ABSTRACT

The externally-bonded fiber reinforced polymer (FRP) technique has been used to repair steel structures in recent years. As an essential parameter to analyze the crack propagation and fatigue life of cracked steel elements, the stress intensity factor (SIF) can be utilized to assess the repair effectiveness of FRP laminates. In this paper, a finite element (FE) analysis was conducted to evaluate the SIF of cracked steel plates repaired with FRP laminates using ANSYS software. Effect of three FRP configurations on the SIF at the crack tip was investigated under the condition of the same amount of FRP laminates. Parameters influencing the SIF were also discussed, including the crack length, the thickness of FRP, the elastic modulus of FRP, the shear modulus of the adhesive, and the thickness of the adhesive. FE results showed that the SIF of FRP-repaired specimens can be significantly reduced compared to the un-repaired specimens. FRP configurations had an obvious effect on the SIF at the crack tip. The increase of the FRP thickness, the elastic modulus of FRP, and the shear modulus of the adhesive can decrease the SIF, and the thicker adhesive resulted in a higher value of SIF.

KEYWORDS

Stress intensity factor, FRP, steel plate, repair, finite element analysis.

INTRODUCTION

The epoxy-bonded fiber reinforced polymer (FRP) technique has received more attention in repairing steel structures due to the high stiffness, high strength, and light weight of FRP materials. Compared with traditional repair methods, such as welding steel plates, externally-bonded FRP has some obvious advantages in improving the fatigue behavior of damaged steel structures (Wu et al. 2010). Some experimental tests have shown that the application of FRP can effectively reduce the crack growth rate and prolong the fatigue life of cracked steel members (Liu et al. 2009a; Tavakkolizadeh et al. 2003; Jones et al. 2003; Ye et al. 2010). However, experimental tests are time-consuming and costly, therefore plentiful fatigue tests are impractical. Theoretical analysis is considered as an alternative way to study the fatigue and fracture behavior of FRP-repaired steel structures, and the stress intensity factor (SIF) can be utilized to assess the repair effects of FRP laminates. However, a closed-form solution to calculate the SIF is difficult due to the geometrical and mechanical complexity of FRP-repaired steel members.

In recent years, numerical methods, such as the finite element (FE) and boundary element (BE), have been used in the analysis of the SIF for FRP-repaired cracked steel structures. Some two dimensional (2-D) and three dimensional (3-D) models have been presented in the literatures. Based on Mindlin plate theory, Sun et al. (1996) presented a plate-spring model. Naboulsi et al. (1996) analysed the SIF using a three layers model. Lam et al. (2010) modified the three layers model by modeling cracked steel plates with the 3-D brick elements, instead of shell elements. Lee et al (2004) conducted the study using the 3-D model in which the steel, the adhesive layer, and the FRP were modelled with 3-D brick elements. Besides, the BE method was used in the study conducted by Liu et al. (2009b). These studies have shown that numerical analysis is an efficient method to assess the SIF at the crack tip of cracked-metallic members.

In this paper, a liner elastic FE analysis was conducted using the ANSYS software. The SIFs of FRP-repaired cracked steel plates were investigated to evaluate the repair effect of FRP laminates. The effects of the FRP configurations, the crack length, the FRP thickness, the FRP modulus, the shear modulus of the adhesive, and the adhesive thickness on the SIF were analysed.
GEOMETRY OF SPECIMENS

In this study, steel plates with a central initial crack were repaired symmetrically by FRP laminates. The length of the steel plate was 700 mm, the width 120 mm, and the thickness 10 mm. A through-thickness initial crack, $2a_0$, was used to simulate damage in the steel plates. Firstly the effect of FRP configurations on the SIF was investigated, and three different FRP configurations were designed under the condition of equivalent tensile stiffness, i.e. the same amount of FRP laminates. The basic geometries of three FRP configurations were shown in Figure 1. For configuration 1 and configuration 2, the width of FRP was 100 mm; for configuration 3, the width of FRP was 50 mm, while the FRP thickness was twice that of configurations 1 and 2 to keep the equivalent tensile stiffness of FRP laminates. The length of FRP was 300 mm for all specimens. When analyzing the effect of other parameters on the reduction of the SIF, the width of FRP was equal to that of the steel plate.

