Experimental Study on Propagation Rule of Semi-elliptical Surface Crack in Steel Plate Strengthened with FRP under Cyclic Bending Load

Zhao Chuanyu[1], Huang Peiyan[1,2]*, Feng Fajuan[1], Zhou Hao[1]

[1] School of Civil and Transportation, South China University of Technology, Guangzhou 510640, China

[2] State Key Laboratory of Subtropical Construction Science, South China University of Technology, Guangzhou 510640, China

* Corresponding author: pyhuang@scut.edu.cn

Abstract: Strengthening steel structures containing semi-elliptical surface crack with fiber reinforced polymer (FRP) can delay crack propagation, and increase the service life of structures. In this paper, carbon fiber laminate (CFL), which has independent intellectual property, was adopted to strengthen X80 steel plate containing a 3D semi-elliptical surface crack, and based on this study object, the surface crack propagation rule in the specimens was studied by experimental method under cyclic bending loads. The results show that 3D semi-elliptical surface crack propagation rates in the crack length direction and crack depth direction can be described by corresponding Paris equation for the specimens strengthened with CFL, the constant coefficients in Paris equation can be obtained by fitting the data from fatigue crack propagation experiments, and stress intensity factor of the surface crack in steel plate strengthened with CFL can be obtained by numerical calculation with FEM.

Keywords: 3D surface crack, fiber reinforced polymer (FRP), fatigue crack growth, beach-mark, stress intensity factor (SIF)

1. Introduction

Surface crack is a common defect in oil and gas pipelines, offshore oil platform, aviation mechanical and other steel structures [1,2]. Such kind of crack is easy to propagation and results in shortage of service life, especially can bring catastrophic results. So many researchers have done a lot of studies on surface crack [3,4]. In order to improve service life of structures which contain surface crack, some researchers propose to strengthen structures with fiber reinforced polymer (FRP), and have studied the strengthening method and strengthening effect [5,6]. Liu et al [7] discussed the fatigue lives and stress intensity factors of steel plate containing through crack strengthened with FRP, and their results indicate that fatigues lives of steel plates strengthened with FRP can increase 1.3 times than that of non-strengthened steel plates, and stress intensity factors can be reduced by 28%~60%. Tsai and Shen [8] studied the aluminum alloy plate containing through crack strengthened by FRP, and their results show that two face sides strengthening can delay crack propagation obviously, and fatigue lives can increase 2.6 times than non-strengthened plates. C.C.LAM's studies [9] show that stress intensity factors of through crack can be reduced by 54% in steel pipe after strengthening by FRP. However, the research for propagation rule of the semi-elliptic surface crack in steel structure strengthened with FRP has not yet been reported. For this reason, in this article, propagation behavior of the three dimensional semi-elliptic surface crack in X80 steel plate strengthened with carbon fiber laminate (CFL) [10] was experimentally studied, and the stress intensity factor of the surface crack was computed by FEM method.

2. Fatigue crack propagation experiments

2.1 Specimens and pre-cracking

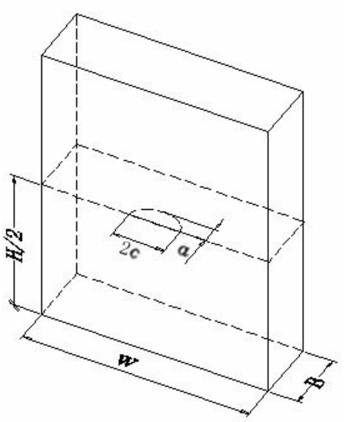
Specimens are made of X80 steel, which is a kind of high strength pipe steel. The size of steel plate was: length H=110mm, width W=70mm, thickness B=8mm. The mechanical properties were: yield strength $\sigma_{0.2}$=522MPa, Young' modulus E_s=200GPa and Poisson's ratio ν_s=0.3. In the surface centre of the specimen, an artificial semi-elliptical crack starter is machined by electrical discharge machining, show in figure 1(a), and fatigue pre-cracking is carried out on testing system by three-point bending method. The maximum load P_{max} of prefabricated fatigue crack can be calculated with the following equation [11] :

