Surface Crack Propagation Rules of CFL-Strengthened Steel Plate under Fatigue Loading

Yi Yang1,*, Chihui Huang1, Peiyan Huang1

1 School of Civil Engineering and Transportation, South China University of Technology, Guangzhou China 510641

Corresponding author, E-mail address: yiyang@scut.edu.cn (Yi Yang).

Abstract: Steel is a kind of common materials in construction. Surface crack in steel components can reduce the bearing capacity and durability of steel structures, so it is important to strengthen the steel components with crack defects. Strengthening with fiber reinforced polymer (FRP) is a reliable reinforcement method to improve structural mechanics properties. This paper presents an experimental study on surface crack propagation rules. Carbon fiber laminate (CFL) is adopted to strengthen X80 steel plate with a semi-elliptical surface pre-crack. Specimens are tested under cyclic bending load and fatigue lives, crack lengths and depths in various stages, and crack propagation rates are discussed.

1. Introduction
In steel structures, such as gas pipeline, offshore oil platform, steel bridge, portal crane, surface crack is a common defect [1]. The surface crack is easy to propagate, reduce structural strength and shorten structural life, even cause catastrophic break. It is important to study the crack propagation rules and reinforcement method for cracked steel structures. Fiber reinforced polymer (FRP), a kind of composite material, is widely applied in strengthening structural components because of its high strength, light weight, corrosion-resistant, and convenient for construction. There are some studies on strengthening method, effect and mechanism [2-4], and some design guidelines for the application of FRP in the field of civil engineering [5, 6]. Tsai and Shen [7] studied the aluminum alloy plate containing through crack strengthened with FRP and came to conclusions that two sides strengthening could delay crack propagation obviously and increase fatigue lives 2.6 times than un-strengthened specimens. C.C. LAM and his cooperators’ study [8] showed that after strengthened steel pipes with FRP, stress intensity factors of through crack in steel pipe can be reduced by 54%. Aljabar et al [9] made an experimental investigation on the fatigue performance of FRP-strengthened steel plates with different crack orientations subjected to mixed-mode fatigue load, and a shifting phenomenon was identified to describe the influence of mixed mode.

CFL is a kind of carbon fiber laminate and different from other FRPs for it can be weaved on-site based on reinforcing design. The research on CFL mainly focus on static bearing capacity [10], fatigue property [11], pre-stressed technique [12] and interface fatigue fracture mechanism under thermo-mechanical coupled [13]. This paper provides an experimental investigation on crack propagation rules of CFL-strengthened steel plate with semi-elliptic surface crack.
2. Experimental preparation

In this study, twenty-seven CFL-strengthened steel plates with central cracks were designed and tested under fatigue three-point bending load. All steel plates are artificially pre-cracked a three-dimensional semi-elliptical surface crack to investigate the fatigue crack propagation behavior and CFL strengthening performance. CFL is bonded on the surfaces with crack. Five un-strengthened cracked steel plates were prepared as control specimens.

2.1. Material properties

The plates are made of X88 steel, with sizes of 110mm×80mm×8mm. The mechanical properties of the steel plates are listed in Table 1. CFLs, whose size are 90mm×70mm×0.23mm, are sticked to the steel plates. The measured mechanical properties of the CFL and epoxy are also listed in table 1.

| Material       | Steel CFL Adhesive |
|----------------|--------------------|
| Tensile strength (MPa) | 4030               |
| Yield strength (MPa)     | 522                |
| Shear strength (MPa)     | 14                 |
| Young’s modulus          | 200 220 5          |
| Poinsson’s ratio         | 0.3 0.25 0.38      |
| Thickness (mm)           | 8 0.23 0.8         |

2.2. Specimens

Steel plates are made following the guideline of ASTM E647. At the surface center of the plates, an artificial semi-elliptical crack starter is machined by electrical discharge machining, as shown in figure 1, in which $T$, $a$, $c$ denote the crack starter’s width, depth, and half length, and $H$, $W$, $B$ are the plate’s length, width, and thickness, respectively. Thirty-two specimens are divided into ten groups and three or four pieces per group according to the crack starter size. The specimen’s division is shown in table 2.

