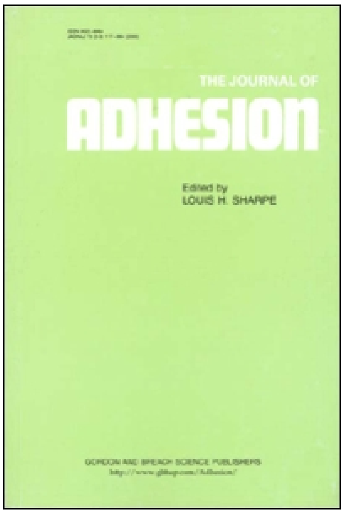

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The Design of Double-Overlap Joints Using Thermoplastic-Fibre Composites

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The present paper considers the adhesive bonding of thermoplastic fibre-composites using an epoxy-paste adhesive. The joint design used for these studies is a double-overlap geometry. Firstly, it is shown that to obtain good joint strengths the thermoplastic fibre-composite substrates need to be subjected to a corona surface treatment prior to bonding. Secondly, it is established that the use of tapered composite substrates and angled adhesive-fillets can substantially increase the joint strength. Indeed, the joint efficiency can approach 100% for such designs of double-overlap joints. Thirdly, finite-element analyses have been employed to study theoretically the various designs of joints, and the results from such analyses are in good agreement with the experimental measurements.

INTRODUCTION

Previous work[1,2] has studied the adhesive bonding of thermoplastic fibre-composites, such as carbon-fibre poly(ether-ether ketone) composites, using a continuum fracture mechanics approach. This work clearly established that to obtain high values of the adhesive fracture energy when using epoxy adhesives to join thermoplastic fibre-composites it was necessary to pretreat the composite substrates using a corona-discharge treatment. The aim of the present paper is to extend this earlier work by examining the adhesive bonding of thermoplastic fibre-composites when employing a double-overlap joint design.

Sharpe[3] has reviewed the basic principles of joint design and discussed the complex stress concentrations which arise in lap joints. In particular, the effect of tapering the fibre-composite substrates and the use of angled adhesive-fillets will be considered, since Adams et. al.[4] have shown that by optimising such parameters the strength of double overlap joints may be greatly increased.

THEORETICAL

The PAFEC finite element analysis package was employed to model the double-overlap joints. The details of the analysis have been reported[5] elsewhere but, essen-

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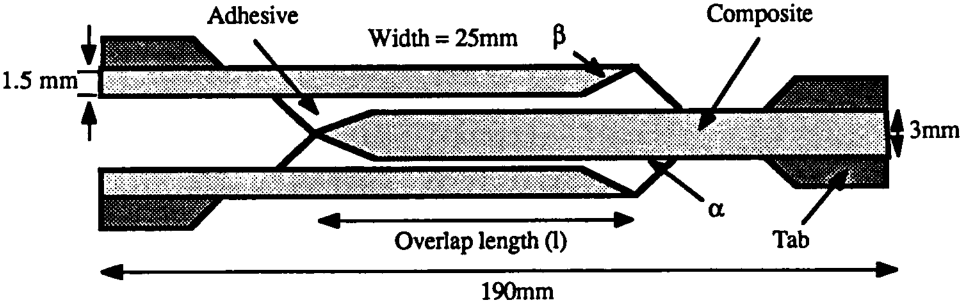

FIGURE 1 Schematic diagram of the symmetrical double-overlap joint (the design as shown possesses an "inner" taper).

tially, it was assumed that (i) the adhesive behaved in an elastic-plastic manner, with a constant strain-hardening slope, (ii) the composites behaved in an elastic manner, and (iii) the joint was under plane-strain loading. Following the work of Adams and Harris,[6] the ends of the composite substrate were taken to be rounded with a radius of 125 μm and the end of the adhesive fillet (where $\alpha = 90°$; see Figure 1) assumed to have a radius of 70 μm. These values for the radii were estimated from optical micrographs. Rounding of the corners in this manner avoids the presence of large regions which are dominated by singular stresses.

EXPERIMENTAL

Materials

Two different thermoplastic-based fibre-composites, and one thermosetting-based composite, included for comparative purposes, were studied. These were:

(a) Unidirectional carbon-fibre/PEEK ("APC-2" composite from ICI plc)—a continuous carbon-fibre composite containing a volume fraction of fibres of about 60% and a matrix of thermoplastic poly(ether-ether ketone); termed: u-carbon/PEEK in the present paper. The composite substrate was prepared by laying unidirectional tape into a twelve-ply stack; the ply direction being $[0°]_{12}$. The moulding of the sheeting was undertaken using a heated press at 380°C for 5 minutes and under a pressure of 1.4 MPa.

