Crack propagation and debonding development of CFRP laminate strengthened high-strength steel plates under fatigue loadings

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Abstract. Carbon fiber reinforced polymer (CFRP) has been used to strengthen steel structures to enhance fatigue life. A crack growth induced debonding region in the adhesive-steel interface has been observed in failure modes. However, limited studies focus on its gradual development with fatigue loadings, especially for CFRP laminate strengthened cracked high strength steel plates. The purpose of this paper is to obtain the corresponding relationship of crack propagation and debonding development. Thus fatigue tests with measuring real-time change of CFRP strain distribution by Digital Image Correlation (DIC) system were conducted for Q345, Q460, Q690 steel under fatigue loading at the same stress level 50% but difference stress ranges. Although debonding at the adhesive-steel interface is invisible, through calculation of strain gradient, it is found that as the increase of crack length, the debonding region around the crack tip occurs and gradually becomes larger. Furthermore, the shape of debonding region is always similar to an ellipse from the beginning of loading to failure.

1. Introduction

CFRP has been proved to be effective to strengthen metal to achieve good behaviors [1, 2, 3], especially crack steel structures under fatigue loading [4-6]. Based on previous studied, there are three main failure modes of CFRP strengthened cracked steel structures, that is, CFRP debonding, CFRP delamination and CFRP rupture [7]. As for the CFRP debonding failure, it may occur within the adhesive (cohesion failure) or at the interfaces between the adhesive and the adherents (adhesion failure). Besides, debonding in CFRP-strengthened steel structures can be divided into end debonding and intermediate debonding [8]. For cracked specimens, intermediate debonding is more common because high interfacial shear stressed is induces by the crack, which is called IC debonding (intermediate-crack debonding). Especially, it was observed that elliptical debonding occurred around the crack tip after fatigue loadings in many previous tests [9, 10, 11]. Due to the non-uniform stress distribution of cracked steel plates under static tensile loading, the debonding at the region of high stress has a great influence on the crack propagation under fatigue loading [12], as is shown in Figure
1. However, limited studies focus on the gradual development of debonding with crack propagation, especially for CFRP laminate strengthened cracked high strength steel plates. As a result, this paper firstly highlights the importance of considering the debonding around the crack tip. Then fatigue tests with strain measurement were done to get debonding development speed and shape of CFRP strengthened high strength steel plates under different stress ranges.

![Figure 1. Influence of debonding on the crack propagation under fatigue loading.](image)

2. Material

Material properties and testing of steel, CFRP and adhesive have been described in paper [13]. For steel, the elastic modulus of Q345, Q460 and Q690 steel is 201 GPa. And the yield stress of them is 390, 481, 805 MPa, respectively. For CFRP laminate, the thickness is 1.4 mm, the width is 50 mm, the ultimate tensile strength is 2454 MPa and the elastic modulus is 168 GPa. For adhesive, the elastic modulus is 2.10 GPa, the ultimate tensile strength is 23.5 MPa, and the ultimate tensile strain is 1.71%.

3. Specimen and test setup

The specimen configuration and test machine are shown in Figure 2, the same as paper [13]. Three CFRP laminate strengthened (LS) specimens were investigated, as shown in Table 1. The subscripts 345, 460, or 690 are used to denote the nominal yield stress of the steel. The number following yield stress is the maximum stress in fatigue loading. The maximum stress is 50% of the yield stress and the stress ratio is 0.1, which is called base loading cycles. To track crack propagation, “beach marking” was adopted with marking loading cycles, whose stress ratio is 0.6, as shown in Table 1.

For strain measurement of the CFRP laminate surface in a fatigue loading, conventional strain gauges have many disadvantages. For example, strain gauges can only collect strain at discontinuous points, thus cannot obtain a continuous stress-strain field; Strain gauges have a limited range and may fail because of stress concentrations; Fatigue loads may cause strain gauges to fall off the specimen during loading. Based on this, Digital Image Correlation (DIC) system was used to measure the longitudinal strain of CFRP laminate surface during the fatigue loading, which is a non-contact strain acquisition method. A 3D optical strain measurement system (ARAMIS 3D) developed by GOM from Germany is used to achieve the non-contact strain acquisition method, which mainly includes cold light source, two CCD cameras and a computer equipped with digital image correlation algorithm software. Specifically, the resolution of the CCD camera used in this experiment is 2352 pixels × 1728 pixels; the CCD is used to collect the surface image of the object when it deforms; the computer is used to process the gray scale information of the speckle field randomly distributed on the surface of the object before and after the deformation, thus finally obtain a three-dimensional strain field distribution. In this test, black matt lacquer was applied as a primer on the surface of CFRP laminate,
and then white matte paint was sprayed as a speckle mark. The measuring system and the specimen after painting are shown in Figure 2.

