Effect of repair methods on mechanical behaviors of repair area in composite laminate fuselage skin with different damage size

Liping Liu1*, Yucan Wang1, Jing Tian1, Rui Feng Wang1, Jianxin Xu1

1 School of Aviation Engineering, Civil Aviation University of China, Tianjin, China, 300300

Abstract: Composite laminates are widely used in the large civil aircrafts because of their excellent mechanical properties. The maintenance and repair of composite laminates become essential. In this paper, a new adhesive-rivet hybrid repair of composite laminate fuselage skin is presented. For the circular hole damage with the diameter of 90mm and 50mm, the finite element simulation models of adhesive repair and adhesive-rivet hybrid repair were built respectively. Uniform pressure load was applied on these finite element models. The mechanical properties of laminate motherboard, patch and adhesive film for these four models were analyzed. The effects of adhesive repair, adhesive-rivet hybrid repair on mechanical behaviors of repair areas of composite laminate fuselage skins with different damage size were studied. By analyzing the mechanical behaviors of these two repair methods, a suitable repair method can be obtained.

Keywords: stress distribution; adhesive repair; adhesive-rivet hybrid repair; composite laminate fuselage skin

1. Introduction

Composite laminate is a kind of ideal light structural material with high strength and specific stiffness, fatigue resistance, vibration resistance, thermal stability[1]. They are widely used in aerospace field because of their excellent mechanical property[2]. With the extensive use of composite laminate in large civil aircraft, airlines and aviation maintenance enterprises will spend a large number of resources for maintenance and repair of composite laminate.

The main repair methods of composite laminate are adhesive repair, rivet repair and adhesive-rivet hybrid repair. The adhesive repair is relatively mature, and is a major way used in engineering. For adhesive repair, Erdogan[3] and et al used complex variable function method to analyze the stress distribution and the stress intensity factor of the crack tip. Cheng[4] and et al used acoustic emission technology to locate structural damage of the adhesive repair composite laminate. They also studied the load carrying capacity and failure process. It was showed that the damage process of repairing structure process was affected by the stiffness of patch, and initial damage was mainly on the adhesive edge and gradually extended to the patch and the motherboard. In consideration of stiffener-skin debonding, web plate delamination and upper flange damage, Zhao[5] and et al designed corresponding repair programs and manufactured necessary specimens. All experiments showed that the influences of different repair parts, different repair methods on the mechanical properties of stiffened panels were different.

Mechanical connection repairs which are suitable repair in field which don’t need strict restriction of the repaired surface. The repaired structures are less susceptible to environment[6]. Xie[7] and et al built the finite element model of load distribution existed in multi-bolt joints of composite laminate, and analyzed the effect of stacking sequence and the number of the bolts on load distribution, and then done some optimizing design. Zhao[8] and et al used numerical simulation method to study the strength of the single-pin joint, and calculated the distributions of contact forces and the stress around hole and the limit strength of the single-pin joint, and then analyzed the effect of ply scheme proportions.

Copyright © 2018 Liping Liu et al.
doi: 10.18063/msacm.v2i3.797
This is an open-access article distributed under the terms of the Creative Commons Attribution Unported License (http://creativecommons.org/licenses/by-nc/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.
and orientations of the composite laminate on the stress distribution around the hole. Nie[9] and et al designed mechanical fastening repair of composite laminate with a circular hole. The repair effects on the failure loads, failure modes, stress distributions, and bolt load distributions were evaluated by tensile tests. The results of experiment and finite element analysis showed that the recovery rate of failure strength of bolted repair composite laminates reached about 55%-60%. The stress concentration was mainly produced nearby the outermost bolt holes in the repair area of the composite laminates.

Compared with the above two repair methods, the study of the hybrid repair of composite laminate was less. Furthermore, hybrid repair methods is also divided into adhesive-rivet hybrid repair and adhesive-bolt hybrid repair. For adhesive-bolt hybrid repair, Kelly[10] and et al built 3D finite element model to predict the load distribution of the hybrid (bonded/bolted) joints. Force transferring mechanism was analyzed. The load transferring ratios of adhesive films and bolts were calculated. The load distribution of hybrid joints was measured through experiments. Barut[11] and et al analyzed the mechanical property of adhesive-bolt hybrid joints of composite laminate on the condition of pre-tightening bolts. Dhanasekar[12] and et al analyzed the effect of loose bolt on the adhesive-bolt hybrid joints using finite element method. Kweon[13] and et al studied the effect of the properties of adhesive film material on the adhesive-bolt hybrid joints. Hart-Smith[14] have confirmed that bonding and bolting together do not achieve any significant advantage over adhesive bonding in well-designed intact structures. Zhang and et al conducted the tensile load experiments for the adhesive-bolt hybrid joints[15]. Chowdhury[16] and et al showed the FE models are able to accurately predict the bolted, bonded and hybrid joint strengths. However, all above reports were adhesive-bolt hybrid connection/repair instead of adhesive-rivet hybrid repair.

For adhesive-rivet hybrid method, Yao[17] and et al found that adhesive can strengthens the rivet in a joint during the early stage of loading, enhancing the stiffness of the structure. Gomez[18] and et al developed a damper spring model to simulate adhesive-rivet hybrid joints and the corresponding computing method. The reliability of the model was proved through experiments. Sadowski[19] and et al studied the influence of rivets’ lay-out geometry on the hybrid adhesive bonded/riveted joints response to the uniaxial tensile loading.