(b) Unidirectional carbon-fibre/PA ("carbon-fibre/J2" composite from Du Pont, USA)—a continuous carbon-fibre composite containing a volume fraction of fibres of 55% and a matrix of a thermoplastic amorphous polyamide copolymer; termed: u-carbon/PA. The polyamide is based on bis(para-aminocyclohexyl methane). The composite substrate was prepared by laying unidirectional tape into a twelve-ply stack; the ply direction being $[0°]_{12}$. The moulding was undertaken using a heated press at 300°C for 25 minutes and under a pressure of 2MPa.

(c) Unidirectional carbon-fibre/epoxy ("913C XAS-5-34%" composite from Ciba Geigy Ltd)—a thermoset composite with a modified-epoxy resin matrix; termed:

u-carbon/epoxy. It was a continuous carbon-fibre composite containing a volume fraction of fibres of about 63%. The composite substrate was prepared by laying unidirectional tape into a twelve ply stack, the ply direction being $[0°]_{12}$. The moulding was undertaken using a heated press at 150°C for 20 minutes under a pressure of 2.0 MPa. This thermoset composite was included for comparative purposes.

The structural adhesive employed was a cold-cured two-part epoxy-paste adhesive ("EA 9309.3NA" from the Hysol Dexter Corp., USA). This was cured at room temperature for five days under a pressure of 69 kPa.

Mechanical Properties of the Materials

The uniaxial tensile stress versus strain behaviour of the fibre-composite materials were measured following ASTM Standard D3039-74. Similarly, the uniaxial tensile stress versus strain behaviour of the adhesive was measured by casting a 7 mm thick sheet of the material and following ASTM Standard D638-77.

The shear stress versus strain properties of the adhesive were measured using a cone-and-plate test specimen, similar to that previously described by Grant and Cooper.[7] The substrates were made from aluminium-alloy and treated using chromic-acid to prevent premature interfacial failure of the test specimen. The cone-end was manufactured to give two different angles of 3° and 5°, so as to investigate any differences that the thickness of the adhesive might have upon the measured shear properties. No effects of adhesive thickness were observed. The shear strain was measured by bonding steel cams to the aluminium substrates, adjacent to the adhesive layer. The movement of the cams was then followed by mounting two linear-variable displacement-transducers (LVDTs) at right-angles to each other and touching against the cams. The rotational movement of the cams was then measured via the linear-stroke movement of the LVDTs.

Joint Preparation and Testing

The surface treatment employed for the thermosetting epoxy-based composite prior to bonding was a simple abrasion/solvent-wipe. This involved lightly abrading the composite sheets using 180/220 mesh alumina, then cleaning the surfaces using methyl-ethyl ketone to remove surface debris.

The surface treatment used for the thermoplastic fibre-composites was a 'corona' treatment and involved exposing the sheets to an air plasma formed at atmospheric pressure. The major components of the corona discharge equipment were the generator producing high frequency (15–20 kHz) power (0.1–0.9 kW), the high-power transformer giving the high voltage (15–20 kV) and the high-power cables carrying the high-voltage to the electrodes and the treater-station. The equipment was designed to include two special features. Firstly, conventional corona can readily treat non-conducting materials but the transformer of the present equipment was re-designed to give good impedance and capacitance matching between the electrode and the composite. For conducting materials a modified electrode was designed with a rubber silicone covering the surface whilst for non-conducting materials a conventional knife-edged electrode was used. The second feature was that the power output from the electrode was current controlled, and not voltage controlled. Hence the power output from the electrode was directly obtained from the power gauge of the generator. After a light abrasion and a solvent wipe treatment, which is described above but which is not a critical requirement, the thermoplastic-composite substrates were placed on an automatically controlled table which travelled horizontally backwards and forwards under the discharge electrode. The velocity of the table could be selected to be between 14.5 to 62 mm/s and the velocity output was controlled accurately by a stepper motor and a pulse generator (0.1–4.8 kHz). The energy output per unit area from the electrode onto the composites may be determined from:

$$E = PN/LV \tag{1}$$

where E is the energy output per unit area, P is the power of the high-frequency generator, N is the number of cycles of the table, L is the length of the treater and V is the velocity of the table. The carbon-fibre-PEEK composite was pretreated using an intensity of corona treatment of 20 J/mm^2 and the carbon-fibre-PA composite using 5 J/mm^2. In both cases, these levels of treatment were sufficient to ensure that the locus of joint failure was not via crack growth along the adhesive/composite interface.[2]

