Analysis of Adhesively Bonded Joints in Composite Materials – Radial Abrasive Surface Preparation

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Abstract— This work is concerned with the effects of abrasive surface preparation on epoxy adhesive joints in Glass Fibre Composite materials. The Glass Fibre Composite was prepared from unidirectional woven glass fibres. Araldite LY556 and Aradur HY 951 served as the epoxy and hardener respectively. The abrasion was performed in a radial surface pattern before the adhesion of the composite materials in a single shear lap joint. The test variables for abrasion include varying grades of abrasive sanding sheets and varying abrading time periods. Shear testing of the specimens was carried out in a Universal Testing Machine. The yield point and failure mechanisms were analysed and discussed. Using this data, the viability of using radial abrasion as a surface preparation technique was determined.

Keywords— Adhesive Bonding, Radial Abrasive Surface Preparation, Glass Fibre Composite Materials

I. INTRODUCTION

Composite materials have seen a wide variety of applications in recent times. Composite materials are widely used in applications where a high tensile strength is required and in areas where weight is considered to be a premium. When referring to the structural integrity, the structural integrity of the composite materials does not only depend on the strength of the composite laminate but perhaps, more importantly on the joints between the composite materials. Usually, the joint is considered to be the weakest part of the composite material so efforts must be taken to strengthen the joints [1, 2].

The methods of joining are divided into Mechanical methods and Adhesive methods. The Mechanical methods include riveting and bolting. However, these methods cause a substantial increase in weight and also create an unequal stress distribution over the surface. Conversely, adhesive bonding methods do not cause a substantial increase in weight. Adhesive bonding methods also create a smooth load transfer and an equal stress distribution over the surface whilst minimizing stress concentration at any particular point.

However, simply bonding two composite materials does not yield a durable joint as determined by Winefield [3]. Suitable surface preparation must be performed to ensure that a strong and durable joint is formed. Though extensive study has been performed on surface treatment methods such as Alkaline Etching method [4, 5] and Laser treatment method [6], the study on the effects of radial surface abrasion using abrasive sheets has been limited.

Testing was carried out by performing the surface abrasion using different grades of abrasive sanding sheets and varying time periods. The different grades of abrasive sanding sheets and the varying time periods were taken as the test variables. The result analysis of the abrasion procedures led to the determination of the efficiency of the abrasion procedure. Efforts were taken to ensure that the entire experimental process involved as little machine – human interaction as possible. The reduced human interaction resulted in good experimental accuracy. Another advantage that was observed was the presence of consistent results. Though some work has been performed on surface preparation in composite materials, with researchers such as Niem P.I.F. et al. [7], who studied the surface characteristics of the composite material after the application of suitable surface preparation techniques. However, as with most of the work previously done with abrasive surface preparation, the effects of radial surface abrasion has not been widely studied or analysed. Through this study, we have been able to find that the advantages of using the radial abrasive methods over bonding without abrasive surface preparation.

With regard to the variables used for the experimental study, three different grit grades of abrasive sheets and three different time periods were considered as the testing variables. The three different grit grades that were used were 36 Grit, 40 Grit and 50 Grit. The different grit grades were utilized for abrasion along an axis, radial to the test specimens. Three different time periods were considered. A time period difference of 5 seconds was taken for the tests. The objective of abrasive testing is to create an appropriate surface roughness to aid in the adhesion process. Theoretically, the presence of grooves and ridges result in a greater surface roughness which translates to a larger bonding area.

Based on the work of Renton et al. [8], a single lap shear joint proved to be most efficient for our test procedure. A tensile test was used to determine the adhesive bond strength of the bonded specimens. The tensile load capability of the adhesively bonded joint was suitably investigated using
this procedure. S. Mall and W.S. Johnson [9] determined the conditions for failure and the correlated the mode of failure for the same. The failure mode analysis was performed to
determine the mode of failure of the individual bonded
specimens. With the results obtained from the tensile test and
the failure mode analysis, it was possible to correlate the
degree of surface abrasion and its effects of the bond strength
of an adhesively bonded single shear lap joint.

