# Experimental Study on Repair of Cracked Steel Members Using GFRP and Stop Holes

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Fatigue failure is often encountered in steel bridge members and a simple and effective repair method is needed. Glass fiber reinforced polymer (GFRP) is a potential candidate for application in the repair of fatigue cracks. This paper describes the results of fatigue tests conducted on cracked steel plate repaired using GFRP combined with stop holes, and using only GFRP. The effects of these repair methods are discussed based on S-N curves and the relationship between crack length and number of cycles. Also described is the effect of adhesive type on the repair of cracked steel plate. The experimental results revealed that the method using GFRP combined with stop holes has high potential for application in fatigue crack repair.

*Keywords: GFRP, steel members, repair, stop hole, fatigue crack.*

## 1. INTRODUCTION

The application of fiber reinforced polymer (FRP) to repairing and/or strengthening steel bridge members is being studied throughout the world including in Japan. Glass fiber reinforced polymer (GFRP) and its application to steel members is attracting increasing attention. However, GFRP might not be as suitable as CFRP (carbon fiber reinforced polymer) due to its low elastic modulus, Eg = $1.4\times10^4$ MPa, compared to CFRP, Ec = 1.6 to $6.4\times10^5$ MPa. It has been found that CFRP strengthening could increase the fatigue life of cracked steel plates by 2 to 12 times. However, GFRP is less costly than CFRP. In addition, GFRP is semitransparent and it offers the advantage of easy removal of air bubbles left in the adhesive in practical work. If GFRP could be applied to repairing and/or strengthening steel bridge members, the merits of the above characteristics would be significant. There are few studies on the application of GFRP to strengthening of steel members in Japan and apparently no studies on applying GFRP to the repair of steel members, particularly steel members having fatigue cracks. Therefore, it is necessary to verify the feasibility of applying GFRP to the repair of steel members having a fatigue crack.

This paper describes the results of fatigue tests conducted on cracked steel plate repaired using GFRP combined with stop holes, and using only GFRP. The effects of these methods are discussed based on S-N curves and the relationship between crack length and number of cycles. Also described is the effect of adhesive type on the repair of cracked steel plate since GFRP requires the use of adhesive.

## 2. REPAIR USING GFRP AND STOP HOLES, AND USING ONLY GFRP

### 2.1 Experimental procedures

The specimen used is SS400 steel with dimensions 100 mm wide, 6 mm thick, and 500 mm long. The notch and the crack machined in the center of the specimen are shown in Fig. 1. The experiment uses a welded-joint specimen, required for examining the effect of GFRP and stop holes on the repair of a steel member having a fatigue crack, because cracks generally start from a welded joint. However, a welded-joint specimen was not used in this study for the following reason: as numerous cracks initiate at the welded joint and then propagate to the base metal, the welded joint has no influence on the crack at the base metal. Therefore, the specimen in this study is considered sufficient for examining the effect of GFRP and stop holes on the repair of the cracked steel member. In the N-type specimen in Fig. 1(a), it was assumed that both the GFRP and stop holes would be

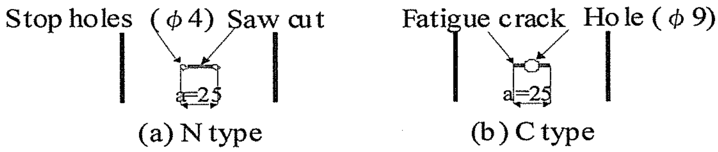


**Fig. 1** The notch and the crack

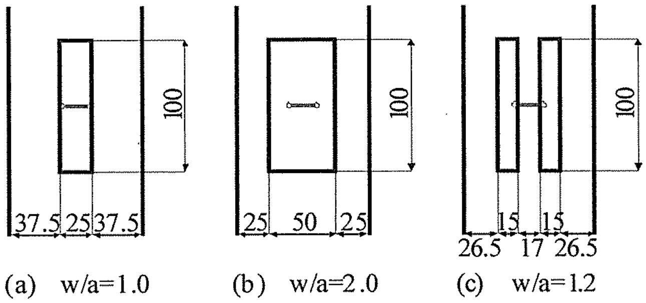


**Fig. 2** The GFRP bonded to the N-type

**Table 1** Specimen type

| Specimen | Width of GFRP (w) | Ratio of GFRP width to crack length (w/a) |
|---|---|---|
| N-0.0 | 0 | 0.0 |
| N-1.0 | 25 | 1.0 |
| N-2.0 | 50 | 2.0 |
| NS-1.2 | 2×15 | 1.2 |
| C-0.0 | 0 | 0.0 |
| C-1.0 | 25 | 1.0 |
| C-2.0 | 50 | 2.0 |

