Interfacial stress of carbon fiber patch bonded to transverse cracked steel plate reinforcement

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Abstract: A three-dimensional elastic-plastic finite element model was established in finite element software ANSYS to investigate the interfacial stress of carbon fiber patch bonded to transverse cracked steel plate reinforcement. The patch and adhesive were modeled as linear elastic. The steel plate was modeled as elastic-plastic. The load-deflection curve of the steel was obtained by bending test. The influence of crack depth, adhesive thickness, patch thickness and patch length on reinforcing efficiency was studied. The results show that the peel stress of the adhesive was distributed symmetrically along the center line, mainly concentrated on the crack center, near the crack and the patch ends. The peel stress at the crack center was always greater than the near crack. The shear stress is anti-symmetric along the center line, and the shear stress at the crack center is zero, mainly concentrated near the crack and plate end. The debonding may be initiated from the vicinity of the crack. Increasing the crack depth can significantly increase the peel stress and shear stress at the crack, but has little effect on the stresses at the end. Increasing the thickness of the adhesive can reduce the peel stress and shear stress at the crack center and near the crack, and the shear stress at the ends, but has little effect on the peel stress at the ends. Increasing the patch thickness can reduce the stress at the crack but increase the stress at the end. Increasing the patch length cannot reduce the stress at the crack, but significantly reduce the stress at the end.

1. Introduction
Metal materials in their service life-span, in addition to the applied external load, will inevitably be subjected to the erosion under the natural environment, thereby affecting the overall performance of the structure [1]. Carbon fiber composite has some excellent properties, such as high modulus, high strength and corrosion resistance and has been widely used in composite bonding repair metal materials [2].

Composite bonding repair technology has the advantages of simple operation, short repair time and no secondary damage to the repair parts [3]. The method is applied to the rehabilitation of airplane wings [4]. The early studies were mainly conducted by testing method. The researchers found that the size and shape of the patch has a great influence on the performances of the reinforcement. For example, the stress can significantly be reduced by employing an optimal shape patch [5]. The aluminum plate with holes bonded by a circular composite patch can restore to the mechanical properties before damaged [6]. Later, some researchers studied the stress distribution across the bondline of the composite bonding repaired structure [7]. The results showed that increasing the thickness of the patch would increase the stress at the end of the adhesive, and increasing the patch length can reduces the stress near the patch end, and increasing the thickness of the adhesive can reduce the bonding stresses. Other researchers use fracture mechanics methods to analyze the effects of composite reinforcement, focusing on the effects of parameter changes on stress intensity factors [11].
Although a lot of research has been done on the effectiveness of composite bonding repair technology, few scholars pay attention to the performance of the composite bonding reinforcement under bending load. In this paper, a three-dimensional finite element model was established in commercial numerical software ANSYS, the effect of crack depth, adhesive thickness, patch thickness and patch length on the repair effectiveness under bending load is explored, and the feasible suggestions are put forward for practical applications.

2. Finite element model and boundary conditions
The geometrical dimensions of carbon fiber patch bonded to transverse cracked steel plate are shown in Figure 1. Letting the center of the interface between the steel plate and the adhesive as the coordinate origin, the length direction as the X-axis, the width direction as the Z-axis, and the height direction as the Y-axis, finite element model was established in the commercial numerical software ANSYS.

![Figure 1. Geometric dimensions of the bonded reinforcement](image)

![Figure 2. Stress-strain curve of the steel](image)

Patch and adhesive are set as linear elastic materials. Material properties are shown in Table 1. Steel plate is set as elastic-plastic materials, and stress-strain curve is measured by bending test, as shown in Figure 2.

| Material       | Elastic modulus /Gpa | Poison's ratio | Tensile strength/Mpa | Specific elongation/% |
|----------------|----------------------|----------------|----------------------|----------------------|
| Steel plate    | 200                  | 0.3            | 450                  | 25                   |
| Adhesive       | 2.8                  | 0.3            | 30                   | 1.5                  |
| Carbon fiber patch | 210                | 0.28           | 3400                 | 1.6                  |

Table 1. Properties of materials

The steel plate, adhesive and patch were discretized by Solid185 element. The large deformation and automatic time step were turned on. The load step, the maximum load step and the minimum load step were set as 100, 1000 and 50, respectively. The displacement in the x direction and y direction at location of x=-70, y=0 were imposed to be zero, the displacement in the y direction at location of x=70, y=0 was constrained, the displacement load of -4mm was applied in the y direction at the line of x=0, y=4.6. Meshing and boundary condition are shown in Figure 3.
3. Parametric studies
Scaling studies have been conducted to examine the effects of the geometrical parameters of carbon fiber patch bonded to transverse crack steel plate reinforcement on the interfacial adhesive stresses in the bondline. The parameters studied include crack depth, adhesive thickness, patch thickness and patch length.