At present, the study for composite laminate repair was mainly focused on adhesive repair and mechanical connection repair. Although some studies on adhesive-rivet hybrid repair have been reported in little literature, still the mechanical properties of adhesive-rivet hybrid repair under out-plane uniform pressure load are unknown. In this study, the adhesive-rivet hybrid repair of composite fuselage skin is developed. For different circular hole damage size, the effects of adhesive-rivet hybrid repair and adhesive repair on stress distribution of motherboard, adhesive film and patch are analyzed respectively on the condition of applying out-plane uniform pressure load. By comparing the mechanical performances of these two repair methods with different circular hole damage size, suitable repair method can be acquired.

2. Validation of the FE Model

The machining properties of composite laminate are different from traditional materials. Preparation of test specimens is so difficult and the cost of composite laminate is very high. That makes the cost of time and material for the experimental study of the composite laminate repair to be very high. Due to the limits of experimental equipment, the mechanical performances of rivet, adhesive film and et al can’t be obtained. It makes the experiment can only get the ultimate load that the repair parts can tolerate. Experimental study of the composite laminate repair is bounded. In this study, the finite element simulation of the mechanical properties of composite laminate repair was conducted. The accuracy of the model had an important effect on the results. In order to ensure the accuracy of the finite element model of composite laminate repair, the following model was used to compare the finite element simulation results with the experimentation results.

The experimental product simulated by finite element analysis was composite laminate X850[9]. It mechanical properties are shown in Table 1. The total thickness and dimensions of motherboard were respectively 3.056mm and 420mm×120mm. Its plies sequence was [45/0/-45/90]₂₀. 30 mm circular hole damage was in center of the motherboard.
The patch with the same material had dimensions of 156mm×114mm×1.528mm. The plies sequence of the patch was [45/0/-45/90]s.

The meshing of motherboard and patch was swept with ANSYS Mechanical software employing Solid46 finite elements. This element has 8 nodes with 3 degrees of freedom in each node. Motherboard was divided into four layers along the thickness direction, and the patch was divided into two layer along the thickness direction, namely each layer contains 4 plies. The rivets were automatically meshed by Solid95 finite elements. This element has 8 nodes with 3 degrees of freedom in each node.

The rivet s were automatically meshed by Solid95 finite elements. The mesh model of repair parts is shown in Figure 1.

The contact between rivet and plate adopted the surface-surface contact with a friction coefficient of 0.2. Comparing results between finite element simulation and experimentation are shown in Table 2[9]. Seen from Table 2, the error between finite element simulation results and experimentation results was controlled within 10%. The error between the calculated value and experimental value was in an acceptable range. The results of calculation were reliable. The established finite element model of composite laminate repair was reasonable.

![Finite element model of mechanical connection repair](image)

**Figure 1.** Finite element model of mechanical connection repair

<table>
<thead>
<tr>
<th>Properties</th>
<th>Value</th>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>E_{11}/GPa</td>
<td>168.50</td>
<td>X_{11}/MPa</td>
<td>2785.60</td>
</tr>
<tr>
<td>E_{22}=E_{33}/GPa</td>
<td>10.30</td>
<td>X_{c}/MPa</td>
<td>1071.30</td>
</tr>
<tr>
<td>G_{12}=G_{13}/GPa</td>
<td>6.21</td>
<td>Y_{11}/MPa</td>
<td>74.80</td>
</tr>
<tr>
<td>G_{23}/GPa</td>
<td>3.0</td>
<td>Y_{c}/MPa</td>
<td>332.90</td>
</tr>
<tr>
<td>$v_{12}=v_{13}=v_{23}$</td>
<td>0.33</td>
<td>S/MPa</td>
<td>120.9</td>
</tr>
</tbody>
</table>

**Table 1.** Unidirectional material properties of X850

<table>
<thead>
<tr>
<th></th>
<th>Experimental broken load/kN</th>
<th>Calculation value/kN</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intact plate</td>
<td>401.2</td>
<td>440.3</td>
<td>9.71%</td>
</tr>
<tr>
<td>Damaged plate</td>
<td>180.9</td>
<td>196.3</td>
<td>8.53%</td>
</tr>
<tr>
<td>Repair plate</td>
<td>223.2</td>
<td>243.6</td>
<td>9.17%</td>
</tr>
</tbody>
</table>

**Table 2.** Comparing between calculated results and experimental results

### 3. Finite Element Model

Composite patch was adopted to repair the damaged composite laminate. The material of patch and motherboard was T300/QY8911 material whose material parameters is shown in Table 3[20]. The material properties of adhesive film are shown in Table 4. The material of rivet was titanium alloy as shown in Table 5. In this research, wedge models for
adhesive repair and adhesive-rivet hybrid repair were respectively built to study the different mechanical properties after repairing, and the diameters of circular hole damages were respectively 90mm and 50mm. All these models were applied by uniform load.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{11}$/GPa</td>
<td>135</td>
<td>$V_{23}$</td>
<td>0.48</td>
</tr>
<tr>
<td>$E_{22} = E_{33}$/GPa</td>
<td>8.8</td>
<td>$X_f$/MPa</td>
<td>1627.5</td>
</tr>
<tr>
<td>$G_{12} = G_{13}$/GPa</td>
<td>4.47</td>
<td>$Y_f$/MPa</td>
<td>68.4</td>
</tr>
<tr>
<td>$G_{23}$/GPa</td>
<td>3.2</td>
<td>$S$/MPa</td>
<td>89.1</td>
</tr>
<tr>
<td>$v_{12} = v_{23}$</td>
<td>0.33</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3. Material properties of T300/QY8911

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>E/GPa</td>
<td>1</td>
<td>$\mu$</td>
<td>0.3</td>
</tr>
<tr>
<td>S/MPa</td>
<td>45</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4. Material properties of adhesive film

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>E/GPa</td>
<td>135</td>
<td>$\mu$</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Table 5. Material properties of titanium alloy

3.1 Geometry Sizes of Two Repair Models

The wedge model of motherboard with the damaged composite laminate is shown in Figure 2. The diameter D of the damaged hole on the composite laminate is 90mm. The motherboard whose dimension is 584.9mm (L)×548.9mm (W)×3.86mm (t) consisted of 20 plies with a sequence of [0/45/90/-45/0]s. Each ply can be modeled as an homogeneous orthotropic elastic continuum. Each ply had a thickness of 0.193mm. The wedge angle $\alpha$ is 1.9°. The maximum radius R of the wedge area in the motherboard is 161mm. The adjoining patch and adhesive film as shown in Figure 3. The thickness of patch is half of that of motherboard. The sequence of patch is [0/45/90/-45/0]s. The radius of patch is 232.45mm as shown in Figure 4.