$$P_{\max} = k\frac{2\sigma_{0.2}B^2W}{3S} \tag{1}$$

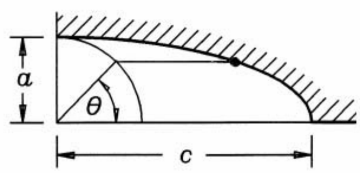
Where, S is the span of the specimen, and k is set to 1.0 for pre-cracking, and 0.5 for crack propagation. If the fatigue crack cannot be initiated by crack starter under current load after several ten thousand cycles, the current load should be increase by 10% of the maximum load. The stress ratio for pre-cracking is $R=P_{min}/P_{max}$=0.1. Crack size for pre-cracking is approximately following the empirical equation:

$$\frac{a_0}{B}+\frac{a_0}{c_0}=1\pm 0.1 \tag{2}$$

Where, a_0 and c_0 is initial depth and initial length of the surface crack. Based on Eq.(2), initial crack depth a_0 can be estimated by observation and controlling initial crack length approximately to $2c_0$.



(a) Non-strengthened specimen

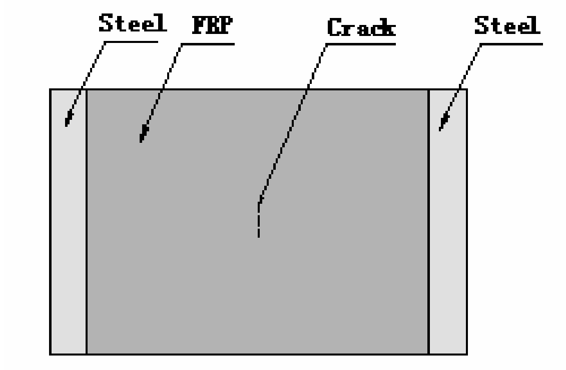


(b) Parametric angle for the crack

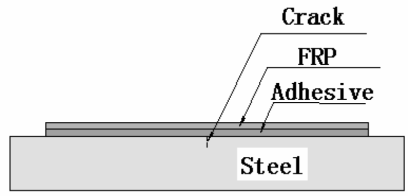
Figure 1. Steel plate specimen with a semi-elliptical surface crack

After pre-cracking, CFL was bonded on the crack front side surface of the steel plate as shown in figure 2. The CFL has length H=90mm, width W=70mm, thickness t_f=0.2mm, Young' modulus E_f=230GPa and Poisson's ratio ν_f=0.25. After 5~7 days for adhesive to solidify, then the specimens can be used in fatigue crack propagation experiments.

Six specimens were tested in the studies. Three non-strengthened specimens were symbolized by S1, S2 and S3, and three strengthened specimens were symbolized by SC1, SC2 and SC3.



(a) Plane view



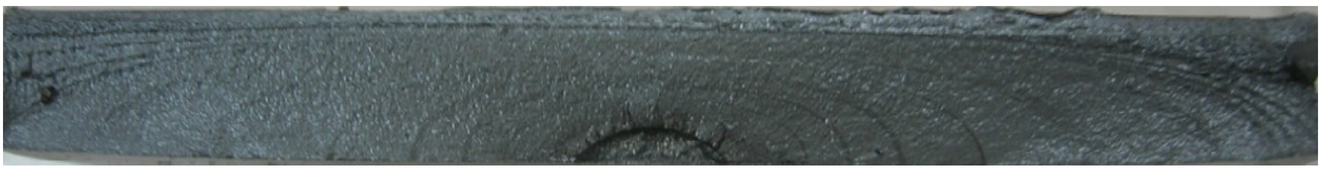
(b) Section view

Figure 2. Strengthened specimen

2.2 Experimental method

The test was carried out on electro-hydraulic servo dynamic and static testing machine which produced by Changchun Institute of Testing Machine. The testing data, such as load, time, strain, and corresponding fatigue loading cycles, are recorded automatically. Fatigue loads applied by force control mode with sinusoidal wave, and a frequency of 15 Hz and a stress ratio of 0.1. P_{max} and P_{min} denote the peak load and volley load respectively, corresponding to N cycles applied on the specimen. The non-strengthened specimens were applied to the maximum load, P_{max}, as 8.0kN, and the strengthened specimens as 9.5kN.

For the measurement of crack depth and length, beach-mark method was used to obtain beach-mark boundary, as shown in figure 3. After a certain number of cycles of normal propagation, reduce the applied load to 2/3 of normal propagation load to slow down the propagation rate, then a clear striation will appear following the slow propagation. And repeating above procedures, more of striation, the beach-mark can be obtained. Based on this beach-mark, crack depth, a, and length, 2c, which is corresponding to a certain number of cycles, N, can be easily measured, and then a~N curves and c~N curves, and fatigue crack propagation rate, da/dN and dc/dN, can be easily obtained.



