Repairing of fatigue-damaged steel component with single sided CFRP lamellas under tensile cyclic stress

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Abstract. Many bridges withstand the increasing loadings and fatigue damage, which threaten the safety of the bridges. In order to investigate the effect of CFRP on repairing fatigue damaged steel plate, the experimental test of a center-notched steel plate bonded CFRP lamellas was carried out. XFEM was used to further study the main factors affect the repairment of CFRP sheets. The quantified index of the effect of CFRP on steel member using the ratio of the remaining fatigue life of fatigue damaged steel plate strengthened of CFRP to that without any reinforcement. The result show that the effective stress range, prestress level in the CFRP, relative initial fatigue crack length, and the width of CFRP dramatically affect the rehabilitation of CFRP.

1. Introduction

Fatigue damage threatens the safety of various engineering structures. Fatigue damage of steel components caused by cyclic dynamic loadings and their general degradation over time has received considerable research attention. The fracture in a wheel tyre of a high-speed ICE train occurred in 1998 [1]. A survey showed 1885 aircraft accidents that since 1927 were determined to be related with fatigue damage [2]. Undercarriage turning tube of aircraft had only undergone 1300 flight cycles as an accident occur, which was much lower than the expected service life, due to fatigue damage [3]. It was found that over 90% of the 100 damaged bridges occurred deformation-induced cracks, which may initiate or propagate fatigue failure [4].

Adhesive technology has been widely used in engineering, including buildings, bridges, ships, aircrafts [5]. Due to high tensile strength, light weight, and good corrosion resistance, composite materials have been widely used in rehabilitation or strengthening structures. CFRP was investigated to be effective in improving fatigue life of steel structures [6].

Using experimental and numerical method to strengthen riveted bridge members subjected to fatigue loading, [7] pointed out that prestressed CFRP bonded on steel structures can be used to repair steel components by improving the stiffness of the cracked region, decreasing the rate of crack opening, or applying compressive stresses and producing a crack closure effect. Unbonded CFRP plate used to strengthen steel structures [8, 9], [10] applied digital image method to investigate the effect of CFRP on repairing steel members. Observing the CFRP peeling rate and energy release rate, [11] predicted the fatigue life time of steel beams.

The mechanism of fatigue crack growth is not yet well understood. Therefore, experimental study is necessary. In this study, the test of remaining fatigue life of fatigue-cracked steel plates strengthened
with single side bonding CFRP was carried out to investigate the effect of CFRP on repairing a steel plate of a fatigue-damaged center-notched specimen (CNS).

The residual fatigue life of the CNS bonding CFRP and that without CFRP under tensile cyclic loading were compared, other things being equal, to investigate the effect of CFRP on the repairing effect on CNS, using the ratio $f_E$ of the remaining lifetime of CNS bonded CFRP to that of without CFRP. Numerical study using Abaqus with extended finite element method (XFEM) based on Linear Elastic Fracture Mechanics (LEFM) was applied to discuss the main factors of affecting the reinforcement. The results shown stress ratio and stress range of the periodical load, width of the CFRP, relative initial fatigue crack length, and the pretension force on the CFRP were all evidently affect the repairing effect of CFRP on CNS.

2. Model test

2.1. Material properties and test procedure

The experimental tests were conducted in Karlsruhe Institute of Technology and Brandenburg University of Technology Cottbus-Senftenberg. The key parameters of CFRP lamella and CNS made of S355 J2 steel plate are listed in Table 1. The specimen of CNS and CNS bonded CFRP was biaxial symmetry.

| Material | Length, Width, Thickness (mm) | Yield Strength (MPa) | Ultimate Tensile Strength (MPa) | Young’s Modulus (GPa) | Poisson's Ratio |
|----------|-------------------------------|----------------------|-------------------------------|----------------------|----------------|
| CNS      | 700, 105, 10                  | 355                  | -                             | 210                  | 0.3            |
| CFRP     | 300, 20, 1.4                  | -                    | 3400                          | 192                  | 0.27           |

The CNS was of a 1mm-radius hole in its geometric center. There were two initial seams of 7.5 mm in lengths besides of the hole oriented to the width of the CNS, which was applied tensile cyclic load until the crack in each side reached to proximately 28.5 mm, including the preset seam from the geometric center of CNS. Hereafter, the initial fatigue crack length refers to the fractured length for this stage. The width of the CFRP was 20 mm, which could proximately cover the new cracked area of the CNS. The crack propagation length was expected to be exactly 20 mm, which could hardly be controlled exactly in experiment.

