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Hybrid composites based on polyethylene and carbon fibres
Part V Energy absorption under quasi-static crash conditions

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Fibre-reinforced composites offer great potential for use in aircraft and automotive primary structures. However, the rather brittle failure mode of most advanced composite systems has been a continuous concern for engineers in using these materials in structures in which energy absorption under impact conditions is a key design parameter. Consequently, crash protection or the crashworthiness of composite structures is still an important issue in the helicopter and automotive industries. A major advantage of composite materials is the potential to tailor mechanical properties in general, or the crashworthiness of a structure in particular, by means of constituent properties such as fibre, matrix and interface, or design variables such as fibre orientation, stacking sequence, hybridization, etc. Fracture processes of composite materials typically involve multiple individual microfracture mechanisms including fibre pullout, debonding and delaminations, resulting in a significant synergistic effect with respect to the fracture energy of a composite based on that of its constituent, i.e. fibre and matrix.

Previous studies demonstrated that the specific energy absorption of composite materials can, under some conditions, be better than for metals when tubes are axially compressed [1–8]. Upon axial loading, composite tubes can either collapse by failure at the centre of the tube or by progressive crushing from one end. Jahnle [1] and Thornton [2] have shown that a 45° bevel at one end of the tube, in order to "trigger" local fracture processes, leads to a stable propagation of the collape from that end and, consequently, a more effective energy absorption process. Various types of progressive crush modes have been identified, depending on the fibre [2–6] and matrix [6] properties, fibre orientation [5, 8], specimen geometry [7, 9] and trigger geometry [10]. With regard to the influence of fibre properties on crushing behaviour, roughly two different failure modes can be observed. Composites incorporating ductile fibres exhibit a local buckling crushing mode, whereas brittle fibre composites generally fail by a brittle failure mode of interlaminar shear failure, fibre fracture and microfragmentation. Although composites that fail by a brittle crush mode generally exhibit higher values for energy absorption, their loss of structural integrity after fracture is a major drawback with respect to their use in primary structures. Besides specific energy absorption, post-crushing structural integrity is another important requirement for a crashworthy structure, since the structure must remain intact to provide protection after a crash.

An approach to overcome this problem of post-crush structural integrity of brittle fibre-reinforced composites is via hybridizing with ductile fibres. Hybridization of brittle carbon fibres with ductile high-performance polyethylene (HP-PE) fibres has proven to be highly effective in improving the impact properties of carbon fibre-reinforced composites in terms of improved damage tolerance [11, 12] as well as enhanced energy absorption capability [13, 14]. Previous work by Kindervater and Scholle [15] on energy absorption of HP-PE/carbon hybrid tubes was limited solely to one hybrid configuration with HP-PE fibres at an orientation of ±75° at the inner and outer diameter and at the midsection carbon fibres with a ±15° fibre orientation, resulting in specific energy absorption levels comparable with those of pure carbon tubes with a fibre orientation of ±45°. However, since energy absorption of carbon/epoxy composites generally decreases with increasing fibre angle [5, 8], comparison of both types of tubes is somewhat deceptive.

The objective of this study was to investigate the crush performance of intermingled HP-PE/carbon hybrid composite tubes with a constant fibre orientation. Since in previous studies a strong positive synergistic (or hybrid) effect was observed in the case of intermingled hybrids and fracturing under the influence of a shear stress field using Charpy impact type of tests [13, 14], the fibre orientation was chosen at ±45°, which generally also results in reasonably high values for crush energy absorption of plain carbon/epoxy composite tubes. Upon Charpy impact testing, intermingling resulted in the creation of a larger amount of new surface than in a segragated hybrid, since these hybrids have the maximum number of shear failure sites and, consequently, the optimum composition for numerous delaminations and maximum energy absorption capability [14].

Tube specimens were fabricated by impregnating woven fabric of high-strength carbon fibres (T 300, Toray Industries Inc., 370 g m^{-2}) and HP-PE fibre (Dyneema SK 60, DSM High Performance Fibers, 200 g m^{-2}) with an epoxy resin (Araldite LY-556/HY917/DY070, Ciba-Geigy) based on bisphenol A and an anhydride curing agent. Hybrid composite tubes were fabricated from two types of hybrid twillweave fabric of 258 and 270 g m^{-2} weight, incorporating 77 and 55 vol % HP-PE fibres, respectively. Impregnated fabrics were wound at a ±45° fibre orientation with the tube axis on a collapsible steel mandrel of 25 mm outer diameter. To ensure demoulding, polytetrafluoroethylene foil was wrapped around the mandrel. Specimens were cured in an oven for 4 h at 80 °C and 12 h at 100 °C, rotating them inside the oven during curing. After curing and removing the mandrel, specimens of length 70 mm were cut from this tube. All tube specimens had an internal diameter of 25 mm, a nominal wall thickness of 1.45 mm and a total fibre volume fraction of approximately 50%. Triggering was provided by a 45° bevel at one end of the tubes.

