FAILURE MECHANISM OF A SINGLE-LAP HYBRID JOINT OF COMPOSITE LAMINATE SCREWED AND BONDED TO A STEEL PLATE

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1 Introduction

Adhesive bonding and mechanical joints are most frequently used in composite structures. When load is small, the adhesive bonding is usually used, while mechanical joints are applied when load is large with drilling holes on the composite structure for bolts, screws or rivets. Mechanical joints are much more reliable but heavier due to the introduction of fasteners compared with adhesively bonded joints. Thus, it is better choice to combine the mechanical joints and the adhesive bonding together. This kind of hybrid joints usually provide higher static strengths, better damage tolerance and resistance to peel stresses, fatigue properties and higher stiffness. Also, the use of adhesive provides a leak proof joint \cite{1-3} and additional locking devices are not needed during curing process \cite{1}.

G. Kelly and C. Hoang-Ngoc \cite{4, 5} studied the hybrid joint and reported the stress distribution of the joint. Kelly \cite{4} found the factors which would affect the load transferred by the bolt/screw such as the thickness of adhesive, adhesive modulus overlap length and pitch distance. C. Hoang-Ngoc \cite{5} compared the stress distribution of hybrid joint with corresponding bolted joint. Based on stresses calculated by FEA(Finite Element Analysis) software and the input of damage criteria, it’s possible to make the damage analysis. C. Santiuste et al., R.H. Lopez et al. and H.A. Whitworth \cite{6-8} studied different criteria in order to put up modified criteria that can be used in specified research work. The stiffness degradation is also important in FEA model as they greatly affect the failure behavior and ultimate strength of the joints \cite{9}.

In this paper, tensile test was carried out to study and acquire the failure process of the single-lap hybrid composite joints with flange. Finite element model was established using ABAQUS to simulate the failure process in hybrid joint. The holes and screws were modeled and friction between all contact surfaces was defined. Linear material model was used due to the weak adhesive bonding in this joint. It was found that the results from calculation of FEA model consistent well with the tensile test results. The influence of the flange on the failure behavior was also studied through the same FEA model.

2 Specimen design

The specimen used for tensile testing in this research work was a part from engineering structure. A composite laminate is fixed with a steel plate through 4 screws and adhesive as shown in Fig. 1. There is a flange at the end of the laminate because of the space limitation. The laminate was prepared using Resin Transfer Molding process and then four holes were drilled by sintered cutting tool. The adhesive film was inserted between the metal plate and the laminate, and then cured using Secondary Bonding.

The composite laminate consists of 12 plies of 3327/6808 (carbon fiber plain woven ply/epoxy), the ply sequences of the laminate are [(±45)/(0,90)]\textsubscript{2S}. The properties of 3327/6808 ply are shown in Table 1.
The plate made of steel 30CrMnSi was clamped to the laminate with 4 screws transversally distributed. The width of the composite laminate is 80 mm and the thickness is 3 mm with the flange height 12 mm, while the width of the metal plate is 80 mm and the thickness is 8 mm. All the 4 screws are of the same material of 30CrMnSi with diameter of 6 mm. The span between two adjacent screws is 20 mm, and the edge side distance is 10 mm, as shown in Fig. 2. The Young’s modulus of 30CrMnSi is 196 GPa, and Poisson’s ratio ν is 0.3. Yield of the steel was also taken into consideration, and the yield strength is 1105 MPa. The adhesive used for bonding is J-47A and the properties are: shear strength, τ =30 MPa, shear modulus, G=3 GPa and Poisson’s ratio, ν=0.3. Due to the adhesive is brittle, the material properties are considered to be linear.

3 Experiment and results

Tensile testing was carried out on material testing machine of INSTRON 8802 with loading speed 1 mm/min. The results for each material are averaged on 3 specimens with flange. The size and tensile failure load of each specimen are shown in Table 2. Fig. 3 and Fig. 4 show the digital images of the joint with flange before testing and after failure. Failure mode of the three specimens was almost the same. Damage was initiated within adhesive layer and the load was shifted or transferred to screws when the adhesive film completely broke. Fiber breakage of the composite started from the hole, and then expanded transversally to both right and left sides. Delamination occurred around the holes and the flange corner. The first cracking sound of the three specimens was heard at about 20 kN while applying load, but the ultimate strength of the specimens were dispersed. The composite failed at transversal center line of the hole while the screws were intact.