(a) Non-strengthened specimen S1

(b) Strengthened specimen SC1

Figure 3. Beach-mark on fracture surface of the specimens

3. Propagation rates of 3D surface crack

Three non-strengthened specimens（S1, S2, S3）and three strengthened specimens（SC1, SC2, SC3）were tested in fatigue crack propagation experiments by adopting experimental method in the above Chapter 2, and fatigue crack propagation curves ($a \sim N$ curves) of each specimen were obtained.

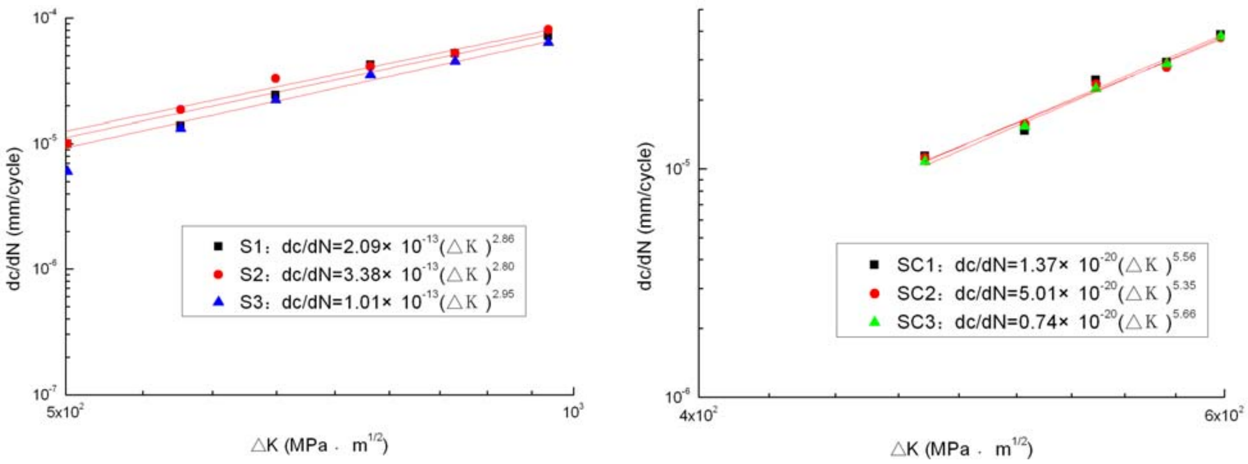
Based on the research results from the other metal materials, we assume that the propagation rates, da/dN and dc/dN (mm/cycles), of the surface crack in X80 steel plate strengthened with CFL and non-strengthened specimens all can be described by Paris formula [11] as,

$$\frac{dc}{dN} = C_L(\Delta K_c)^{m_L} \tag{3}$$

$$\frac{da}{dN} = C_D(\Delta K_a)^{m_D} \tag{4}$$

Where, C_L, C_D, and m_L, m_D were material constants, ΔK_c and ΔK_a ($MPa \cdot m^{1/2}$) were the amplitude values of the stress intensity factors of the surface crack ($\Delta K=K_{max}-K_{min}$), whereas the stress intensity factor K can be calculated by Newman-Raju formula [2] for the non-strengthened specimens, but for the strengthened specimens, it has need to use the FEM [12].

Based on the test data obtained from the non-strengthened specimens S1, S2 and S3, and strengthened specimens SC1, SC2 and SC3, the relationship of ΔK_c and dc/dN, ΔK_a and da/dN were obtained and shown in figure 4 and figure 5.