The adhesive-rivet hybrid repair is based on adhesive repair and rivet connection. This case consists of two cycles of rivets. Each cycle had 36 rivets. The arrangement of these rivets is based on staggered form as shown in Figure 5. The radius surrounded by inner rivets is 177mm, and the radius surrounded by outer rivets is 218.73mm. The diameter of the rivet is 6.35mm. Meshing diagrams of adhesive repair and adhesive-rivet hybrid repair are shown in Figure 6 and Figure 7 respectively.

![Figure 2](image-url)
3.2 Loading and Boundary Conditions

The boundaries of these repair models are constrained. The repaired composite laminates are applied a uniform
pressure of 0.06 MPa which is perpendicular to the plane. The loading condition is shown in Figure 8.

4. Results and Analysis

4.1 Repairing effect for 90 mm circular hole damage under two kinds of repair methods

In the Classical Laminate Theory, stress state of a single composite ply with very small thickness relative to other directions (length and width) in the plane can be approximated as plane stress state, that is, stress $\sigma_3$, $\tau_{23}$, $\tau_{31}$ is very small relative to stress $\sigma_1$, $\sigma_2$, $\tau_{12}$, and stress $\sigma_3$, $\tau_{23}$, $\tau_{31}$ can be approximately regarded as zero. However, when the stress state of laminated plates was examined in reference[21], it was found that the stress $\sigma_3$ was close to the failure strength of the material, and the reference[21] believed that ISO standard have underestimated the magnitude of the stress $\sigma_3$. Therefore, in order to characterize the stress state of parallel direction and vertical direction of each ply, stress $\sigma_1$, $\sigma_2$, $\sigma_3$, $\tau_{12}$ in ply are selected to consider.

Each ply with the same lay-up angle has the same stress distribution, so the first four plies (0° ply, 45° ply, 90° ply, -45° ply) are chosen to observe the stress distribution characteristics.

4.1.1 Comparison of the repairing effect between the motherlands under these two kinds of repair with 90mm circular hole damage

The stress distribution of the motherboard in two repair methods for 90mm circular hole damage is shown in Figure 9. As shown in Figure 9, for the stress $\sigma_1$ of motherboard by adhesive repair, the stress of 0° ply is concentrated around the outer border of the circumference with radius of 161mm, 0° direction of damaged hole and left and right edges of motherboard. The stress of 45° ply is mainly concentrated on upper and lower edges of motherboard. There is a low degree of stress concentration on -45° direction of motherboard and 45° direction of damaged hole. The stress of 90° ply mainly concentrate on upper and lower edges of motherboard. There is a low degree of stress concentration around the border of the circumference with radius of 161mm. The stress of -45° ply is mainly concentrated on upper and lower edges of motherboard. There is a low degree of stress concentration on 45° direction of motherboard and -45° direction of damaged hole.
The maximum stress of 0° ply appears on the 0° direction of damaged hole, while the maximum stresses of plies with other angles are on upper and lower edges of motherboard.

Compared with the stress $\sigma_1$ of motherboard by adhesive repair, the addition of rivets reduces the stress $\sigma_1$ of the motherboard by hybrid repair, there is a little stress concentration around the rivet holes. However, this does not change the stress distribution of the motherboard and the position of the maximum stress. Because the rivets bear shear load under uniform load, the stress $\sigma_1$ of motherboard by hybrid repair is lower than that by adhesive repair.

**Figure 9.** Distribution of stress $\sigma_1$ of the motherboards for two repair methods with 90mm circular hole damage.
Figure 10. Distribution of stress $\sigma^2$ of the motherboards for two repair methods with 90mm circular hole damage
The distribution of stress $\sigma_2$ of the motherboards for two repair methods with 90mm circular hole damage is shown in Figure 10. As shown in Fig.10, for the stress $\sigma_2$ of motherboard by adhesive repair, the stress of $0^\circ$ ply is concentrated around the outer border of the circumference with radius of 161mm, $90^\circ$ direction of damaged hole and upper and lower edges of motherboard. The stress of $45^\circ$ ply is mainly concentrated on left and right edges of motherboard. There is a low degree of stress concentration around damaged hole and $45^\circ$ direction of motherboard. The stress of $90^\circ$ ply mainly concentrates on left and right edges of motherboard. There is a low degree of stress concentration around the border of the circumference with radius of 161mm and $0^\circ$ direction of damaged hole. The stress of $-45^\circ$ ply is mainly concentrated on left and right edges of motherboard. There is a low degree of stress concentration around damaged hole and $-45^\circ$ direction of motherboard. The maximum stress of $0^\circ$ ply appears on the upper and lower edges of the motherboard, while the maximum stresses of plies with other angles are on left and right edges of motherboard.