II. MATERIALS AND EXPERIMENTAL PROCEDURES

A. Materials

The materials used for making the composite laminate are E
type Glass Fibre (GSM 220), Araldite LY556 liquid bisphenol –A Epoxy resin and Aradur HY951 anhydride
Hardener. The glass fibre used is unidirectional and exhibits
excellent tensile characteristics when reinforced with epoxy
resin. The reason for choosing these particular materials is that
they are relatively cheaper to procure and are readily available in the market.

<table>
<thead>
<tr>
<th>Elastic Constants</th>
<th>Values (Gpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal Modulus $E_l$</td>
<td>53 – 59</td>
</tr>
<tr>
<td>Transverse Modulus</td>
<td>16 – 20</td>
</tr>
<tr>
<td>Axial Shear Modulus</td>
<td>6 – 9</td>
</tr>
<tr>
<td>Poisson’s Ratio</td>
<td>0.26 – 0.28</td>
</tr>
</tbody>
</table>

Table 1. Properties of the Glass Fibre Composite

B. Laminate Preparation

The glass fibre was cut into dimensions of 50x50cm. Eight
such sheets of glass fibre were used for preparing the
laminate. The weight of 8 sheets of glass fibres was
measured collectively. The collective weight was found to be 500gms.
10% of the Total weight of the fibre is to be the weight of the
resin i.e 0.1 x 500 =50gms. 10% of the weight of the resin is to
be the weight of hardener i.e. 0.1 x 50 = 5gms. 50gms of resin
and 5gms of hardener is used to between layer of glass
fibre sheet. A 60x60cm tile was used for the preparation of the
laminate. A Mylar sheet of (150 microns) was placed on either
surface of the laminate to prevent adhesion between glass fibre
and the tile. 8 Layers of glass fibres were adhered to each
other by using suitable quantity of epoxy resin and hardener.
The sheets of glass fibres were placed in the same direction as
the previous sheet and the application of the resin had to be
unidirectional. A layer of Mylar sheet was placed on either
side of the laminate. An Iron Plate of weight 60 Kilograms
was placed over the wet laminate and the laminate was
allowed to cure. The duration for which the laminate was
allowed to cure was 30 hours.

C. Test Specimens

The Test specimens were cut from the laminate to make
Shear Lap joints. Shear lap joints were found to be ideal for
the testing of bond strength [8]. The test was applicable for the
determination of adhesive strengths, surface preparation
parameters and adhesive environmental durability. There are a
variety of ASTM single lap joint shear tests including ASTM
D1002, ASTM D3163 for plastic joints, and ASTM D5868 for
Fibre Reinforced Plastics (FRP) against itself or metal [10].
The Table for dimensions of specimen is illustrated below.

<p>| Thickness of | Thickness of | Length of | Width of | Overlap |
| Adhesive     | Specimen     | Specimen   | Specimen  | between |</p>
<table>
<thead>
<tr>
<th>layer(mm)</th>
<th>(mm)</th>
<th>(mm)</th>
<th>(mm)</th>
<th>two</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>2.5</td>
<td>100</td>
<td>25</td>
<td>25</td>
</tr>
</tbody>
</table>

Table 2: Dimensions of the test specimen

An expression proposed Davies et al. [11] was used to obtain
the optimal joint thickness.

\[ h = 2.6r_0 \left( \frac{E_G}{\sigma_f} \right) \]

The overlap distance (30 millimetres) is the area on the
specimen which is abraded by different grades of abrasive
sheets. After reducing the specimens to required dimensions, the
test tiles were bonded to form shear lap joints. A
rectangular Mylar sheet window of inner dimension 24x24x2
mm and outer dimension 26x26x2 mm was cut from the Mylar
sheet which was placed between the two bonding specimens.
This was done to maintain the adhesive layer thickness of
0.2mm [11]. After bonding, the specimens were clamped
together and allowed to cure for a time period of 48 hours.

