Experimental Study on Repair of Cracked Steel Member by CFRP Strip and Stop Hole

Hiroyuki SUZUKI

Meisei University, Hino-city, Tokyo, JAPAN, suzukihi@ce.meisei-u.ac.jp

ABSTRACT

In this paper, repair of steel members with fatigue crack by carbon fiber reinforced polymer strip (hereinafter, called CFRP strip) is studied experimentally. Specimens are the following three types; (i) Repair by Stop holes only (N-1), (ii) Repair by both Stop holes and the CFRP strip with 10mmx1.2mmx100mm (N-2), and (iii) Repair by both Stop holes and the CFRP strip with 25mmx1.2mmx100mm (N-3). Fatigue tests are done using the specimens.

The effect of the CFRP strip was recognized clearly. Endurance limit of N-1, N-2 and N-3 were stress range of 90MPa, higher than 100MPa and much higher than 130MPa, respectively. And, it was known from the relation between crack propagation rate and stress intensity factor range that crack propagation rate can be slowed by attaching the CFRP strip on a fatigue crack, and the wider CFRP strip has a better effect to slow crack propagation rate.

It was concluded that the CFRP strip is applicable with a stop hole to repair of a fatigue crack initiated in steel members.

1. INTRODUCTION

It is reported that many fatigue cracks initiate in steel structures in civil engineering, especially steel bridges, not only in Japan but also in the world. A lot of them initiates from the stress concentration part such as a weld toe, a weld defect and others. When a fatigue crack initiates in a steel bridge once, the crack propagates with increasing rate. When the crack is left alone, the crack may cause collapse of the bridge. So, the crack has to be repaired as fast as possible. Therefore, development of easy repair and strengthening method to prevent crack re-initiation or delay crack propagation is expected very much.

In a general repair and strengthening method, a fatigue crack is filled up with welding. And a reinforcement steel plate is attached over the cracked part by high strength bolts and/or welding. In addition, as a temporary repair, a stop hole method may be used. In a stop hole method, a crack tip is drilled in order to reduce a stress concentration. If the crack does not propagate after drilling the stop hole, the crack may be left alone. However, no one can say that a crack does not initiate again. Therefore, a method using a stop hole and a high strength bolt together is also studied. In addition, there are some studies on applying a carbon fiber reinforced plastic, hereinafter called CFRP, to a cracked part. For example, a method using a CFRP sheet and a stop hole together is studied.

A CFRP strip is a kind of carbon fiber reinforced plastics. The CFRP strip is produced by solidifying carbon fibers in the shape of strip with epoxy resin. The handling of the CFRP strip is easier than a CFRP sheet because it has some rigidity. Furthermore, the CFRP strip has a characteristic of high strength and high durability. Unit volume weight of CFRP strip is around 1/5 of a steel plate. Therefore, the transportation and handling of the CFRP strip are very easy. As the CFRP strip is only attached with epoxy adhesive to an object part, the execution is very simple and a worker does not need specialized technology. This method has the advantage that a patrolman can do a first-aid repair without a tool and, of course, without a heavy industrial machine when the patrolman detected a crack.

In this paper, the CFRP strip is studied experimentally to apply a repair of a fatigue crack initiated in a steel structure together with a stop hole.

2. Experimental procedure

The specimen configuration is shown in Fig.-1. Since this study is a first step for application of the CFRP strip to steel members with a fatigue crack, the specimen shown in Fig.-1 was

