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Compressive strength of unidirectional and crossply carbon fibre/PEEK composites

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The commonly accepted production methods of composite systems generally result in departure of the plies properties from transverse isotropy due to stresses acting during fibre–matrix bond formation. This anisotropy coupled with the composite structure affects compressive loading; the ultimate stresses as well as the direction, in- or out-of-plane, of kink propagation. A unidirectional and a crossply carbon fibre/PEEK composites were compression tested at ambient and elevated temperature as well as exposed to various chemical environments. Significant disruptions in fibre–matrix interface in the crossply composite were indicated. The compression tests showed that failure occurred through in-plane and out-of-plane fibre bucking and kinking in the unidirectional and crossply composites, respectively. Failure of the longitudinal plies in the crossply laminate occurred at significantly higher compression stress than for the unidirectional composite. Compressive failure mechanisms in unidirectional and multi-directional laminates are considered.

1. Introduction

Most publications concerning compressive strength of fibre reinforced composites are restricted to the study of unidirectional composites [e.g. 1–6]. The models describing longitudinal compression behaviour of these composites are becoming more detailed and complicated. Some models take into account a few possible modes of failure, depending on components' properties and content, such as fibre buckling fibre compression failure, matrix shear failure, matrix non-linearity, initial fibre waviness, and fibre–matrix debonding. However, all design models are far from complete regarding the prediction of compressive properties of these unidirectional composites [6]. At the same time, most practical structures are made of composites with more than one fibre orientation; the model representations and experimental data for unidirectional composites were presumed to be adequately used to predict a layer behaviour in multi-directional laminates.

It is only recently that composites with complicated structures are being investigated. The task of experimental investigation and the failure process modelling for these composites is very intricate and presently, insufficient data and only first simplified models are available [7–10]. Sohi *et al.* [7] measured significantly increased compressive failure strains in quasi-isotropic laminates as compared to unidirectional ones. On the basis of comparison tests of unidirectional composite and $[(\pm 45/O_2)_3]$ laminates, Soutis [9] concluded that the $\pm 45°$ plies have little influence on the apparent strength of the 0° plies. Just before failure of these laminates the Poisson's ratio for the $\pm 45°$ plies may approach the value of unit, resulting in significant shear stress between 0° and $\pm 45°$ plies, and transverse tensile stress in the longitudinal plies. These stresses, resulting from the plies interaction, may explain the observed in-ply splitting parallel to the fibres and delamination between the 0° and $\pm 45°$ plies, which could adversely affect the apparent strength of the 0° plies in the laminate. Swanson [10] considered in-plane buckling of initially wavy fibres in a unidirectionally compressed multi-layered composite. He took into account the restraining influence of adjacent differently oriented plies through an action of shear stress on plies interface (τ_{zy}, see Fig. 1c). Comparison of the model prediction with experimental data on tubular specimens, having a few different laminate structures, shows that the model reflects a dependence of the apparent strength of the plies, with fibres in the axial direction, on the relative shear stiffness of the adjacent plies. It should be pointed out that, generally, the fibre waviness and buckling may occur in as well as out of the layer's plane. In compression tests of tubular specimens [10], increasing out-of-plane fibre waviness (see Fig. 1d) results in

