1 Introduction

The Conformal Load-Bearing Antenna Structure (CLAS) enhances the new technology for aircraft antenna. This approach can reduce weight, drag and enhance electromagnetic performance, damage resistance and structural efficiency. However the technology is required to solve structural design difficulty, manufacturing complexity and limited electromagnetic performance.

For efficient structural design concept, adhesive bonding will be applied to form structural joint in CLAS. Adhesive bonding is a simple and cost-effective method compared to fastener joint. However there are some challenges in the bonding areas regarding adhesive selection, proper surface preparation and confidence in analysis. In this study, analytical model of adhesive allowable shear load and peel stress is provided and analysis results are compared with experimental data.

2 Lap shear strength test

2.1 Materials

Carbon U.D. Tape, Carbon Plain Weave & Fiber Glass Fabric prepreg were manufactured by Toray Composite America (TCA). DACC manufactured all the mechanical test laminates by laying up plies of the prepreg and the test panels were cured in accordance with Fig. 1 and Fig. 2.

2.2 Specimen Configuration

Figure 3 and 4 shows the configuration of the specimen and two holes were drilled to diameter 9mm into the adherend. Upon testing, the fixture was mounted to the specimens by inserting bolts to the holes and inserting the bolts into the mounting holes proved to protect surface damage of the specimen caused by wedge gripping directly. Each specimen was attached to the test fixture as shown in Fig. 5, 6, 7 and all testing was carried out on a 22.5 kip MTS test stand. All tests used displacement control at a rate of 2mm/min and data for the cross head displacement and load were collected using TEST WORKS software.

2.3 Test Matrix

The test matrix is designed to (1) evaluate the use of different substrate materials (2) evaluate the effect of bondline thickness (3) evaluate the effect of overlap length on the adhesive joint strength. Test matrix, shown in Table 1, made use of three different substrate materials, two different overlap lengths and three different bondline thicknesses. The effects of cold, room, and elevated temperatures as well as high moisture content were studied. The test matrix is designed to study the environmental condition on the adhesive joint strength as a function of bondline thickness and overlap length.

2.4 Testing at Elevated Temperatures

Before beginning the test, the temperature chamber and test fixture should be pre-heated to the specified temperature. Each specimen should be heated to the required test temperature as verified by a thermocouple in direct contact with the gage section. The heat up time shall not exceed 15 minutes and the test start 2+1/-0 minutes after the specimen has reached the test temperature. During the test, the temperature, as measured on the specimen, shall be within $\pm 3 \, ^\circ C$ ($\pm 5 \, ^\circ F$) of the required test temperature.

2.5 Testing at Sub-zero Temperatures
Each specimen should be cooled to the required test temperature as verified by the thermocouple. The test should start $5+1/-0$ minutes after the specimen has reached the test temperature. During the test, the temperature, as measured on the specimen, shall be within $\pm 3 \degree C$ ($\pm 5 \degree F$) of the required test temperature.

2.6 Traveler Specimens

Since the individual specimens may not be measured to determine the percentage of moisture content (due to size), traveler coupons (approximately $25.4 \text{ mm} \times 25.4 \text{ mm} \times$ specimen thickness) should be used to measure the weight gain. Individual traveler specimens should be obtained from the same panel of composite specimen.

2.7 Equilibrium Criteria for Solid Laminate

Effective moisture equilibrium is achieved when the average moisture content of the traveler specimen changes by less than 0.05% for two consecutive readings within a span of $7 \pm 0.5$ days. It may be expressed by

$$\frac{W_i - W_{i-1}}{W_b} < 0.0005$$

where:

$W_i$ = weight at current time

$W_{i-1}$ = weight at previous time

$W_b$ = baseline weight prior to conditioning

If the traveler coupons pass the criteria for two consecutive readings which are $7 \pm 0.5$ days apart, the specimens are removed from the environmental chamber and placed in a sealed bag along with a moist paper towel for a maximum of 14 days until mechanical testing.

3 Adhesive allowable shear load and peel stress

The analytical model compared with experimental data and it was found that the maximum lap shear strength can deviate as much as 10% from the analytical model. The adhesive allowable shear load can be evaluated as following;

$$P_{shear\ allow} = \frac{r_s \cdot 2c}{1 + 1 + \frac{3(1-\nu^2)}{k_s} \left(1 + \frac{r_s \cdot 2c}{(4r_s)^2} \frac{2\Delta^2}{\tan(2\Delta r)} - 1\right)}$$

(1)

$$\lambda = \sqrt{\frac{2G}{E_{s-f} \cdot t_f \cdot \eta}}$$

(2)

$$\lambda' = \sqrt{\frac{1 + \frac{3(1-\nu^2)}{k_s}}{G}}$$

(3)

where:

$k = \frac{1}{1 + \frac{P}{D} \cdot \frac{\nu^2 - c^2}{6}}$

$\xi = \sqrt{\frac{P}{D}}$

$k_s = \frac{E_s}{E_{s-f}}$

$E_s = \frac{12D(1-\nu^2)}{t_c^2}$

The peel stress can be evaluated as following:

$$\sigma_p = \sigma_{m} \cdot k_s \cdot \frac{3E_s (1-\nu^2) r_s}{2k_s E_{s-f} t_f \cdot \eta}$$

(4)

where, $\sigma_{m} = \frac{P}{t}$

To compare with experimental data, the minimum value of the analytical results is chosen and the general trend of lap shear strength was characterized as a function of bondline thickness, overlap length and environmental effects.

4 Results and Discussion

The RSP (Reliability Solution Provider, Inc., Ansan City) has been carried out the lap shear strength test using 22.5 kip MTS test stand and TEST WORKS software has been used to generate load and displacement data points. The obtained analysis data were measured using the peel stress method as shown in equation (4) and each experimental data point was an average of 3
specimens. Figure 9, 10, 11 shows the results for lap shear strength of specimens with three different adherend materials as a function of bondline thickness. The general trend remains the same for all three adherend types, i.e., decreasing strength with increasing bondline thickness in RTD condition. The failure mode for all composite adherend specimens was a result of interlaminar shear failure dominantly. The rotation of the adherends induces high peel stresses at the edges of the overlap while load is applied. The peel stresses exceed interlaminar shear strength of the matrix before the adhesive reaches a critical point therefore the lap shear strength is a characteristic of the adherend and of the bonded joint. Figure 12, 13, 14 also shows lap shear strength of specimens for two environmental conditions (CTD and ETW). The non-cohesive failures were pre-dominant in the cold dry conditions but the temperature was increased, these failure modes changed a mixed mode of substrate and cohesive failure. The wet $T_g$ value of adhesive was might be below the 82 °C testing environment and this explains the drop cause in strength values.

5 Conclusions

Composite specimen was tested using three adherend types, three different bondline thickness. As the adhesive bondline thickness increased, the lap shear strength decreased. It was observed that thicker bondlines decrease the strength of a joint by increasing the load path eccentricity induced to increase the peel stress in the joint. The increased peel stresses are most likely the only contributor to the decrease in strength of thicker bonds. Specimens were also tested over a range of environmental conditions. Lap shear strength was found to decrease as the adhesive was exposed to heat and moisture. The wet $T_g$ value of the adhesive was might be a significant effect on the lap shear strength of the adhesive joint.
Fig. 5. Experimental Setup (RTD)

Fig. 6. Experimental Setup (ETW)

Fig. 7. Experimental Setup (CTD)

Fig. 8. Geometry, nomenclature in bonded joint

Fig. 9. Lap shear strength (MPa) vs Paste adhesive thickness (mm), (Carbon U.D.)

Fig. 10. Lap shear strength (MPa) vs Paste adhesive thickness (mm), (Carbon Fabric)
LAP SHEAR STRENGTH OF ADHESIVELY BONDED COMPOSITES

Fig. 11. Lap shear strength (MPa) vs Paste adhesive thickness (mm), (Glass Fabric)

Fig. 12. Lap shear strength (MPa) vs Experimental Test Condition (Carbon U.D.)

Fig. 13. Lap shear strength (MPa) vs Experimental Test Condition (Carbon Fabric)

Fig. 14. Lap shear strength (MPa) vs Experimental Test Condition (Glass Fabric)

Table 1. Test matrix: Evaluation of different adherend materials, overlap length, bondline thickness and environmental effect

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>Lap pattern</th>
<th>Overlap length</th>
<th>Paste thickness (mm)</th>
<th>CTD (-54°C)</th>
<th>RTD (24°C)</th>
<th>ETW (82°C)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>SL001-Carbon U.D.</td>
<td>45°/45°/45°/45°</td>
<td>11.7 mm</td>
<td>0.2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>SL002-Carbon U.D.</td>
<td>45°/45°/45°/45°</td>
<td>20 mm</td>
<td>0.2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>SL003-Carbon U.D.</td>
<td>45°/45°/45°/45°</td>
<td>25.4 mm</td>
<td>0.2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>SL004-Carbon U.D.</td>
<td>45°/45°/45°/45°</td>
<td>11.7 mm</td>
<td>2.0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>SL005-Carbon U.D.</td>
<td>45°/45°/45°/45°</td>
<td>20 mm</td>
<td>4.0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>SL006-Carbon U.D.</td>
<td>45°/45°/45°/45°</td>
<td>25.4 mm</td>
<td>4.0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

6 References