Effects of Different Fiber Orientations on the Shear Strength Performance of Composite Adhesive Joints

Ferhat Kadioglu, Hasan Puskul

Abstract**—**A composite material with carbon fiber and polymer matrix has been used as adherent for manufacturing adhesive joints. In order to evaluate different fiber orientations on joint performance, the adherents with the 0°, ±15°, ±30°, ±45° fiber orientations were used in the single lap joint configuration. The joints with an overlap length of 25 mm were prepared according to the ASTM 1002 specifications and subjected to tensile loadings. The structural adhesive used was a two-part epoxy to be cured at 70°C for an hour. First, mechanical behaviors of the adherents were measured using three point bending test. In the test, considerations were given to stress to failure and elastic modulus. The results were compared with theoretical ones using rule of mixture. Then, the joints were manufactured in a specially prepared jig, after a proper surface preparation. Experimental results showed that the fiber orientations of the adherents affected the joint performance considerably; the joints with ±45° adherents experienced the worst shear strength, half of those with 0° adherents, and in general, there was a great relationship between the fiber orientations and failure mechanisms. Delamination problems were observed for many joints, which were thought to be due to peel effects at the ends of the overlap. It was proved that the surface preparation applied to the adherent surface was adequate. For further explanation of the results, a numerical work should be carried out using a possible non-linear analysis.

Keywords**—**Composite materials, adhesive bonding, bonding strength, lap joint, tensile strength.

I. INTRODUCTION

COMPOSITES, which consist of two or more separate materials combined in a macroscopic structural unit, are made from various combinations of the different metals, polymers and ceramics [1], [2]. Nowadays, carbon fiber reinforced polymer matrix composite materials become more and more important in the construction of primary aerospace structures. Aircraft parts made from composite materials, such as fairings, wings, radome, spoilers, and flight controls, were developed during the 1960s for their weight savings and strength over aluminum parts. New generation large aircrafts are designed using composite materials for manufacturing of fuselage and wing structures. For an aircraft, glass, aramid and carbon fibers are commonly used for reinforcement, and epoxy for matrix materials.

Advantages of composite materials are as follows; high resistance to fatigue and corrosion degradation, high resistance to impact damage, fiber-to-fiber redundant load path, high strength or stiffness to weight ratio. On the other hand, some disadvantages of composite materials should also be mentioned such as high cost of raw materials and fabrication, weak transverse properties, some difficulties in reuse and disposal, limited shelf life, low toughness, and difficulties in analysis.

Luckily, proper design and material selection of the composites can circumvent many of the above disadvantages. New technology has provided a variety of reinforcing fibers and matrices that can be combined to form composites having a wide range of exceptional properties. Since the advanced composites are capable of providing structural efficiency at lower weights as compared to equivalent metallic structures, they have emerged as the primary materials for future use.

One of the main challenges in aerospace structural parts is joining of these parts together. In joining process, several methods are used, bolted joints, bonded joints and use of both bolt and adhesive together named as hybrid joints, just examples of these methods. An adhesively-bonded single lap joint (SLJ), in which two sheets are joined together with an overlap, is one of the most common joint designs employed in industry. It is used for quality assurance, and by many researchers due to its simplicity to manufacture. Many uses of bonded structures occur in aerospace situations. This joint is usually manufactured and tested according to the ASTM Standard specification D1002. Adhesive bonding technique of fiber reinforced plastics has been studied by a number of researchers [3]-[11].

Mathews and Tester [3] investigated the effect of changes in a composite laminates' stacking sequence on the SLJ. Three different laminate thicknesses and 12 different fiber orientations were conducted under test. This allowed both the effect of the laminates' bending stiffness and the effect of fiber orientation to be investigated. It was observed that an increase in laminate bending stiffness resulted in an increase in joint strength. Mortensen [4] studied numerically the effect of different the stacking sequence of the plies in a laminate. The results showed that the transverse normal stresses within the adhesive layer increased by up to 58% at the overlap ends when the stacking sequences were changed from 0˚ to 45˚fiber orientations. The shear stresses also increased by up to 39% when the stacking sequences were changed. De Goeij [5] observed that when composite joints were subject to cyclic loading, the fatigue life of specimens was larger when the surface fiber orientation was 0^0 compared to $\pm 45^0$. More works have been carried out by some other researchers [6]-[11]. In general, it can be concluded that the strength of adhesively bonded joints depends on several factors such as joint

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geometry, adhesive type, adhesive thickness, adherent properties, loading directions and loading conditions.

The aim of this study is to investigate the effects of the adherents with different fiber orientations on the bonding strength. For this purpose, first, mechanical properties of a carbon fiber reinforced polymer matrix composite material with different fiber orientations were studied, then, the materials were bonded using a two-part epoxy. The joints manufactured according to the single lap joint configurations were tested in tensile loading.

II. Experimental Works

A. Materials Used

The adherent material used in this study was a carbon fiber reinforced polymer matrix composite material, and the adhesive used for bonding was a two-part epoxy, Hysol EA 9394 [12], a very common adhesive for structural applications in aerospace and aircraft components.