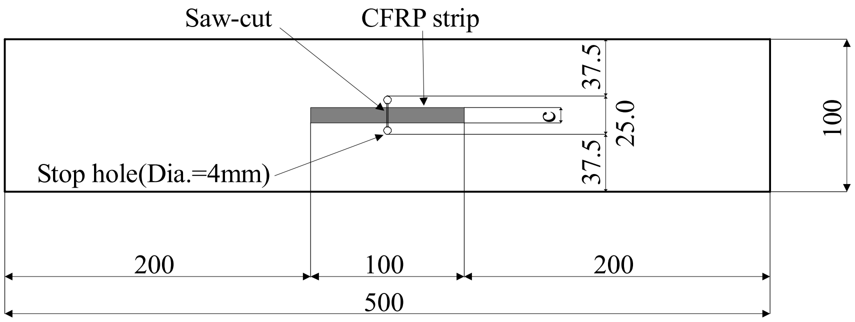


Fig.-1　Specimen configuration

Table-1　Specimen types

Type	c※1(mm)	c/a※2
N-1	0	0.0
N-2	10	0.4
N-3	25	1.0

※1:Width of the CFRP strip

※2:The ratio of the width of the CFRP strip to the length of the crack part

Table-2　Mechanical properties

	Steel(SM400)	The CFRP strip
Tensile strength(MPa)	427	2,352
Elastic modulus(MPa)	2.1×10^5	1.55×10^5
Elongation(%)	31.0	1.9

used. Study on the effect of the CFRP strip using a welded joint specimen will be done after this study. In this study, the effect by the use of the CFRP strip and a stop hole together is examined. So, a saw-cut supposing the fatigue crack was prepared in the center of the specimen and circular holes with a diameter of 4mm, which corresponds to a stop hole, were drilled at the both tips of saw-cut. The width of the used CFRP strip is two kinds of 10mm and 25mm. The CFRP strips were attached to the assumed crack part using epoxy adhesives before the specimen was set up to a testing machine. Specimen type, the width of the CFRP strip and the ratio of the width of the CFRP strip to the length of the crack part are shown in Table-1. The thickness of the steel plate is 6.0mm and the CFRP strip is 1.2mm. The mechanical properties of the steel plate and the CFRP strip used for the experiment are shown in Table-2. The used CFRP strip is a uni-direction material, in which a carbon fiber is arranged only in the longitudinal direction. The minimum stress was 10MPa in a fatigue test and the maximum stress was changed. The shape of a stress range was a sine wave. Crack gauges were attached at the tip of the stop holes as shown in Fig.-2 to investigate a fatigue crack initiation life and a fatigue crack propagation rate. And strain gauges were also attached at the tip of the stop holes to examine a stress distribution on the section with the saw-cut and the stop holes.

