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A performance versus cost analysis of prepreg carbon fibre epoxy energy absorption structures

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ABSTRACT

Carbon fibre epoxy composites are sought after for their excellent specific energy absorption (SEA) but are costly. A range of prepreg carbon fibre epoxy layups were subjected to a 10 m/s impact with 4 kJ of energy. Fibre volume fraction and voidage were determined for each sample and the fracture analysed in detail. SEA ranged from 35.27 J/g to 60.25 J/g with the highest performance from 8 plies of 200 gsm 2×2 twill all laid at 0°. Vacuum assisted oven cure resulted in higher voidage than autoclave cure (2.52% versus 0.17%) but did not affect SEA. According to a ratio of performance to cost the highest rated samples were an 8 ply oven cure and a 3 ply autoclave cure specimen and there was little difference between them. This work has highlighted that there is enormous potential for cost reduction of prepreg carbon fibre epoxy energy absorption structures through the use of heavier areal weight fabrics and fewer plies as well as through the use of oven cured prepreg.

1. Introduction

Carbon fibre reinforced polymers (CFRP) have been widely used in the aerospace and motorsport sectors for more than twenty years [1]. The high specific strength and stiffness of carbon fibre (CF) have given it a reputation as a high performance engineering material [2]. It is highly valued in motorsport thanks to its ability to fulfil a structural role whilst offering high energy absorption in collisions. In these cases the aim is to absorb the kinetic energy of the impact in a controlled manner such that the vehicle will decelerate at a rate that preserves life.

However, the cost of CF is prohibitively high for many other industry sectors: £6.38/kg, compared to steel and aluminium at £0.30/kg and £1.36/kg respectively [3–5]. The high embodied energy from the manufacturing process, expensive precursor material and elevated manual labour costs for layup mean its use is restricted to sectors which can pay for performance. CFRP is now the material of choice for supercars and expanding into mainstream production vehicles whose price can justify it. In other areas such as lower level motorsport e.g. Formula Ford, wind energy and rail sectors its high price remains a barrier to uptake [6–8].

Composite energy absorption structures offer the opportunity for significant weight savings over metallic structures. Composites absorb energy though buckling, interlaminar failure, fibre–matrix debonding, fibre pull-out, matrix deformation/cracking, friction and fibre breakage giving them a greater specific energy absorption (SEA) than metallic structures [9–11]. Research has demonstrated that glass–epoxy composites are capable of twice the energy absorption of steel due to their more continuous mode of failure [12].

Previous research has shown that glass–epoxy tubes have a SEA approximately 20% lower than carbon–epoxy tubes when subjected to a compressive impact test [13]. Agarwal et al. (2006) states that glass and Kevlar composites have a higher impact energy than carbon/graphite epoxy using a Charpy test which is a flexural test [14]. However, current estimates put the energy associated with crack propagation during crush of composite sections at 5–20% of the total energy absorbed [15–17]. Thus, a higher impact energy (Charpy) does not necessarily lead to a higher SEA of a structure undergoing dynamic testing e.g. tube or cone as there are more dominant energy absorption mechanisms at play such as friction. There is a link between interlaminar shear strength (ILSS) and SEA [18] but there is little research linking impact energy or fracture toughness and SEA.

In the automotive and aerospace sectors composites give the opportunity to increase payload and reduce emissions and fuel costs but there is a consensus that performance improvements

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must be tempered by financial concerns [19]. Cost reduction strategies include the use of natural fibres [6], recycled carbon and glass fibres [20–22] and supplementation with less expensive low modulus fibre [23]. Process research has been undertaken on production of aligned, shorter fibre composites through methods such as the 3D Engineered Preforms (3DEP) [24] and Direct ReInforced Fibre Technology (DRIFT) processes [25], particularly in conjunction with recycled carbon or glass fibres. Cheaper manufacturing processes such as vacuum assisted resin transfer moulding (VARTM) have also been developed offering as much as 60% reduction in manufacturing costs [26]. This work investigates energy absorption performance for the same conical structure with a range of different CFRP layups considering cost of material, layup and cure.