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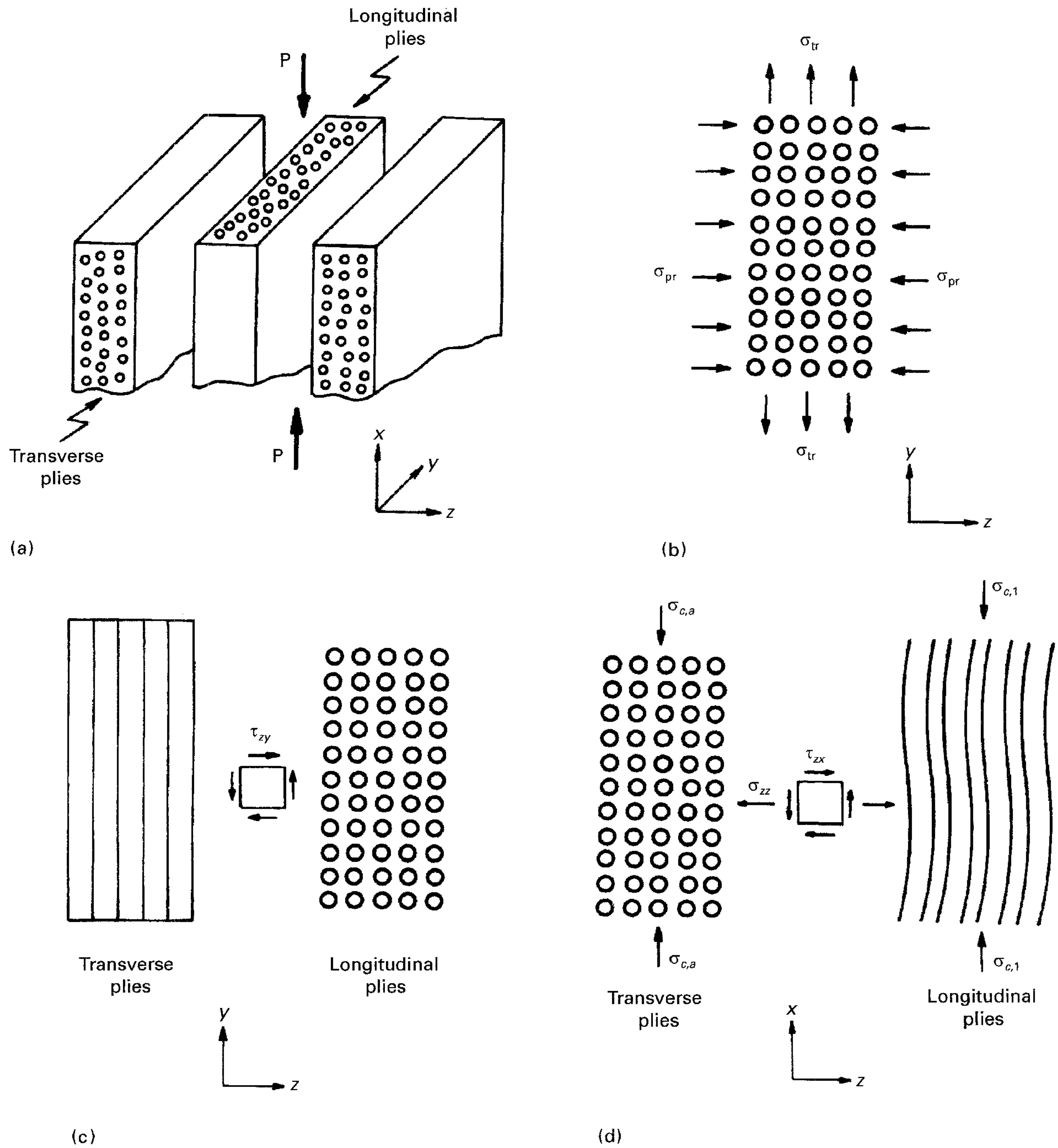

Figure 1 Schemes of a crossply composite: (a) model of composite; (b) processing stresses in a layer; (c) restricting stresses at in-plane and (d) at out-of-plane fibre buckling.

a change of the tube's radius (z direction). This leads to the appearance of a tangential stress in the differently oriented plies, which have high stiffness in this direction. This kind of fibre waviness effect on stresses in adjacent plies is lacking in planar specimens.

In the present work, compressive tests of unidirectional and crossply carbon fibre/PEEK composites were performed, and some special features of the failure process, which were not discussed in previous literature, are revealed and analysed.

2. Some considerations of the compressive failure mechanisms in continuous fibre composites

All proposed models for the compressive failure in continuous fibre composites assume transverse isotropy in unidirectional composites and identical layer properties in both unidirectional and multi-directional laminates. However, the common production methods, such as compression moulding and winding, may result in differences in various in-plane and out-of-plane composites parameters such as average distances between fibres, micro- and macro-level residual stresses and fibre–matrix bond strength [11]. Moreover, different in-plane and out-of-plane fibre misalignments may occur [12]. Some experimental data for unidirectional composites [13, 14] show differences between the Young's and shear moduli (E_{22}, E_{33} and G_{12}, G_{13}: 1 – the fibre direction) in the orthogonal directions. Differences between the strength parameters are expected to be even more notable. Orthotropy, in which the axes of symmetry coincide with the plane and orthogonal to the plane directions, may be expected. The main reasons for layer orthotropy and its influence on the ultimate strength and mechanisms of compressive failure, of both unidirectional and crossply compression moulded composites, will now be discussed.

Significant thermal residual stresses are developed in fibre–matrix composites upon cooling from the moulding temperature due to the fibres and matrix thermal expansion coefficients (TEC) mismatch. The stresses resulting from different processing forces combined with the residual stresses field, affect the ultimate properties of the composites [15–18]. During compression moulding of a composite plate, the transverse pressure (σ_{pr}, Fig. 1b) enhances [19] the fibre–matrix bond at the interfaces close to the in-plane (xy, Fig. 1). Due to the high transverse TEC, cooling of a unidirectional composite plate (while still in the mould) generates, through coupling and friction forces, transverse in-plane tensile stresses (σ_{tr}, Fig. 1b). These stresses result in deterioration of fibre–matrix bonding at interfaces close to the out-of-plane (xz, Fig. 1) [17]. In the plies of a multi-directional laminate, however, the transverse (relative to fibre orientation) tensile stresses (σ_{tr}) are generated also as a result of an interaction between differently oriented layers. Because of interlayer slippage in such complicated structure laminates, their transverse tensile stresses are higher than in unidirectional composites. These stresses in the multi-directional composites, differently from the unidirectional case, reside after the extraction of the plate from the mould. These residual tensile stresses cause significant deterioration of the fibre–matrix bonds [18], hence, decreasing the in-plane shear strength of the plies. Thus, the effective fibre–matrix interface shear resistance to out-of-plane is higher than to in-plane macro-stresses.