Then the CNS was strengthened by two CFRP lamellas (prestressed or not). The prestressing force was applied in the CFRP by using a specially designed set up (Figure 1). The specimen of CNS bonded CFRP with end anchoring system is illustrated in Figure 2. The new component of the CNS bonded CFRP withstood axial cyclic load again until the crack grew a more 20 mm in its two sides, and the number of loads was taken as the remaining fatigue life of the component. The crack propagation was measured by FAC-20 type strain gauge with measuring range of 20 mm from Tokyo Measuring Instruments Lab. The crack length of the CNS or CNS bonded CFRP and the related number of cyclic loads could be acquired from the resistance variation of the strain gauge as crack growing. Note the remaining fatigue life of the CNS and CNS bonded CFRP in the experiment, which generally smaller than the real fatigue life, were measured using the number of the cyclic load as the crack length reached the maximum range of the strain gauge. However, in most of the tests, the state of ultimate ductile failure always occurred as the crack length in each side of the CNS reached to proximately 48 mm. The transverse section of ¼ model of CNS bonded CFRP, shown the test procedure can be seen in Figure 3.
The period of sinusoidal tensile loadings was 0.125 s. The data collection interval was set to be 0.01 s. Because fatigue failure always occurs after several million cycles of loading, it is difficult to collect all the vast amounts of data for a fatigue failure. Therefore, the data points were only recorded continuously for 1s at intervals of 300 s. In order to keep the steel plate moved in a plane, the ends of the CFRP lamellas were fixed by end anchoring system, covering 60 mm in length of the CFRP from its end. Strips of white paper were glued on the steel surface before CFRP contact the plate to assure the adhesive only bond CFRP avoid of contaminating the steel plate. The CNS with CFRP lamellas was cured under normal climatic conditions for 7 days before the fatigue test. The lap length, equal to that of CFRP was 300 mm.

Three of the important factors stress ratio $R = \sigma_{\text{max}}/\sigma_{\text{min}}$, stress range $\Delta \sigma = \sigma_{\text{max}} - \sigma_{\text{min}}$, and mean stress $\sigma_m = (\sigma_{\text{max}} + \sigma_{\text{min}})/2$ of the cyclic loading should be defined, $\sigma_{\text{max}}$ and $\sigma_{\text{min}}$ are the maximum and minimum stress for a fatigue stress cycle, respectively. Table 2 gives out the magnitude on the CNS subjected to the sinusoidal cyclic axial load and the value of pretension force on the CFRP.
Table 2. Testing sets of CFRP repairing the CNS.

| Kind of cyclic loading | Stress ratio $R$ and the stress range $\Delta\sigma$ of the cyclic load | Magnitude of prestress level in the CFRP (MPa) |
|------------------------|-------------------------------------------------|-----------------------------------------------|
|                        | $R = 0.5, 50$                                    | Epoxy 1 | Epoxy 2 |
| Cyclic loading 1       | 0                                               | 0       | 0       |
| Cyclic loading 2       | $0.5, 70$                                       | 178.57  | 107.14  |
| Cyclic loading 3       | $0.091, 100$                                    | 357.14  | 214.29  |

2.2. Test results

The results show CFRP lamellas have an evident effect on prolonging fatigue life on CNS. Adhesive failure occurs for most of the specimens. About 50% of the adhesive layers were still kept intact. Under the axial cyclic loading, necking phenomenon could be observed near the crack area (Figure 4). The crack was observed to develop nearly linearly. The whole structure was axial symmetry, and the CFRP sheets were anchored at the two ends, curved crack surface could be only observed as the crack length rise to a high value, always higher than 48 mm.

![Figure 4. Fatigue crack propagation of the CNS with CFRP](image)

3. Numerical simulation

Due to symmetry, 1/4 model of the CNS and CNS bonded CFRP was adopted to reduce the calculation time. Refined mesh was applied near the fractured area, and transition meshes from fine to coarse elements using wedge-shape elements were adopted away from the cracked region to avoid a time-consuming process (Figure 5). The initial seams in CNS were exactly on the axial symmetry plane along the width of the specimen, which is on the boundary of the 1/4 model. Therefore, it was offset by 0.1 mm from the axial symmetry plane so that it was placed in the elements rather than the boundary. In this way, the fatigue crack lengths with respect to the load cycles can be determined more accurately using XFEM.