The double-lap joints were prepared using 3 mm thick sheets of fibre-composites for the inner substrate and 1.5 mm thick sheets for the outer fibre-composites, and the design of the symmetrical double-lap joint is shown schematically in Figure 1. The desired scarf taper angle, β, was obtained by machining the composite substrates. This angle was machined to an accuracy of ±1°. The joints were prepared using a steel mould to ensure good alignment of the substrates. The substrates were inserted into the mould, together with steel shims which permitted an adhesive fillet angle, α, to be moulded into the adhesive layer. The two-part epoxy-paste adhesive, which had been previously degassed using a vacuum oven, was then poured between the substrates. The thickness of the adhesive layer was 350 ± 40 μm. The adhesive was allowed to cure for five days at room temperature and the joint was then removed from the mould.

Prior to testing end-tabs of woven carbon-fibre epoxy composite were bonded onto the substrates using a room-temperature curing epoxy adhesive. The joints were then tested in uniaxial tension at a constant rate of displacement of 1 mm/min.

RESULTS AND DISCUSSION

Mechanical Properties of Adhesive and Fibre-Composites

The mechanical properties of the adhesives and fibre-composite substrates are shown in Tables I, II and III. The epoxy-paste adhesive is a rubber-toughened material and this is reflected in the relatively high values of both the tensile and shear fracture strains for this structural adhesive. Considering the fibre-composites,

TABLE I
The uniaxial tensile properties of the epoxy-paste adhesive

Young's modulus (GPa)	Elastic limit stress (MPa)	Elastic limit strain (%)	Fracture stress (MPa)	Fracture strain (%)	Poisson's ratio
1.85	37.0	2.0	44.0	16	0.36

TABLE II
The shear properties of the epoxy-paste adhesive

Shear modulus (GPa)	Elastic limit stress (MPa)	Elastic limit strain (%)	Fracture stress (MPa)	Fracture strain (%)
0.66	24.0	3.7	36.5	160

TABLE III
The tensile properties of the fibre-composite substrates

Material	Young's modulus, E_{11} (GPa)	Longitudinal fracture stress, σ_{11} (MPa)	Transverse fracture stress, σ_{22} (MPa)	Poisson's ratio, ν_{11}
u-carbon/PEEK	133	1380	84.3	0.28
u-carbon/PA	122	1330	83.7	0.29
u-carbon/epoxy	128	1140	58.9	0.26

then as expected, the values of the transverse fracture stresses, σ_{22}, are far lower than the values of the longitudinal fracture stresses, σ_{11}. This has considerable implications for the strength of bonded fibre-composite joints,[8] as discussed later.

Experimental Failure Behaviour of Adhesive Joints

Non-tapered fibre-composite substrates The results for the simple double overlap joints, possessing adhesive corners of approximately 90° and no taper on the composite substrates (see Figure 4), are shown in Figures 2 and 3. In these figures the load per unit width is shown as a function of the length of the overlap length. The results for the unidirectional carbon-fibre PEEK composite in Figure 2 reveal that if the thermoplastic fibre-composite substrate is subjected to only an abrasion/solvent wipe treatment prior to bonding then the failure loads are low. This is because in such cases the joints fail by fracture occurring at the adhesive/composite interface. However, as found in previous work, if a corona treatment is employed then premature interfacial failure is prevented and relatively high failure loads may be observed. Similar results were found for the unidirectional carbon-fibre PA composite, where again a corona treatment was required to ensure the high joint strengths shown in Figure 3. On the other hand, unidirectional carbon-fibre epoxy composite needed only an abrasion/solvent wipe surface treatment to ensure high joint strengths. These results have been explained in detail in a previous paper where it was shown that a critical surface polarity has to be attained in order to

