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Effects of manufacturing defects on the mechanical properties of carbon fibre reinforced polyethersulphone laminates

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The effects of defects on the mechanical properties of carbon fibre reinforced polyethersulphone laminates have been measured. The defects studied were cut fibre plies, omission of polymer films and local delamination produced by the inclusion of foreign matter. Of these it was found that only cut plies had a significant detrimental effect on the strength of a laminate. For specimens with two cut plies, the failure stress, tensile, flexural and compressive in the remaining continuous plies was the same as in the defect-free material, provided that the cut plies were widely separated. However the failure stresses were 15–18% lower in the continuous plies in the specimens containing two cut plies which were more closely spaced and in specimens containing four cut plies.

1. Introduction

A knowledge of the effects of defects on the mechanical properties of carbon fibre reinforced plastics (CFRP) is important for structural applications of these materials. While the effects of cracks produced by static and dynamic loads must be understood in order to estimate the failure conditions of in-service components, it is also essential to consider the effects of defects introduced during manufacture. Results are reported here of a study of the latter type of defect in carbon fibre reinforced polyethersulphone (PES). Most previous work on the role of defects has been concerned with carbon fibre reinforced epoxy materials, see for example, Bishop [1] and Hancox [2].

Three types of defect were identified as being the most likely to be introduced during the manufacture of CF PES laminates by the film stacking technique. These were (i) broken or cut carbon fibre plies, (ii) omission of polymer films and (iii) localized delaminations due to the inclusion of foreign matter, e.g. pieces of paper, or aluminium foil. Specimens were produced with all these types of defect and their mechanical properties compared with control specimens. In addition, tests were made on a laminate manufactured using a higher pressing temperature than normal, to simulate an accident in temperature control during production.

2. Production of panels containing defects

Test panels were fabricated by Specmat Ltd, each panel consisting of ten layers of unidirectional, commercially produced prepreg. An extra layer of PES film was placed on the outer faces of the premoulded stack, giving a total of 13 polymer films within each laminate. The carbon plies consisted of Fothergill and Harvey AO062 unidirectional carbon fibre cloth containing 3000 filament tow Toray T300 fibres, preimpregnated with 15% by weight of polyethersulphone. Grade 600p PES film was employed, which exhibited similar properties to other grades, but was more viscous and environmentally durable than grade 300p.

Where possible, the panels were fabricated in such a manner as to enable both control and defect-containing specimens to be extracted from the same test panel. This was clearly only possible with the localized defects, i.e. cut plies and delamination by inclusion of aluminium foil. These localized defects were contained within two large panels designated B1 and B2. Panel B1 consisted of ten layers of unidirectional prepreg and 13 layers of PES and was produced in a $760 \times 760\,mm^2$ mould at a temperature of 325° C. The panel was pressed for 15 min at 10 MPa before being air cooled under pressure. Panel B1 was considered to consist of three distinct regions, (a) an area containing aligned cuts in fibre plies 2 and 9, (b) an area containing aligned cuts in fibre plies 4 and 7 and (c) a defect-free area from which control specimens could be extracted. The cuts in the fibre layers were perpendicular to the fibre direction and stretched almost the whole width of the panel. A short length

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was left uncut at each edge of the prepreg to reduce any opening up of the cuts during the moulding. The production of panel B2 employed identical moulding conditions and materials as described for panel B1. Similarly, panel B2 was considered to consist of three distinct regions, namely: (a) an area containing aligned cuts in fibre plies 2 and 9, (b) an area containing a delamination caused by the insertion of aluminium foil. The foil was in the form of a folded strip, 15 mm wide, which stretched across the whole width of the panel in a direction perpendicular to the fibre direction. The inside surfaces of the folded foil were sprayed with release agent to promote a true delamination. The foil was placed between layer 5 and 6 of prepreg, i.e. in the centre of the panel thickness, (c) a defect-free area from which control specimens could be extracted.

Two non-localized manufacturing defects were investigated, namely the omission of polymer films from the premoulded stack and moulding at 360° C rather than the normal 325° C. In order to investigate these defects, three panels, designated B3, B4 and B5 were manufactured.