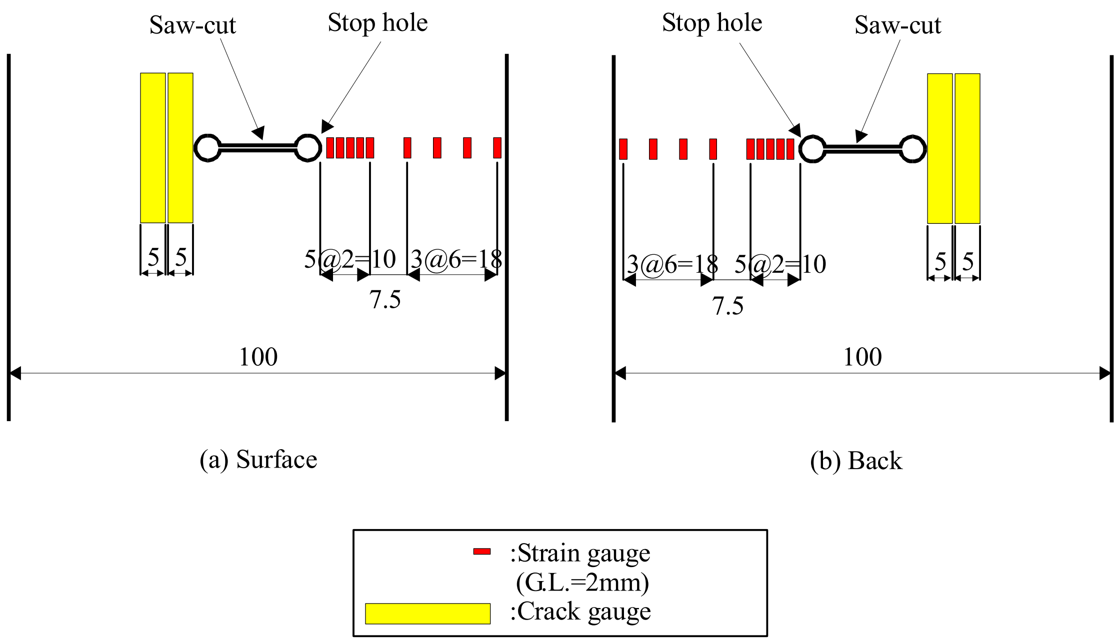


Fig.-2 Position of gauges

3. Results and discussions

3.1 S-N curves

Fatigue test results are shown in Fig.-3. A crack initiation life and a specimen fracture life are shown respectively in the figure. An open mark shows a crack initiation life and a solid mark shows a specimen fracture life. The fatigue crack initiation life was defined as the number of cycles till the first grid of a crack gauge was cut. Regression curves of each type are also shown in the figure. The vertical axis is the stress range in gross section of the specimens. The horizontal axis is the number of cycles.

When a stress range at two million cycles is defined as an endurance limit, the endurance limit

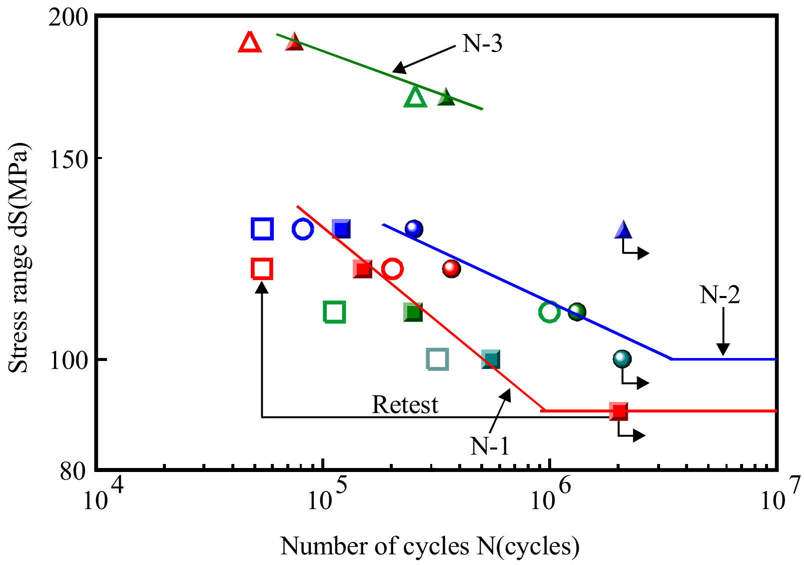


Fig.-3 S-N curves

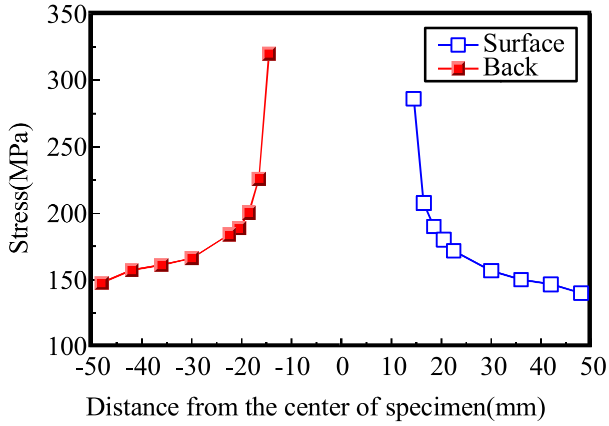
of N-1, which was only drilled the stop holes with a diameter of 4mm at the both tips of a crack, is stress range of 90MPa. N-2, which was attached the CFRP strip with a width of 10mm (c/a=0.4) to N-1, is higher stress range than 100MPa. N-3, which was attached the CFRP strip with a width of 25mm (c/a=1.0) to N-1, is much higher stress range than 130MPa. Therefore, it is concluded that it is possible to prevent a re-initiation of a crack, if stress range is less than 90MPa in N-1, 100MPa in N-2 and 130MPa in N-3, respectively.
When the regression curves of N-1 and N-2 are compared, the regression curve of N-2 is close to N-1 in high stress range. However, in low stress range, the fatigue life of N-2 is still longer than N-1. From the results, when the ratio of the width of the CFRP strip to the length of the crack part is c/a=0.4, it can be concluded that the repair effect may be unable to be expected in a high stress range region, but that the repair effect increases according as the stress range becomes low.
N-3 is found from the Fig.-3 to have the repair effect also in a still higher stress range region than N-2. Therefore, it can be said that a fatigue life improves rapidly according as width of the CFRP strip is enlarged to a crack length.
The S-N curves of Fig.-3 are expressed as follows.

