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After treating the composites with corona discharge treatment, the crack ran either in the adhesive in a cohesive mode or in the composite in an interlaminar mode. To understand these two types of crack propagation, various techniques have been adopted. Failure stresses of the composites have been quantified using butt joints and these values have been compared with finite element analysis (FEA) predictions. There was good correlation between the two sets of data, i.e. when the stress in the composite predicted from FEA was higher than the measured failure stress from a butt joint experiment the crack propagated in the composite and viceverra.

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THE ADHESIVE BONDING OF THERMOPLASTIC COMPOSITES

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1.INTRODUCTION

In the previous Periodic Reports [1-4] work was carried out on bonding thermoplastic composites with conventional engineering adhesives. It was shown in the earlier Reports that thermoplastic carbon-fibre composites exhibit a fundamental problem upon adhesive bonding due to poor adhesion at the composite/adhesive interface. This weak adhesion was overcome by using a corona-discharge treatment which led to crack growth either (i) in the adhesive layer in a cohesive mode or (ii) in the composite in an interlaminar mode. To understand the mechanisms involved in the adhesive bonding of thermoplastic carbon-fibre composites X-ray photoelectron spectroscopy and contact angle analyses were conducted which were all outlined in the previous Reports.

2. PROGRESS OF RESEARCH

As mentioned above, after treating the thermoplastic fibre composites with a corona discharge treatment the crack ran either in the adhesive in a cohesive mode or in the composite in an interlaminar mode. This report will outline the research work carried out to understand these two different types of crack propagation observed for different combinations of adhesives and thermoplastic fibre composites.

2.1 Experimental Observations

Double-cantilever-beam (DCB) specimens were prepared from the various composites and the adhesives as described in the previous Interim Reports [1-4]. The specimens were loaded in an Instron tensile testing machine and a microscope was placed in front of the specimens to monitor the crack propagation. For the specimens which failed cohesively through the adhesive layer, then one crack developed in front of the precracked region; whereas for the specimens which failed in an interlaminar mode at least one extra crack developed in the composite above or below the precracked region. (Recall that the precrack is placed approximately in the centre of the adheisve layer by using a piece of release-coated aluminium foil.) This latter mode of crack growth behaviour suggests that as the load is increased then the tensile stresses generated in the composite arms of the specimen reach the interlaminar tensile fracture stress of the composite. This occurs before the crack tip stresses are high enough to propagate the crack in a self-similar mode, namely through the adhesive layer.

2.2 Scanning Electron Microscopy

Scanning electron microscopy (SEM) was conducted on failed specimens and the observations on the level of fibre/matrix adhesion are summarised in Table 1, together with the crack propagation modes for the adhesively-bonded composite joints.

Table 1. Comparison of the quality of bonding between the fibres and the matrix resins and the type of crack propagation.

Composite	Quality of bond between fibre and resin	Fibre orientation	Adhesive	Type of crack propagation
APC2	Very good	Unidirectional	9309.3	Cohesive*
APC2	Very good	Unidirectional	FM73M	Cohesive
J2/Carbon	Good	Unidirectional	9309.3	Cohesive
J2/Carbon	Good	Unidirectional	FM73M	Cohesive
J2/Carbon	Good	Woven	9309.3	Interlaminar
J2/Carbon	Good	Woven	FM73M	Cohesive
J2/Kevlar	Poor	Unidirectional	9309.3	Interlaminar
J2/Kevlar	Poor	Unidirectional	FM73M	Interlaminar
J2/Kevlar	Poor	Woven	9309.3	Interlaminar
J2/Kevlar	Poor	Woven	FM73M	Interlaminar
X7005	Rather poor	Woven	9309.3	Interlaminar
X7C05	Rather poor	Woven	FM73M	Cohesive
AC40-60	Poor	Unidirectional	9309.3	Interfacial**
AC40-60	Poor	Unidirectional	FM73M	Interfacial
JD861	Rather poor	Unidirectional	9309.3	Interlaminar
JD861	Rather poor	Unidirectional	FM73M	Interlaminar
JD861	Rather poor	Woven	9309.3	Interlaminar
JD861	Rather poor	Woven	FM73M	Cohesive
XAS	Good	Unidirectional	9309.3	Cohesive
XAS	Good	Unidirectional	FM73M	Cohesive

* Cohesive means "cohesively through the adhesive layer".

** Interfacial means "along the composite/adhesive interface".

From the table above it can be seen that the type of adhesive employed, and more importantly the adhesion between the fibres and resin and fibre orientation decide the mode of crack propagation. For this reason an experimental approach was developed to quantify the stresses at which the composites failed.

2.3 Measured Interlaminar Transverse Tensile Fracture Stresses of the Composites

To understand the fracture mode of the DCB bonded composite specimens it was first necessary to measure the interlaminar transverse tensile fracture stress of the composites being bonded. Therefore, the composites were treated by the corona-discharge pretreatment and bonded with a cold-cure epoxy adhesive to steel adherends and tested in tension as shown in Figure 1. The dimensions of the adherends were 8 X 12 mm in cross-section with a height of 5 cm. However, it should be noted that another geometry of adherends was also used, this time the cross-section was circular with an area of 20.27 cm^2. Five of the rectangular butt joints were tested and one of the circular butt joints for each type of composite. All the tests resulted in interlaminar fracture of the composites and the results are shown in Table 2. The stresses required for failure of the composites which have good adhesion between fibre and resin are indeed high whereas for the composites when the adhesion between resin and fibre is weak the transverse tensile fracture stresses are indeed low.