4 Numerical modeling

4.1 FEA model

To simplify this model, one eighth of the joint was modeled as shown in Fig. 4 and 3D solid element was used to get 3D stress distribution. Because we were mainly interested in the stress distribution in the highly concentrated stress areas, the mesh around the hole was relatively dense compared with the region away from the hole as shown in Fig. 6. In this model, the thread on the screw may cause a lot of difficulties in simulating the contact between the metal plate and the screw, so it was neglected to simplify the model as shown in Fig. 5. The screw and the steel plate were adhered together. Under external loading, the surface around the hole of the laminate deforms due to the pressure from the screw. Meanwhile the screw itself also deforms under bending and shearing loads, both of the deformations are highly nonlinear. Therefore, contact was added on the model in ABAQUS as shown in Fig.7.

In order to study the effect of the flange of the laminate, another FEA model was conducted after removing the flange as shown in Fig. 8.

4.2 Failure criteria and degradation rules for laminate plies

According to the joint failure phenomena and mode, the ply damage and interlaminar damage were assumed to be the major damage modes in the FEA model.

For plain woven ply, there are fibers in transverse direction providing constraints, so the Hasin classified damage criteria [10-13] modified for plain woven composites was introduced and F. K. Chang’s criteria [14] was used for failure of delamination. Equations for all criteria are given as followings:

Tensile failure of warp fibers (σ11>0):
\[
\left(\frac{\sigma_{11}}{Y_T}\right)^2 + \left(\frac{\tau_{12}}{S_{12}}\right)^2 + \left(\frac{\tau_{13}}{S_{13}}\right)^2 \geq 1
\]  
(1)

Compressive failure of warp fibers (σ11<0):
\[
\left(\frac{\sigma_{11}}{-Y_T}\right) \geq 1
\]  
(2)

Tensile failure of weft fibers (σ22>0):
\[
\left(\frac{\sigma_{22}}{Y_C}\right)^2 + \left(\frac{\tau_{12}}{S_{12}}\right)^2 + \left(\frac{\tau_{23}}{S_{23}}\right)^2 \geq 1
\]  
(3)

Compressive failure of weft fibers (σ22<0):
\[
\left(\frac{\sigma_{22}}{-Y_C}\right)^2 \geq 1
\]  
(4)

Fiber shear out of the resin:
\[
\left(\frac{\sigma_{11}}{Y_T}\right)^2 + \left(\frac{\tau_{12}}{S_{12}}\right)^2 + \left(\frac{\tau_{13}}{S_{13}}\right)^2 \geq 1
\]  
(5)

Tensile delamination (σ33>0):
\[
\left(\frac{\sigma_{33}}{Z_T}\right)^2 + \left(\frac{\tau_{13}}{S_{13}}\right)^2 + \left(\frac{\tau_{23}}{S_{23}}\right)^2 \geq 1
\]  
(6)

Compressive delamination (σ33<0):
\[
\frac{(\sigma_{11})^2}{Z_c} + \frac{(\tau_{13})^2}{S_{13}} + \frac{(\tau_{23})^2}{S_{23}} \geq 1
\]

(7)

In the previous criteria, \(\sigma_{11}\) and \(\sigma_{22}\) stand for longitudinal and transversal normal stress, \(\tau_{12}\), \(\tau_{13}\), \(\tau_{23}\) stand for shear stress in different directions, \(X_T\), \(X_C\) stand for longitudinal tensile and compressive strength, \(Y_T\), \(Y_C\) stand for transversal tensile and compressive strengths, \(Z_T\), \(Z_C\) stand for normal tensile and compressive strengths, \(S_{12}\), \(S_{13}\), \(S_{23}\) stand for inplane and interlaminar shear strengths.

Reddy focused on fiber damage and established a new stiffness degradation rules for damaged ply elements [15]. For plain weave ply, similar modification was made to the stiffness degradation rules according to the damage criteria mentioned above; consequently, the rules can be used to calculate the modulus of the weave ply after damage. For different damage forms, degradation rules are shown in Table 3.

4.3 Failure criterion and degradation rules for adhesive

As the adhesive is brittle, criterion of maximum shear stress was used for the adhesive. While the maximum shear stress is larger than the shear strength of the adhesive, the adhesive will fail. The maximum shear stress was calculated with formula as follows:

\[
\tau_{\text{max}} = \sqrt{\frac{(S_{11} - S_{33})^2}{2} + S_{13}^2}
\]

(8)

The properties of failed adhesive were reduced as following:

\[E_a = 0.01E_a, \nu = 0.01\nu\]

5 Results and discussion

Fig. 9 shows that the maximum stress of the screw reaches 879MPa, which is below the yield stress of 1105MPa, so the screws were kept intact throughout the tensile process. And this matches observation in the process of tensile testing.