used to repair the fatigue crack. Therefore, a saw-cut was machined in the center of the specimen, and stop holes 4 mm in diameter were drilled at the tip of the saw-cut. Length between the outside of the stop holes is 25 mm. In the C-type specimen in Fig. 1(b), it was assumed that only the GFRP would be used to repair the fatigue crack. Therefore, a hole 9 mm in diameter was drilled in the center of the specimen as a crack initiator and cyclic load was applied until the crack length reached 25 mm. The GFRP in this study was a resin sheet hardened by ultraviolet rays and unidirectional fabric in which glass fibers were arranged in one direction. Therefore, the GFRP had anisotropic material properties. Thickness of the GFRP was 0.6 mm. Two layers of GFRP were bonded to both faces of the cracked area of the specimen. The adhesive used in the experiment was an epoxy acrylate adhesive that required the mixing of two liquids and that hardened at normal temperature. The GFRP was bonded to the specimen after having grinded the adhesive area in a downward direction without loading, at room temperature. Table 1 shows the specimen type, GFRP width, w, and ratio of GFRP width to crack length, w/a. Figure 2 schematically shows the GFRP bonded to the N-type specimen. The GFRP used for C-1.0 and C-2.0 was bonded in the same manner as shown in Fig. 2(a), (b). Crack gauges and strain gauges were installed in front of the crack or the stop holes to measure the crack propagation rate and stress distribution. Table 2 shows the mechanical properties of the steel plate, GFRP and adhesive. The minimum stress was 10 MPa and the maximum stress was changed during the fatigue test. The stress range was in the shape of a sine wave.

### 2.2 Results and discussion

The fatigue test results are shown in Fig. 3. Regression curves for each type of specimen are also shown in the figure. The vertical axis of the figure is the stress range of the parallel part of a specimen and the

**Table 2** Mechanical properties

| | Yield stress (MPa) | Tensile stress (MPa) | Elastic modulus (MPa) | Elongation (%) | Fiber content (w/w%) |
|---|---|---|---|---|---|
| Steel | 269 | 426 | $2.1\times10^5$ | 31 | - |
| GFRP | - | 201 | $1.4\times10^5$ | - | 22–36 |
| Adhesive | - | 52 | $4.6\times10^3$ | - | - |