![Figure 1. Steel plate with crack starter](image)

| Specimen’s division |
|---------------------|
| $a$(mm) | $c$(mm) | Quantity | $a/c$ | $a/B$ |
|-------|---------|----------|-------|-------|
| 1     | 1       | 4        | 1.00  | 0.125 |
| 1     | 2       | 4        | 0.50  | 0.125 |
| 1     | 4       | 4        | 0.25  | 0.125 |
| 2     | 2       | 4        | 1.00  | 0.250 |
| 2     | 4       | 4        | 0.50  | 0.250 |
| 2     | 8       | 3        | 0.25  | 0.250 |
All steel plates with crack starter are disposed under three-point bending test for pre-cracking by electro hydraulic servo testing machine, which shown in figure 2. The maximum load in this work is $F_{\text{max}} = 10\text{kN}$. Fatigue load is applied in sinusoidal mode, with stress ratio $R = F_{\text{min}}/F_{\text{max}} = 0.1$, and loading frequency 15Hz. The length of pre-crack can be measured directly by measuring instrument, and then the depth can be calculated by the empirical equation:

$$\frac{a_0}{c_0} = 1 \pm 0.1 \quad (1)$$

where $a_0$ and $c_0$ are initial length and initial depth of surface pre-crack, respectively.

After pre-cracked, five plates are picked up to constitute an un-strengthened group. The other plates are divided into nine groups with three specimens and strengthened by bonding CFL on the surface with crack, as shown in figure 3. The size of the CFL is mentioned in Section 2.1. The thickness of the adhesive is controlled in 0.8mm. Twenty-seven steel plates strengthened with CFL are numbered beginning with SC, and five un-strengthened specimens are numbered beginning with S.
2.3. **Testing procedures**

The test is carried out on the testing machine mentioned in Section 2.2. The maximum load, stress ratio and loading frequency are set equal to those in pre-cracking process. The testing data, such as loading, time, strain, mid-span displacement, and the number of cycles, are recorded automatically.

For the un-strengthened specimens, the crack sizes in testing can be measured by crack width gauge. But, for the strengthened specimens, they cannot be measured directly because the cracks are covered by CFL. In this work, Beach-mark Method is used to obtain the crack depths and lengths. In some previous research, the mid-span deflection of steel plate varies from 0 to 0.3mm. This displacement is divided into six sections as control displacement, as shown in table 3. When the mid-span deflection comes to the first control displacement, the maximum loading should be reduced one third to slow down propagation rate, then a clear striation will appear around the crack, which is a beach-mark. And then resume the maximum loading, continue the fatigue test, and reduce the loading again when the deflection reaches the second control displacement to obtain the second beach-mark. Repeating the procedure, more beach-marks can be obtained. Based on these beach-marks, crack depth, \(a\), and length, \(2c\), corresponding to a certain number of cycles, \(N\), can be easily measured, and then curves of \(da/dN\) and \(dc/dN\), can be obtained conveniently.

![Table 3. Mid-span displacement division (mm)](image)

3. **Experimental results**

3.1. **Fatigue lives**

All the specimens’ crack propagation lives are listed in table 4. Note that the average fatigue life of Group S, whose specimens are un-strengthened, is \(60 \times 10^4\). The specimens in Group SC21 have crack sizes and shapes like those in Group S but have the average fatigue life increased 116% to \(145 \times 10^4\). It can be concluded that strengthening with CFL can greatly enhance the fatigue lives of steel plate with semi-elliptical crack.

![Table 4. Fatigue lives](image)
3.2. \( a-N \) curves and \( c-N \) curves

Based on the Beach-mark Method described in Section 2.3, the crack depth \( a \) and length \( 2c \) and the cycle numbers corresponding to every beach-mark are recorded, and then curves of \( a-N \) and \( c-N \) of some specimens can be obtained, as shown in figure 4. It indicates that the crack’s length propagates faster than the depth, \( a-N \) curves and \( c-N \) curves of un-strengthened specimens rise rapidly, and the curves of strengthened specimens have smaller slopes. It shows that CFL can effectively slow down crack growth of center cracked steel plates.