One panel, B3, ($330 \times 330\,mm^2$), was produced in which layers of PES were omitted between carbon plies 4–5 and 6–7. All other moulding conditions were as detailed for panels B1 ad B2. Panel B4, ($330 \times 330\,mm^2$), was moulded at 360° C, all other conditions being kept as for panels B1 and B2. Although panels B3 and B4 contained identical materials to those used in B1 and B2 and were moulded to the same time and pressure parameters they were moulded on a different press. Hence, to eliminate any discrepancies due to inherent differences between the two presses, a separate defect-free panel was fabricated to act as a control to the panels B3 and B4. This panel, labelled B5, was moulded under ostensibly identical conditions as panels B1 and B2.

3. Mechanical tests

As far as was practically possible, all the mechanical tests undertaken followed the recommendations set out by Dootson [3]. Reference was also made to the earlier recommendations of Sturgeon [4]. All specimens were approximately 2 mm in thickness and 10 mm in width. The mechanical testing was conducted on a "Losenhausen UHS6" universal testing machine.

3.1. Three point bend strength

The composite bending strength was determined under three-point loading. The specimen and roller dimensions employed were $100 \times 10 \times 2\,mm^3$, with a span ($L$) of 80 mm between rollers of diameter 6 mm and a central roller of diameter 10 mm.

3.2. Flexural modulus

Three-point loading tests were made on specimens with a large span to depth ratio, to reduce the effects of shear on the deflection. The specimen and roller dimensions were $200 \times 10 \times 2\,mm^3$ with a span $L = 180$ mm between rollers of diameter 10 mm and a central roller of diameter 25 mm.

The maximum load was kept to approximately one fifth of the failure load in order to eliminate any effects due to creep at high loads. The specimen deflection was measured by placing a calibrated transducer under the centre of the specimen.

The flexural modulus E_f was obtained from the equation

$$E_f = \frac{ML^3}{4wt^3} \qquad (1)$$

where M is the ratio of the applied load to the deflection, w the width and t thickness of the specimen. Equation 1 assumes that the tensile and compressive moduli are equal.

3.3. Interlaminar shear strength (ILSS)

Specimens were placed under three-point loading with a span to depth ratio of 5 : 1. The dimensions of the specimen and rollers were $12 \times 10 \times 2\,mm^3$, with span 10 mm and all rollers of diameter 6 mm. The interlaminar shear stress τ was calculated from

$$\tau = \frac{3P}{4wt} \qquad (2)$$

where P was the load at failure.

3.4. Tensile modulus and strength

In a tensile test much of the load transferred from the testing machine to the specimen is by shear, thus a long tensile specimen is required in order that the shear stresses may diffuse into the gauge length. For the determination of the longitudinal tensile modulus a simple parallel-sided specimen, 200 mm in lengths, was selected. Aluminium end plates, 50 mm in length, were glued to the specimens to allow easy gripping and to spread and load over the desired area. The tensile strain was recorded with the use of Kyowa KFC-5-C1-11 strain gauges which were connected to a standard strain gauge bridge yielding a direct reading of μ strain.

The waisting of a tensile strength specimen containing no localized defect is necessary in order to ensure that the specimen may fail away from the stress concentrations present in the gripping region. In order that any induced shear stresses are kept below the ultimate shear stress, this waisting must be gradual. The appropriate tensile modulus specimens were reduced in thickness to approximately 1 mm, in their central region, this being half their normal thickness.

3.5. Compressive strength

The compressive strengths were measured employing a "Celanese" compression rig, comprised primarily of two conical grips held inside a shaped sleeve, causing the grips to close as the load is applied. This arrangement enabled simple parallel-sided specimens to be employed. A short gauge length was used to ensure a compressive failure preceded a buckling failure.

4. Results

The results of the mechanical tests are summarized in Tables I and II. The results in Table I are for the localized defects only, namely, cut fibre tows and a

TABLE I Results of mechanical tests for specimens with localized defects. Values are normalized to a volume fraction $V_f = 0.5$. Quantities in parentheses are the coefficients of variation.