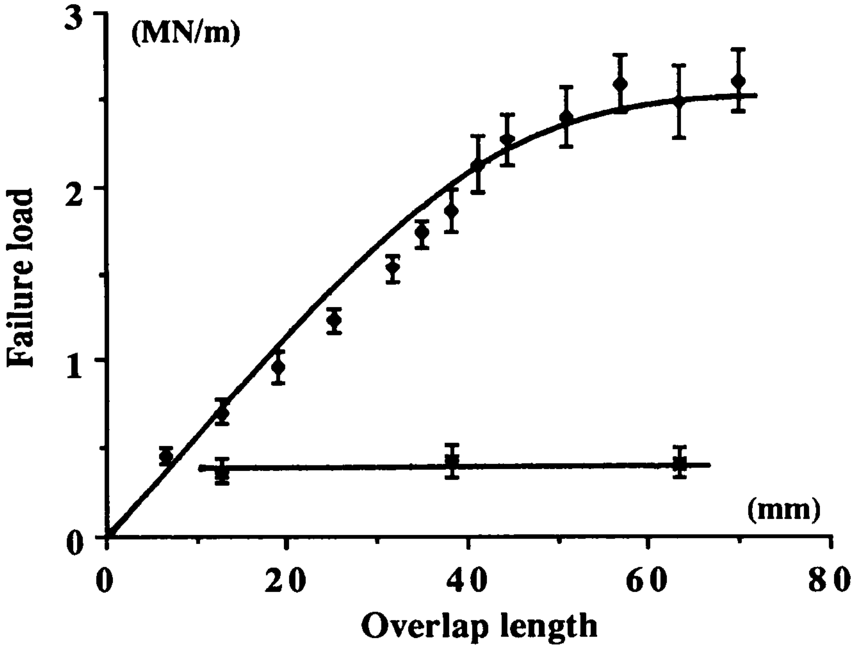

FIGURE 2 Failure load per unit width versus the overlap length for the bonded u-carbon/PEEK composites with $\alpha = 90°$ and $\beta = 90°$. ◆ : using a corona surface treatment prior to bonding. X : using an abrasion/solvent-wipe treatment prior to bonding.

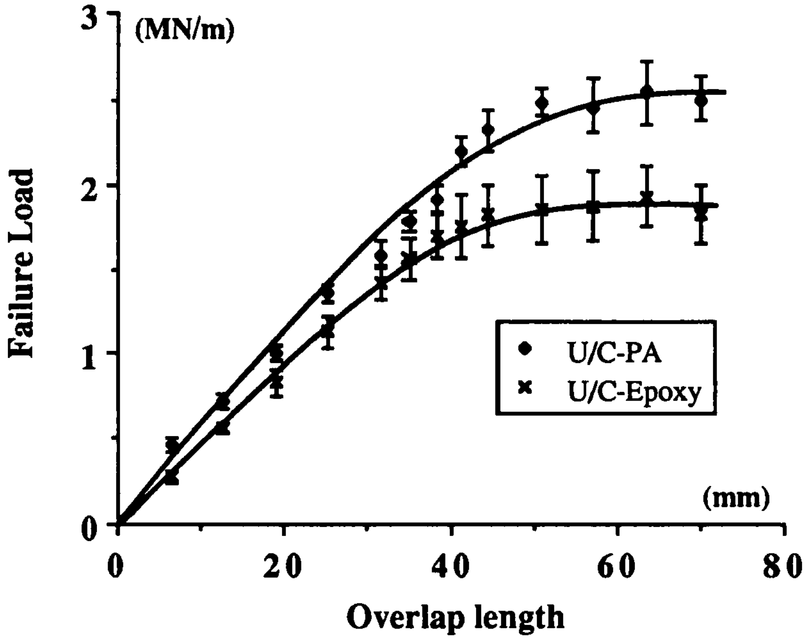

FIGURE 3 Failure load per unit width versus the overlap length for the bonded u-carbon/PA and u-carbon/epoxy composites, with $\alpha = 90°$ and $\beta = 90°$.

achieve relatively high adhesion, and so prevent interfacial failure.[9] This requires the use of a corona, or similar, treatment for the thermoplastic fibre-composites prior to bonding whilst the epoxy composite requires only a simple abrasion/solvent wipe. Thus, for all subsequent studies the thermoplastic fibre-composites were subjected to a corona treatment prior to being bonded.

The relationships shown in Figures 2 and 3 indicate that overlap lengths of about 50 to 60 mm are needed to achieve the plateau failure loads for the corona-treated thermoplastic fibre-composites and the abraded epoxy fibre-composite. However, even at these overlap lengths the joint efficiencies are only about 60%. (The joint efficiency being defined as the failure load of the joint divided by the load to fracture the weakest substrate material, outside of the joint region; expressed as a percentage.) This relatively low joint efficiency obviously arises from stress concentrations in the joint, and these are reflected in the locus of joint failure being via interlaminar fracture of the inner composite substrate at the end of the bonded overlap, as shown in Figure 4. Therefore, various other designs of double overlap joints were studied in order to improve the joint efficiency.