3.1 Crack depth
The effect of crack depth was evaluated by setting as 0.76mm, 1.53mm, 2.30mm, 3.08mm and 3.83mm respectively, while the other parameters were held constant. The shear and peel stress of the adhesive was extracted at the load of 2kN. The stress distribution of the adhesive along the bondline is shown in Figure 4, and the variation of peak stresses occurred at the crack center, near the crack and the patch ends with crack depth is shown in Figure 5. The peel stress at the ends of the patch was approximately 9, 2.7, 1.5, 1.1 and 1.1 times that at the crack center, and approximately 26, 6.6, 3, 2.1 and 2 times the secondary peak peel stress occurred at the near crack. The shear stress at the patch ends was approximately 6, 1.4, 0.8, 0.6 and 0.5 times that near the crack. It can be seen from the Figure 5, the shear stress at the near crack maybe great than that at the patch end. The debonding failure is dominated by the interfacial shear stress, therefore, the debonding caught be initiated from the vicinity of the crack.

The shear stress and peel stress of the adhesive change in a similar way with the crack depth. With the increases of crack depth, the peak peel and shear stress at and near the crack increase significantly. When the crack depth exceeds half of the thickness of the steel plate, the growth rate of peak stress begins to slow down. The peel stress and shear stress at the end change little. Therefore, changing the crack depth mainly affects the stress near the crack, but has little effect on the end stress.
3.2 Adhesive thickness

The adhesive thickness was set as 0.4mm, 0.8mm, 1.2mm and 1.6mm respectively, while the other parameters were held constant. The shear and peeling stresses are extracted at the load of 3kN. The interfacial shear and peel stress distribution along the bondline are shown in Figure 6. The variation of peak shear and peel stresses occurred at and near the crack and at the patch ends with the thickness of the adhesive are shown in Figure 7. The peak peel stress at the patch ends is 1.2, 1.5, 1.9 and 2.5 times that at the crack center, 2.3, 3.5, 7.4 and 25 times the secondary peak at near the crack. The shear stress at the end of the patch was 1.5, 1.1, 0.8 and 0.6 times that at near the crack.

As the thickness of the adhesive increases, the peak shear stress and peel stress of the adhesive at the crack decrease, while the peel stress at the patch end decreases slowly and then basically held unvaried. The shear stress at the patch ends also decreases. Therefore, increasing the thickness of the adhesive can reduce the peel stress and shear stress at the crack center and near the crack, and can also reduce the shear stress at the patch ends, but has little effect on the peel stress at the end of patch.

Figure 5. The variation of stress in adhesive with crack depth

Figure 6. Influence of thickness of adhesive on stress
3.3 Patch thickness

The patch thickness was set as 0.24mm, 0.48mm, 0.72mm and 0.96mm respectively, while the other parameters were not changed. The distribution of adhesive stresses was extracted at the load of 3kN and shown in Figure 8. The variation of the peak stress with the patch thickness is plotted in Figure 9. The results indicate that the peak peel stress at the patch end is approximately 0.6, 1.2, 2 and 2.4 times that at the crack center, and 1.2, 2.3, 4 and 7 times the secondary peak peel stress at the near crack. The peak shear stress at near the crack is 3.1, 1.5, 0.9 and 0.7 times that at the patch end.

With the increase of patch thickness, the peel and shear stresses at and near the crack decrease, while the peel and shear stress at the patch end increase. Therefore, increasing the thickness of patch can effectively reduce the stress at the crack, but increase the shear and peel stresses at the patch end, making the bondline more prone to debonding at the patch end. The initial debonding load of the structure is thus reduced in some situation.
3.4 Patch length

The patch length was set as 0.4mm, 0.8mm, 1.2mm and 1.6mm respectively, while the other parameters were held constant. The peel stress and shear stress of the adhesive were extracted at the load of 3kN, and shown in Figure 10.

It can be seen from Figure 10, the peak stresses at the crack center and near the crack almost do not vary with different patch lengths, which are about 7Mpa and 4Mpa respectively. When the length of the patch is 50mm, the peak peel and shear stress at the patch end are 19.1Mpa and 36.3Mpa respectively. The large value of interfacial stresses requires the adhesive to have a strong tensile strength. When the patch length is 100mm, the peak peel and shear stress are 8.7Mpa and 16.1Mpa respectively. When the patch length is 150mm, the peak peel and shear stress are 0.7Mpa and 1.4Mpa respectively, far lower than the failure stress of ordinary adhesives. When the patch length is 200mm, the peak peel and shear stress are almost close to 0. It can be concluded that increasing the length of patch cannot reduce the crack stress concentration, but can reduce the stress at the patch end.

4. Conclusion

(1) The peel stress of the adhesive was distributed symmetrically along the center line, mainly concentrated at the crack center, near the crack and the patch ends. The peel stress at the crack center was always greater than that near the crack. The shear stress is anti-symmetric along the center line, and the shear stress at the crack center is zero, mainly concentrated near the crack and the patch ends. The stresses at the patch end and the crack and the ratio between them vary with different parameters.
(2) Increasing the crack depth can significantly enhance the peel stress and shear stress at the crack, but has a little effect on the stresses at the patch end. When the crack depth is more than half the thickness of the steel plate, the stress increment starts to slow down. Increasing the thickness of the adhesive can reduce the peel stress and shear stress at the crack center and near the crack, and reduce the shear stress at the patch ends, but has little effect on the peel stress at the ends. Increasing the patch thickness can reduce the stress at the crack, but also increase the stress at the end of the adhesive. Increasing the patch length cannot reduce the stress at the crack, but can significantly reduce the stress at the ends.

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