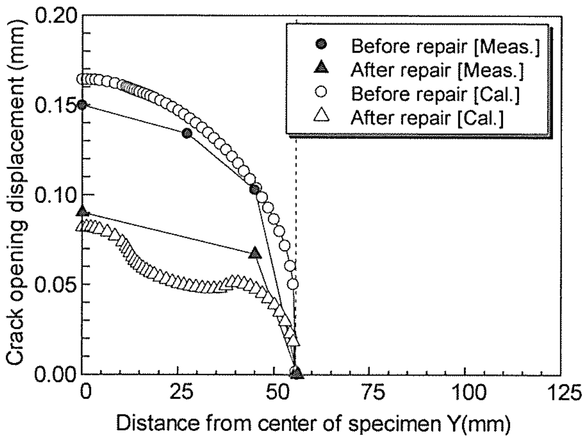


Fig. 8 Distribution of crack opening displacement

lowered about 40% in the center of the specimen. The experimental and analytical results showed the good coincidence, and the validity of the experimental result was indicated.

5. Results of Fatigue Test

5.1 Fatigue Strength

In order to evaluate fatigue life after repair, an *S–N* diagram was described using the number of cycles from the restart after repair to collapse, N_p. In addition, N_f and N_i were defined as follows: The number of cycles from the start of fatigue test to collapse was called N_f, and the number of cycles from the start of fatigue test until the crack length reached 15mm was called N_i. Here, the relationship between N_f, N_i and N_p can be shown in equation (1):

$$N_f = N_i + N_p \tag{1}$$

N_i is considered to be significantly dependent on the dispersion of initial conditions such as residual stress and weld bead shape. In this study, N_i was equivalent to 400,000–4,200,000 cycles. Consequently, the difference in N_p can be purely evaluated as the effect of repair.

An S–N_p diagram of all series is shown in Fig. 9. In Series S of single CFRP strips, a significant improvement in the fatigue life after repair was obtained in comparison with Series N of no repair, despite the stress range.

In Series M, the fatigue life drastically improved as the layers of laminated CFRP strips increased. In M5, the fatigue life improved remarkably in comparison with Series N, and a sufficient repair effect, as shown in Fig. 9, was obtained. This is attributed to the fact that the crack opening was repaired by the high rigidity of laminated CFRP strips, and the opening displacement was reduced sufficiently. However, in this study, the fatigue limit was not obtained by the repair of M5 within the stress range (64–114MPa), although the