FE MODEL

Three-dimensional (3D) linear-elastic FE models were assembled using ANSYS software to obtain the SIF at the crack tip. Only one-eighth of the specimen was modeled due to material and geometry symmetry conditions. Symmetrical boundary conditions and a uniform loading of 150 MPa were applied to the FE models. The steel plates and FRP laminates were modeled using 8-node brick element SOLID45. The adhesive layers were meshed with three linear spring elements (Sun et al. 1996), COMBIN14, to simulate the axial and shear deformation. The length of the spring was equal to the thickness of the adhesive layer. A typical FE mesh is shown in Figure 2. A local debond zone around the crack front was simulated by deleting two shear springs. The debond zone was assumed to be elliptical, and the shape parameter $c/b$ of the ellipse was assumed to be 0.25 in the numerical analysis, where $c$ was the minor semi-axis and $b$ was the major semi-axis of the ellipse, as shown in Figure 2.
In the FE model, the FRP laminate was assumed to be orthotropic, and the steel and adhesive were assumed to be isotropic. The elastic modulus of the steel was the 206 GPa, and the Poisson’s ratio was assumed to be 0.3. The elastic modulus of FRP was 165 GPa, and the Poisson’s ratio was assumed to be 0.28. The shear modulus of adhesive was 900 MPa, and the Poisson’s ratio was assumed to be 0.35. The virtual crack closure method (Krueger et al. 2004) was used to calculate the strain energy release rate \( G \) of the crack tip. This method is insensitive to the FE mesh size, and does not rely on the quarter-point singular element. \( G \) was converted into SIF by assuming a plane stress condition.

The FE analysis was first conducted for un-repaired cracked steel plate with various initial crack lengths. The numerical results of SIFs are compared with theoretical values calculated based on the stress intensity factor handbook (China Aviation Academy 1981), as shown in Figure 3. It can be observed that the numerical results were in good agreement with the theoretical results.

RESULTS AND DISCUSSIONS

Effect of the FRP Configurations

In this section, the effect of FRP configurations on the SIF was analysed. Figure 4 presented the SIF variation with the half-crack length for specimens repaired by configurations 1 and 2. It was observed from Figure 4 that the SIFs were different for the specimens repaired by configurations 1 and 2. When the half-crack length was less than about 50 mm, the SIF for configuration 2 was larger than that for configuration 1. This was mainly because the FRP-constrained regions were different for the specimens repaired by FRP configurations 1 and 2, and that of configuration 1 was obviously larger than configuration 2 for the same crack length. It was also observed that for the same crack length, the SIF ratio between configurations 1 and 2 decreased when the FRP thickness increased from 0.3 mm to 2.8 mm, indicating that the repair superiority of configuration 1 over configuration 2 was more significant with thicker FRPs. When the crack length exceeded approximately 50 mm, the SIF for configuration 1 became gradually greater than for configuration 2 because the crack tips of the specimens repaired by FRP configuration 1 were not constrained by FRP laminates.
Figure 5 illustrates the relationship between the SIF and half-crack length for specimens repaired by FRP configurations 1 and 3. Results showed that the SIF for configuration 3 was smaller than that of configuration 1 when the crack was relatively small. This was because the FRP thickness for configuration 3 was thicker than configuration 1 when the crack was at a specific length. However, the difference in the SIF between configurations 3 and 1 gradually decreased when the FRP thickness in configuration 1 increased from 0.3 mm (0.6 mm in configuration 3) to 2.8 mm (5.6 mm in configuration 3). When the crack exceeded the FRP region in configuration 3, the FRP laminates did not cover the crack tip of the specimens, resulting in a faster rate of increase in the SIF for configuration 3 compared with configuration 1. Therefore, the SIF for configuration 3 would gradually become greater than that of configuration 1 with the propagation of the crack.

It was concluded that the FRP configurations had an effect on the SIF under equivalent tensile stiffness of FRP laminates. Based on the Paris law, the crack propagation life of cracked steel plates can be influenced by FRP configurations (Wang et al. 2013). Therefore, more studies need to be carried out on this issue, such as the development of theoretical formulas of SIF for different FRP configurations (Wu et al. 2013).

**Effect of the Crack Length**

Figure 6 presents the SIF variation with the half-crack length. It can be seen that the SIF increased with the crack growth. Compared to the un-repaired steel plate, SIF dramatically decreased with FRP repair. This was mainly due to the reduction of the stress in the steel and the constraint of the crack opening caused by the bridging effect of FRP laminate. As shown in Figure 6, the effect of FRP was not significant for a short crack, but its effect became more significant with the increase of crack length. From the Figure (b), it was known that for the specimen repaired with 1.4 mm thick FRP, the SIF ratio between repaired and un-repaired specimens decreased from 0.78 to 0.31 when the half-crack length increased from 5 mm to 55 mm. Therefore, the remaining crack growth life ratio between the repaired and un-repaired specimens becomes larger for the specimen with a longer initial crack length. However, a longer initial crack length can lead to a shorter total fatigue life, and hence early repair at a short initial crack length was recommended (Yu et al. 2013).
**Effect of the FRP Thickness**