Tapered fibre-composite substrates The effect of tapering the fibre-composite substrates was first examined for unsymmetrical double-overlap joints using both an "inner" and "outer" taper, as shown in Figures 5a and b respectively. From the results described above, an overlap length of 60 mm was chosen to ensure that the measured failure load would represent the plateau value. The results are shown in Table IV and it is evident from comparing these data to those shown in Figures 2 and 3 that the measured failure loads are not significantly dependent upon whether the fibre-composite substrates are tapered. Further, this observation is valid whether an "inner" or "outer" taper is used. Indeed, the locus of joint failure for these tapered joints was the same as that for the previous non-tapered joints, namely

TABLE IV
Failure loads of double-overlap joints prepared using various taper angles for the fibre-composite substrates

Fibre-composite	Taper angle, β	Position of taper	Failure load per unit width (MN/m)	Locus of failure
u-carbon/PEEK	50°	Inner	2.45 ± 0.28	Interlam/inner
u-carbon/PEEK	30°	Inner	2.58 ± 0.23	Interlam/inner
u-carbon/PEEK	10°	Inner	2.55 ± 0.25	Interlam/inner
u-carbon/PEEK	50°	Outer	2.52 ± 0.19	Interlam/inner
u-carbon/PEEK	30°	Outer	2.49 ± 0.22	Interlam/inner
u-carbon/PEEK	10°	Outer	2.61 ± 0.23	Interlam/inner
u-carbon/PA	30°	Inner	2.51 ± 0.27	Interlam/inner
u-carbon/PA	30°	Outer	2.48 ± 0.24	Interlam/inner
u-carbon/epoxy	30°	Inner	1.84 ± 0.19	Interlam/inner
u-carbon/epoxy	30°	Outer	1.91 ± 0.17	Interlam/inner

Notes: a. Adhesive fillet angle, α, ≅90°.
b. Overlap length = 60 mm.
c. Unsymmetrical design (see Figure 5).

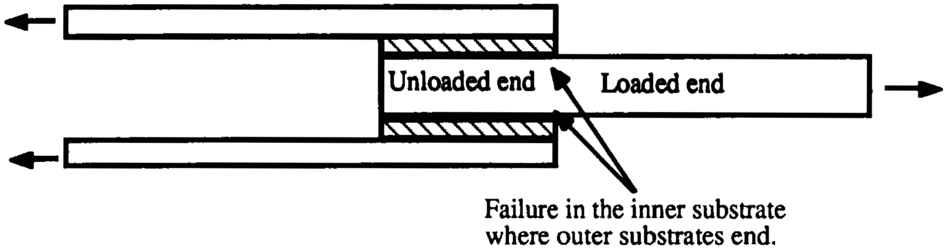

FIGURE 4 Failure initiation sites in the double-overlap joint, shown with $\alpha = 90°$ and $\beta = 90°$.

via interlaminar fracture of the inner composite substrate at the end of the bonded overlap, as shown in Figures 4 and 5.

Effect of using angled adhesive fillets and non-tapered fibre-composite substrates The next step was to prepare joints where the adhesive fillet was shaped to a given angle, as shown in Figure 1. The adhesive fillet angle, α, was therefore varied whilst maintaining the angle, β, of the fibre-composite at 90°. An overlap length of 60 mm was again used for these experiments. It was found that varying the adhesive fillet angle had no significant effect on the measured failure loads and the locus of joint failure was again via interlaminar fracture of the inner composite substrate at the end of the bonded overlap, as shown previously for the case of $\alpha = 90°$ in Figure 4.

Effect of tapering the fibre-composite substrates and using angled adhesive fillets So far in the work it had been found that the joint efficiency was about 60%, assuming that in the case of the thermoplastic fibre-composites a corona surface treatment