Fig. 10 shows the load-displacement curve of the joint with/without flange. The curve shows that the joint with flange maintained higher stiffness after first damage occurring and achieved higher ultimate strength.

Investigating the failure process was the first part of this research work. In the second part, damage propagation was analyzed to find out the failure mechanism. Fig. 11-20 show different damage modes occurred in the joint with/without flange and their propagation paths.

Figs. 11-15 show the damage propagation of the adhesive and the laminate. It can be observed from the graphs that the adhesive between the laminate and metal plate failed before the laminate. When the load reached 20.6 kN as shown in Fig. 10, the damage area of adhesive reached the transversal center line as shown in Fig.11 (b). Meanwhile the laminate fibers started to break as shown in Fig. 14 (a) and Fig. 15 (a). It was the same time that the specimen sent out the first cracking sound. At the load of 36.8 kN, the surface of the hole extruded by the screw arbor was crushed as shown in Fig. 15 (c).

Fiber breakage propagated throughout the transversal center line. Fig. 13 shows that delamination occurred not only in the region around the hole, but also in the base of the flange, which consistent with the observation in the test.

Figs. 16-20 show that the damage propagation of the model without flange is quite different from the model with flange. At load of 21.5 kN, the damage area of adhesive reached transversal center line as shown in Fig. 16 (b) and meanwhile laminate fibers started to fail as shown in Fig. 19 (a) and Fig. 20 (a).

At the load of 32.1 kN, fiber breakage in the model without flange occurred and then propagated from the upper end (where the flange existed) towards the hole, thus resulting in an significant decrease in the ultimate strength as shown in Table 4.

6 Conclusion

Tensile test results of hybrid joint specimens show that damage is firstly initiated in adhesive layer and when the fibers start to fail, there will be a slight drop in the load. After the adhesive totally failing, there are only screws left to carry the load. The laminate failed throughout the transversal center line. Delamination occurred both in the region around the hole and the base of flange. During the whole process of tensile test, all the screws were intact.

The FEA model established with modified degradation rules for woven fabric agreed well with the test results. Average error in calculation of ultimate strength is 14.9%. And according to Fig. 11 and Fig. 15, shear out occurs in a lot of area. Thus, in this model, it should not be neglected.

After verification of FEA model, it was used to study the failure mechanism of the hybrid joint. The propagation in various failure modes show that the adhesive failed firstly from the lower end of metal plate, and propagated around the hole. When damage propagated towards the transversal center...
line, the stress concentration in the laminate increases instantly and fibers started to fail, resulting in cracking sound and a slight decrease in load. Fiber breakage went along the transversal center line to the side boundary and load fell in the end. Delamination was found around the hole first and later in the flange corner. Stress on the screw was always below the yield stress during the whole test. All these calculated results show good agreement with the tensile testing results.

The flange on the hybrid joint was important because it changed the failure mechanism of the joint. When first damage occurred in the composite laminate, the stiffness of the joint with the flange was slightly better than the one without flange. When damage occurred in the region around the hole, the removal of flange reduced the stiffness of the upper end, and changed the damage propagation path to the upper end (the end where the flange existed), resulting in a 22.1% decrease in ultimate strength.

Fig. 1 3D structure of the joint

Fig. 2 Dimensions of the joint with flange

Fig. 3 The picture of the joint with a flange before failure

Fig. 4 Tensile failure mode of the joint with a flange

Fig. 5 FEA model of the joint with flange

Fig. 6 Mesh of the adhesive
FAILURE MECHANISM OF A SINGLE-LAP HYBRID JOINT OF COMPOSITE LAMINATE SCREWED AND BONDED TO A STEEL PLATE

Fig. 7 Contact area in the model

Fig. 8 FEA model of the joint without flange

Fig. 9 Stress distribution of the steel and screw

Fig. 10 Load vs displacement of the joint with/without flange

Fig. 11 Damage propagation of the adhesive in the laminate with flange

Fig. 12 Damage propagation of fiber shear out in the laminate with flange

Fiber breakage occurs in the inner surface of the hole due to extrusion by the bolts as shown in Fig. 14 (c). Fiber breakage occurs in the upper end of the laminate.