The steel plates repaired with different FRP thickness, i.e. 0.3 mm, 0.9 mm, 1.4 mm, 2.0 mm, and 2.8 mm, were investigated to compare the effect of FRP thickness on the SIF at the crack tip. Figure 7 plotted the SIF variation with the FRP thickness. It can be observed that the SIF reduced significantly with the increase of the FRP thickness. For the specimen with a crack of 25 mm, the SIF was decreased from 1083.5 MPa·mm$^{1/2}$ to 658.2 MPa·mm$^{1/2}$ when the FRP thickness increased from 0.3 mm to 2.8 mm, and the SIF ratio between repaired and un-repaired specimens reduced from 0.82 to 0.47 (Figure 7b). Therefore, the repair effect was more obvious with a thicker FRP.

![Figure 7. Variation of the SIF with the FRP thickness](image)

**Effect of the FRP Modulus**

Figure 8 shows the relationship between the SIF and the FRP elastic modulus. The steel plates were repaired by FRP laminates with the elastic modulus of 165 GPa, 210 GPa, 300 GPa, and 460 GPa, respectively. Results indicated that a higher FRP modulus resulted in a smaller SIF. From the Figure 8b, when the FRP modulus increased from 165 GPa to 460 GPa, the SIF ratios were about 0.78, 0.74, 0.67, and 0.58, respectively, for the 5 mm long crack; and were about 0.60, 0.56, 0.49, and 0.40, respectively, for the 25 mm long crack. It can be concluded that the FRP modulus had a considerable effect on the reduction of SIF.

![Figure 8. Variation of the SIF with the FRP modulus](image)

**Effect of the Adhesive Shear Modulus**

To assess the influence of the adhesive shear modulus on the SIF reduction, the steel plates repaired by 1.4 mm thick FRP were analysed with a shear modulus of 500 GPa, 900 GPa, 2000 GPa, 3000 GPa, and 4500 GPa, respectively. Figure 9 shows the SIF variation with the different adhesive shear modulus. The results showed that the SIF at the crack tip can be reduced by a higher adhesive modulus, demonstrating a more effective repair effect. For the specimen with a 25 mm long crack, the SIF decreased by 36.9%-46.9% compared to the un-repaired specimen. However, it can be also seen that the SIF reduction rate was slowed down with the
increase of the shear modulus. Moreover, it should be noted that a high shear modulus of adhesive can cause a high energy release rate of the FRP-to-steel interface (Colombi et al., 2003), which may introduce the risk of adhesive failure. Therefore, a proper adhesive modulus should be selected to make the balance between the SIF reduction and the FRP debond.

![Graph showing effect of shear modulus on SIF and SIF ratio](image)

**Figure 9. Variation of the SIF with the shear modulus of the adhesive**

**Effect of the Adhesive Thickness**

Figure 10 illustrates the effect of the adhesive thickness on the SIF at the crack tip; the adhesive thickness is 0.3 mm, 0.5 mm, 1.0 mm, 1.5 mm, and 2.0 mm, respectively. It can be seen that the SIF increased with the increase of the adhesive thickness, e.g. when the crack length was 25 mm, the SIF increased from 867 MPa·mm$^{1/2}$ to 1012 MPa·mm$^{1/2}$, and the SIF ratio increased from 0.58 to 0.67 when the adhesive thickness increased from 0.3 mm to 2.0 mm. Therefore, a thinner adhesive resulted in a smaller SIF. However, a factor should be taken into account that the thin adhesive may cause the risk of the FRP debond.

![Graph showing effect of adhesive thickness on SIF and SIF ratio](image)

**Figure 10. Variation of the SIF with the adhesive thickness**

**CONCLUSIONS**

This study was carried out to investigate the SIF of cracked steel plates repaired by FRP laminates using FE method. The effects of various parameters on the SIF were analyzed. The following conclusions can be drawn:

1. FRP repair can greatly reduce the SIF of cracked steel plates. The reduction effect of SIF became more significant with the increase of the crack length.
2. The FRP configurations had an effect on the SIF, so a proper FRP configuration may increase the repair effect of FRP laminates under equivalent tensile stiffness.
3. A higher FRP modulus, FRP thickness, and the adhesive shear modulus resulted in more reduction of the SIF, while the SIF became greater with the increase of the adhesive thickness.

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