Longitudinal compressive strength of unidirectional composites is well known to increase with their shear strength [20, 21]. Thus, the anisotropy of the fibre–matrix shear resistance affects the composite failure direction. Taking into account this anisotropy, one would expect failure in unidirectional composites due to in-plane fibre buckling. Fracture surface obtained during the compressive failure is inclined to the loading direction [3, 7] and perpendicular to the plies plane. The case of longitudinal splitting [1] is not discussed here.

In multi-directional laminates, however, because of restricting effects of the adjacent layers, failure in the longitudinal ply occurs due to either in-plane or out-of-plane, depending on energy profit, fibre buckling. For the in-plane case (Fig. 1c), the adjacent differently oriented layers and/or their interlayer bond must fail (acting stresses are $\sigma_{c,a}$ and τ_{yz} or τ_{yz}, respectively). In this case, the fracture surface in the longitudinal layer is inclined to the transverse direction (y) [1, 3, 7] and perpendicular to the plate surface (xy); generally it does not coincide with the fibre orientation in the adjacent layer. In case of failure due to out-of-plane fibre buckling (Fig. 1d), the effective fibre–matrix interface shear resistance is higher than that in the in-plane case. However, other restricting effects of the adjacent layers take place. For this case, the adjacent differently oriented layers and/or their interlayer bond must fail, affected by $\sigma_{c,a}$ and τ_{xz} and/or out-of-plane shear (τ_{xz}) and tension (σ_{zz}), respectively (Fig. 1d). Fracture surface in the longitudinal layer is inclined to the plies plane (xy) [1, 3, 7] and perpendicular to the transverse plane xz (Fig. 1). For the particular case of plane crossply composites, one would expect failure due to out-of-plane fibre buckling. This choice is suggested since fracture propagation parallel rather than perpendicular to fibres of the adjacent layers seems to be more likely.

To test the validity of the above discussed mechanisms of compressive failure, the following experimental investigations of unidirectional and crossply composites were performed: (a) evaluation of fibre–fibre distance; (b) evaluation of fibre-matrix bond disruptions through exposure to various chemical environments; and (c) ambient and high temperature compression tests and fractography.

3. Experimental procedure

Carbon fibre reinforced PEEK plates (61 vol % fibre content, 2 mm thickness) were fabricated by pressing of stocked commercially available APC-2 prepreg tapes. They were either unidirectional $(0)_{16s}$ or crossply $(0/90)_{8s}$ symmetric composites. Specimens, $80.7 \times 12.7 \times 2$ mm, were cut out of these plates with their axis coinciding with the fibre direction in the surface layers.

To study the fibre–matrix bond disruptions, samples of the unidirectional and crossply composites were exposed to humidity (95% RH, $T = 75$ °C), distilled water ($T = 75$ °C) and benzine (SBP) 55/90 (ambient temperature), and weight gain was followed. The humidity exposures were performed by placing the samples in a desiccator with a saturated $Pb(NO_3)_2$ solution, which was placed in an oven (provides 95% RH at 75 °C [22]).

Compression tests at ambient and 120 °C were carried out according to a modified SACMA recommended SRM 1-88 method (Fig. 2). No bonded tabs were used to eliminate any effects of the bonding process on the specimens' properties and to provide the required shear strength for high temperature tests. This specimen geometry, without tabs, also significantly simplifies the investigation of the environmental effects. To eliminate "brooming effect" at the specimen ends a special jig has been designed and used (Fig. 2a). This jig consists of two pairs of grooved steel tabs bolted together to restrict the specimen's transverse deformation and to force the failure to occur at the specimen's centre. The steel tabs grooved surfaces were serrated to minimize the specimen slippage and thus decreasing the required contact pressure. To minimize the specimen's non-axial loading, the specimens were loaded through a ball support (see Fig. 2c).

Compression tests at ambient and high temperature were performed using an Instron universal testing machine equipped with a temperature chamber. For the high temperature tests the specimens were exposed to 120 °C for about 2 min. At least eight specimens of