(a) non-strengthened specimens (b) strengthened specimens

Fig.4 Relationship between ΔK_c and dc/dN

Fitting the data to Eq.(3), the average of C_L, and m_L were determined, and the fatigue crack propagation equations in crack length direction for non-strengthened and strengthened specimens were as follows:

$$\frac{dc}{dN} = 2.16\times10^{-13}(\Delta K_c)^{2.87}\text{, for non-strengthened specimens} \tag{5}$$

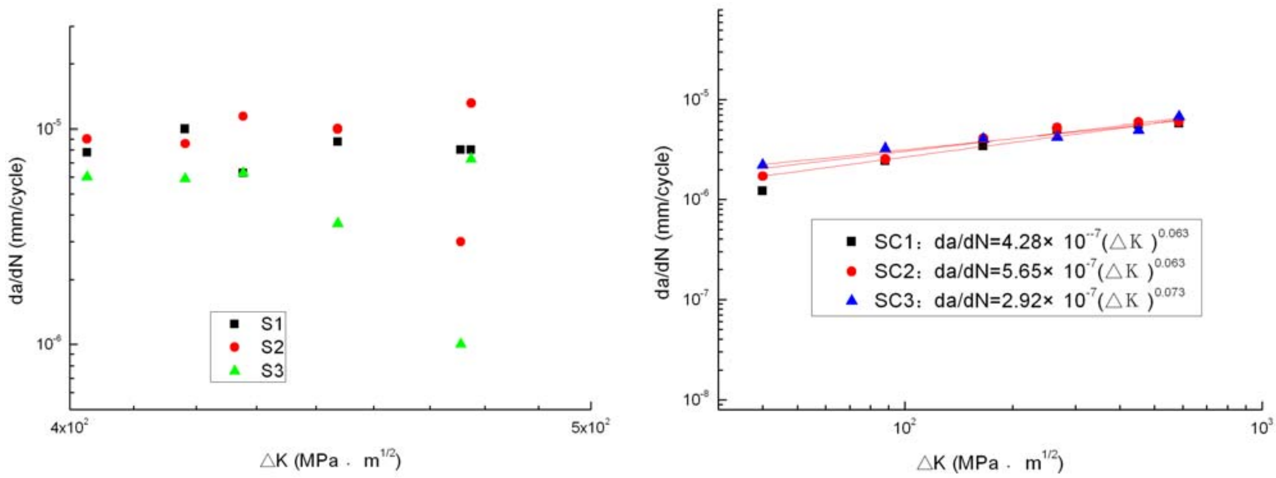
$$\frac{dc}{dN} = 2.37 \times 10^{-20} (\Delta K_c)^{5.52}, \qquad \text{for strengthened specimens} \tag{6}$$

In surface crack length direction, the above two equations show that strengthened with CFL can change the crack propagation coefficient C and the index m in Paris law. The crack propagation coefficient C decreases, while the crack propagation index m increases.

In surface crack depth direction, there is no obvious regularity for the relationship of ΔK_a and da/dN for the non-strengthened specimens, shown in figure 5(a). This may be because the position of neutral axis in the non-strengthened specimens has been changing as crack propagation in depth direction, and this change has a great effect on propagation rate. But the relationship of ΔK_a and da/dN for the strengthened specimens agrees well with Paris law as shown in figure 5(b). This is because the position of neutral axis in the strengthened specimens became more stable than that of the non-strengthened specimens.

Fitting the data to Eq.(4), the average of C_D, and m_D were determined, and the fatigue crack propagation rate equation in crack depth direction for the strengthened specimens was as follows:

$$\frac{da}{dN} = 4.28 \times 10^{-7} (\Delta K_a)^{0.66} \tag{7}$$



(a) Non-strengthened specimens (b) Strengthened specimens

Figure 5. Relationship between ΔK_a and da/dN for strengthened specimens

4 Conclusions

A method of combination of experiment and numerical analysis was applied to study the 3D semi-elliptical surface crack propagation rule in non-strengthened and strengthened steel plate with carbon fiber laminate (CFL), and the main results are as follows:

1) Strengthening with CFL can reduce fatigue crack propagation rate, and increase fatigue life of the specimen.

2) 3D semi-elliptical surface crack propagation rate in crack length direction can be described by corresponding Paris equation. The constant coefficients in Paris equation can be obtained by fitting the data from fatigue crack propagation experiments, and stress intensity factor can be obtained by numerical calculation with FEM.

3) Beach-mark method was a better way to obtain data like the change of crack size in fatigue

surface crack propagation.

4) Crack propagation rule in crack depth direction in non-strengthened specimens do not accord with Paris law, while after strengthened with CFL, the crack propagation rule go back to accord with Paris law. The mechanism to be further discussed.

Acknowledgments

The project is supported by National Natural Science Foundation of China (No.51078145 and No.11132004) and Guangdong Province Natural Science Foundation of China (No.9251064101000016).

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