The crack was constrained to propagate linearly in order to calculate the exact number of load cycles corresponds to its length, although it can grow along a randomly, solution-dependent path. The crack faces of the specimens in experimental tests were smooth before fracture occurred. Therefore, it has little effect on the result.
4. Factors influencing the effect of repairing the CNS on CFRP

The extension of residual fatigue life of the CNS was adopted to quantify the effect of the CFRP on the repairing on the CNS. The factor of extension of residual fatigue life \( f_E \) is given by the ratio of the remaining fatigue life of the CNS bonding CFRP with different pretension forces to that without CFRP under the same conditions.

4.1. Stress range of the cyclic loading

It is well known that as the stress range \( \Delta \sigma \) of the cyclic loading increases, the fatigue life of a material will decrease. However, the index of \( f_E \) with respect to \( \Delta \sigma (=15, 20, 30, \ldots 70 \text{ MPa}) \) as \( R=0.5 \) shows the different result in Figure 5. It can be seen that the value of \( f_E \) drops sharply as stress range \( \Delta \sigma \) large than 20MPa, with \( f_E \) reaching the maximum magnitude of approximately 3.8. However, as \( \Delta \sigma \) not higher than 15MPa, \( f_E \) is generally on a downward trend. The value of \( f_E \) basically keeps unchanged as \( \Delta \sigma >60 \text{ MPa} \).

4.2. Stress ratio and the prestress level in the CPRP

The residual fatigue life of CNS with and without CFRP under the mean stress \( \sigma_m=75 \text{ MPa} \) of the cyclic loading and different prestress levels in CFRP were compared. It is found that the factor of \( f_E \) decreases with \( R \) increasing from 0.91 to 0.60 as prestress level in the CPRP \( P_s \) remains invariable, and there is little difference in \( f_E \) (Figure 7). There is an exponential function trend of \( f_E \) with respect to the prestress level in the CFRP, which is shown in Figure 6 as \( R=0.60, \sigma_m=75 \text{ MPa} \).
4.3. Ratio of the length of the CFRP from the initial fatigue crack tip to the crack length
The distance between the hole center of the CNS and the side of the CFRP nearest to the hole of 13.5, 18.5, 23.5, and 28.5 mm and the prestress level $P_s=178.57$ MPa in CFRP were calculated. The result show it has little effect of location of the CFRP on the remaining fatigue life of the CNS, and which differed only 0.2% for the four sets. The result complies well with Paris–Erdogan Law of Equation 1. Because the rate of crack propagation $da/dN$ mainly depends on the material and the environment [12].

4.4. Relative initial fatigue crack length of $a/b$
The ratio of the initial fatigue crack length $a$ to half the width of 1/4 CNS model $b$ was used to examine its influence against $f_E$. The factor of the remaining fatigue life extension $f_E$ under cyclic loading 1 is illustrated in Figure 8. It can be seen that $f_E$ is proximately 1.5 as $a/b$ is in the order of 0.17 as the prestress level in the CFRP is 0, which is proximately 1.9 with 178.57 MPa prestress level in the CFRP. With the rise of $a/b$, $f_E$ grows rapidly, especially as $a/b$ higher than 0.6. In addition, an obvious effect of the prestress level on $f_E$ can be seen from Figure 8.

4.5. Width of the CFRP
Figure 9 gives out the relation of $f_E$ and the relative width of the CFRP under the cyclic loading 1 of different initial fatigue crack length of 21.5 and 26.5 mm. There is a similar trend of $f_E$ in Figure 7 on the width of CFRP.

5. Conclusions
Based on experimental tests and numerical simulation, expected service life of steel plate could be improved dramatically by bonding CFRP. In this study, the effect of CFRP on repairing the center-notch steel plate CNS with initial fatigue crack were investigated by comparing the residual life of the same steel plate bonded and without CFRP (pretensioned or not). The ratio of the residual fatigue life of CNS bonded CFRP to that without CFRP, that is the index of extension of residual fatigue life $f_E$, was used to quantify the effect of CFRP on repairing CNS. The results showed that $f_E$ were dominated by the relative initial fatigue crack length, the relative width of the CFRP, stress ratio, and stress range. However, the position of the CFRP has little effect on $f_E$. The magnitude of $f_E$ can be in the order of 1.5 to 3.8. With the rise of $a/b$, $f_E$ grows obviously, especially as $a/b$ higher than 0.6. The factors of width of the CFRP and the prestress level in the CPRP $P_s$ are similar to those of $f_E$.

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