The tubes were quasi-statically crushed in axial compression between two plates on a servohydraulic testing machine (Zwick Rel) at a velocity of 500 mm min^{-1} while fixed with a centre-pin of height 10 mm at the bottom plate. For each type of composite configuration a minimum of five specimens were tested. All specimens were crushed over a length of 40 mm. During crushing, a load–displacement curve was generated from which energy absorption could be determined.

Fig. 1 shows the load–displacement curves for the various composite tubes. The corresponding failure modes of the crushed tubes are shown in Fig. 2.

HP-PE/epoxy tubes failed in a typical local buckling crush mode by forming new folds adjacent to the original folds, similar to those exhibited in metallic, thermoplastic and aramid/epoxy tubes. The crush force for HP-PE/epoxy tubes had an average value of 3.6 kN, and remained almost constant during the whole crush, with only small variations indicating the formation of folds. No fibre fracture was observed after crushing the HP-PE composite tubes. Consequently, matrix cracking, debonding and interlaminar shear failure were the dominant energy absorbtion mechanisms. It is important to notice that the tubes did not fail catastrophically and maintained a high level of post-crush structural integrity.

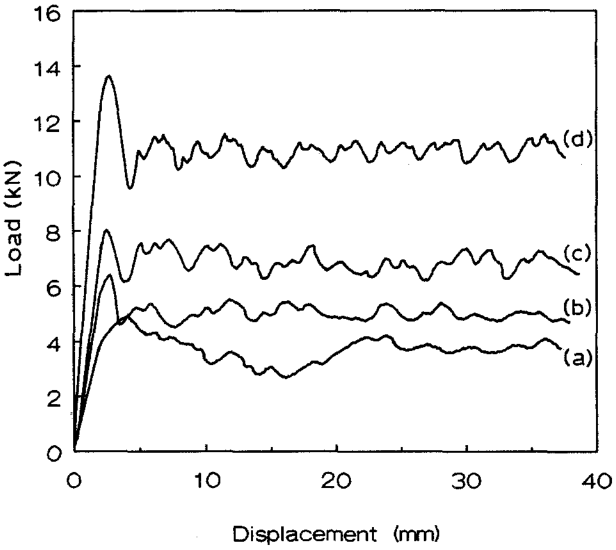

Figure 1 Load–displacement curves for (a) HP-PE/epoxy tube; (b) hybrid tube, 77 vol% HP-PE; (c) hybrid tube, 55 vol% HP-PE; and (d) carbon/epoxy tube.

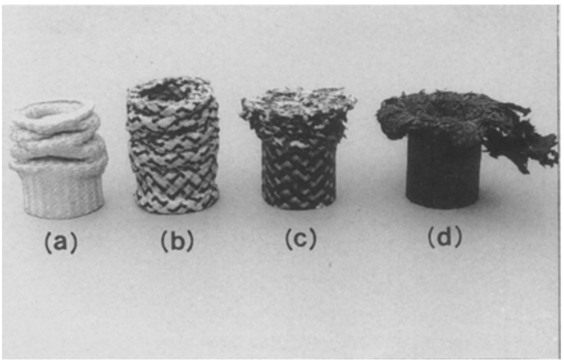

Figure 2 Crushing characteristics of (a) HP-PE/epoxy tube; (b) hybrid tube, 77 vol% HP-PE; (c) hybrid tube, 55 vol% HP-PE; and (d) carbon/epoxy tube.

Plain carbon/epoxy tubes failed in a typical brittle crush mode at a relatively high average crush load of 10.8 kN, with the edges of the tubes shearing away forming a conical cross-section and some fragmentation, resulting in complete disintegration of the specimen and negligible post-crush structural integrity.