Defect	Panel	V_f	Void content by volume	Tensile strength (MPa)	Tensile modulus (GPa)	Flexural strength (MPa)	Flexural modulus (GPa)	ILSS (MPa)	Compressive strength (MPa)
Control 1	B1/B2	0.470	0.018	1093 (7.0)	104 (2.8)	1120 (6.3)	81 (2.6)	80 (2.0)	710 (7.8)
Cut Plies 2 + 9	B1	0.470	0.018	848 (3.7)	–	736 (8.6)	64 (2.4)	–	586 (10.8)
Cut Plies 4 + 7	B1	0.470	0.018	711 (8.8)	–	663 (14.0)	65 (3.9)	– –	345 (10.7)
Cut Plies 2 + 4 + 7 + 9	B2	0.470	0.018	555 (8.1)	–	768 (8.0)	67 (3.0)	–	406 (3.6)
Delamination (Aluminium Foil)	B2	0.470	0.018	971 (3.6)	113 (6.9)	1063 (2.6)	78 (2.7)	–	700 (3.8)

delamination caused by aluminium foil. Table II contains the results obtained from laminates containing non-localized defects, namely, the omission of polymer films from the premoulded stack and the effect of a high moulding temperature.

It was observed, upon measuring the thicknesses of the test specimens, that a variation of up to 15% was present within a single laminate. Assuming that the thickness variation is attributed solely to inconsistencies in the resin content, similar variations in the volume fraction fraction V_f may be expected and the measured property values displayed in Tables I and II were normalized to a V_f value of 0.5 by scaling. The fibre volume fraction was determined by the measurements of the density and weight of the constituents before moulding and by similar measurements of the final laminate. The average void content was calculated and, assuming a constant value, this was used to determine the variation of V_f with laminate thickness.

The results are also presented in Figs 1 and 2. In order that all the test results could be included in these figures, the results from Table II, for the non-localized defects, have been normalized to the control results shown in Table I, for the localized defects.

The localized defects (cut fibres and aluminium foil) were all contained within the two laminate panels B1 and B2. Upon testing the two sets of control specimens, and correcting for fibre volume fraction, the results were found to agree within the standard deviation limits and were thus combined to produce one set of control values. This set of control results, designated Control 1, is shown in Table I. The control results for the non-localized defects, designated Control 2, were obtained from laminate B5 and are shown in Table II.

The three series of specimens produced for the investigation of cut fibre plies may be described in general terms as

(a) a series of specimens containing cut plies near to the specimen surfaces (cut plies 2 and 9)

(b) a series of specimens containing cut plies in the central region of the specimen thickness (cut plies 4 and 7)

(c) a series of specimens containing both configurations described above (cut plies 2, 4, 7 and 9).

It was expected that an amount of movement of the fibre plies may occur during the moulding process. In order to establish how much misalignment had occurred, the sides of each specimen were polished before testing and viewed under the microscope. Measurements of the extent to which the cuts "opened-up" and the relative displacement between the fibre discontinuities were recorded for each specimen.

Figs 3, 4 and 5 show, schematically, the results of these observations. The visual examination of the failure surfaces of the tensile specimens enabled an estimation of the fracture path to be made and this information is shown in Fig. 3. The compression failures present in the flexural and compression specimens prevented similar information being extracted from these tests.

5. Discussion

5.1. Tensile tests

Some results of the effects of discontinuous plies on the tensile strength of unidirectional CFRP have been reported by Potter [5]. It was found that the mean failure stress in the continuous plies was reduced by approximately 15% from the value found in

TABLE II Results for specimens containing non-localized defects, normalized to $V_f = 0.5$. Quantities in parentheses are the coefficients of variation

Defect	Panel	V_f	Void content by volume	Tensile strength (MPa)	Tensile modulus (GPa)	Flexural strength (MPa)	Flexural modulus (GPa)	ILSS (MPa)	Compressive strength (MPa)
Control 2	B5	0.493	0.015	1038 (8.8)	106 (2.7)	1220 (11.0)	82 (3.7)	90 (2.0)	842 (10.6)
Omission of PES Films	B3	0.518	0.015	–	105 (1.3)	1228 (2.2)	75 (3.2)	84 (4.0)	902 (9.2)
High Temp. Moulding	B4	0.49	0.010	1115 (3.5)	108 (3.9)	1075 (12.8)	78 (4.2)	71 (3.7)	923 (11.8)