D. Test Procedure

Two specimens, each 100 x 25 x 2.5 mm were bonded

together with the adhesive (Epoxy resin) and cured. Overlap
was sufficient to provide failure in the adhesive, and not in the substrate. The test specimens were placed in the grips of a Universal Testing Machine. ASTM D5868 for Fibre Reinforced Plastics, Specifies a loading rate of 13mm/min (0.5 in/min) until failure. The Data obtained from this testing is 1) Max Failure load / Ultimate Breaking Load 2) Failing Stress / Ultimate Stress 3) Type of Failure (Cohesive, Adhesive or Mixed Mode Failure). The Data is represented in a graphical form.

E. Experimental Setup

The sanding apparatus was designed and fabricated to uniformly abrade the composite test specimens. The abrasive test setup involves the use of abrasive sheets of varying grit size. The composite specimen is fixed while the abrading disk moves radially along a fixed axis of rotation. The abrasion takes place when the abrasive sheet makes contact with the surface of the composite specimen.

The test variables include varying grit grades of abrasive sheets and varying time periods. To account for the first test variable, three different rotating disks are affixed with different grit grades of abrasive sanding sheets. To account for the second test variable, a common rotating disk is utilized and a stopwatch is used to time the test periods.

Fig 3. Front View and dimensions of the rotating abrasive disk

The setup consists of a circular disk of diameter 160 millimetres and a thickness of 10 millimetres. A tapered hole is drilled at the centre of the circular disk of diameter 13 millimetres to hold a 125 millimetre long steel tube. The abrasive sheets of varying grit grades are affixed to the circular disks using Yamapoxy – an industrial grade adhesive manufactured by dendrite. After performing TIG welding between the tube and the disk, the tube is clamped in the jaws of a radial drilling machine. This allows for rotation of the abrading disk. The base on which the specimen is to be abraded is carefully leveled to ensure a smooth surface contact with the abrading disk. Aluminium fasteners hold the composite specimen firmly in place during abrasion process.

Fig 4. Isometric view and dimensions of the rotating abrading disk

III. RESULTS

As the objective of the study is to determine the bond strength, the most suitable joint to study the bond strength as described by Renton W.J. and Vinson V.R. [8] was found to be the shear lap joint. By placing the individual bonded specimens between the Universal Testing Machine and applying an axial load, the point of failure of the bonded specimen was determined. The bonded specimens were tested in order, according to the test variables. The tests for both Grit Grade and time period were carried out in ascending order.

From the test data obtained, graphs are plotted with Displacement along the X axis and the Load along the Y axis. The Displacement is measured in millimetres and the load is measured in Kilo Newton. The Stress vs. Strain graph was also plotted with the Strain taken in percentage, along the X axis and the Stress, taken in Kilo Newton per millimetre square, taken along the Y axis. To account for deformities and external factors, three samples were tested for every test variable. These tests are represented in the corresponding graphs by the use of different coloured graph lines.

In the following graphs, the red graph line corresponds to the first test or TEST 1, the green graph line corresponds to TEST 2 and the blue graph line corresponds to TEST 3.

A. Load Versus Displacement

The Load Versus Displacement graph denotes the displacement of the test specimen for the corresponding load applied. The displacement value rises with the increase in load, until the yield point is reached. The yield point is the point on the graph at which the material failure occurs.
B. Stress Vs. Strain

The Stress Versus Strain graph denotes the degree of Stress produced to percentage of strain produced. The Stress value rises with the increase in Strain, until the yield point is reached. The yield point is the point on the graph at which the material failure occurs. By plotting these points on a graph, the curve can be observed and studied.
IV. DISCUSSION