The adherents with 0^0, $\pm 15^0$, $\pm 30^0$ and $\pm 45^0$ different fiber orientations were manufactured consisting of 12 layers, balanced and symmetric.

The adherent materials were cured in a autoclave with the given values below;

- Cure temperature (^{0}C): 180 ±5
- Pressure (bar): 6.5 ± .30
- Hold time (min): 120-190
- Heat up rate (^{0}C/min): 0.5-3.5
- Cold down rate (^{0}C/min): 0.5-3.5

The composite materials were first manufactured as a plate with a dimension of 350 mm X 350 mm X 2.3 mm. Then, the plate was cut into beams with two different dimensions, 80 mm X 25 mm X 2.3 mm, and 113.5 mm X 25 mm X 2.3 mm. While the first types of the composite beams were used for three bending test, for measurements of mechanical properties of the material, the latter were used as adherents to be bonded, in the SLJ configurations.

1. Composites Beams under Three Point Bending Test

In order to evaluate the effects of the composite adherents with different fiber orientations on the adhesive joint performance, first, mechanical properties of the material were obtained using three point bending test. In investigating, considerations were given to dependence of elastic modulus and maximum bending stress against the different fiber orientations, 0^0, $\pm 15^0$, $\pm 30^0$ and $\pm 45^0$**.** The test specimens were prepared according to ASTM D792 [13], and the test configuration shown is in Fig. 1. All the tests were carried out using a universal Tenson tensile machine.

In order to determine the maximum bending stress (σ) and Young's Modulus (E) of the test specimens, (1) and (2) are used, respectively.

$$\sigma = \frac{M\gamma}{I} \tag{1}$$

$$\delta = \frac{PL^3}{48EI} \tag{2}$$

where; σ is the maximum bending stress at the top or bottom of the specimen (Pa); *M* is the bending moment (Nm); *y* is the distance from neutral axis (m); *I* is the moment of inertia (m^4); *P* is the applied force (N); *E* is Young's modulus (Pa); *L* is the length of the specimen between the supports (m); δ is the displacement of the specimen at the midpoint (m)

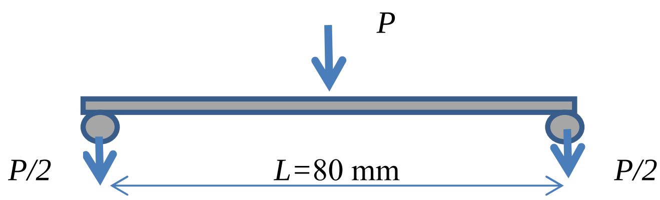

Fig. 1 Three point bending test for the composite material beams

2. Single Lap Joints under Tensile Loading

As mentioned above, the composite adherents were cut as beams for manufacturing of SLJs according to ASTM 1002 specifications [14]. A specially designed jig was used to accommodate the joints, which was able to give the specimens with a good quality. Before applying the adhesive, Hysol EA 9394, to the adherent surfaces, first, a sand paper, and then a chemical solvent, acetone was used to clean the surfaces. Since the adhesive was a two-part epoxy, a proper mixture of the adhesive was prepared and then applied to both surfaces of the specimens with an area of 25x25mm^2. In order to adjust thickness of the adhesive layer, some metal shims were used. After placing the specimens in the jig which was able to accommodate six ones at the same time, the jig was put in an oven for an hour at 70 ^{0}C, for curing the adhesive. All the specimens were tested at room temperature and 50% relative humidity. The dimension of the SLJ is shown in Fig. 2.

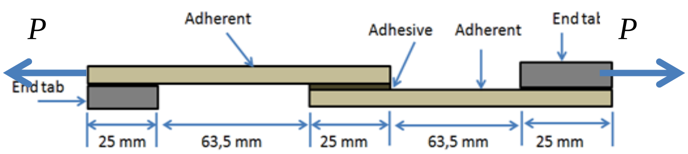

Fig. 2 Single lap joint specimens for shear performance of the adhesive under tensile loading

For calculation of the shear stress of the adhesive, (3) was used

$$\tau = \frac{P}{A} \tag{3}$$

where; τ is the shear stress of the adhesive in the overlap region (Pa); *P* is the applied load (N); *A* is the cross-sectional area (m^2).

III. Results and Discussions

In order to make sure that the specimens give reliable and repeatable results, at least five specimens were tested for each type. The test speed was 2 mm/min for every specimen.

Table I shows the values of maximum bending stresses verses different fiber orientation angles, from the composite material beams under three point bending test. It is seen that while the beams with 0^0 fiber orientations give the maximum stress, about 2144 MPa, those with $\pm45^0$ give the minimum value, about 396 MPa. It is clear that the stresses decrease with increases in fiber orientation angles. The lost in the stress is about 36%, 50% and 82% for $\pm15^0$, $\pm30^0$ and $\pm45^0$ fiber orientations, respectively, compared to the unidirectional beams.