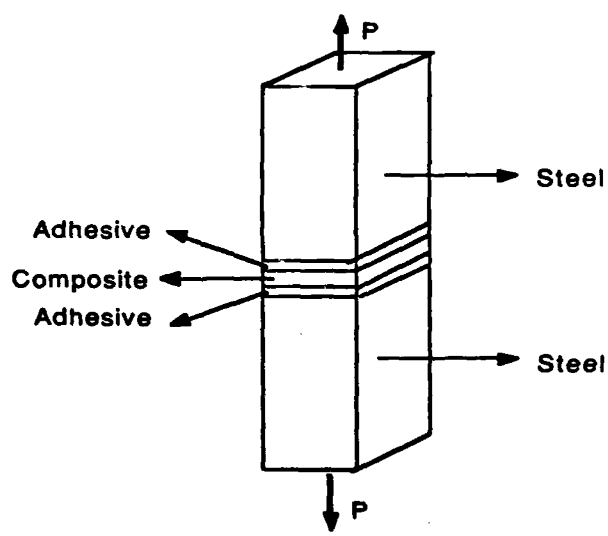

Fig. 1. Schematic diagram of the butt joint used to measure the transverse tensile fracture stresses of the different composites.

Table 2. The transverse tensile fracture stresses, σ_{yyc}, for different composites from the butt joint experiments.

Composite	Fibre orientation	Rectangular butt joint		Circular butt joint
		σ_{yyc} (MPa)	Deviation (MPa)	σ_{yyc} (Mpa)
APC2	Unidirectional	38.4	4.55	37.2
J2/Carbon	Unidirectional	32.1	3.63	32.7
J2/Carbon	Woven	34.4	3.71	34.9
J2/Kevlar	Unidirectional	7.5	1.28	8.6
J2/Kevlar	Woven	8.2	1.52	8.7
X7005	Woven	27.1	3.79	28.5
AC40-60	Unidirectional	8.9	1.31	8.4
JD861	Unidirectional	15.8	2.72	14.7
JD861	Woven	21.0	3.80	21.8
XAS	Unidirectional	36.4	4.09	37.6

It may be seen from the above table that the stresses, σ_{yyc}, for fracture are independent of the detailed geometry of the butt joint employed and that these values correlate well, in a semi-quantitative sense, with the SEM observations listed in Table 1.

2.4 Finite Element Analysis (FEA) Predictions

Secondly, finite element analysis (FEA) was carried out to establish the out-of-plane tensile stresses, σ_{yy}, around the crack tip in a bonded DCB test specimen. The crack tip was taken at 25mm from the load application point. The analysis was carried out as an "elastic fully plastic" problem and the results are summarised in Table 3 for the σ_{yy} stresses just across the adhesive /composite interface in a bonded DCB specimen.

From Tables 1 and 3 it can be seen that for joints which exhibited cohesive failure in the adhesive layer, then the out-of-plane tensile stresses, σ_{yy}, predicted from FEA, are indeed lower than the measured interlaminar transverse tensile fracture stresses, σ_{yyc} of the composite. However, when $\sigma_{yy} > \sigma_{yyc}$ then interlaminar failure of the bonded composite occurs. The only joint which does not agree with the predictions is in fact the J2/woven-carbon composite bonded using the EA9309.3 adhesive. Nevertheless, the FEA prediction falls well within the experimental deviations observed for this particular composite, see Table 2.

Table 3. Finite element analysis (FEA) predictions of the out-of-plane tensile stress, σ_{yy}, and the corresponding transverse tensile fracture stresses, σ_{yyc}, for different combinations of composites and adhesives.

Composite and fibre orientation	Adhesive	FEA σ_{yy} (MPa)	Experimental σ_{yyc} (MPa)
APC2 Unidirectional	9309.3	30.4	38.4
APC2 Unidirectional	FM73M	18.8	38.4
J2/Carbon Unidirectional	9309.3	30.5	32.1
J2/Carbon Unidirectional	FM73M	18.9	32.1
J2/Carbon Woven	9309.3	31.3	34.1
J2/Carbon Woven	FM73M	19.5	34.1
J2/Kevlar Unidirectional	9309.3	31.1	7.5
J2/Kevlar Unidirectional	FM73M	19.3	7.5
J2/Kevlar Woven	9309.3	32.4	8.2
J2/Kevlar Woven	FM73M	20.2	8.2
X7005 Woven	9309.3	31.4	27.1
X7005 Woven	FM73M	19.5	27.1
AC40-60 Unidirectional	9309.3	30.5	8.9
AC40-60 Unidirectional	FM73M	18.0	8.9
JD861 Unidirectional	9309.3	30.6	14.7
JD861 Unidirectional	FM73M	19.0	14.7
JD861 Woven	9309.3	31.3	21.0
JD861 Woven	FM73M	19.5	21.0
XAS Unidirectional	9309.3	30.5	36.4
XAS Unidirectional	FM73M	18.9	36.4

3. CONCLUSIONS

The different failure modes observed in the bonded DCB composite joints have been quantitatively explained by measuring the interlaminar transverse tensile fracture stresses, σ_{yyc}, of the various composites and comparing these values to the values of the interlaminar transverse tensile fracture stresses, σ_{yy}, generated in the bonded composite arms of the DCB joint specimen above and below the crack tip in the adhesive layer.

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