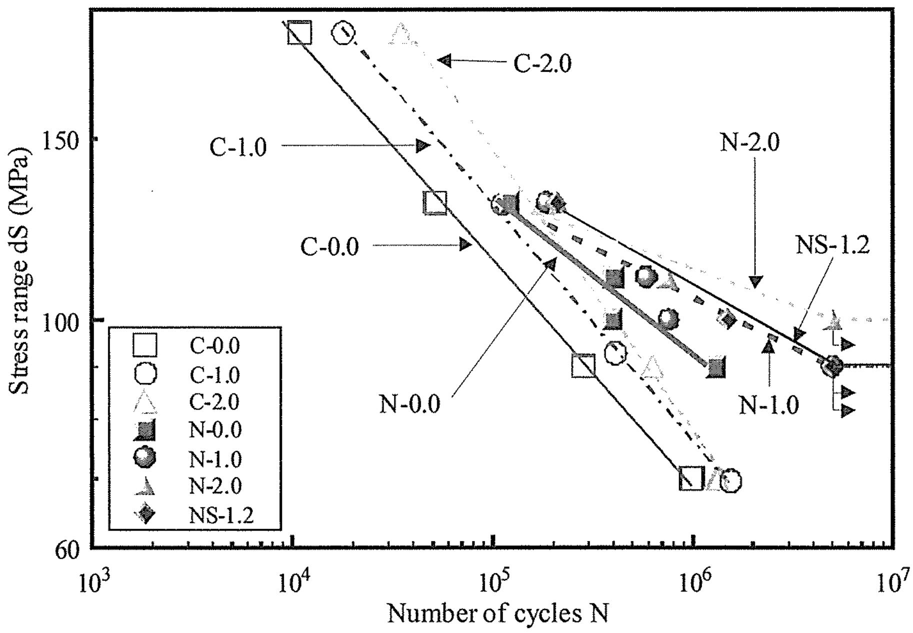


**Fig. 3** Fatigue test results

horizontal axis is the number of cycles at the specimen fracture. Comparing C-0.0, C-1.0 and C-2.0, the effect of the GFRP is obvious. The improved fatigue life of C-2.0 is nearly equal to C-1.0 in the low stress range. However, the fatigue life of C-2.0 exceeds that of C-1.0 with an increase in the stress range. Therefore, it can be concluded that the wider GFRP has a greater effect on fatigue life in the high stress range after repairing the cracked steel member. The fatigue life of C-0.0, C-1.0, and C-2.0 at dS = 70 MPa, which is the lowest stress range in this experiment, is $9.9\times10^5$ cycles, $1.38\times10^6$ cycles and $1.33\times10^6$ cycles, respectively. The fatigue limit for C-0.0, C-1.0, and C-2.0 was not obtained. Therefore, it is considered that the application of only GFRP to the repair of fatigue cracks is not suitable for the long term because fatigue crack propagation cannot be stopped completely.

Supposing fatigue strength at $5\times10^6$ cycles as the fatigue limit, the following can be obtained from Fig. 3: dS = 90 MPa for N-1.0, to which GFRP with w = 25 mm (w/a = 1.0) is bonded after drilling stop holes of d = 4 mm at both tips of the saw-cut; dS = 100 MPa for N-2.0, to which GFRP with w = 50 mm (w/a = 2.0) is bonded; and dS = 90 MPa for NS-1.2, to which two sheets of GFRP with w = 15 mm (w/a = 1.2) are bonded from the inner side end of the stop holes over the outer side end of the stop holes. The fatigue limit for N-0.0, in which GFRP was not used, could not be obtained from this experiment. It can be seen from Fig. 3 that the fatigue life of N-1.0 and NS-1.2 increases more than that of N-0.0 in the low stress range, but does not show a significant difference in the high stress range. In addition, the fatigue life of N-2.0 increases more than that of N-1.0 and NS-1.2 in the low stress range, but does not show a significant difference in the high stress range. Therefore, it is concluded that the fatigue life can be improved in the low stress range by drilling stop holes and bonding GFRP having w/a = 1.0 over the crack area, and that the

**Table 3** Crack initiation life, crack propagation life and total fatigue life

| | | N-0.0 (PCT*) | N-1.0 (PCT*) | N-1.0/N-0.0 |
|---|---|---|---|---|
| 100 MPa | Initiation life | 19 (48) | 35 (46) | 184% |
| | Propagation life | 21 (52) | 41 (54) | 195% |
| | Total fatigue life | 40 | 76 | 190% |
| 130 MPa | Initiation life | 4 (33) | 12 (63) | 300% |
| | Propagation life | 8 (67) | 7 (37) | 88% |
| | Total fatigue life | 12 | 19 | 158% |

*Percentage of initiation life and propagation life to total fatigue life

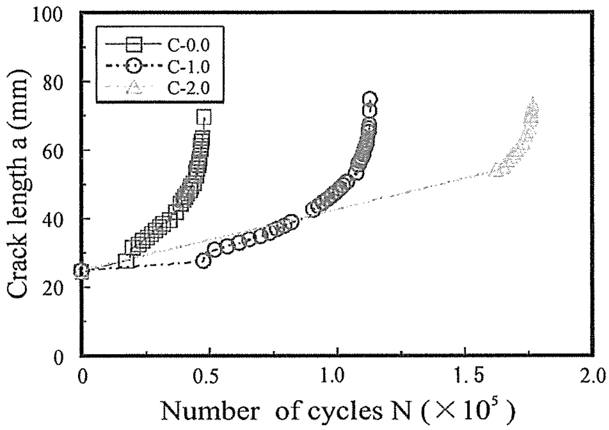


**Fig. 4** Relationship between crack length and number of cycles (C type, ds=130MPa)

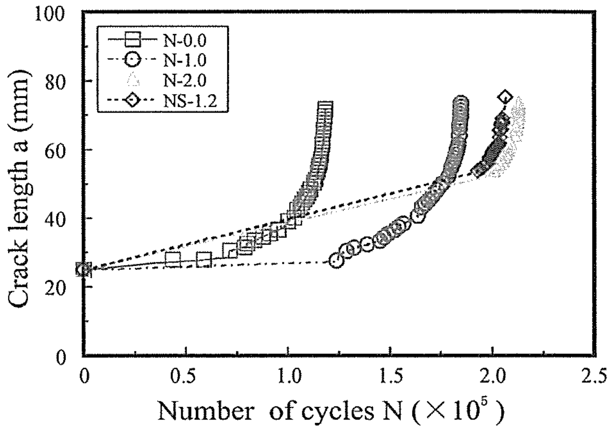


**Fig. 5** Relationship between crack length and number of cycles (N type, ds=130MPa)

fatigue life can be further improved in the low stress range if w/a could be doubled. Moreover, fatigue life can be improved by drilling stop holes at both tips of the crack and by bonding GFRP over the stop holes if it is not possible to bond it over the crack.