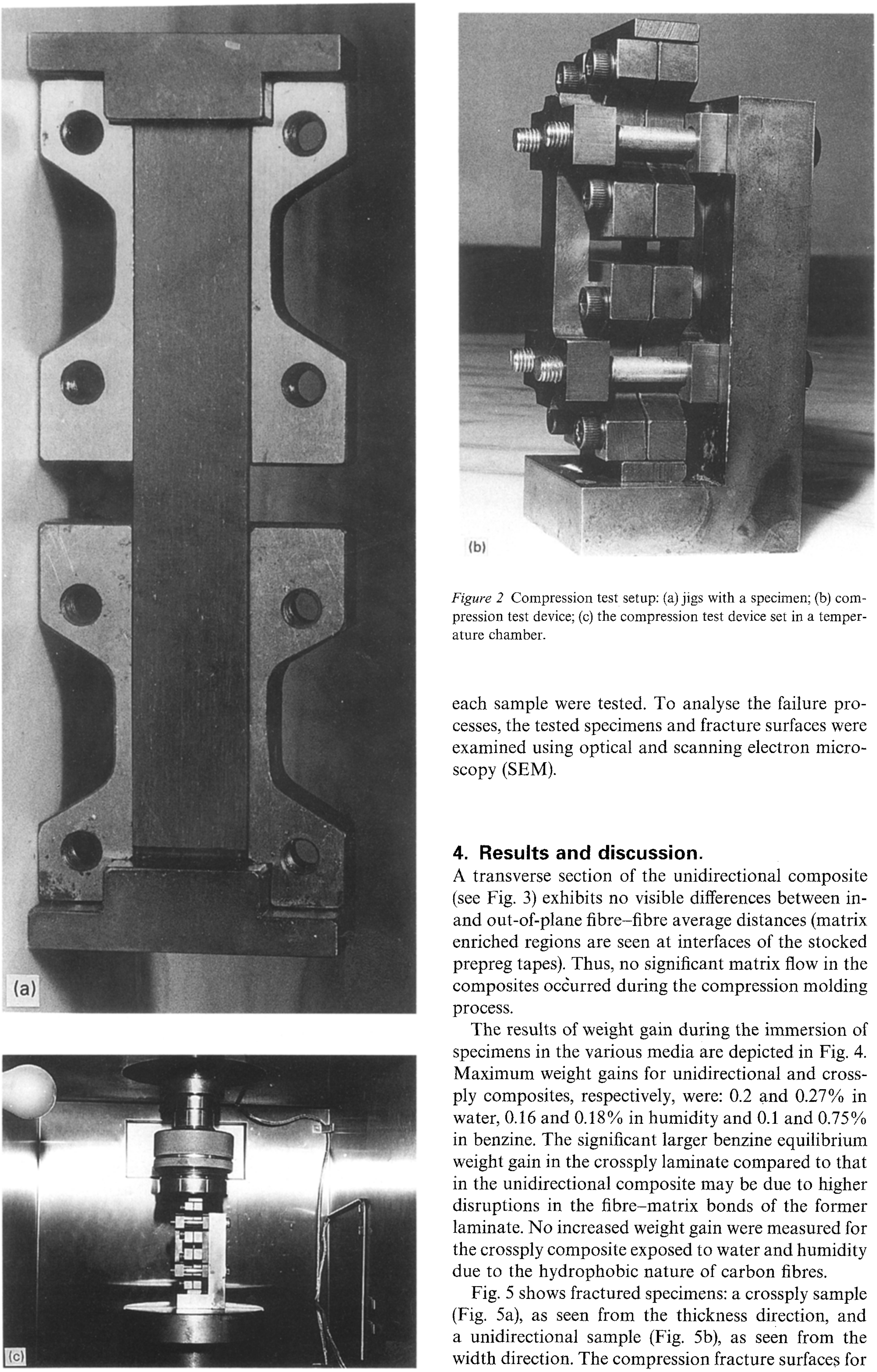

Figure 2 Compression test setup: (a) jigs with a specimen; (b) compression test device; (c) the compression test device set in a temperature chamber.

each sample were tested. To analyse the failure processes, the tested specimens and fracture surfaces were examined using optical and scanning electron microscopy (SEM).

4. Results and discussion.

A transverse section of the unidirectional composite (see Fig. 3) exhibits no visible differences between in- and out-of-plane fibre–fibre average distances (matrix enriched regions are seen at interfaces of the stocked prepreg tapes). Thus, no significant matrix flow in the composites occurred during the compression molding process.

The results of weight gain during the immersion of specimens in the various media are depicted in Fig. 4. Maximum weight gains for unidirectional and crossply composites, respectively, were: 0.2 and 0.27% in water, 0.16 and 0.18% in humidity and 0.1 and 0.75% in benzine. The significant larger benzine equilibrium weight gain in the crossply laminate compared to that in the unidirectional composite may be due to higher disruptions in the fibre–matrix bonds of the former laminate. No increased weight gain were measured for the crossply composite exposed to water and humidity due to the hydrophobic nature of carbon fibres.

Fig. 5 shows fractured specimens: a crossply sample (Fig. 5a), as seen from the thickness direction, and a unidirectional sample (Fig. 5b), as seen from the width direction. The compression fracture surfaces for the crossply composite is parallel to the fibres in the

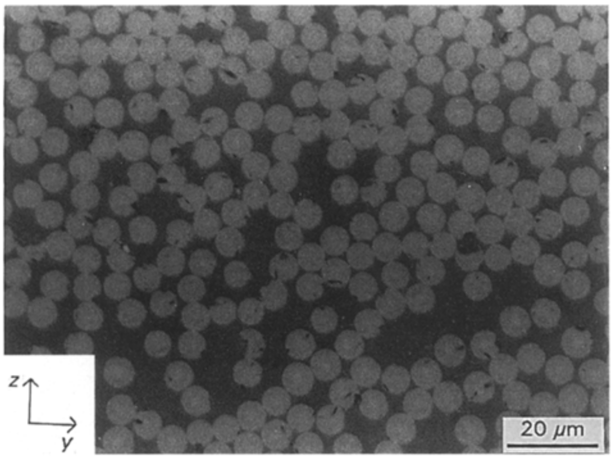

Figure 3 An optical micrograph of a transverse section of the unidirectional composite (*z*, pressing direction).