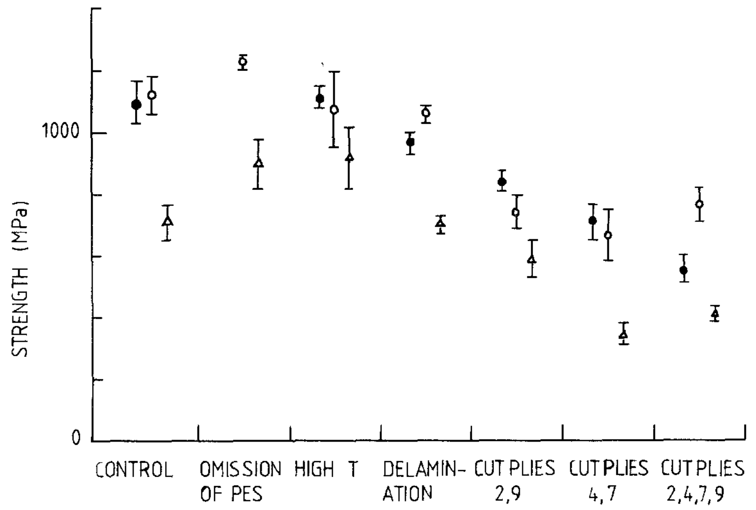

Figure 1 The tensile strength (○), flexural strength (●) and compressive strength (△) of laminates containing defects. All values normalized to a volume fraction of $V_f = 0.5$.

defect-free material. Moreover, this reduction was independent of the number of discontinuous plies in a specimen. A similar effect was found here for specimens with the two plies 4 and 7 cut and for specimens with four cut plies. However, for specimens with discontinuities in plies 2 and 9, the mean failure stress in the continuous plies was found to be only a few per cent lower than in the control specimens.

A reduction in the mean failure strength of the continuous plies can be understood qualitatively in terms of the stress concentration in the region near a cut ply. It was proposed by Darby *et al.* [6] that an ineffective length can be defined for a single cut ply, δ_L say, and this is calculated to be of order 1 mm for the material under test. This means that the neighbouring continuous plies carry an excess stress over a length of approximately $2\delta_L$. In the case of two cut plies, an analogous argument to that of Zweben and Rosen [7] for broken fibres suggests that the two cuts act independently unless they are aligned within a single band of width $2\delta_L$ oriented perpendicular to the applied stress, thereby producing a weak link.

In the specimens studied, the situation was complicated by the fact that the separation between the ends of a cut ply was found to be increased as a result of ply movement during the moulding process, see Figs 3, 4 and 5. A further consequence of this movement was that the cuts in the plies were not aligned across the thickness of a coupon. The effect of a large gap between the cut ends of a ply, of magnitude δ_g say, will be to extend the region in neighbouring plies over

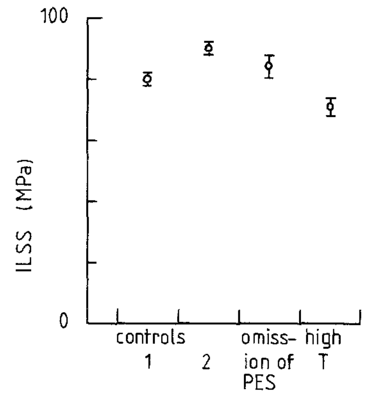

Figure 2 The interlaminar shear stress for laminates containing defects, normalized to $V_f = 0.5$.