Table 3 shows the crack initiation life, crack propagation life and total fatigue life at 100 and 130 MPa. The crack initiation life is the number of cycles at the time that the measured value of the crack gauge changes. The crack propagation life is the number of cycles after subtracting the crack initiation life from the total fatigue life, which is the number of cycles at specimen fracture. It can be seen from the table that the percentage of crack initiation life and crack propagation life to total fatigue life is about 50% in N-0.0 and N-1.0 in the stress range of 100 MPa. In addition, the crack initiation life and crack propagation life of N-1 is about 190% of that of N-0.0 and the total fatigue life of N-1 is also about 190% of that of N-0.0. Therefore, it is concluded that GFRP improves both the crack initiation life and crack propagation life in the stress range of 100 MPa. Moreover, the table shows that the percentage of crack initiation life and crack propagation life to total fatigue life is about 30% and 70%, respectively, in N-0.0 and about 60% and 40%, respectively, in N-1.0 in the stress range of 130 MPa. The crack initiation life and crack propagation life of N-1 is about 300% and 90%, respectively, of that of N-0.0 and the total fatigue life of N-1 is about 160% of that of N-0.0. Therefore, GFRP greatly improves the crack initiation life but does not improve the crack propagation life after reinitiation of a crack in the stress range of 130 MPa.

Here, we compare the fatigue test results between the C-type specimen repaired by bonding GFRP over the crack and the N-type specimen repaired by bonding the GFRP after drilling stop holes. Supposing fatigue strength at $5\times10^6$ cycles as the fatigue limit, the fatigue limit was not obtained in the C-type specimen even at 70 MPa, the lowest stress range in this experiment. In the N-type specimen, the fatigue limit was not obtained in N-0.0 with only drilled stop holes in the crack tip. However, in the other N-type specimens, the fatigue limit was

**Table 4** Specimen type

| Specimen | Width of GFRP (w) | Ratio of GFRP width to crack length (w/a) |
|---|---|---|
| N-0.0 | 0 | 0.0 |
| NE-1.0 | 25 | 1.0 |
| NA-1.0 | 25 | 1.0 |

**Table 5** Mechanical properties

| | Yield stress (MPa) | Tensile stress (MPa) | Elastic modulus (MPa) | Elongation (%) | Fiber content (w/w%) |
|---|---|---|---|---|---|
| Steel | 278 | 433 | $2.1\times10^5$ | 28 | - |
| GFRP | - | 201 | $1.4\times10^5$ | - | 22-36 |
| Epoxy acrylate adhesive | - | 52 | $4.6\times10^3$ | - | - |
| Acrylic adhesive | - | 40 | $1.8\times10^3$ | - | - |

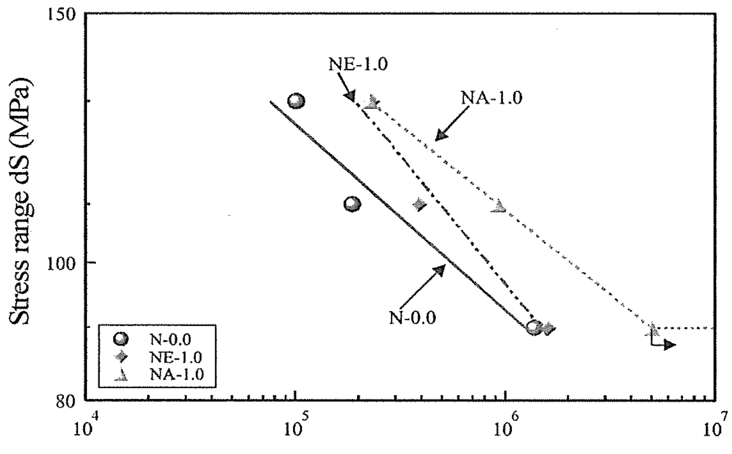


**Fig. 6** Fatigue test results

obtained: dS = 90 MPa in N-1.0 and NS-1.2, and dS = 100 MPa in N-2.0. Therefore, it is concluded that reinitiation of a fatigue crack can be prevented in the low stress range by using GFRP combined with stop holes.