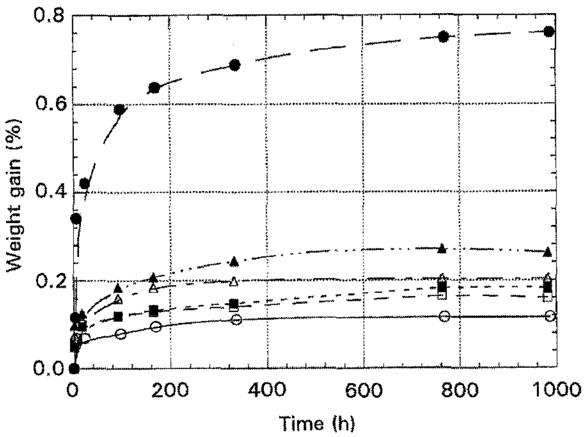

Figure 4 Weight gain of the composites during exposure to various environments:—○— benzine, unidirectional; —●— benzine, crossply; —□— humidity, unidirectional; —■— humidity, crossply; —△— water, unidirectional, — ·▲· — water, crossply.

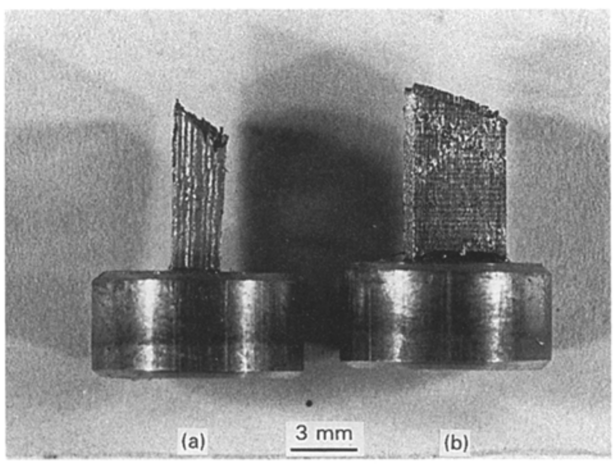

Figure 5 Typical compression tested specimens: (a) crossply, as seen from the thickness direction; (b) unidirectional, as seen from the width direction.

transverse plies, while in the unidirectional composite is orthogonal to the plies' plane. The inclination angle of the fracture surface is higher for the unidirectional composite than for the crossply one.

Due to the high matrix ductility, especially at elevated temperature, it was possible to investigate the tested specimens which still kept their integrity. Optical micrographs of an in-plane longitudinal section (*xy*) of a unidirectional tested specimen are shown in Fig. 6. An in-plane relative displacement of fragments and characteristic z-shaped fibre fractures (kinks) can be observed (Fig. 6a,b). In addition, two oppositely inclined bands of highly damaged composite are observed (Fig. 6c,d). Thus, these micrographs clearly show that the unidirectional composites' failure occurs through in-plane fibre buckling and kinking, as discussed above. By contrast, in the compression failed crossply composite, relative out-of-plane displacement of fragments is observed (Fig. 7). Here also, two oppositely inclined bands are seen. Thus, the crossply composites failed through out-of-plane fibre buckling and kinking, as discussed above.

The SEM micrographs for the unidirectional composite (Fig. 8a,b) confirm a stepped character of the fracture surfaces, previously described by Shikhmanter *et al.* [23]. This feature is typical for failure of unidirectional composites in a buckling mechanism. To determine the buckling plane orientation, fibre fracture surface should be examined [23]. One can observe a demarcation line, which corresponds to the crack front-position (propagating from the tensile to the compressive side of the fibre) when a change in the crack propagation regime occurs. This line is orthogonal to the buckling direction. As can be seen from the fibres fracture surface, Fig. 8c (e.g. arrow), failure occurred due to fibre buckling at a plane close to the in-plane.

The crossply composite fracture surface (Fig. 9) has a more complicated and less distinct character than the unidirectional one, due to an extensive post-fibre-failure damage. The matrix is significantly deformed due to its high ductility, resulting in regions in the fracture surface where the layers are hardly recognizable (Fig. 9a). However, there are regions in the fracture surface which do resemble the transverse (Fig. 9b) and longitudinal (Fig. 9c,d) layers. Observation of the fibres, fracture surface (Fig. 9c,d) explicitly indicates that the longitudinal layers failed through out-of-plane fibre buckling. Failure of the transverse layers was, as expected, through fibre–matrix debonding and matrix fracture, without significant fibres breakage (Fig. 9b). Thus, optical and SEM fractography confirm the proposed mechanism of compression failure of the unidirectional and crossply composites, namely, through in-plane and out-of-plane fibre buckling, respectively.