![Figure 4. (a) a-N curves, and (b) c-N curves of some specimens.](image)

3.3. Crack propagation rate of un-strengthened specimens

The crack propagation rates in two directions are usually described by \( \frac{da}{dN} \) and \( \frac{dc}{dN} \), which can be worked out from \( a-N \) curve and \( c-N \) curve. In Newman and Raju’s two-degree-of-freedom fatigue crack propagation rules, the crack propagation rates can be expressed in Paris formula:

\[
\frac{da}{dN} = C_a (\Delta K_a)^{m_a}, \quad \frac{dc}{dN} = C_c (\Delta K_c)^{m_c} (2)
\]

in which, \( C_a, m_a \) and \( C_c, m_c \) are parameters related to materials of specimen and irrelevant to crack shape or specimen’s size; \( \Delta K_a \) and \( \Delta K_c \) are amplitudes of stress intensity factor in depth and length direction, respectively. For un-strengthened specimens, \( \Delta K_a \) and \( \Delta K_c \) can be worked out by Newman-Raju formula. And for strengthened specimens, they should be worked out by the Finite Element Method.

Figure 5 shows \( \frac{da}{dN} - \Delta K_a \) curves and \( \frac{dc}{dN} - \Delta K_c \) curves of un-strengthened specimens. It can be seen from figure 5(a) that the crack propagation rates vary complicatedly along the depth direction. \( \frac{da}{dN} \) increases linearly at the beginning of the propagation, and changes to increase slowly even decrease from the mid-term. Then the propagation rules in the depth direction cannot be expressed in the Paris formula, because in three-point bending test, the crack propagating along the depth direction may cause the cross-sectional neutral axis to move upward. The data in \( \frac{dc}{dN} - \Delta K_c \) curves, which shown in figure 5(b), have less disperstiveness and present almost straight lines. Fitting the data, the parameters of materials are obtained as \( C_c = 9.62 \times 10^{-10} \), \( m_c = 3.12 \). Hence the crack propagation rate along the length direction can be expressed in Paris formula:

\[
\frac{dc}{dN} = 9.62 \times 10^{-10} (\Delta K_c)^{3.12} (3)
\]
3.4. Crack propagation rates of strengthened specimens

Python is an explanatory and object-oriented programming language. People can use Python programming to access Abaqus, a finite element simulation software, to build, verify and analyze a finite element model by parameter mode. Based on the data of crack depth, length and cycle number recorded in the test, the authors design a stress intensity factor solver by Python to calculate $\Delta K_a$ and $\Delta K_c$ of CFL-strengthened specimens.

Figure 6 shows $da/dN - \Delta K_a$ curves and $dc/dN - \Delta K_c$ curves of Group SC21. The two kinds of curves are almost straight lines, and both can be expressed in Paris formula. Because it is the attached CFL, instead of the steel plate, bears the tensile stress, the cross-sectional neutral axis moves very slowly when the crack propagating. Using the stress intensity factor solver and fitting the curves, the crack propagation rates along depth direction and length direction are:

$$\frac{da}{dN} = 3.40 \times 10^{-7} (\Delta K_a)^{0.69}$$
$$\frac{dc}{dN} = 1.25 \times 10^{-8} (\Delta K_c)^{2.41}$$

Comparing figures 5 and 6, it can be found that the specimens in group SC21 group have less stress intensity factors $\Delta K_a$ and $\Delta K_c$, and company with smaller crack propagation rates along the depth direction and length direction than those in group S. Obviously, Strengthening with CFL can improve the stress distribution on the cross-section of plate, markedly restrain the crack propagation and enhance the fatigue performance. Repeating the work for all groups, the crack propagation rates in Paris formulae can be obtained.

4. Conclusion

This paper provided an experimental study on semi-elliptical surface crack propagation rules of CFL-strengthened steel plates. Thirty-two steel plates with surface pre-crack were prepared for the experiment.
All the specimens were tested under three-point bending load. Beach-mark Method was used to obtain clear striations of crack propagation. The experimental results showed that: (1) strengthening with CFL could greatly enhance the fatigue lives of steel plates with semi-elliptical crack; (2) $a-N$ curves and $c-N$ curves of un-strengthened specimens rose rapidly, and the curves of strengthened specimens had smaller slopes; (3) for the un-strengthened specimens, the crack propagation rate in depth direction could not be expressed in the Paris formula and that in length direction could be done. The investigation method in this work can be applied in studying the semi-elliptical crack propagation behavior of tubular steel structures strengthened with CFL under tensile load or bending load.

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