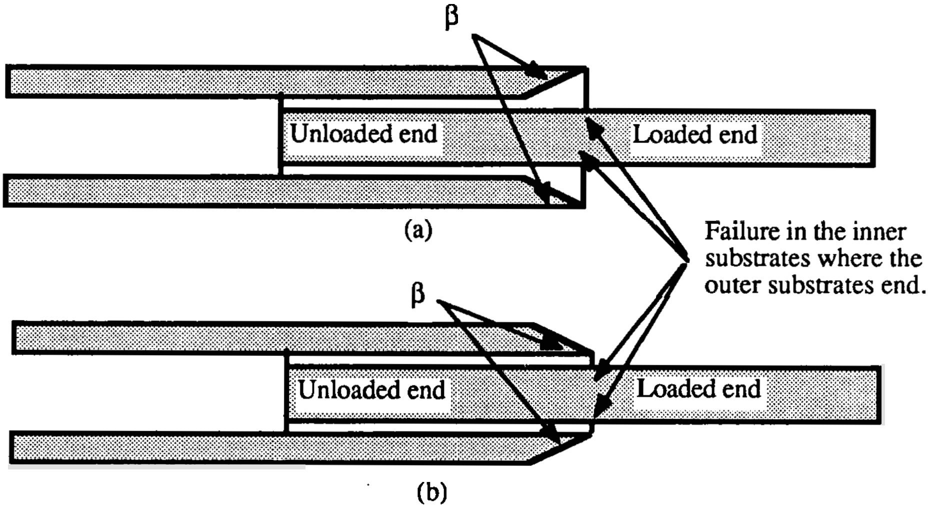

FIGURE 5 Designs of unsymmetrical double-overlap joints with (a) "inner" taper and (b) "outer" taper, with $\alpha = 90°$

was employed prior to adhesive bonding. Therefore, double overlap joints were prepared where both an "inner" taper was machined on the fibre-composite substrates at various angles, β, and various adhesive fillet angles, α, were also employed. In all cases the overlap length was 60 mm. It was found from both theoretical and experimental studies[4] that to obtain the highest possible failure loads the joints had to be symmetrical; i.e. the joints needed to possess tapered composite substrates and adhesive fillets at both ends of the bonded overlap as shown schematically in Figure 1.

Results for the symmetrical double overlap joints prepared using both tapered fibre-composites and adhesive fillets are shown in Table V. Several interesting points emerge from these data. Firstly, for the bonded carbon-fibre/PEEK composite joints the failure load increases as both the adhesive fillet angle, α, and the taper angle, β, become more acute, up to values of these angles of about 20°. Making the values of α and β less than 20° has no further effect on the measured failure load. Secondly, a similar picture emerges for the bonded carbon-fibre/PA and carbon-fibre/epoxy composite joints. Thirdly, in all cases a very high joint efficiency of approaching 100% is observed when relatively acute angles for α and β are employed. Fourthly, the locus of failure was not via interlaminar fracture of the inner fibre-composite substrate in these joints, as it was for the joints discussed above. Instead, these symmetrical double overlap joints prepared using both tapered fibre-composites and adhesive fillets failed by a cohesive crack initiating in the adhesive fillet and then propagating through the adhesive, with an occasional excursion of the crack into the fibre-composite substrates when the crack had reached the central regions of the bonded overlap.

TABLE V
Failure loads for the double-overlap joints prepared using both tapered fibre-composites and adhesive fillets

Fibre-composite	Adhesive fillet angle, α	Taper angle, β	Failure load per unit width (MN/m)	Joint efficiency (%)
u-carbon/PEEK	50°	50°	3.05 ± 0.17	74
u-carbon/PEEK	40°	40°	3.31 ± 0.14	80
u-carbon/PEEK	30°	30°	3.60 ± 0.19	87
u-carbon/PEEK	20°	20°	3.92 ± 0.14	95
u-carbon/PEEK	10°	10°	3.96 ± 0.16	96
u-carbon/PA	50°	50°	2.87 ± 0.17	72
u-carbon/PA	40°	40°	3.24 ± 0.15	81
u-carbon/PA	30°	30°	3.55 ± 0.10	89
u-carbon/PA	20°	20°	3.78 ± 0.19	95
u-carbon/PA	10°	10°	3.88 ± 0.20	97
u-carbon/epoxy	50°	50°	2.95 ± 0.23	86
u-carbon/epoxy	40°	40°	3.12 ± 0.21	91
u-carbon/epoxy	30°	30°	3.21 ± 0.13	94
u-carbon/epoxy	20°	20°	3.15 ± 0.16	92
u-carbon/epoxy	10°	10°	3.24 ± 0.19	95

Notes: a. Overlap length = 60 mm.
b. Symmetrical design and "inner" taper on fibre-composite substrates (see Figure 1).