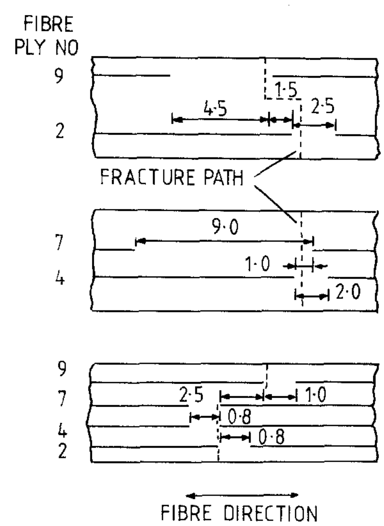

Figure 3 Positions of cut fibre plies in specimens used in the tensile strength and modulus tests and in the flexural modulus tests. Dimensions in mm.

which the stress is increased from $2\delta_L$ to a length $2\delta_L + \delta_g$, which may be many millimetres. This would imply that the width of the weak link is of this size. In the case of specimens with plies 4 and 7 cut, it can be seen from Fig. 3 that a single weak link region encompasses both discontinuities. On the other hand, for specimens with plies 2 and 9 cut, the regions of stress concentrations produced by the two cuts may not overlap. For coupons with four cut plies, it would appear from Fig. 3 that three of the cuts produce stress concentration regions which overlap. Hence, employing the weak link argument, it would be expected that the failure stress in the continuous plies would be greater in specimens with plies 2 and 9 cut, and weaker in specimens with four cut plies.

Compared with the analogous situation for a cut single fibre, it might be expected that the stress concentrations near cut plies would extend beyond the nearest neighbour plies, at least to the next-nearest-neighbour ones. In this case the separation of the cut plies in a laminate stacking sequence would be important, and it would again be expected that coupons with plies 2 and 9 cut would be relatively stronger than the other two types of specimen.

Fracture mechanics would seem to offer an alternative approach to the weak link theory, even though

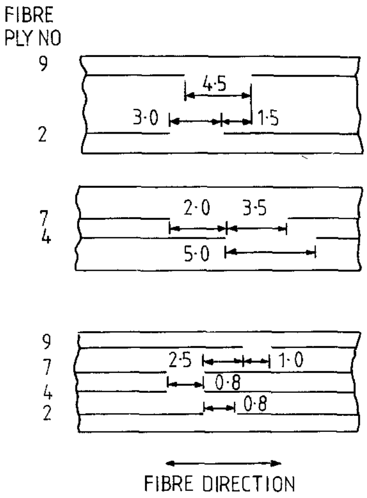

Figure 4 Positions of cut fibre plies in specimens used in the flexural strength tests. Dimensions in mm.

the application of fracture mechanics to composite materials poses many problems. Employing linear fracture mechanics with an estimate for the critical stress intensity factor K_{IC} of $20\,\mathrm{MNm}^{-3/2}$, the failure stress of 1.1 GPa for the control coupons indicates that cracks of effective total length $2a$ equal to 0.2 mm would be responsible for failure. This size is comparable with the thickness of a single ply.

In considering specimens with two cut plies, it is of interest to identify the cuts as the cracks and use fracture mechanics to study the failure conditions. For two off-set cracks, as illustrated in Fig. 6, the stress intensity factors have been tabulated [8, 9] as a function of the ratio of crack length to lateral separation a/b for various values of the off-set distance h. For specimens with plies 4 and 7 cut, $a/b \geqslant 0.25$ and for plies 2 and 9 cut, $a/b \geqslant 0.125$. For such small values, the K_{IC} values differ only negligibly from that of a single crack, implying that specimens with two cut plies should have the same strength as specimens with only one cut ply. The worst case would be if two neighbouring plies were cut, so that $a/b = 0.5$. In this case, if the off-set distance h is very small, e.g. $h \simeq 0.1a$, then the effective critical stress intensity factor may become less than half of that for a single crack. However, for h values of order $h \geqslant a$, the failure stresses are again predicted to vary insignificantly from that for a single crack. For the specimens listed, it is clear that fracture mechanics suggests that the cut pies should act independently, and the failure strength should be no different from that of specimens with one cut ply. A specimen with one cut ply will in turn have a lower strength than a defect-free specimen, provided that the effective crack length associated with the crack is greater than 0.2 mm. Employing an average value for the failure stress of specimens with two cut plies, Table I, the predicted effective length of a single crack is approximately 0.4 mm. The results for specimens with four cut plies show that the strength is significantly lower than for the two cut ply cases, and this indicates that the effective length of a single critical crack is larger. It must therefore be concluded that fracture mechanics is not applicable in a simple way to the failure of specimens with cut plies.