$$\text{N-1}: \; dS=859 \text{x} N^{-0.16} \quad (N<9.6\text{x}10^5) \qquad (1)$$
$$dS=90 \quad (N>=9.6\text{x}10^5)$$
$$\text{N-2}: \; dS=404 \text{x} N^{-0.093} \quad (N<2.0\text{x}10^6) \qquad (2)$$
$$dS=100 \quad (N>=2.0\text{x}10^6)$$
$$\text{N-3}: \; dS=427 \text{x} N^{-0.072} \quad (N<2.0\text{x}10^6) \qquad (3)$$
$$dS=130 \quad (N>=2.0\text{x}10^6)$$

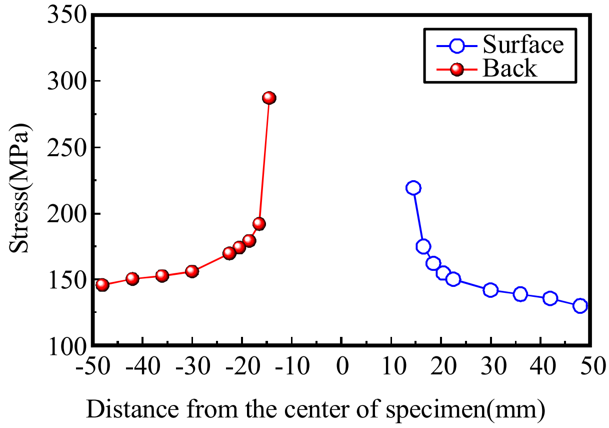
3.2 Stress distributions
Stress distributions on the cracked section of N-1, N-2 and N-3 in nominal stress 140MPa are shown in Fig.-4. The vertical axis is stress and the horizontal axis is a distance from the center of the specimen. Stress was obtained from multiplying the output of a strain gauge by Young's modulus.

$$S = E \text{ x } e \qquad (4)$$

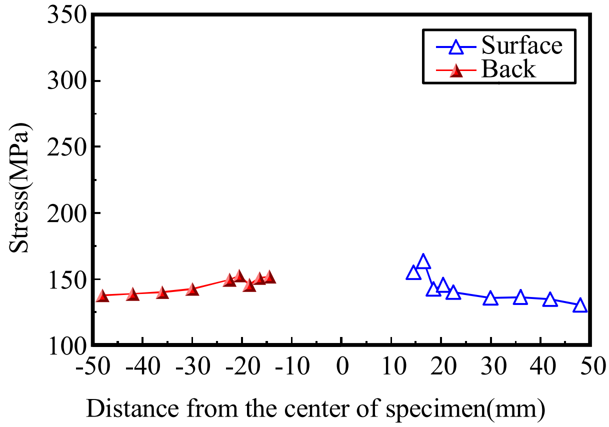
where S is stress (MPa), E is Young's modulus ($2.1\text{x}10^5$MPa), e is strain ($\text{x}10^{-6}$).
Figure-4 shows that attachment of the CFRP strip decreases stress concentration at the tip of the stop hole. The stress obtained from the strain gauges in surface and back of the nearest to the stop holes was averaged and compared. The stress of N-2 was 13.6% low from N-1. The stress of N-3 was 52.4% low from N-1. Especially stress concentration at the tip of the stop holes of N-3 was decreased greatly. Since the Young's modulus of the CFRP strip is nearly equal to the Young's modulus of steel plate, it is considered that external force was transferred through the CFRP strip by cover over full length of the cracked part with the CFRP strip. And it is confirmed that fatigue life has been prolonged because stress concentration at the tip of the stop holes decreased.