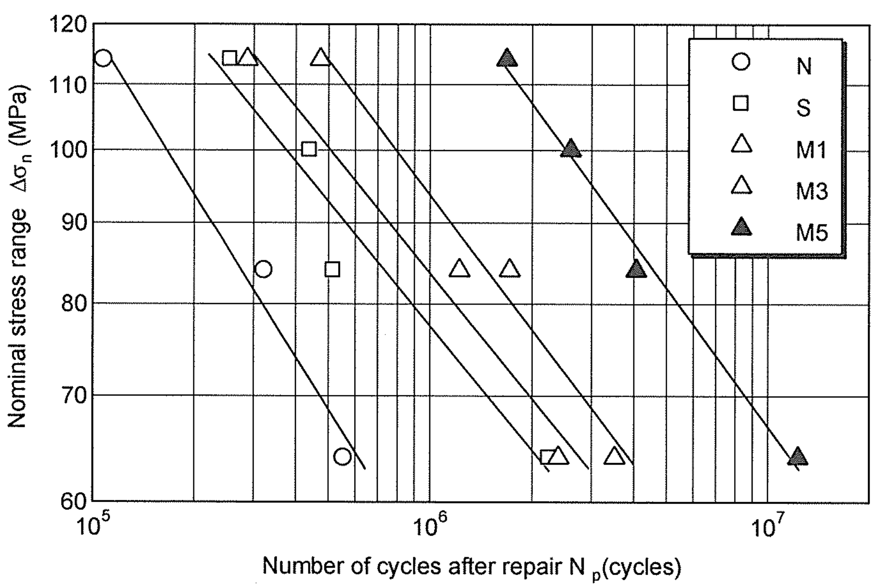


Fig. 9 S–N_p diagram

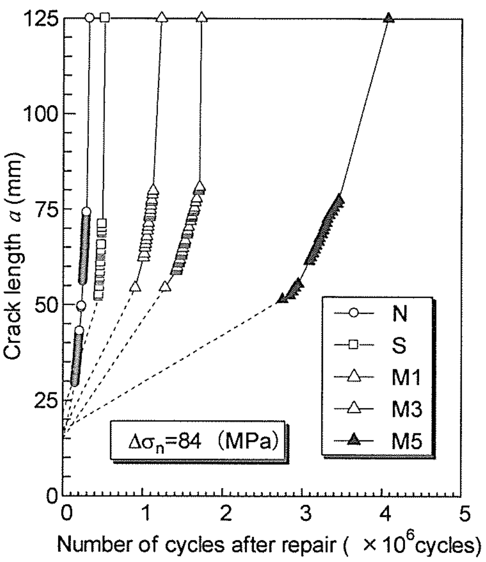


Fig. 10 Crack propagation

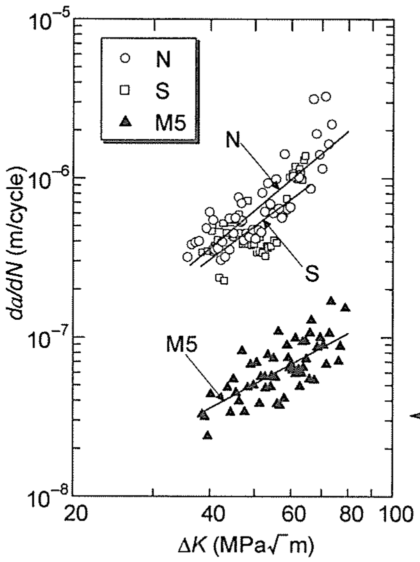


Fig. 11 Relationship between stress intensity factor range and propagation rate

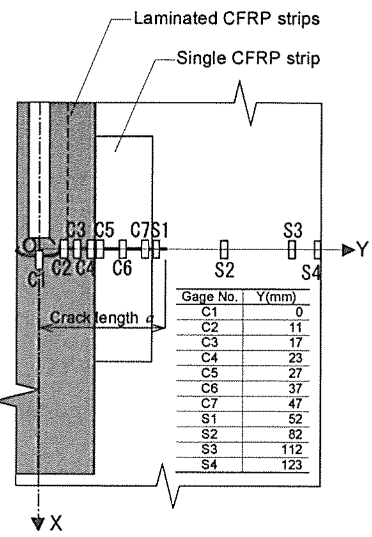


Fig. 12 Location of strain gages

fatigue life greatly exceeds 10 million cycles within the lowest stress range, 64MPa.

5.2 Propagation of Fatigue Crack

Fig. 10 shows the relationship between the crack length and the number of cycles after repair in $\Delta\sigma_n$=84 (MPa). The crack lengths were measured within about 50–70mm, using crack gages installed at the side of the CFRP strip. Since crack lengths could not be measured in the bonding area of CFRP strips, the dotted straight lines are shown in the figure. In Series S and M, the fatigue life after repair was shown to be improved. In particular, crack propagations were delayed in the bonding area of CFRP strips, indicated by the dotted line, in comparison with Series N. In Series M, this tendency was indicated to a remarkable extent, and the sufficiently delayed property of the crack propagation also traversed the bonding area of the CFRP strips when the number of layers of laminated CFRP strips increased.

Fig. 11 shows the relationship between the stress intensity factor range, ΔK and propagation rate, da/dN. The stress intensity factor range ΔK is calculated by equation (2).

$$\Delta K = \Delta\sigma\sqrt{\pi a}\left(\sec\frac{\pi a}{w}\right)^{1/2} \qquad (2)$$

ΔK : Stress intensity factor range (MPa $\sqrt{\text{m}}$)
$\Delta\sigma$: Stress range (MPa)
a : Crack length (m)
w : Width (m)

In Series S, the propagation rate decreases a little bit in comparison with Series N, as shown in Fig. 11. In Series M of laminated CFRP strips, the propagation rate considerably decreased.

5.3 Axial Force Shared by CFRP Strips

In order to show the effect concretely, the relationship between the axial force shared by CFRP strips and the number of laminations was considered as the cracks progressed. The positions of strain gauges are shown in Fig. 12. They were measured by the static loading tests during the fatigue test ($\Delta\sigma_n$=64MPa). The nominal stress σ_n of the specimen was taken as 82MPa of the maximum stress within the stress range 64MPa. In order to roughly investigate the axial force (tension), shared by CFRP strips, they were calculated based on the axial stain distribution of CFRP strips shown in Fig. 12.

The calculation result is shown in Fig. 13. In this figure, not only the ratio of the axial force, which all CFRP strips shared, to the total axial force but also that

