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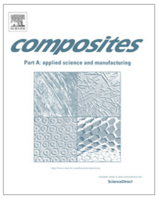

The importance of translaminar fracture toughness for the penetration impact behaviour of woven carbon/glass hybrid composites

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ABSTRACT

The impact resistance of fibre-reinforced composites is vital in many applications, and can be improved by exploiting synergies in fibre-hybridisation. These effects are however not sufficiently well understood in the literature. Penetration impact tests were hence performed on carbon/glass hybrids, and the results were linked to the flexural behaviour and translaminar fracture toughness. The results revealed large synergetic effects of up to 40% compared to the linear rule-of-mixtures. The results are also the first to reveal that creating a translaminar fracture surface can strongly contribute to the energy absorbed during penetration impact: 56% for an all-carbon fibre composite and 13% for an all-glass fibre composite. These results prove that strategies for maximising the translaminar fracture toughness can also be exploited to maximise the penetration impact resistance of fibre-hybrids. In carbon fibre composites in particular, ply blocking, using larger yarns and introducing micro-cuts should therefore increase the penetration impact resistance.

1. Introduction

The term "fibre-hybrid" composite applies to composites containing more than one type of reinforcement fibre [1]. These composites are a fast-growing class of composites, as they allow combining the benefits of both fibre types, while alleviating some of their drawbacks. The top layer of a carbon fibre composite can for example be replaced by a glass fibre layer to make the part more damage tolerant with minimal loss of stiffness and strength. Another common driver for fibre-hybridisation is cost reduction. This can, for example, be achieved by using the more expensive fibre type only in regions where it is needed the most, and using an inexpensive fibre type elsewhere. In general, the greater design freedom of fibre-hybrid composites will lead to more optimal designs.

The hybrid effect has been studied extensively in the literature [1–3]. With reference to the failure strain in tension, the hybrid effect is defined as the apparent increase in the initial failure strain of the low elongation fibre composite in the hybrid composite relative to the composite with only low elongation fibres. In general terms, the hybrid effect can be described as any deviation from a simple rule-of-mixtures [1]. Many authors found positive hybrid effects in hybrid composites [3–8]. The challenge of fibre-hybridisation lies in understanding, predicting and eventually optimising the hybrid effect and associated complex behaviours.

While the state of the art has greatly advanced since the start of fibre-hybridisation in high-performance composites [9,10], the majority of the progress was achieved for tensile loading. Other, more complex loading conditions received less attention and are lacking a solid understanding. This is especially true for impact, as revealed by a recent review paper on fibre-hybrid composites [1]. For example, shifting the carbon fibre layers more towards the middle layers in symmetric carbon/glass hybrids had varying effects on various impact-related parameters. While this shift increased the damaged area according to Naik et al. [11] and Sevkat et al. [12], it decreased according to González et al. [6]. Similarly, this shift deteriorated the compression-after-impact according to Kowsika and Mantena [13] and Naik et al. [11], whereas González et al. [6] found no effect. Following these publications, there is a strong need for developing a clear understanding of how the change in layup causes a change in performance.

While advanced finite element models for impact on composites have been developed [14–19], they have rarely been applied to fibre-hybrid composites [20,21]. As a consequence, the current state-of-the-art in impact on fibre-hybrid composites is mainly limited to visual observations rather than being governed by a gen-

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eral framework for understanding their behaviour. This paper aims to provide a better understanding of the penetration impact resistance of fibre-hybrid composites by linking it to the translaminar fracture toughness and flexural behaviour. It also presents one of the first translaminar fracture toughness results on fibre-hybrid composites.

2. Materials and methods

2.1. Materials

The properties of the fibres, yarns and fabrics are summarised in Table 1. Values with standard deviations were measured, whereas the others come from the respective data sheets or literature [22,23]. The carbon fibre weave consisted of HTA 6K carbon fibres in a balanced twill 2/2 architecture. The weave had 3.5 yarns/cm in both directions, resulting in an areal density of 285 g/m^2. A glass fibre weave was selected that also had a balanced twill 2/2 architecture and that would yield a similar layer thickness. The chosen weave consisted of E-glass fibres with 6.8 yarns/cm, resulting in an areal density of 390 g/m^2. The resin was an EPIKOTE™ 828LVEL epoxy resin mixed with 1,2-diaminocyclohexane hardener in a 100/15.2 ratio. Previous measurements showed that this epoxy has a stiffness of 3 GPa, and the Poisson's ratio was estimated to be 0.4.