Comparison of Theory to Experimental Results

Effect of overlap length For values of the adhesive fillet angle, α, of 90° it was found that for all taper angles, β, the locus of failure was via the interlaminar failure of the inner fibre-composite substrate. The theoretically predicted values of the transverse tensile stress in the inner fibre-composite substrate are shown in Figures 6 and 7 for bonded overlap lengths of 20 and 50 mm respectively and for $\alpha = 90°$ and $\beta = 90°$. The applied loads are 1 MN/m and 2.45 MN/m respectively, and these values represent the experimentally measured values. In both cases the maximum value of the transverse tensile stress in the inner fibre-composite substrate occurs at the loaded end just inside the composite, adjacent to the interface. Further, in both cases the maximum value is in excellent agreement with the measured value for the transverse fracture stress of the fibre-composite, namely 83.7 MPa. When the maximum values of the principal tensile stresses and modified von Mises stresses in the adhesive layer were examined then these were found[4] to be significantly lower than the experimentally measured values. Hence, the theoretical FEA studies predict that the joints would fail via interlaminar fracture of the inner fibre-composite substrate at the failure loads which were experimentally measured, as was indeed observed. Further, these studies reveal that the maximum transverse tensile stress is a function of overlap length, thus explaining the dependence of the measured joint failure load upon the bonded overlap length.

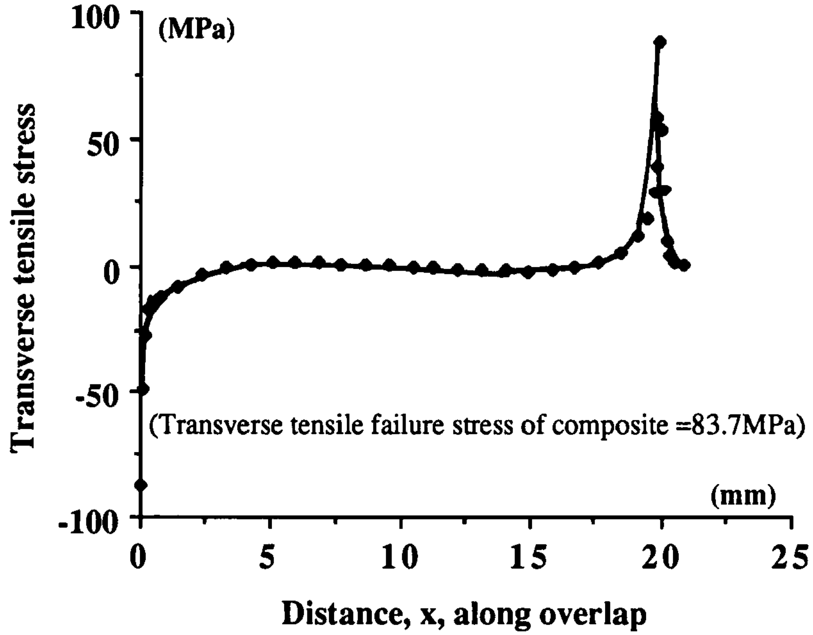

FIGURE 6 Transverse tensile stresses in the inner composite substrate adjacent to the adhesive. Applied load is 1 MN/m and the overlap length is 20 mm. (For the u-carbon/PA bonded joint, with $\alpha = 90°$ and $\beta = 90°$.)

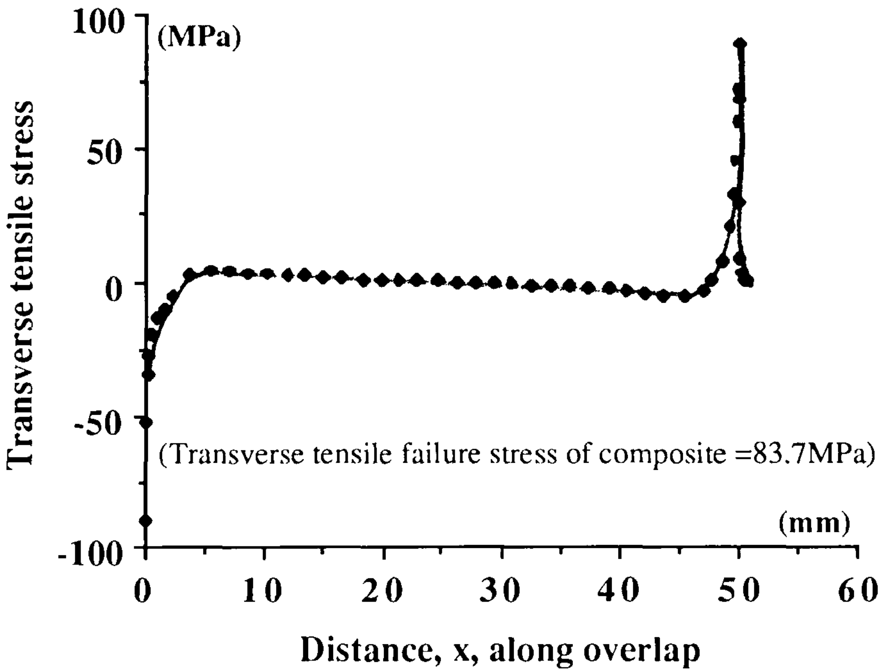

FIGURE 7 Transverse tensile stresses in the inner composite substrate adjacent to the adhesive. Applied load is 2.45 MN/m and the overlap length is 50 mm. (For the u-carbon/PA bonded joint, with $\alpha = 90°$ and $\beta = 90°$.)