(a) N-1



(b) N-2

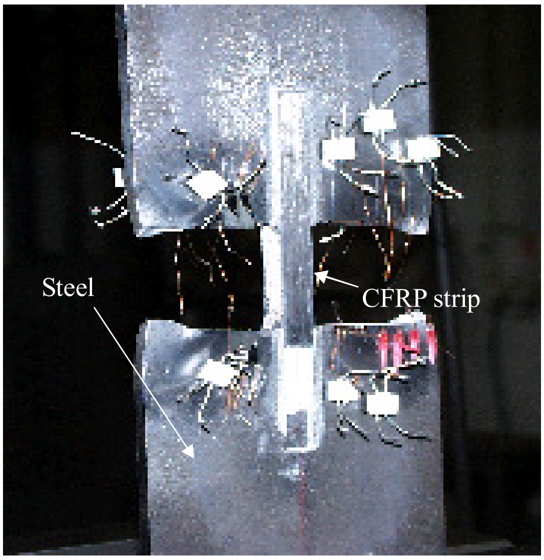


(c) N-3

Fig.-4　Stress distributions($\sigma_{nominal}$=140MPa)

3.3 Fracture pattern

A specimen of N-2 after fracture is shown in Photograph-1. In the experiment, after a fatigue crack initiated from the stop hole end and propagated, the CFRP strip came off steel plate because of increase of crack opening displacement caused by crack propagation. As the result, crack propagation rate became faster and the specimen fractured.



Photograph-1: Specimen after experiment(N-2)

3.4 Fatigue crack propagation rate

The relation between crack propagation rate da/dN and stress intensity factor range dK in each type of specimen is shown in Fig.-5. The vertical axis of the figure is crack propagation rate and the horizontal axis is a stress intensity factor range. The stress intensity factor range was computed by the following equation.

$$dK = dS \text{ x } (pi \text{ x } a)^{1/2} \text{ x } F(2a/w) \qquad (5)$$

where dK is a stress intensity factor range (MPa x $m^{1/2}$), dS is an applied stress range (MPa), pi is the ratio of the circumference of a circle to its diameter, 2a is a crack length (m), w is a plate width (m), and

$$F(A) = \{\sec(pi \text{ x } A/2)\}^{1/2} \qquad (6)$$

where A=2a/w.

It is found from Fig.-5 that crack propagation rate can be delayed by attaching the CFRP strip on the crack part. The wider CFRP strip is known to be able to induce a larger delay of crack propagation rate. However, in the high stress intensity factor range region, where the CFRP strip comes off according to fatigue crack propagation, the crack propagation rate of N-2 and N-3 are nearly equal to that of N-1.

The regression curves of the data of each type are also shown in Fig.-5. The regression curves are expressed as follows.

$$\begin{aligned} &\text{N-1}: \; da/dN=1.0\text{x}10^{-13}(dK)^{4.3} && (21<dK<40) \\ &\text{N-2}: \; da/dN=5.0\text{x}10^{-14}(dK)^{4.4} && (23<dK<40) \qquad (7) \\ &\text{N-3}: \; da/dN=3.0\text{x}10^{-20}(dK)^{7.9} && (35<dK<62) \end{aligned}$$

When dK=35 (MPa x $m^{1/2}$) is substituted for Eq.(7) as an example to verify the effect of the CFRP strip on crack propagation rate, the following equations are obtained.