Compression strength of the unidirectional composite at 23 °C was assumed, in accordance with the APC-2 manufacturer, as 1100 MPa [12], and that for the crossply composite was presently measured to be 805 ± 25 MPa. The high temperature tests of the unidirectional and crossply composites yielded compression strengths of 887 ± 38 MPa and 753 ± 12 MPa, respectively. To evaluate the compression strength of longitudinal plies in the crossply composite the following data of the APC-2 based ply [24] were used: Young's moduli $E_{11} = 128.9$ GPa, $E_{22} = 9.4$ GPa

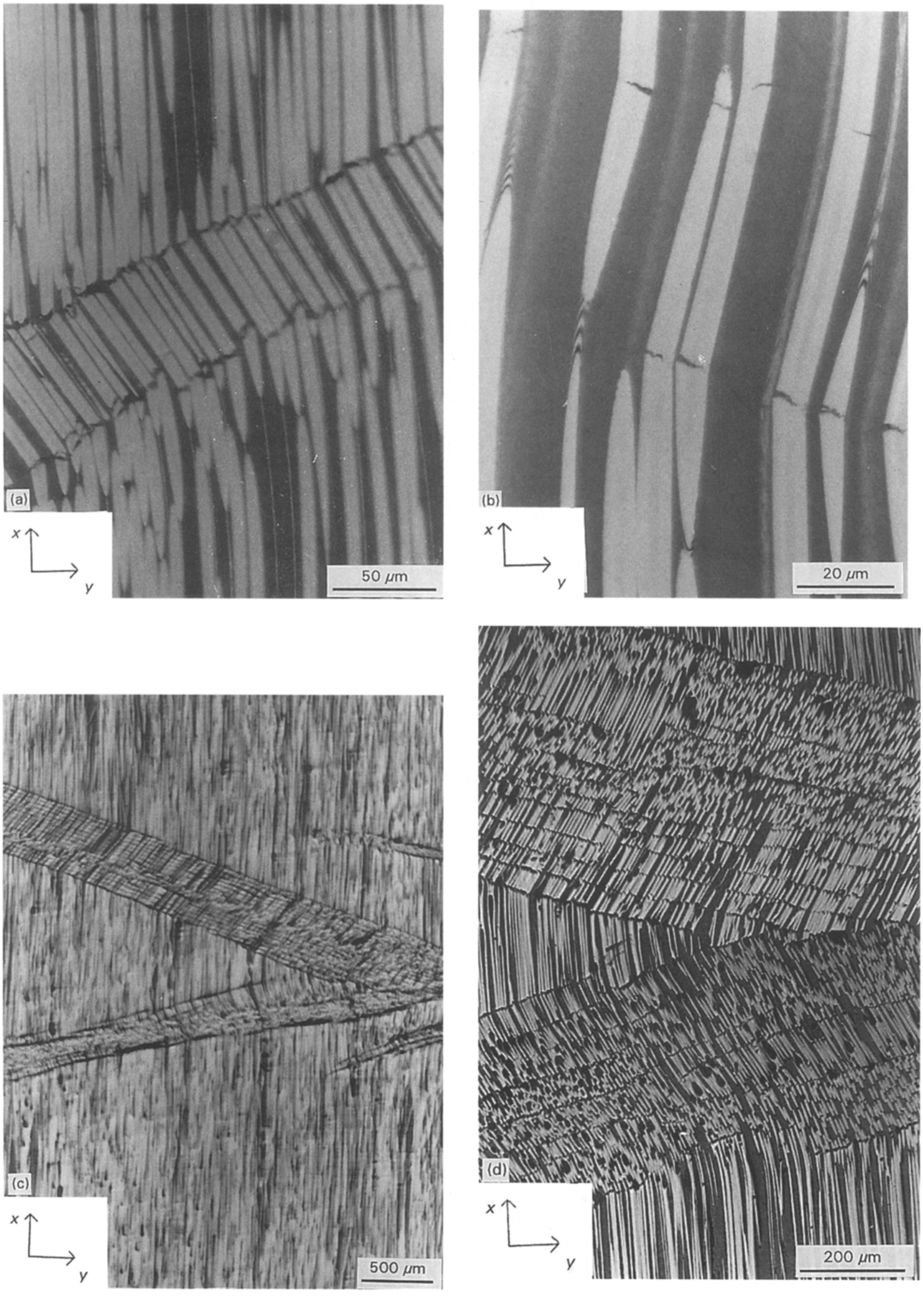

Figure 6 Optical micrographs of an in-plane section of a compression tested unidirectional composite.

and Poisson's ratio $\nu_{12} = 0.31$. Hence, stiffness of the transverse plies is just 7.3% of the longitudinal one; at elevated temperature this difference is even more striking. Evaluation of the high temperature compression strength of longitudinal plies, based on these ambient temperature data, results in lower estimated than actual values. Estimations, based on the laminate theory (longitudinal piles are half of the composite thickness),