Figure 4 shows the relationship between crack length and number of cycles in the stress range of 130 MPa for the C-type specimens. It can be seen from the figure that the crack propagation rate, da/dN, is reduced by bonding GFRP over the crack. In addition, the degree of reduction in the crack propagation rate is found to be high for a short crack length. However, no significant difference is seen in the crack propagation rate over a crack length of 60 mm. The relationship between crack length and number of cycles in the stress range of 130 MPa for the N-type specimens is shown in Fig. 5. It can be seen from the figure that the reinitiation of a crack is delayed by bonding the GFRP over the outside of the stop holes. In addition, the GFRP does not appear to affect the crack propagation rate after reinitiation of the crack.

## 3. INFLUENCE OF ADHESIVE TYPE ON REPAIR USING GFRP

### 3.1 Experimental procedures

Specimen configuration is the same as for N-1.0. Table 4 shows the specimen type, GFRP width, w, and ratio of GFRP width to crack length, w/a. Table 5 shows the mechanical properties of the steel plate, GFRP and adhesives. Two types of adhesives were used in the experiment: epoxy acrylate adhesive (NE-1.0) and acrylic adhesive (NA-1.0). These adhesives are easily available in Japan. The minimum stress was 10 MPa and

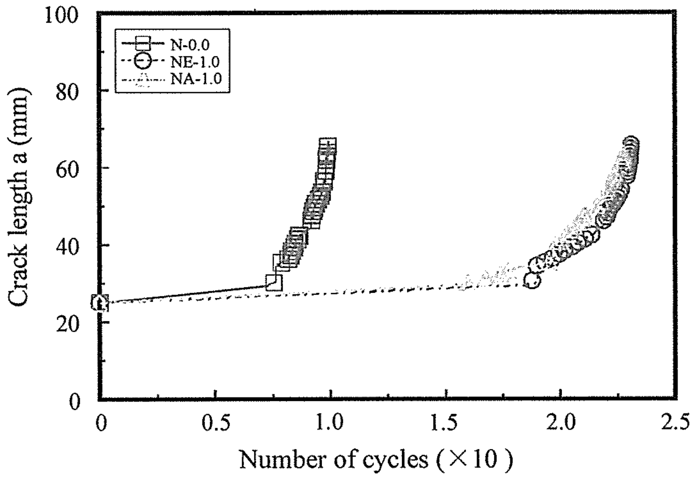


**Fig. 7** Relationship between crack length and number of cycles (dS=130MPa)

the maximum stress was changed during the fatigue test. The stress range was in the shape of a sine wave.

### 3.2 Results and discussion

The fatigue test results are shown in Fig. 6. Regression curves for each type of specimen are also shown in the figure. The effect of using GFRP can be seen in the stress range of 130 MPa, but any meaningful difference between adhesive types is not seen. However, as the stress range lowers, the effect of repairs to NE-1.0 deteriorates and that of NA-1.0 is maintained. Therefore, the acrylic adhesive is more effective than the epoxy acrylate adhesive in a low stress range. Supposing fatigue strength at $5\times10^6$ cycles as the fatigue limit, the fatigue limit of N-0.0 and NE-1.0 is not obtained, but that of NA-1.0 is dS = 90 MPa.

Figure 7 shows the relationship between crack length and number of cycles in the stress range of 130 MPa. It can be seen from the figure that the crack reinitiation life increases by bonding GFRP over the crack, and the crack propagation rate, da/dN, decreases. A significant difference between adhesive types is not seen in the reduction of the crack propagation rate, da/dN.

## 4. CONCLUSIONS

In this study, fatigue tests were first carried out on a cracked steel plate (t = 6 mm) repaired using only GFRP. The following results were obtained:

(1) The GFRP was not able to completely stop crack propagation. However, it was effective in increasing the fatigue life.

(2) The effect of the repair increased in a high stress range when the ratio of GFRP width to crack length, w/a, was large.

Secondly, fatigue tests were carried out on a cracked steel plate (t = 6 mm) repaired using GFRP combined with stop holes. The following results were obtained:

(3) The GFRP could prevent crack reinitiation in a low stress range when combined with stop holes. Therefore, the method of using GFRP together with stop holes has high potential for application in repairing fatigue cracks.

(4) The effect of the repair increased in the low stress range when the ratio of GFRP width to crack length, w/a, was large.

(5) Even if GFRP cannot be bonded at the center of a crack, fatigue life is improved by drilling stop holes at the crack tips and bonding the GFRP over the stop holes.

Finally, the difference between types of adhesive used to bond the GFRP to the steel plate was examined experimentally.

(6) The fatigue life of the specimen to which GFRP was bonded using acrylic adhesive improved to a greater extent compared to that of the specimen using epoxy acrylate adhesive.

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