Compared with the stress $\sigma_2$ of motherboard by adhesive repair, the addition of rivets reduces the stress $\sigma_2$ of the motherboard by hybrid repair, there is a little stress concentration around the rivet holes. However, this does not change the stress distribution of the motherboard and the position of the maximum stress. Same reason for stress $\sigma_1$, the rivets bear shear load under uniform load, which makes the stress $\sigma_2$ of motherboard by hybrid repair is lower than that by adhesive repair.
Figure 11. Distribution of stress $\sigma_3$ of the motherboards for two repair methods with 90mm circular hole damage

The distribution of stress $\sigma_3$ for two repair methods with 90mm circular hole damage is shown in Figure 11. As shown in Figure 11, for the stress $\sigma_3$ of motherboard by adhesive repair, the stresses of 0° ply, 45° ply, 90° ply, -45° ply are mainly concentrated on the area from the damaged hole to the border of the circumference with radius of 161mm. 0° ply bears compressive stress near the damaged hole. As the radius increases, the stress value increases gradually, and stress state changes from compression to tension. The 0° ply has a tendency to curl around the damage hole. 45° ply bears tensile stress near the damaged hole. With the increase of radius, the stress value increases sharply, and stress state changes from tension to compression. The 45° ply has a tendency to curl around the damage hole. 90° ply bears tensile stress near the tensile damage hole. As the radius increases, the stress value of ply decreases gradually, and stress state changes from tension to compression. The 90° ply has a tendency to curl around the damage hole. -45° ply is in compressive stress near the damaged hole. As the radius increases, the stress state of -45° ply changes from tension to compression. This ply has a tendency to curl on the area from the damaged hole to the border of the circumference with radius of 161mm.

Compared with the stress $\sigma_3$ of motherboard by adhesive repair, the addition of rivets reduces the stress $\sigma_3$ of the motherboard by hybrid repair on the area from the damaged hole to the border of the circumference with radius of 161mm. There is a little stress concentration around the rivet holes. However, rivets do not change the stress distribution of the motherboard and the position of the maximum stress.

The distribution of stress for two repair methods with 90mm circular hole damage is shown in Figure 12. As shown in Figure 12, for the shear stress of motherboard by adhesive repair, the direction of shear stress of each ply around
damaged hole is opposite to that around the outer border of the circumference with radius of 161mm. Shear stress of 0° ply or 90° ply is mainly concentrated on ±45° direction of the damaged hole and outer border of the circumference with radius of 161mm. The direction of shear stress of 0° ply is opposite to that of 90° ply in the same position. Shear stress of 45° ply or -45° ply is mainly concentrated on 0° and 90° direction of the damaged hole and outer border of the circumference with radius of 161mm. The direction of shear stress of 45° ply is opposite to that of -45° ply in the same position.
After the rivets are added, there is a low degree of stress concentration around rivet holes about the shear stress $\tau_{12}$ of motherboard by hybrid repair. However, compared with the shear stress $\tau_{12}$ of motherboard by adhesive repair, the distribution of shear stress $\tau_{12}$ of motherboard by hybrid repair has not changed. Because the rivet bears the shear load under the condition of uniform loading, the shear stress value of motherboard by hybrid repair decreases to some extent.

The stress concentration degree of the repaired structure is related to the magnitude of the stress, and the stress concentration degree will seriously affect the service life of the repaired structure. Therefore, the stress concentration degree is studied by taking the stress absolute value of the plies of the motherboard.

The comparison of the stress $\sigma_1$, $\sigma_2$, $\sigma_3$ and $\tau_{12}$ for two repair methods with 90mm circular hole damage is shown.
in Figure 13. As shown in Figure 13, stress $\sigma_1, \sigma_2, \sigma_3$ and $\tau_{12}$ of motherboard by hybrid repair are less than that by adhesive repair, especially stress $\tau_{12}$ of 0° ply, where the hybrid repair method plays an important role in reducing stress. This indicates that the rivets indeed bear load, which reduces the strain of the motherboard plies. Thus, compared with stress $\sigma_1, \sigma_2, \sigma_3$ and $\tau_{12}$ of the motherboard by adhesive repair, the stress $\sigma_1, \sigma_2, \sigma_3$ and $\tau_{12}$ of the motherboard by hybrid repair is reduced.

4.1.2 Comparison of the repairing effect between the patches under these two kinds of repair with 90mm circular hole damage

0° ply by adhesive repair  0° ply by hybrid repair

45° ply by adhesive repair  45° ply by hybrid repair

90° ply by adhesive repair  90° ply by hybrid repair
The distribution of stress $\sigma_1$ of the patches for two repair methods with 90mm circular hole damage is shown in Figure 14. As shown in Figure 14, for the stress $\sigma_1$ of patch by adhesive repair, the stress of 0° ply is concentrated on ±45° direction. The abrupt structure of patch in the circumference with radius of 161mm causes its strain to abrupt change, so the maximum stress of 0° ply appears the circumference with radius of 161mm. The stress of 45° ply is mainly concentrated on -45° direction. For the same reason with 0° ply, the maximum stress of 45° ply also appears in the circumference with radius of 161mm. The stress of 90° ply is mainly focused on 90° direction. For stress of the patch, the effect of the sudden change of the patch structure at the circumference with radius of 161mm was reduced. The maximum stress of 90° ply does not appear in the location with the radius of 161 mm, and appears in the central region of the patch. The stress of -45° ply is mainly concentrated on 45° direction. For the same reason with 90° ply, the maximum stress of -45° ply and all plies after it also appears in the central region of the patch.