2.2. Vacuum assisted resin infusion

All plies were cut and stacked together aligned with the fibre directions of the weave. Panels were made with either 8 or 16 layers (see Table 2). The 8-layer panels were used for bending and impact tests, whereas the 16-layer panels were used for compact tension tests (see Table 2). After the layers were stacked, a peel ply and distribution medium were added to the top. For the 16 layers however, the peel ply and distribution medium were also added to the bottom to facilitate impregnation. The entire assembly was placed on a 5 mm thick aluminium plate, after which a vacuum bag was added on top. The assembly was placed on a hot plate to raise the impregnation temperature to 50 °C. The resin was mixed and then degassed for 15 min, after which it was infused at a 0.99 bar vacuum pressure. After the entire layup was impregnated, the temperature was increased to 150 °C and insulation material was added on top. After a 90 min cure cycle, the hot plate was switched off to cool to room temperature. Optical microscopy confirmed that the laminates were well impregnated with very limited porosities.

Different layups were manufactured and these are summarised in Table 2. The indicated variations in Table 2 and anywhere else in this paper refer to the 95% confidence intervals. The thickness values confirm that the carbon and glass layers have nearly the same layer thickness, thereby avoiding any thickness effects when changing the layup.

Table 1
Fibre, yarn and fabric properties.

	Carbon fibre	Glass fibre
Fibre type	HTA40 E13	E-glass
Density (kg/m^3)	1760	2560
Diameter (μm)	6	13 ± 0.3
Fibre longitudinal modulus (GPa)	238	78
Fibre transverse modulus (GPa)	15	78
Fibre in-plane Poisson's ratio (-)	0.25	0.22
Tensile strength (MPa)	3950	–
Elongation at break (%)	1.7	–
Yarn K-count	6000	–
Yarn linear density (tex)	400	274 ± 8.5
Weave architecture	Twill 2/2	Twill 2/2
Picks and yarns (yarns/cm)	3.5	6.8 ± 0.1
Fabric areal density (g/m^2)	285	390

Table 2
Overview of the manufactured layups (C and G stand for the carbon and glass layer, respectively).

Layup	Volume fraction of glass fibre composite	Thickness (mm)	Tested in:
C_8	0%	2.33 ± 0.04	Impact and bending
$(C_3G)_s$	25%	2.26 ± 0.03	
$(GC_3)_s$		2.29 ± 0.02	
$(C_2G_2)_s$	50%	2.29 ± 0.02	
$(CG)_{2\ s}$		2.31 ± 0.01	
$(G_2C_2)_s$		2.40 ± 0.03	
$(GC)_{2\ s}$		2.29 ± 0.02	
$(CG_3)_s$	75%	2.30 ± 0.02	
$(G_3C)_s$		2.28 ± 0.02	
G_8	100%	2.39 ± 0.02	
C_{16}	0%	4.41 ± 0.03	Compact tension
$(G_4C_4)_s$	50%	4.48 ± 0.03	
$(GC)_{4\ s}$		4.60 ± 0.03	
G_{16}	100%	4.72 ± 0.05	

2.3. Penetration impact tests

Falling weight impact tests were performed on a Fractovis CEAST 6789 drop tower according to ISO 6603-2 [24]. The striker was hemispherical with a 20 kN load cell in the tip and a 20 mm diameter. The drop height was 1 m, resulting in an impact velocity of about 4.4 m/s. The total weight of the striker was 26.17 kg, which ensured penetration in all samples. The specimens were cut to 100 × 100 mm using a band saw and were clamped on a support ring with an inner/outer diameter of 40/60 mm. A minimum of six specimens were tested for each configuration. The support ring was roughened to maximise friction and the total gripping force was 2800 N. As the manufacturing process resulted in a smooth bottom surface and a rougher top surface, care was taken to always have the smooth surface facing upwards.

Data reduction was performed by integrating the force-displacement diagram. The integration was stopped either when the load dropped below half the peak load or below zero the first time. These two measures will be referred to as "half peak method" and "full method", respectively. It should be noted that the half peak method is the data reduction recommended by the ISO 6603-2 standard [24]. Fibre-hybrid composites, however, often show a rather long tail in the force-displacement diagram [25,26]. Since the full method may be more appropriate here, results for both methods will be shown. The penetration impact resistance was normalised by the sample thickness to obtain values in J/mm units.

2.4. Flexural tests

Three point-bending specimens were cut using a diamond saw to ensure smooth edges. They were tested according to ASTM D7264M [27] on an Instron 4467 machine with a 1 kN load cell. The nominal dimensions were 10 × 100 × 2.3 mm with a support span of 80 mm. The loading nose and support rollers all had a diameter of 10 mm. The loading nose moved at a displacement rate of 4.54 mm/min, corresponding to a 1%/min nominal strain rate. Five specimens were tested for each configuration. The manufacturing resulted in a smooth bottom surface and a rougher top surface. To improve consistency and to reduce the likelihood of compressive failure, the samples were tested with the smooth side facing the loading nose. The test was monitored with a camera to track the damage progression.