A. Maximum Yield Point

The above graphs represent the maximum yield point for the Load vs. Displacement and the Stress vs. Strain Graphs. On closer examination of the above graphs, a pattern becomes apparent in the Load vs. Displacement series of graphs. The highest yield point in the Load vs. Displacement was noted for the specimen that was abraded using the 36 Grit Grade abrasive sheet, for 15 seconds (Fig. 5). The ultimate breaking load that was observed on a specimen that underwent the aforementioned surface preparation was 4.270 kN. The next highest yield point was noted in the specimen abraded using 40 Grit Grade abrasive sheet, for 20 Seconds (Fig. 8). The ultimate breaking load that was observed was 3.725 kN. The next highest yield point was the specimen that was abraded using 40 Grit Grade for 10 Seconds. An ultimate breaking load of 2.155 kN was observed. The specimen that was abraded using 40 Grit Grade and 50 Grit Grade for 15 seconds each registered ultimate breaking loads of 2.335 kN and 2.125 kN respectively.

The same exact trend was observed in the series of Stress vs. Strain graphs. The specimen abraded using 36 Grit Grade abrasive sheet for 15 seconds registered the highest stress value of 0.037 kN/mm². From these experimental findings, we can infer that a coarser radial surface abrasion for a longer time period results in a greater bond strength. The trends observed present a behavioral pattern identical to that observed by Lloyd and Pothakamuri [12].

B. Failure Mode Analysis

There are three common failure modes that are noted across the specimen tests. However, as noted in earlier studies [12, 13], cohesive failure is predominantly seen across the different test specimens.

Cohesive bond failure refers to the fracture between the layers of adhesive in between both the adhered surfaces. Cohesive failure in a joint is characterize by the presence of a thin layer of adhesive coating on both of the adhered surfaces. Almost always, cohesive failure occurs only as a result of shear tests [14]. Another feature that characterizes cohesive
failure is the presence of an increased degree of surface roughness over the adhesive surface. However, it has been noted that a high void content may lead to cohesive failure [14]. Abrading the surface of the composite material specimen leads to the formation of surface ridges and pores. This increased porosity can be linked to the cohesive failure that is observed across the majority of the test specimens. All three specimens that were placed under the varying abrasive sheet test variable displayed cohesive failure.

Adhesive bond failure refers to the failure between the adhesive layer and the adherent surface. An adhesive bond failure is characterized by the presence of a clean or smooth bonding surface on one part of the bonding specimen and the adhesive layer bonded to the other specimen. The main region of failure occurs at the point of interaction between the adhesive layer and the adherent surface. Cohesive failure may point at the failure of the adhesive, whereas adhesive failure points at the failure of the bond interaction between the adhesive and adherent surface.

Only a single specimen (50 Grit, 15 Seconds) that was placed under the shortest abrasive testing time period displayed Adhesive Failure.

Mixed Mode Failure is a combination of cohesive and adhesive failure. This failure type is said to be a transitional phase between cohesive and adhesive failure. From their work, Davis and McGregor [13] inferred that the strength of a bond which fails by mixed mode failure is less than that of a bond that fails by cohesive failure.

A single specimen (40 Grit, 15 Seconds) failed by mixed mode failure. The specimen that failed by Mixed Mode Failure was subject to the highest testing time period for surface abrasion (20 Seconds).

V. CONCLUSIONS

- A coarser Grit Grade of Abrasive sheet causes a greater degree of surface abrasion on the composite material. A stronger degree of surface abrasion yields a stronger adhesive bond.
- An increased time period for abrasion results in a greater degree of surface abrasion on the composite material. A stronger degree of surface abrasion yields a stronger adhesive bond.
- Cohesive bond failure is the most commonly noted failure mode among adhesively bonded joints in composite materials that have been treated with abrasive surface preparation.
- Any increase in coarseness of the abrasive sheet beyond 36 Grit Grade, for a minimum time period of 10 Seconds causes damage to the structural integrity of the composite material laminate.
- Radial Abrasion as a composite surface preparation technique is economically viable, less complex and produces tangible results.
VI. ACKNOWLEDGMENT

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REFERENCES