$$\begin{aligned} &\text{N-1}: \; da/dN=4.8\text{x}10^{-7} && \text{(m/cycle)} \\ &\text{N-2}: \; da/dN=2.9\text{x}10^{-7} && \text{(m/cycle)} \qquad (8) \\ &\text{N-3}: \; da/dN=4.7\text{x}10^{-8} && \text{(m/cycle)} \end{aligned}$$

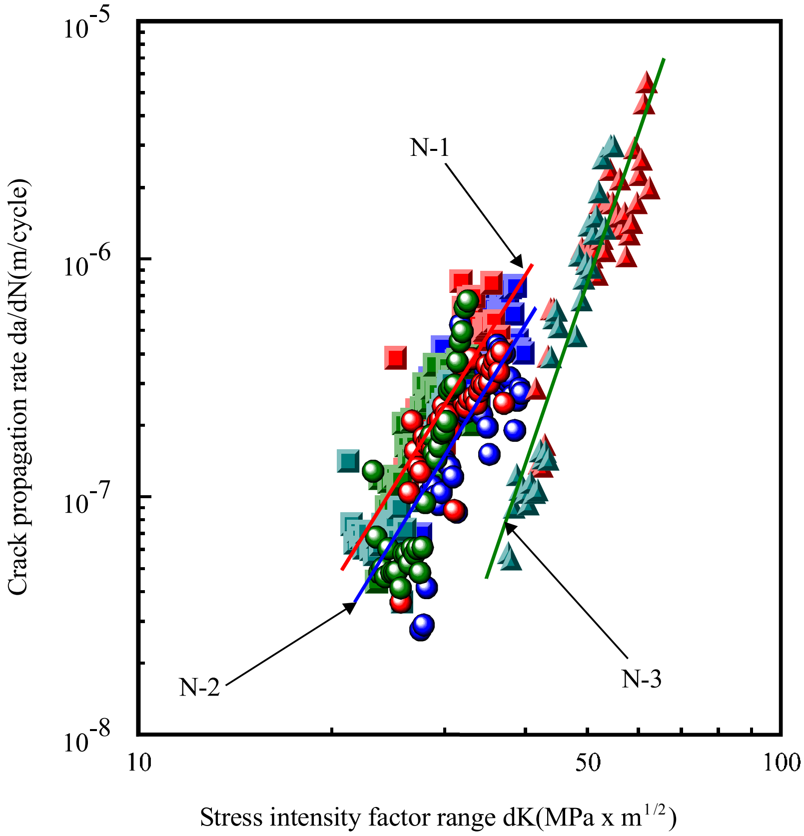


Fig.-5 Relation between crack propagation rate and stress intensity factor range

The crack propagation rate of N-2 is 60.4% of N-1. And N-3 is 9.9% of N-1 and is 16.2% of N-2. So, it is verified that attaching the CFRP strip to a cracked part in steel members can be decreased crack propagation rate.

4. Conclusions

The following conclusions were obtained from this study.

(1) The CFRP strip is applicable with a stop hole to repair of a fatigue crack initiated in steel members.

(2) When applying the CFRP strip to repair, the effect becomes large according to increase of width of the CFRP strip.

(3) The case of c/a=0.4 is also enough as a first-aid repair. The c/a is the ratio of the width of the CFRP strip to the length of a crack part.

References

1) ‘Recommendation for Fatigue Design of Steel Highway Bridge’, Japan Highway Association, 2002.3 (in Japanese)

2) T. MORI and D. UCHIDA, ‘Fatigue Strength of Out-of-Plane Gusset Welded Joints Repaired by Bolting-Stop-Hole Method’, Steel Construction Engineering, Vol.8, No.29, pp. 15-26, 2001.3 (in Japanese)

3) I. OKURA, T. FUKUI, K. NAKAMURA, T. MATSUGAMI and Y. IWAI, ’Application of CFRP Sheets to Repair of Fatigue Cracks in Steel Plates’, Journal of Constructional Steel, Vol.8, pp. 689-696, 2000.11 (in Japanese)