Compared with patch by adhesive repair, the stress $\sigma_1$ of patch by hybrid repair is larger around the rivet area of patch, and the maximum stresses of all the plies occur around the rivet hole. The degree of load bearing decreases in the central region of the patch, but the stress distribution in the central region do not change. Because of the stress concentration around the rivet holes caused by the addition of rivet, the stress $\sigma_1$ of the patch by hybrid repair is greater than that of the patch by adhesive repair.
Figure 15. Distribution of stress $\sigma_2$ of the patches for two repair methods with 90mm circular hole damage

The distribution of stress $\sigma_2$ of the patches for two repair methods with 90mm circular hole damage is shown in Figure 15. As shown in Figure 15, for the stress $\sigma_2$ of patch by adhesive repair, the stress of 0° ply is concentrated on $\pm45^\circ$ direction. Because the abrupt structure of patch in the circumference with radius of 161mm causes its strain to abrupt change, the maximum stress of 0° ply appears the circumference with radius of 161mm. The stress of 45° ply is mainly concentrated on 45° direction. For stress of the patch, the effect of the sudden change of the patch structure at the circumference with radius of 161mm was reduced. The maximum stress of 45° ply does not appear in the location with the radius of 161 mm, and appears in the central region of the patch. The maximum stress of 45° ply and all plies after it also appears in the central region of the patch. The stress of 90° ply is mainly focused on 90° direction. The stress of
-45° ply is mainly concentrated on -45° direction.

Compared with patch by adhesive repair, stress $\sigma_2$ of patch by hybrid repair is larger around the rivet area of patch, and the maximum stress of all the plies occurs at the rivet hole. The degree of load bearing decreases in the central region of the patch, but the stress distribution in the central region do not change. Because of the stress concentration around the rivet holes caused by the addition of rivet, the stress $\sigma_2$ of the patch by hybrid repair is greater than that of the patch by adhesive repair.
Figure 16. Distribution of stress $\sigma_3$ of the patches for two repair methods with 90mm circular hole damage

The distribution of stress $\sigma_3$ of the patches for two repair methods with 90mm circular hole damage is shown in Figure 16. As shown in Figure 16, for the stress $\sigma_3$ of motherboard by adhesive repair, the stresses of 0° ply, 45° ply, 90° ply, -45° ply are mainly concentrated on the area connected with the adhesive film, and the maximum stress value of each ply also appears in this area.

Compared with the patch by adhesive repair, after the rivets are added, there is a certain degree of stress concentration around the rivet holes in the patch by hybrid repair. Furthermore, the maximum stress value of each ply also appears around the rivet hole. However, the degree of stress concentration around the rivet hole is small, and the stress value $\sigma_3$ of the patch by hybrid repair do not exceed that by adhesive repair.
90° ply by adhesive repair 90° ply by hybrid repair

-45° ply by adhesive repair -45° ply by hybrid repair

Figure 17. Distribution of stress $\tau$ of the patches for two repair methods with 90mm circular hole damage

The distribution of the in-plane shear stress $\tau$ of the patches for two repair methods with 90mm circular hole damage is shown in Figure 17. As shown in Figure 17, for the stress $\tau$ of patch by adhesive repair, the stress of 0° ply or ±45° ply are concentrated on ±45° direction. The stress of 90° ply is concentrated on 0° direction and 90° direction. The maximum shear stress $\tau$ of each ply appears in the central region of the patch.

Compared with patch by adhesive repair, the addition of rivets reduces stress $\tau$ of the central region of the patch by hybrid repair. But, this does not change the stress distribution in the central area of the patch. The stress concentration also occurs around the rivet hole. And, because the stress concentration degree around the rivet hole is larger, the maximum shear stress of the patch by the adhesive-rivet hybrid repair is greater than that by adhesive repair.
The comparison of the stress $\sigma_1$, $\sigma_2$, $\sigma_3$ and $\tau_{12}$ of the patches for two repair methods with 90mm circular hole damage is shown in Figure 18. As shown in Figure 18, stress $\sigma_1$, $\sigma_2$ and $\tau_{12}$ of patch by hybrid repair are larger than that by adhesive repair, while stress $\sigma_3$ of patch by hybrid repair is less than that by adhesive repair. This is because the addition ofrivets brings stress concentration around the rivet holes of the patch by hybrid repair, which makes the in-plane stress $\sigma_1$, $\sigma_2$ and $\tau_{12}$ of patch by hybrid repair larger than that by adhesive repair. But, the maximum value of stress $\sigma_3$ of the patch by adhesive repair is not exceeded.

4.1.3 Comparison of the repairing effect between the adhesive film under these two kinds of repair with 90mm circular hole damage

Figure 19. Von Mises stress of adhesive film

Figure 20. Peeling stress of adhesive film
Table 6. Comparison of adhesive film stresses for two kinds of repairs

<table>
<thead>
<tr>
<th></th>
<th>Adhesive-rivet</th>
<th>Adhesive</th>
<th>Rangeability/%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Von Mises/MPa</td>
<td>5.34</td>
<td>6.70</td>
<td>20.29</td>
</tr>
<tr>
<td>Maximum peeling stress/MPa</td>
<td>3.059</td>
<td>3.629</td>
<td>15.71</td>
</tr>
<tr>
<td>Maximum shear stress of XZ direction/MPa</td>
<td>2.76</td>
<td>3.689</td>
<td>25.18</td>
</tr>
<tr>
<td>Maximum shear stress of YZ direction/MPa</td>
<td>2.55</td>
<td>3.158</td>
<td>19.25</td>
</tr>
</tbody>
</table>

The Von Mises stresses and peeling stresses of adhesive film for these two kinds of repair methods are shown in Figure 19 and Figure 20 respectively. As shown in Figure 19, the Von Mises stress concentration at the peripheral edge of adhesive repair is more severe than that of adhesive-rivet hybrid repair. Because the rivets are added in the adhesive-rivet hybrid repair, the Von Mises stress concentration at the peripheral edge is decreased. As shown in Figure 20, the maximum peeling stress for these two kinds of repair methods are still at the peripheral edge because of the stress concentration.