2. Experimental procedure

2.1. Materials

This work utilised three different CF prepregs supplied by Umeco structural materials Ltd. A 135 grams per square metre (gsm) unidirectional (UD) with Toray intermediate modulus (M30SC) and cost £38.60/m^2, a 200 gsm 2×2 twill with generic high strength fibre at £29.60/m^2 and a 660 gsm 2×2 twill with generic high strength fibre at £52.20/m^2 all with 42 wt% resin. All used the same resin system, MTM28B (B designates black) and MTM28-1 (-1 designates formulation for UD fibres). The static mechanical properties for these materials are published by Umeco and summarised in Table 1.

2.2. Test specimen manufacture

Previous research has demonstrated that cones are more suitable for impact structures than tubes since they do not require crush initiators [21], furthermore, they more accurately reflect real-life geometry found in the automotive and motorsport arenas than simpler plate type specimens. A test cone identical to previous work [6,21] (Fig. 1), designed to absorb 5 kJ of energy was used for these experiments and an aluminium mould tool was manufactured to allow for excellent dimensional accuracy of the finished components. The cone was designed and draped in Catia (Dassault Systemes). The ply patterns were outputted to AutoNEST (SigmaNEST) which generated a nested cutting pattern according to the required fibre direction for each ply and based on the useable width of a standard CF roll of 1182 mm. A typical layout generated by the software is shown in Fig. 2, each ply consists of two pieces: 1A and 1B, 2A and 2B and so on. For each cone the first and last plies extend into the tip.

Six different layups were investigated, as described in Table 2. Each ply was laid up in the mould and the seams of each layer were offset by 10 mm to prevent the creation of weak areas. The mould was then bagged in the conventional manner, evacuated and cured according to Table 2.

CL1 was designed to determine the effect on SEA of changing the orientation of alternate plies. CL2 used the same layup as CL1, but was cured under vacuum in an oven. The prepreg used for CL2 is not specifically designed for out of autoclave cure. CL3 used a 0/90 layup as a direct comparator for CL1, and as a benchmark for the other cones. CL4 used two plies of 660 gsm fabric with both plies extended into the tip of the cone. CL5 used multiple layers of UD and 200 gsm CF to determine the effect of a high stiffness layup. CL6 used three plies of 660 gsm fabric with first and last plies extended into the tip of the cone.

2.3. Impact testing

Each sample was loaded into an Instron impact tower and subjected to an impact test with an initial velocity of approximately 10 m/s with a test mass of 78 kg. In each case the test energy was approximately 4 kJ. Two samples of each layup were tested, one to determine SEA and the other for analysis by microscopy. Previous work has demonstrated the predictability of these impact tests and low standard deviation in the results thereby allowing the use of one sample to give an accurate indication of SEA [21].

2.4. Analysis

2.4.1. Determination of fibre volume and void fraction

2.4.1.1. Sample preparation. The dynamically crushed samples were sectioned using an IsoMet 5000 linear precision saw as shown in Fig. 3 and mounted in opaque red EpoFix epoxy resin (Buehler). These were then ground and polished on a semi-automatic Buehler Phoenix 4000 sample preparation system.

2.4.1.2. Optical microscopy. The sample was levelled and placed under a Nikon Eclipse LV100 D microscope in bright field, at $10\times$ objective, using a Zeiss HXP 120 ultraviolet light source to permit higher resolution. Images were captured by an AxioCam ICc 1 and analysed using Zeiss AxioVision digital imaging system to determine fibre volume fraction (FVF) and void fraction (VF). For each sample ten images taken at pseudo-random intervals along the length of the sample were processed into three phases; fibre, matrix and void. These were then translated into a percentage for voidage and fibre volume fraction for each sample.

2.4.2. Fractography

Sections through the fracture of the cones were cut out and prepared according to the method in Section 2.4.1.1, except for the use of a clear EpoFix resin. Using the same microscope in bright field under high intensity light source (Zeiss illuminator HXP 120), the fracture surface was captured as a montage and stitched together in the AxioVision software.

2.4.3. Cost

The cost of each cone may be broken down into the material, layup and curing costs. The material cost was determined by calcu-

Table 1
Prepreg static mechanical properties.

	Units	200 gsm	600 gsm	135 gsm UD
Normalised to		55% volume fraction	55% volume fraction	60% volume fraction
Tensile strength	MPa	1070	825	1930
Tensile modulus	GPa	67	56	128.8
Compressive strength	MPa	693	450	1296
Compressive modulus	GPa	58.9	51	120.2
Flexural strength	GPa	1070	850	2.164
Flexural modulus	GPa	64	52.0	140.5
ILSS	MPa	77	62	94.8