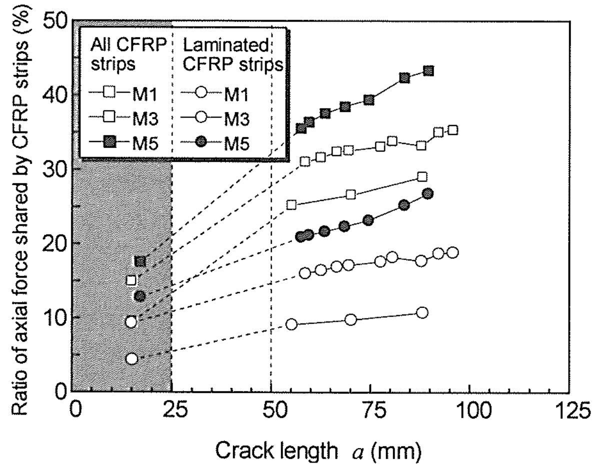
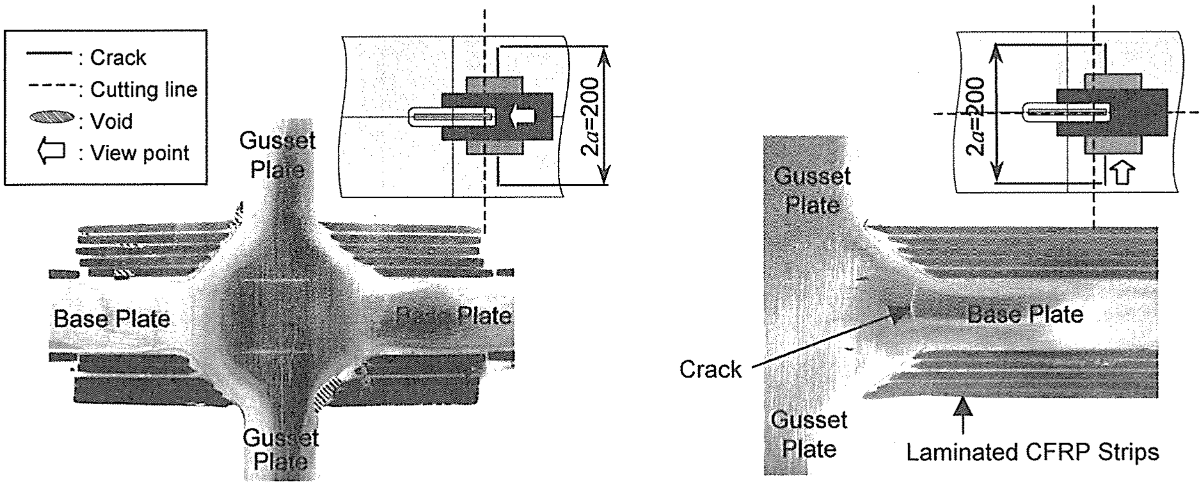


Fig. 13 Axial force shared by CFRP strips



(a) Cross-sectional direction (b) Longitudinal direction

Fig.14 Macro sections in Series M5

of the axial force, which laminated CFRP strips share, was respectively shown. The sharing ratio of the axial forces was found to increase, when the number of laminated CFRP strips increases. Consequently, it was shown that an increased amount of axial force in a specimen could be shared, if the central part of the crack opening were repaired with many laminated CFRP strips.

5.4 Bonding Condition of CFRP Strips

In order to investigate the bonding condition of CFRP strips, the fatigue test was stopped, when the crack length reached about 100mm (a crack length of about 80% as compared to overall width). The specimen was removed from the loading system, and then cut off. Two macro sections are shown in Fig. 14. The CFRP strips laminated gradually were very close and bonded well to the weld bead, though some partial voids remained.

In S, M1 and M3, CFRP Strips did not peel within the bonding area of CFRP strips. However, the cracks propagated gradually, and CFRP strips peeled when the crack length reached around 75–80mm (a crack length of about 60–65% as compared to overall width). In M5, CFRP Strips peeled immediately before the specimen collapsed. In all specimens, peeling was occurred in the interface of adhesive and steel plate.

6. Conclusions

For fatigue cracks initiated at the weld toe of an out-of-plane gusset joint, the repairs were carried out using CFRP strips and epoxy resin adhesive, and the effect of the bonding method of CFRP strips on the fatigue strength was examined experimentally and analytically. Consequently, drastic improvement in the fatigue life is apparent, as the number of layers of laminated CFRP strips increases and a sufficient repair effect obtained in the laminated CFRP strips of 5 layers is detectable. Moreover, it is confirmed that CFRP strip lamination is effective in preventing peeling and sharing axial force.

Therefore, it was indicated that the proposed repair method was sufficiently applicable for first aid repair.

Note

This is a paper arranged the following references 3)–5).

References

1) Japan Road Association: *Guidelines for Fatigue Design of Steel Highway Bridges*, Maruzen Co., Ltd., 2002.3. (in Japanese)
2) T. Yamauchi, H. Nakamura, K. Maeda and H. Suzuki: Fatigue Test on Repair of Steel Members Using CFRP Strips, *Proc. of the 57th Annual Conference of JSCE*, pp.1339-1340, 2002.9. (in Japanese)
3) H. Nakamura, T. Moroi, H. Suzuki, K. Maeda and T. Irube: Repair of Out-of-Plane Welded Gusset Joint Using CFRP Strips, *Journal of Construction Steel, JSSC*, Vol. 12, pp.425-430, 2004.11. (in Japanese)
4) H. Nakamura, H. Suzuki, K. Maeda and T. Irube: Repair of Fatigue Cracks in Out-of-Plane Welded Gusset Joints Using CFRP Strips, *the 8th Japan-Korea Joint Seminar on Steel Bridges*, 2005.8. (under printing)
5) H. Nakamura, T. Moroi, H. Suzuki, K. Maeda and T. Irube: Repair of Fatigue Cracks in Out-of-Plane Welded Gusset Joints Using Laminated CFRP Strips, *Journal of Construction Steel, JSSC*, Vol. 13, pp.89-96, 2005.11. (in Japanese)