Damage of the adhesive reaches the half of the area as shown in Fig. 10 (b). Fibers in composite start to fail as shown in Fig. 13 (a) and Fig. 14 (a). It’s the same in the joint without flange.
Fig. 13 Damage propagation of delamination in the laminate with flange

Fig. 14 Damage propagation of weft fibers in the laminate with flange

Fig. 15 Damage propagation of warp fibers in the laminate with flange

Fig. 16 Damage propagation of adhesive (laminate without flange)

Fig. 17 Damage propagation of shear out in the laminate without flange

Fig. 18 Damage propagation of delamination in the laminate without flange

Fig. 19 Damage propagation of weft fibers in the laminate without flange
FAILURE MECHANISM OF A SINGLE-LAP HYBRID JOINT OF COMPOSITE LAMINATE SCREWED AND BONDED TO A STEEL PLATE

Fig. 20 Damage propagation of warp fibers in the laminate without flange

Table 1 Properties of 3327/6808 ply

<table>
<thead>
<tr>
<th>Properties</th>
<th>E11(GPa)</th>
<th>Xt(MPa)</th>
<th>Xc(MPa)</th>
<th>E22(GPa)</th>
<th>Yt(MPa)</th>
<th>Yc(MPa)</th>
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</thead>
<tbody>
<tr>
<td>Value</td>
<td>75</td>
<td>750</td>
<td>550</td>
<td>74.2</td>
<td>750</td>
<td>550</td>
</tr>
</tbody>
</table>

Table 2 Failure process of the specimen

<table>
<thead>
<tr>
<th>Specimen number</th>
<th>Laminate size Bc×Tc (mm×mm)</th>
<th>Flange size Hf×Tf (mm×mm)</th>
<th>Metal plate size Bs×Ts (mm×mm)</th>
<th>Failure load (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>JJ-1</td>
<td>80.92×3.37</td>
<td>12.78×4.23</td>
<td>81.95×8.02</td>
<td>40.86</td>
</tr>
<tr>
<td>JJ-2</td>
<td>81.26×3.13</td>
<td>13.06×3.95</td>
<td>81.91×8.12</td>
<td>49.08</td>
</tr>
<tr>
<td>JJ-3</td>
<td>81.85×3.40</td>
<td>12.84×3.74</td>
<td>82.05×8.05</td>
<td>41.98</td>
</tr>
</tbody>
</table>

Table 3 Degradation rules of the plain weave plies for different damage forms [7, 16, 17]

<table>
<thead>
<tr>
<th>Damage mode</th>
<th>Degradation rule</th>
</tr>
</thead>
<tbody>
<tr>
<td>Failure of warp fibers</td>
<td>E_{11} = 0.07E_{11}, E_{33} = 0.2E_{33}, G_{12} = 0.07G_{12}, G_{13} = 0.07G_{13}, v_{12} = 0.07v_{12}, v_{13} = 0.07v_{13}</td>
</tr>
<tr>
<td>Failure of weft fibers</td>
<td>E_{22} = 0.07E_{22}, E_{33} = 0.2E_{33}, G_{12} = 0.07G_{12}, G_{23} = 0.07G_{23}, v_{12} = 0.07v_{12}, v_{23} = 0.07v_{23}</td>
</tr>
<tr>
<td>Shear out</td>
<td>G_{12} = 0.01G_{12}, v_{12} = 0.01v_{12}</td>
</tr>
<tr>
<td>Delamination</td>
<td>E_{13} = 0.01E_{13}, G_{12} = 0.01G_{12}, G_{13} = 0.01G_{13}, v_{23} = 0.01v_{23}, v_{13} = 0.01v_{13}</td>
</tr>
</tbody>
</table>
Table 4 Comparison of FEA model results with the test results

<table>
<thead>
<tr>
<th>Comparable items</th>
<th>Failure process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average value of Test</td>
<td>Fibers start to fail at load of 20 kN, laminate fails at 44.0 kN.</td>
</tr>
<tr>
<td>Model with flange</td>
<td>Fibers start to fail at load of 20.7 kN, laminate fails at 51.7 kN.</td>
</tr>
<tr>
<td>Model without flange</td>
<td>Fibers start to fail at load of 21.5 kN, laminate fails at 40.3 kN.</td>
</tr>
</tbody>
</table>

References