Effect of employing tapered composite substrates and angled adhesive fillets The effect on the predicted transverse tensile stresses in the inner fibre-composite substrate from tapering the adhesive fillet, α, and the composite substrate, β, is illustrated in Figure 8, where the values of α and β are both taken to be 30°. In Figure 8 the maximum value of the transverse tensile stresses in the inner fibre-composite substrate again occurs at the loaded end just inside the composite, adjacent to the interface. However, comparing Figures 7 and 8, it may be readily seen that the joint with an angled adhesive fillet and fibre-composite substrate has a far lower value of the maximum predicted transverse tensile stress, even though the applied load of 3.45 MN/m is far higher in this case. (Again, the applied load used in these theoretical calculations is that measured experimentally.) Also, note that the value of the maximum predicted transverse tensile stress is significantly lower than the measured fracture value of 83.7 MPa. Thus, these data clearly support the locus of failure not being via an interlaminar failure of the inner fibre-composite substrate, as noted above. Indeed, further theoretical analyses revealed that, for the joint with α and β of 30° and an applied load of 3.45 MN/m, the maximum values of the principal tensile stresses and modified von Mises stresses in the adhesive layer both were in close agreement with the experimentally measured values of these parameters. These observations explain why the locus of failure in these joints was mainly via cohesive facture through the adhesive.

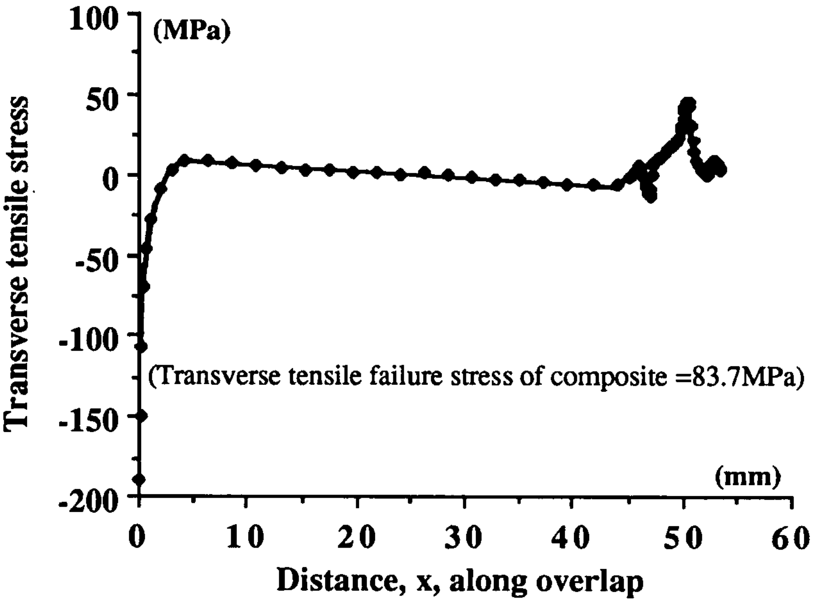

FIGURE 8 Transverse tensile stresses in the intercomposite substrate adjacent to the adhesive. Applied load is 3.45 MN/m and the overlap length is 50 mm. (For the u-carbon/PA bonded joint, with $\alpha = 30°$ and $\beta = 30°$.)

CONCLUSIONS

The following conclusions may be reached from these present studies:

(i) To obtain adequate adhesion of epoxy-based structural adhesives to thermoplastic fibre-composite substrates the substrates need to be subjected to a more effective surface treatment than simply an abrasion/solvent-wipe treatment. A surface treatment based upon a corona-discharge treatment is very effective for these fibre-composites.

(ii) To attain very high joint efficiencies from double-lap joint designs it is necessary to pay particular attention to the stresses generated at the ends of the overlap, and these may be greatly reduced by using an angled adhesive fillet and by tapering the fibre-composite substrates.

(iii) By using the corona discharge to surface treat the thermoplastic fibre-composites prior to adhesive bonding and then designing the double-overlap joints using angled adhesive fillets and tapered fibre-composite substrates with angles of about 20° or less, very high joint strengths may be realised. Indeed, joint efficiencies approaching 100% have been recorded.

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