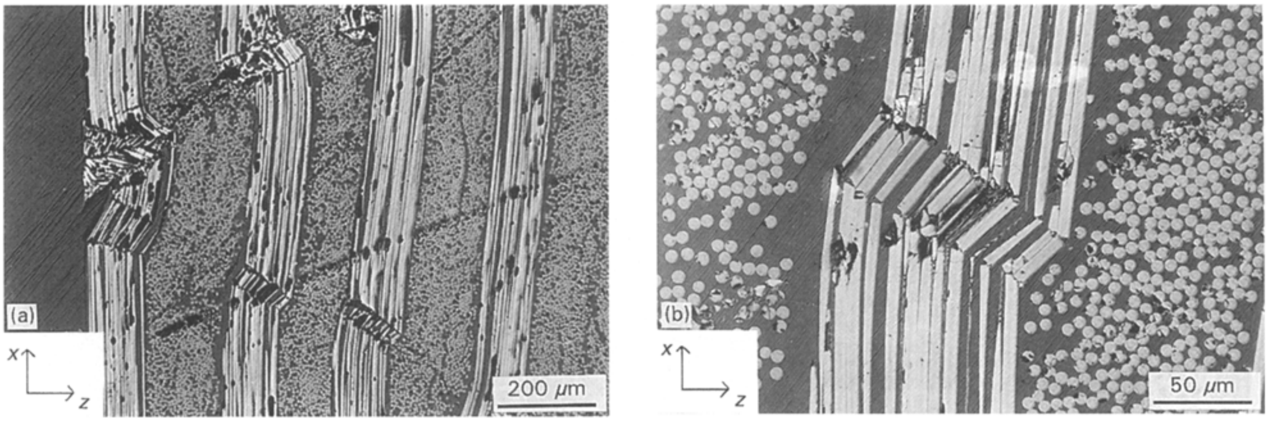

Figure 7 Optical micrographs of an out-of-plane section of a compression tested crossply composite.

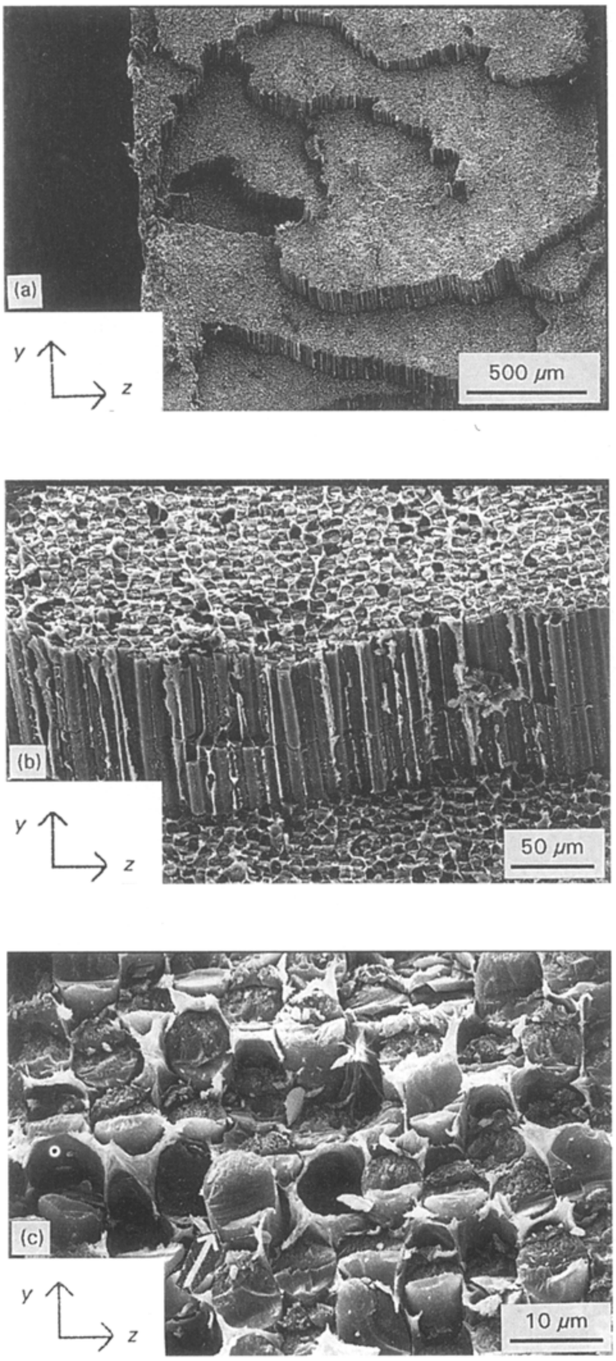

Figure 8 SEM micrographs of a fracture surface of a unidirectional composite.