![Figure 2. Configuration of specimens and test machine.](image)

To obtain the relationship of crack propagation and debonding development, the following steps are conducted: (1) apply base fatigue loadings for $N_1$ cycles, and apply marking loading cycles for 5,000 cycles so that the crack length after $N_1$ cycles was obtained by “beach marking”. (2) then increase the load to the maximum force of fatigue loading, and capture the strain distribution of CFRP laminate by DIC, based on which the strain gradient distribution along the longitudinal direction of CFRP laminate was obtained; thus the shape and the length of debonding at this time is obtained. (3) restart base fatigue loadings for $N_2$ cycles and repeat the above steps until the specimen fails by fracture. The time of capturing strain distribution by DIC (after $N_1$, $N_2$ and next cycles) is shown in Figure 3.

![Figure 3. Time of capturing strain distribution by DIC.](image)

| Specimen   | Base loading cycles (KN) | Marking loading cycles (KN) |
|------------|--------------------------|-----------------------------|
| SL345-195.0| 218–22 kN                | 218–131 kN                  |
| SL460-240.5| 202–20                   | 202–121                     |
| SL690-402.5| 394–39                   | 394–276                     |

4. Test results and analysis

Based on paper [14], because the strain gradient is proportional to the adhesive shear stress, a contour of high strain gradient corresponds to the debonding front where adhesive shear stresses are

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high. The strain gradient in the debonded region that is bounded by this contour is negligible because there is no transfer of shear stress in the debonded region. Thus, strain gradient is calculated based on DIC result.

For SL345-195.0, as shown in Figure 4, when the fatigue crack is small, the stress distribution on the surface of CFRP laminate is relatively uniform. When the fatigue crack increases to 9.75 mm after 150,000 fatigue cycles, stress concentration occurs near the crack. Since then, the stress concentration has become increasingly obvious, in strain gradient a “basin” shape appears near the crack tip, which represents the debonding region. At this point, the maximum strain reaches 1800 μm. It is seen that when debonding occurs, the number of fatigue cycles accounts for 55.6% of the total number of fatigue cycles and the shape of the debonding zone is close to an elliptical.

For SL460-240.5, as shown in Figure 5, strain distribution of CFRP laminate is uniform before 120,000 fatigue cycles. After that, CFRP laminate around the initial crack of the steel begins to exhibit strain concentration. At this stage, as the fatigue crack propagates, the strain gradually increases, and the strain concentration area expands with a relatively low speed. Starting from 250,000 fatigue cycles, the area of the strain concentration area increases rapidly, and the maximum strain value also increases rapidly reaching a maximum of 1900 μm. Therefore, initially, debonding speed is as slow as the crack growth rate. When crack begins to expand rapidly, the debonding speed also begins to increase rapidly. It is found when debonding first appears, the number of fatigue cycles accounts for 43.2% of the total number of fatigue cycles.

For SL690-402.5, as shown in Figure 6, from 10,000 fatigue cycle, strain concentration occurs. Because this specimen bears a larger fatigue loading range compared with the others, the fatigue crack and debonding both rapidly expands from the beginning. The maximum strain in the strain concentration zone reaches 2,800 μm, which is much higher than that of SL345-195.0 and SL460-204.5. When debonding occurs, the number of fatigue cycles only accounted for 25.7% of the total number of fatigue cycles. In summary, larger the fatigue stress amplitude results in an earlier occurrence of debonding.
5. Conclusions

The following conclusions can be drawn:

(1) This paper proves that debonding phenomenon of CFRP laminate at the crack tip under fatigue loading develops with crack propagation by experimental test, and reveals their relationship.

(2) Crack propagation and debonding development are to interactional processes. They are both slow in the early stage of fatigue loading, and become gradually rapidly in the later stage close to fracture.
(3) The shape of the debonding zone is always similar to an elliptical.
(4) The larger the fatigue stress amplitude, the earlier the debonding occurs.

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