Hybrid composite tubes showed crush modes that were intermediate between those of plain HP-PE and carbon composites. Hybrids incorporating 77 vol% HP-PE fibres failed in a more local buckling mode at an average crush load of 4.9 kN, whereas hybrids incorporating 55% HP-PE fibres failed in a more brittle crush mode at an average load of 6.6 kN. However, both hybrids failed without the formation of a conical cross-section, being typical for plain carbon/epoxy tubes. The predominant failure mechanisms in both type of hybrids were interlaminar delaminations at the carbon/HP-PE interface and fracture of carbon fibres. In hybrid tubes with 77 vol% HP-PE fibre almost no HP-PE fibre breakage occurred. Consequently, the post-crush integrity of such tubes is proportional to the amount of HP-PE fibres. Hybrid tubes composed of 55 vol% HP-PE and 45 vol% carbon fibres revealed some cutting of carbon fibres into the HP-PE component, resulting in a relatively more severe reduction in post-crush properties. However, both hybrid tubes exhibited highly improved post-crush structural integrities compared with plain carbon tubes.

The energy absorption parameters for the composite tubes are given in Table I. Specific crush stress, being the sustained crush stress divided by the tube density, is used in this report for specific energy absorption comparison.

TABLE I Energy absorption parameters of composite tubes

Fibre type	HP-PE (vol %)	Initial peak load (kN)	Mean crush load (kN)	Specific crush stress (kJ kg^{-1})
HP-PE	100	4.8	3.6	29.9
Hybrid	77	6.5	4.9	37.6
Hybrid	55	8.0	6.6	44.6
Carbon	0	14.0	10.8	63.5

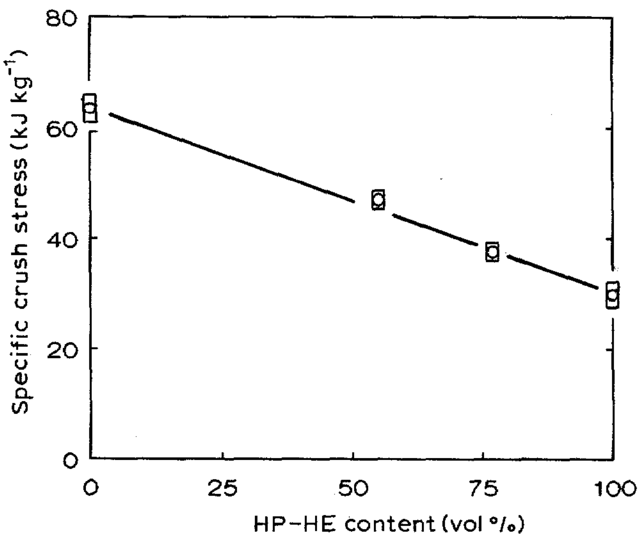

Figure 3 Specific energy absorption of intermingled HP-PE/carbon tubes versus hybrid composition.

Fig. 3 shows the specific crush stress for all tested composite tubes versus the volume fraction of HP-PE fibres, indicating that no hybrid effect occurred. The absence of a hybrid effect, as observed in previous studies, directed towards optimizing energy absorption of hybrid composites [14] can be attributed to the intrinsic characteristics of the crushing process of composite tubes. In the crushing process of tubes, the compressive strength of a structure can be considered as the maximum attainable crush stress. Consequently, fibre-dominated energy absorption processes are more effective in achieving high values for specific energy absorption than interlaminar shear failure processes, the latter being the principal energy absorption mechanism in Charpy impact testing [14]. Since the compressive strength of hybrid HP-PE/carbon composites follows rule-of-mixtures behaviour [13], an increasing amount of HP-PE fibre should, in theory, result in a linear decrease in the ultimate crush stress and, consequently, in the energy absorption. Also, for the tested hybrid composite tubes the average crush force varied linearly with the amount of HP-PE fibres. Consequently, the crush stress and energy absorption of these tubes follows rule-of-mixture-like behaviour. It should be noted that the effect of "triggering", in order to obtain a progressive crush mode, is strongly reduced with increasing amount of HP-PE fibres. This implies that when no "trigger' was used in the plain carbon/epoxy tubes, failure would occur in a more catastrophic manner, leading to a less stable propagation of the collapse and, consequently, a considerable reduction in energy absorption, whereas in the case of HP-PE/epoxy and hybrid composite tubes failure modes would still exhibit some kind of buckling crush mode resulting in high values for energy absorption.

This study showed that the post-crush structural integrity of carbon/epoxy tubes can be improved significantly by hybridization with HP-PE fibres. However, no hybrid effect was observed with respect to specific energy absorption due to a linear reduction in crush load with increasing amount of HP-PE fibre.

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