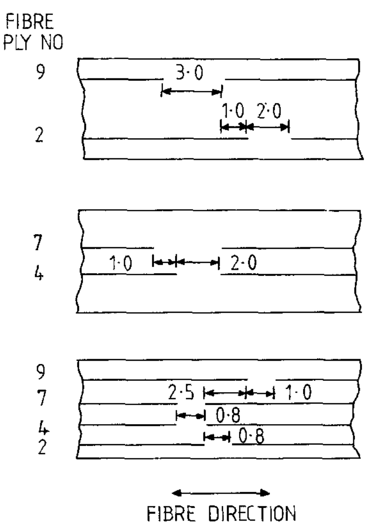

Figure 5 Positions of cut fibre plies in specimens used in the compressive strength and modulus tests. Dimensions in mm.

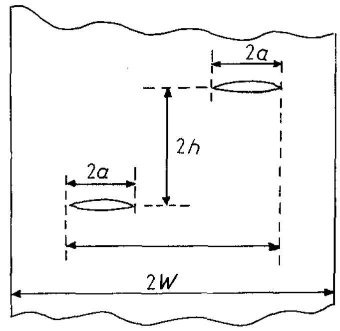

Figure 6 Two off-set parallel cracks of equal width. For theoretical purposes the specimen dimension W was assumed to be infinite.

5.2. Flexural and compressive tests

The errors in the results of the flexural tests obtained from the three series of coupons containing cut plies were somewhat larger than in the tensile tests because of small uncertainties in the relative positioning of the loading points (rollers) with respect to the cuts. A degree of compressive failure was observed on the upper faces of all the flexural strength specimens and it is likely that the "opening-up" of the cuts would have produced areas of high resin concentration with corresponding low compressive strengths. In terms of both the flexural strength and the compressive strength, Fig. 1, the specimens containing cuts in plies 4 and 7 were weaker than those specimens in which fibre plies 2, 4, 7 and 9 had been severed. This was a consequence of the larger "opening-up" of the cuts in the coupons containing cuts in plies 4 and 7.

5.3. Omission of polymer films

The results obtained from the coupons extracted from laminate B3 indicate that the omission of polymer films from between fibre plies 4 and 5, and 6 and 7 has no significant effect on the mechanical properties of a unidirectional, 10 ply composite.

The effect of omitting these two polymer films was to increase the nominal fibre volume fraction of the laminate B3 by 5.1%. In general, the mechanical properties obtained from the coupons extracted from this panel where higher than the control values obtained from panel B5. However, this increase in the observed performance of the coupons in which the polymer films were omitted was completely eliminated when the results were normalized to a common fibre volume fraction.

5.4. Local delamintion

Visual examination of the test coupons containing the folded strip of aluminium foil showed that a perfect delamination had been obtained. However, despite the complete success in achieving this delamination the results displayed in Fig. 1 show that this defect has no significant effect upon the mechanical properties studied.

The presence of a delamination within a composite is expected to affect those mechanical properties in which the role of the matrix is uppermost and, hence, it is of no surprise that Fig. 1 shows that the delamination has had no significant influence upon the tensile properties of the composite.

The width of the inserted aluminium foil was 15 mm and thus extended across the whole length of the 10 mm gauge length employed in the compressive strength specimens. Hence, this test is analogous to a compression test conducted, simultaneously, upon two specimens of half the nominal test coupon thickness. The average compressive strength of the specimens containing the delamination was 700 MPa, which was estimated to be less than one half of the critical buckling stress.

6. Conclusions

The present study of the effects of various simulated manufacturing defects upon the mechanical properties of carbon fibre reinforced polyethersulphone laminates has shown that cut plies produce a reduction in strength which can be understood qualitatively in terms of a weak link model. An attempt to explain the results in terms of linear fracture mechanics was not successful.

The omission of PES films, the introduction of regions of delamination using aluminium foil and the use of a higher moulding temperature, all had little effect on the mechanical properties of the resulting laminates.

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