The values of Von Mises stress, peeling stress and shear stress of these two repair method are listed in Table 6. The maximum value of Von Mises stress of the adhesive film under adhesive-rivet hybrid repair is 20.29% lower than that under adhesive repair. The maximum value of shear stress of adhesive-rivet hybrid repair is approximately 20% much lower than that under adhesive repair. The peeling stress of adhesive-rivet hybrid repair is 15.71% lower than that under adhesive repair. The rivets bear the load in the direction parallel and perpendicular to the laminate plane, which reduces the stress concentration of adhesive film caused by deformation for the 90mm circular hole damage.

4.2 Repairing effect for 50 mm circular hole damage under two kinds of repair methods

In this case, the motherboard had dimensions of 584.9mm (L) × 548.9mm (W) × 3.86mm (t). The repair models have a 50 mm circular hole damage whose wedge angle α is still 1.9°. The maximum radius R of the motherboard wedge area is 141mm. The thickness and sticking sequence of motherboard and patches are the same as the repair models with a 90 mm circular hole damage. For the adhesive-rivet hybrid repair model, the interval and edge distance keep in line with that of the hybrid repair model with a 90 mm circular hole damage. The inner cycle has 20 rivets, and the outer cycle has 26 rivets. The radius of rivets is still 6.35 mm.

4.2.1 Comparison of the repairing effect between the motherboards under these two kinds of repair with 50mm circular hole damage
The stress distribution of repair structure with the 50mm circular hole damage is the same as that of repair structure with the 90mm circular hole damage. So, the stress distribution of repair structure with 50mm circular hole damage will not be repeated. Instead, the stress absolute values of the two kind of repaired structures will be studied directly.

The comparison of the stress $\sigma_1$, $\sigma_2$, $\sigma_3$ and $\tau_{12}$ for two repair methods with 50mm circular hole damage is shown in Figure 21. As shown in Figure 21, stress $\sigma_1$, $\sigma_2$, $\sigma_3$ and $\tau_{12}$ of motherboard by hybrid repair are less than that by adhesive repair, especially stress $\tau_{12}$ of 0° ply, where the hybrid repair method plays an important role in reducing stress. This is because the rivets of repair structure with repair structure indeed bear shear load under the condition of uniform pressure loading, which reduces the strain of the motherboard by hybrid repair. Thus, compared with stress $\sigma_1$, $\sigma_2$, $\sigma_3$ and $\tau_{12}$ of the motherboard by adhesive repair, the stress $\sigma_1$, $\sigma_2$, $\sigma_3$ and $\tau_{12}$ of the motherboard by hybrid repair is reduced.

4.2.2 Comparison of the repairing effect between the patches under these two kinds of repair with 50mm circular hole damage

The comparison of the stress, and of the patches for two repair methods with 50mm circular hole damage is shown in Figure 22. As shown in Figure 22, stress, and of patch by hybrid repair are larger than that by adhesive repair, while stress of patch by hybrid repair is less than that by adhesive repair. For the same reason as 90mm circular hole damage, the addition of rivets brings stress concentration around the rivet holes of the patch by hybrid repair, which makes the stress, and of patch by hybrid repair larger than that by adhesive repair. But, the maximum value of stress of the patch by hybrid repair does not exceed that by adhesive repair.
Figure 22. Comparison of stress values of the patches for two repair methods with 50mm circular hole damage

4.2.3 Comparison of the repairing effect between the adhesive film under these two kinds of repair with 50mm circular hole damage

<table>
<thead>
<tr>
<th></th>
<th>Adhesive-rivet</th>
<th>Adhesive</th>
<th>Rangeability/%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Von Mises/MPa</td>
<td>10.93</td>
<td>11.82</td>
<td>7.52</td>
</tr>
<tr>
<td>Maximum peeling stress/MPa</td>
<td>6.41</td>
<td>7.57</td>
<td>15.32</td>
</tr>
<tr>
<td>Maximum shear stress of XZ direction/MPa</td>
<td>6.14</td>
<td>6.31</td>
<td>2.69</td>
</tr>
<tr>
<td>Maximum shear stress of YZ direction/MPa</td>
<td>5.86</td>
<td>6.36</td>
<td>7.86</td>
</tr>
</tbody>
</table>

Table 7. Comparison of adhesive film stresses for two kinds of repairs

The maximum values of Von Mises stress, peeling stress and shear stress of these two repair methods are listed in Table 7. Compared with adhesive repair, adhesive-rivet hybrid repair makes the maximum Von Mises stress of the adhesive film decrease by 7.5%, the maximum peeling stress of the adhesive film decreases by 15%, and the maximum shearing stress in two directions of the adhesive film decrease by approximately 2.6% and 7.8%. From the above analysis results, for the 50mm circular hole damage, rivets have played an important role in bearing load under the hybrid repair.

4.3 Repairing effect for 50 mm and 90 mm circular hole damage under adhesive repair

4.3.1 Comparison of the repairing effect between the motherboards of 50 mm and 90 mm circular hole damage under adhesive repair
Figure 23. Maximum stresses of motherboard plies with the 50mm and 90mm circular hole damage under the adhesive repair

Comparison of the maximum stress of motherboard plies about 50mm and 90mm circular hole damage under adhesive repair are shown in Figure 23. As shown in Figure 23, for adhesive repair, the stress $\sigma_1$, $\sigma_2$, $\sigma_3$ and $\tau_{12}$ of the motherboard with 50mm circular hole damage is greater than that with 90mm circular hole damage.

For adhesive repair, the patch size of the repair models with 50 mm circular hole damage is smaller than that with 90 mm circular hole damage, which makes that the strain of motherboard with 50 mm circular hole damage is larger than that with 90 mm circular hole damage under uniform pressure loading. According to the relationship between strain and stress, the stress of motherboard with 50 mm circular hole damage is larger than that with 90 mm circular hole damage.