TABLE I
MAXIMUM BENDING STRESSES OF COMPOSITE BEAMS AGAINST DIFFERENT FIBER ORIENTATIONS

Fiber orientation angle	Maximum bending stress, σ, MPa
0^0	2144±286
$\pm15^0$	1390±80
$\pm30^0$	1086±24
$\pm45^0$	396.20±63.80

Table II shows elastic modulus of the adherents verses different fiber orientation angles, which is quite similar to the results from Table I. Again, the maximum elastic modulus was obtained from the unidirectional adherents, while the minimum value was from those with $\pm45^0$ fiber orientations. The lost in the modulus was 17%, 55% and 85% for the beams with $\pm15^0$, $\pm30^0$, $\pm45^0$ fiber orientations, respectively. It should be pointed out that the results from Table II were compared to those using rule of mixture and they were in a good agreement.

In general, it is fair to say that the fiber orientation angles have a great effect on the stress and elastic modulus of the composite beams.

TABLE II
YOUNG'S MODULUS OF COMPOSITE ADHERENTS AGAINST DIFFERENT FIBER ORIENTATIONS

Fiber orientation angle	Young's modulus, E, GPa
0^0	124.25±1.44
$\pm15^0$	103.26±1.82
$\pm30^0$	57.80±1.33
$\pm45^0$	18.71±0.30

Fig. 3 shows shear stress performance of the adhesive, Hysol EA 9394, in SLJ under tensile loading when the adherents with different fiber orientation angles were used. It is seen from the figure that the maximum shear stress, 18 MPa, is obtained with the unidirectional adherents which did not fail during the test, and they remained elastic after the loading (Fig. 4). When the adherents with $\pm15^0$ and $\pm30^0$ fiber orientations were used, the shear stresses decrease considerably, about 12 MPa and 10 MPa, respectively, meaning 33% and 44% lost in shear stress performance compared to those with 0^0 adherents. During the test, some local failures were observed in the layer of composite, next to side edges, seen in Fig. 5. The minimum shear stress value of the joint was from the adherents with $\pm45^0$ fiber orientations, about 9 MPa. In this case, the lost in shear stress performance is about 50%. A global failure of the adherents was observed during the test, prior the failure in the adhesive layer.

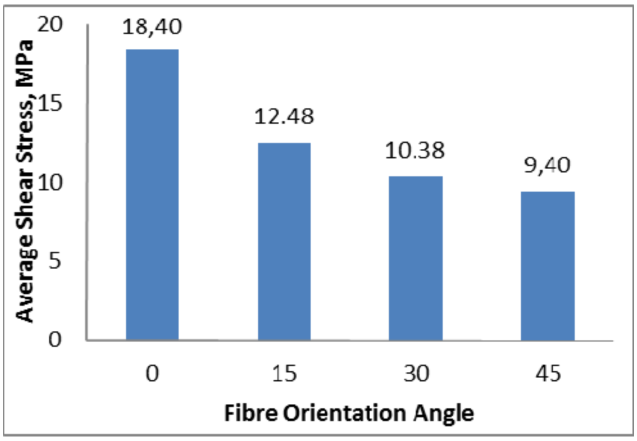

Fig. 3 Shear stresses of the adhesive, Hysol EA 9394, against fiber orientation angle of the composite adherents

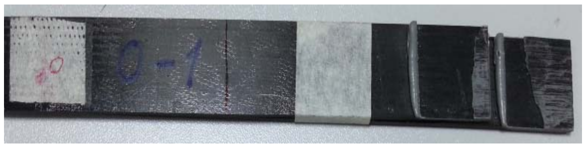

Fig. 4 The unidirectional adherents of single lap joint after the tensile test, which remained elastic without local or global failure

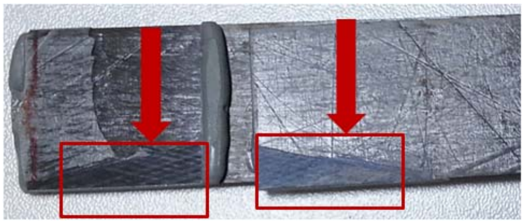

Fig. 5 The adherents of single lap joint after the tensile test, with $\pm30^0$ fiber orientations, which experienced local failure at the side edge

IV. CONCLUSIONS

Shear stress performance of the adhesive, Hysol EA 9394, has been evaluated using single lap joint configuration. In order to see the effects of adherent mechanical properties on the shear performance of the joint, carbon fiber reinforced polymer matrix composite materials with 0°, ±15°, ±30°, ±45° fiber orientations were bonded. It has been shown that the adherents with different fiber orientation angles have great effects on the joint strength. While the best performance was obtained from the adherents with 0° fiber orientations, the worst ones from those with ±45°ones. The results are directly related to the mechanical properties of the composite adherents. For a better understanding of the joint failure, a detailed numerical study should be undertaken.

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