THE HiPerDiF (HIGH PERFORMANCE DISCONTINUOUS FIBRES) TECHNOLOGY FOR THE MANUFACTURING OF PSEUDO-DUCTILE QUASI-ISOTROPIC ALIGNED DISCONTINUOUS FIBRE COMPOSITES

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Abstract
Thanks to their pseudo-ductile behaviour, both in the cured and the uncured status, certain aligned discontinuous hybrid fibre composites (ADFRCs) have the potential to overcome two of the main limiting factors to the widespread adoption of composite materials, i.e. the generation of defects during manufacturing and the catastrophic failure of the cured material. The HiPerDiF (High Performance Discontinuous Fibres) technology, invented at the University of Bristol, produces ADFRCs with mechanical properties comparable with those of continuous fibre composites. Intimately hybridising different types of fibres the HiPerDiF technology allows producing unidirectional ADFRCs with pseudo-ductile tensile behaviour. However, it is usually necessary to balance the load-carrying capability in multiple directions. In this study, glass-carbon and carbon-carbon hybrid ADFRCs are manufactured with the HiPerDiF technology and laid-up in a quasi-isotropic laminate $[0/60/-60]_s$. The obtained laminates demonstrate the high mechanical properties and the pseudo-ductile behaviour of the quasi-isotropic hybrid ADFRC laminated materials.

1. Introduction

Highly Aligned Discontinuous Fibre Reinforced Composites (ADFRCs) have the potential to offer mechanical properties (i.e. stiffness, strength and failure strain) comparable with those of continuous fibre composites provided that the fibre aspect ratio is high enough to allow load transfer and attain fibre failure instead of pull-out (i.e. fibre/matrix interface failure) [1]. Moreover, ADFRCs make it possible to overcome three of the key limitations of conventional continuous fibre composite materials:

- The lack of ductility, i.e. their substantially elastic-brittle behaviour, by intimately hybridising different types of fibres or exploiting pull-out mechanisms [2];
- The difficulties in producing defect-free components of complex shape with high-volume automated manufacturing processes [3];
- The issues associated with implementing a sustainable material lifecycle, e.g. the integration of production and end-of-life recycled waste in a circular economy model [4, 5, 6].

The High Performance Discontinuous Fibre (HiPerDiF) technology, invented and developed at the University of Bristol, is a new, effective and sustainable high performance ADFRCs manufacturing method, with the potential for high production throughput [1]. The HiPerDiF technology is currently able to process synthetic and natural discontinuous fibres with length between 1 a 12 mm [6, 7].

Pseudo-ductile behaviour can be achieved in ADFRC through three different methods of hybridization: intermingled hybrids [2, 8], intraply hybrids [9], and interlaminated hybrids [5, 8]. In all cases, the ductile response is achieved through fragmentation and diffuse debonding or delamination of the low elongation reinforcement fibres. Of interest for the presented work is the intermingled hybrid configuration, for which the possibility to achieve pseudo-ductile tensile behaviour in a unidirectional (UD) lay-up has been demonstrated for E-glass coupled with High Modulus Carbon (GC) and High Strength Carbon coupled with High Modulus Carbon (CC) [2, 8]. However, composite materials are usually required to have load-carrying capabilities, and consequently pseudo-ductility, in multiple directions. In [9], UD ADFRC tapes manufactured by HiPerDiF were laid up in a quasi-isotropic (QI) fashion, i.e. $[0/60/-60]_s$, and tested in tension: compared with a randomly oriented short fibre composite made from fibres of the same length, i.e. 3 mm, and fibre volume fraction, the QI ADFRC showed significant increases of tensile modulus and strength, 34% and 76% respectively, and a more consistent behaviour.

In the presented research work, the tensile response of QI laminates manufactured with pseudo-ductile intermingled hybrid ADFRCs is investigated.

2. Methodology

The two types of hybrid ADFRCs mentioned above, i.e. GC and CC, have been investigated in this research work. The ratio between the low elongation reinforcement fibres, High Modulus Carbon (HMC) and high elongation reinforcement fibres, i.e. E-glass (EG) or High Strength Carbon (HSC) have been selected in accordance with the results obtained in [8]. Two sets of specimens per hybrid type, i.e. UD and QI, have been manufactured and tested in tension.

2.1. Materials

The properties of the used reinforcement fibres, are listed in below in Table 1.

Table 1. Reinforcement fibres properties.