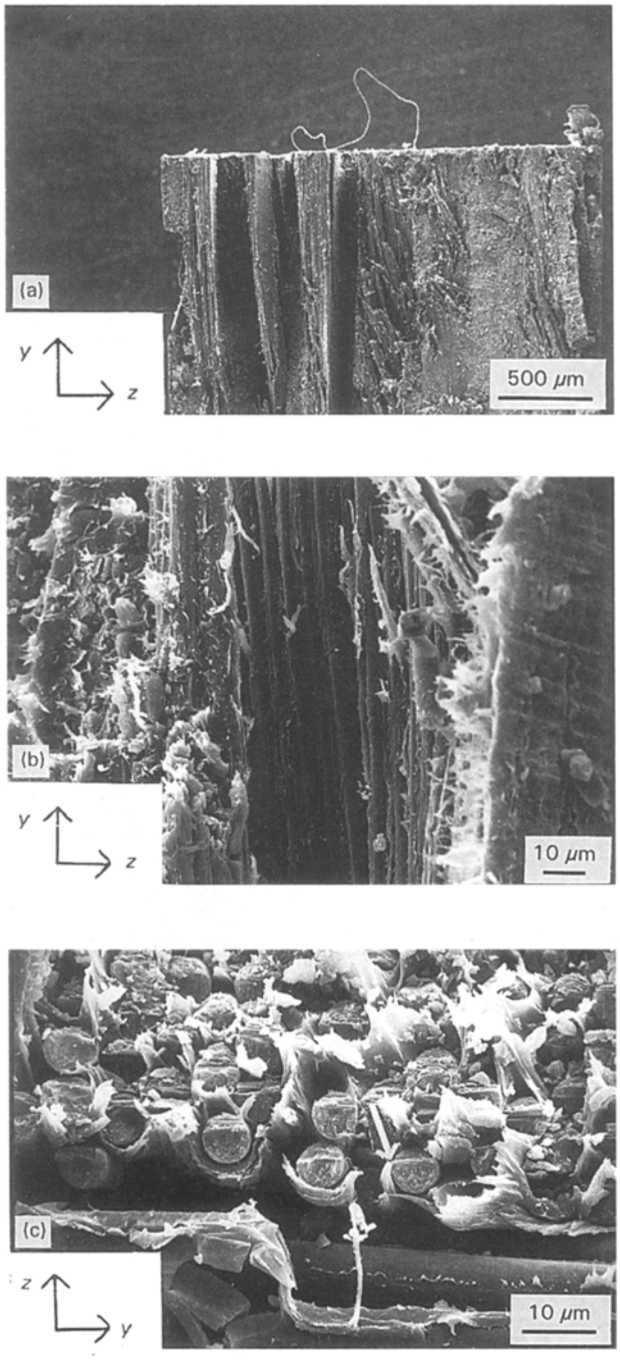

Figure 9 SEM micrographs of a fracture surface of a crossply composite.

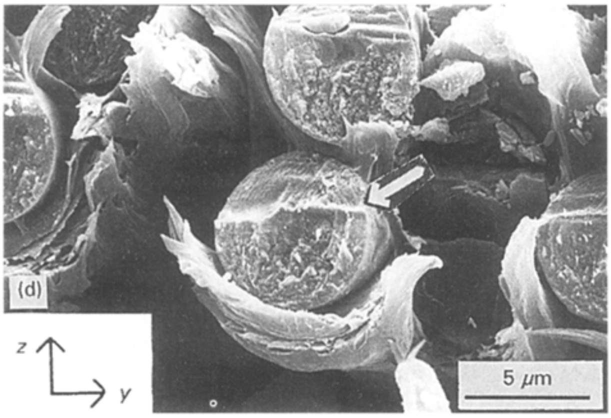

Figure 9 (Continued).

show that for the crossply composite the layers' interaction causes the longitudinal compressive strength of the plies in the laminate to increase by at least 35 and 55%, when tested at ambient and high temperature, respectively.

5. Conclusions

1. Depending upon the fabrication process, a unidirectional composite and a ply in a crossply laminate generally possess an orthotropy of the mechanical properties. The difference between in-plane and out-of-plane shear strength of the plies is one of the main reasons for the orthotropy.
2. Plies of the crossply composite possess significant fibre–matrix bond disruptions which are probably located in the fibre–matrix interfaces close to the out-of-plane.
3. Orthotropy of the plies in the unidirectional carbon fibre/PEEK composite manifests itself through failure due to the in-plane fibre buckling and kinking. Failure in multi-directional laminates may occur due to the in-plane or the out-of-plane fibre buckling and kinking, depending on the energy profit. In the case of the crossply carbon fibre/PEEK composite, failure occurred due to the out-of-plane fibre buckling and kinking.
4. Failure of the longitudinal plies in the crossply laminate occurred at higher ply compression stress than in the unidirectional composite.

It is suggested that these conclusions are applicable to composites, in which compression strength depends on fibre–matrix bonding.

The obtained results have to be taken into account for designing more realistic models, for test method development and test results' analysis, and for the elucidation of routes for composite improvements.

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