4.3.2 Comparison of the repairing effect between the patches of 50 mm and 90 mm circular hole damage under adhesive repair

Figure 24. Comparison of stress values of the patches with the 50mm and 90mm circular hole damage under the adhesive repair
The comparison of the stress $\sigma_1$, $\sigma_2$, $\sigma_3$ and $\tau_{12}$ of the patches with the 50mm and 90mm circular hole damage under the adhesive repair is shown in Figure 24. As shown in Figure 24, stress $\sigma_1$, $\sigma_2$ and $\tau_{12}$ of patch with 90mm circular hole damage are larger than that with the 50mm circular hole damage, while stress $\sigma_3$ of patch with 90mm circular hole damage is less than that 50mm circular hole damage. This is because the size of patch of repair structure with the 90mm circular hole damage is larger than that of repair structure with the 50mm circular hole damage. The patch of the repair structure with 90mm circular hole damage bears more stress in the in-plane of ply. Therefore, the stress $\sigma_1$, $\sigma_2$ and $\tau_{12}$ of the patch of 90mm circular hole damage is greater than that 50mm circular hole damage. However, this also makes the strain of patch of the 50mm circular hole damage larger than the patch of the 90mm circular hole damage in the 3 direction, so the stress of the 90mm circular hole damage is smaller than that of the 50mm circular hole damage.

### 4.3.3 Comparison of the repairing effect between the adhesive film of 50 mm and 90 mm circular hole damage under adhesive repair

<table>
<thead>
<tr>
<th></th>
<th>90mm circular hole damage</th>
<th>50mm circular hole damage</th>
<th>Rangeability/%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Von Mises/MPa</td>
<td>6.70</td>
<td>11.82</td>
<td>43.32</td>
</tr>
<tr>
<td>Maximum peeling stress/MPa</td>
<td>3.629</td>
<td>7.57</td>
<td>52.06</td>
</tr>
<tr>
<td>Maximum shear stress of XZ direction/MPa</td>
<td>3.689</td>
<td>6.31</td>
<td>41.54</td>
</tr>
<tr>
<td>Maximum shear stress of YZ direction/MPa</td>
<td>3.158</td>
<td>6.36</td>
<td>50.35</td>
</tr>
</tbody>
</table>

Table 8. Comparison of adhesive film stresses under adhesive repair

The comparison of adhesive film stresses under adhesive repair with 50 mm and 90 mm circular hole damage is shown in Table 8. As shown in Table 8, for adhesive repair, the maximum value of Von Mises stress of adhesive film with 50mm circular hole damage is 43.32% higher than that with 90mm circular hole damage. The maximum value of peeling stress of adhesive film with 50 mm circular hole damage is 52.06% higher than that with 90 mm circular hole damage. The maximum value of shear stress of XZ direction of adhesive film with 50mm circular hole damage is 41.54% higher than that with 90mm circular hole damage. The maximum value of shear stress of YZ direction of adhesive film with 50mm circular hole damage is 50.35% higher than that with 90mm circular hole damage.

For adhesive repair, the patch size of the repair model with 50 mm circular hole damage is smaller than that with 90 mm circular hole damage, which makes that the Von Mises strain of adhesive film with 50 mm circular hole damage is larger than that with 90 mm circular hole damage. According to the relationship between strain and stress, the Von Mises stress of adhesive film with 50 mm circular hole damage is larger than that with 90 mm circular hole damage. For the same reason as Von Mises stress, the shear stress and peeling stress under adhesive repair with 50mm circular hole damage is larger than that with 90mm circular hole damage.

### 4.4 Repairing effect for 50 mm and 90 mm circular hole damage under hybrid repair

#### 4.4.1 Comparison of the repairing effect between the motherboards of 50 mm and 90 mm circular hole damage under hybrid repair

Comparison of the maximum stress of motherboard plies about 50mm and 90mm circular hole damage under adhesive repair is shown in Figure 25. As shown in Figure 25, for hybrid repair, the stress, and of the motherboard with 50mm circular hole damage is greater than that with 90mm circular hole damage.

For hybrid repair, the patch size of the repair models with 50 mm circular hole damage is smaller than that with 90 mm circular hole damage, which makes that the strain of motherboard with 50 mm circular hole damage is larger than that with 90 mm circular hole damage under uniform pressure loading. According to the relationship between strain and
stress, the stress of motherboard with 50 mm circular hole damage is larger than that with 90 mm circular hole damage.

![Comparison of the stress of motherboards with the 50mm and 90mm circular hole damage under the hybrid repair](image)

**Figure 25.** Comparison of the stress of motherboards with the 50mm and 90mm circular hole damage under the hybrid repair

### 4.4.2 Comparison of the repairing effect between the patches of 50 mm and 90 mm circular hole damage under hybrid repair

![Comparison of the repairing effect between the patches of 50 mm and 90 mm circular hole damage under hybrid repair](image)
Figure 26. Comparison of stress values of the patches with the 50mm and 90mm circular hole damage under the hybrid repair

The comparison of the stress $\sigma_1$, $\sigma_2$, $\sigma_3$ and $\tau_{12}$ of the patches with the 50mm and 90mm circular hole damage under the hybrid repair is shown in Figure 26. As shown in Figure 26, stress $\sigma_1$, $\sigma_2$ and $\tau_{12}$ of patch with 90mm circular hole damage are larger than that with the 50mm circular hole damage, while stress $\sigma_3$ of patch with 90mm circular hole damage is less than that with 50mm circular hole damage.

As can be seen from the stress distribution of patch by hybrid repair, the maximum value of the stress $\sigma_1$, $\sigma_2$, $\sigma_3$ and $\tau_{12}$ of the patch by hybrid repair method appear around the rivet holes for the 50mm and 90mm circular hole damage. For in-plane stress $\sigma_1$, $\sigma_2$ and $\tau_{12}$, the rivets bear shear load, which makes the stress concentration degree around the rivet holes of the patch with the 90mm circular hole damage larger than that with the 50mm circular hole damage under uniform pressure loading. Therefore, the stress $\sigma_1$, $\sigma_2$ and $\tau_{12}$ of the patch of 90mm circular hole damage is greater than that 50mm circular hole damage. However, the patch size of repair structure with the 90mm circular hole damage is larger than that of repair structure with the 50mm circular hole damage, which makes the strain of patch of the 90mm circular hole damage smaller than the patch of the 50mm circular hole damage in the 3 direction. So, the stress $\sigma_3$ of the 90mm circular hole damage is smaller than that of the 50mm circular hole damage.

### 4.4.3 Comparison of the repairing effect between the adhesive film of 50 mm and 90 mm circular hole damage under hybrid repair

<table>
<thead>
<tr>
<th>90mm circular hole damage</th>
<th>50mm circular hole damage</th>
<th>Rangeability/%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Von Mises/MPa</td>
<td>5.34</td>
<td>10.93</td>
</tr>
<tr>
<td>Maximum peeling stress/MPa</td>
<td>3.059</td>
<td>6.41</td>
</tr>
<tr>
<td>Maximum shear stress of XZ direction/MPa</td>
<td>2.76</td>
<td>6.14</td>
</tr>
<tr>
<td>Maximum shear stress of YZ direction/MPa</td>
<td>2.55</td>
<td>5.86</td>
</tr>
</tbody>
</table>

Table 9. Comparison of adhesive film stresses under hybrid repair

The comparison of adhesive film stresses under hybrid repair with 50 mm and 90 mm circular hole damage is shown in Table 11. As shown in Table 11, for hybrid repair, the maximum value of Von Mises stress of adhesive film with 50mm circular hole damage is 51.14% higher than that with 90mm circular hole damage. The maximum value of peeling stress of adhesive film with 50mm circular hole damage is 47.44% higher than that with 90mm circular hole damage. The maximum value of shear stress of XZ direction of adhesive film with 50mm circular hole damage is 55.05% higher than that with 90mm circular hole damage. The maximum value of shear stress of YZ direction of adhesive film with 50mm circular hole damage is 56.48% higher than that with 90mm circular hole damage.

For hybrid repair, the patch size of the repair model with 50 mm circular hole damage is less than that with 90 mm circular hole damage, which makes that the Von Mises strain of adhesive film with 50mm circular hole damage under
hybrid repair is greater than that with 90mm circular hole damage. According to the relationship between strain and stress, the Von Mises stress of adhesive film with 50 mm circular hole damage is greater than that with 90 mm circular hole damage. For the same reason as Von Mises stress, the shear stress and peeling stress under hybrid repair with 50mm circular hole damage are also greater than that with 90mm circular hole damage.

5. Conclusion

This paper studied the effects of adhesive-rivet hybrid repair and adhesive repair on the mechanical properties of repair areas in composite laminate fuselage skins with 90mm and 50mm circular hole damage and the following conclusions were drawn:

For repair structure with 90 mm circular hole damage, stress $\sigma_1$, $\sigma_2$, $\sigma_3$, $\tau_{12}$ of the motherboard, the stress $\sigma_3$ of the patch and Von Mises stress, shear stress, peel stress of adhesive film under adhesive-rivet hybrid repair is lower than that under adhesive repair, while the stress $\sigma_1$, $\sigma_2$, $\tau_{12}$ of the patch under adhesive-rivet hybrid repair is higher than that under adhesive repair.

Repair effect of structure with 50 mm circular hole damage is the same as that with 90 mm circular hole damage. For repair structure with 50 mm circular hole damage, the stress $\sigma_1$, $\sigma_2$, $\sigma_3$, $\tau_{12}$ of the motherboard, the stress $\sigma_3$ of the patch and Von Mises stress, shear stress, peel stress of adhesive film under adhesive-rivet hybrid repair is lower than that under adhesive repair, while the stress $\sigma_1$, $\sigma_2$, $\tau_{12}$ of the patch under adhesive-rivet hybrid repair is higher than that under adhesive repair.

For repair structure by adhesive repair, the stress $\sigma_1$, $\sigma_2$, $\sigma_3$, $\tau_{12}$ of the motherboard, the stress $\sigma_3$ of the patch and Von Mises stress, shear stress, peel stress of adhesive film with 50 mm circular hole damage is higher than with 90 mm circular hole damage, while the stress $\sigma_1$, $\sigma_2$, $\tau_{12}$ of the patch with 50 mm circular hole damage is lower than that with 90 mm circular hole damage.

The hybrid repair structure has the same performance as the adhesive repair structure. For repair structure by hybrid repair, the stress $\sigma_1$, $\sigma_2$, $\sigma_3$, $\tau_{12}$ of the motherboard, the stress $\sigma_3$ of the patch and Von Mises stress, shear stress, peel stress of adhesive film with 50 mm circular hole damage is higher than with 90 mm circular hole damage, while the stress $\sigma_1$, $\sigma_2$, $\tau_{12}$ of the patch with 50 mm circular hole damage is lower than that with 90 mm circular hole damage.

By comparing the repair effect of circular hole damage of different sizes for the two repair methods, we can know the influence of the addition of rivets on the repair structure and the influencing mechanism, which provides the basis for selecting the repair method.

Acknowledgements

This project obtained designated funds from National Natural Science Foundation (No. 51405491, No. 51605331), and Basic Scientific Research Foundation of Central University (No. 3122017028).

References

7. Xie YA. Performance study of composite mechanically fastened joints and joint design [D]. Harbin Engineering University 2013.
8. Zhao MY. Failure analysis of composite mechanically fastened joints and study of effects on failure strength [D]. Northwestern Polytechnical University 2006.