Fibre property		High Modulus Carbon HMC	High Strength Carbon HSC	E-glass EG
Commercial Name		Granoc XN-90, NGF	C124, TohoTENAX	C100, Vetrotex
Diameter	[μm]	10	7	7
Length	[mm]	3	3	3
Density	[g/cm^3]	2.21	1.82	2.60
Stiffness	[GPa]	860	225	73
Failure Stress	[MPa]	3430	4345	2400
Failure Strain	[%]	0.398	1.93	3.29

The fibres are coupled with a 43 gsm areal weight epoxy resin film (K51, SKchemicals).

2.2. The HiPerDiF method

A schematic of the HiPerDiF discontinuous fibre alignment machine is shown in Figure 1. The fibres are suspended in water, accelerated through a nozzle and directed in a gap between two parallel plates. The alignment mechanism relies on a sudden momentum change of the suspension at the impact with the furthermost plate. The fibres then fall on a stainless-steel conveyor mesh belt where the water is removed by suction. The aligned fibre preform is completely dried with infrared radiation. The dry aligned fibres preform is coupled with a resin film and partially impregnated through the application of heat and pressure. Different types of fibres can be mixed in the water suspension, this allows highly intermingled hybrid composites to be obtained.

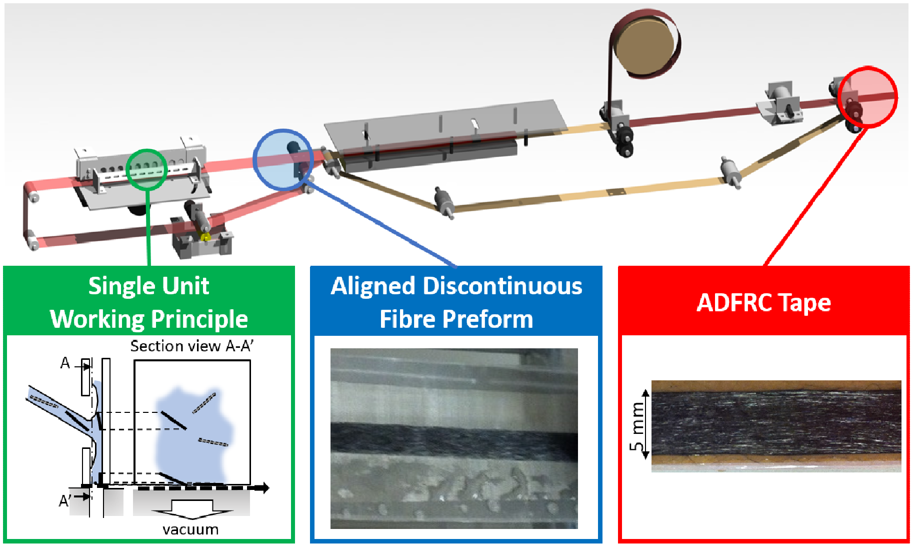

Figure 1. The HiPerDiF Technology

The CC specimens were manufactured with a HMS and HSC fibres content of 50% and 50%, while the GC were manufactured with a HMC and a EG fibres content of 40% and 60%. These low to high elongation reinforcement fibres ratios allow a sharp transition between linear-elastic response and the fragmentation region to be obtained.

2.3. Specimen manufacturing

The UD and the QI specimens were laid-up with UD, i.e $[0_4]$, and QI, i.e. $[0/60/\text{-}60]_s$, lamination sequences. The QI specimens were manufactured, as described by Yu el al. in [9], by placing a series of ADFRC tapes side-by-side to obtain each layer of the laminate; 5 mm wide strips were then cut and placed in a semi-closed mould. The specimens were cured in an autoclave at 135°C for 135 minutes using vacuum bag moulding at a pressure of 6 bar. After manufacturing, burrs at all edges along the length direction were gently removed using sand paper, GFRP end-tabs were bonded with Huntsmann Araldite 2014-1. The obtained specimens presented a 50 mm long and 5 mm wide gauge area.

2.3. Tensile Testing

Tensile tests were performed with an electro-mechanical Shimadzu testing machine at a cross-head displacement speed of 1 mm/min. The load was measured with a 10 kN load cell and the strain was measured with an Imetrum video extensometer over a gauge length of approximately 40 mm. A white speckle pattern over a black background was spray painted on the specimens to allow strain measurement with a video extensometer.

3. Results

Representative curves for the tensile tests are shown in Figure 2.

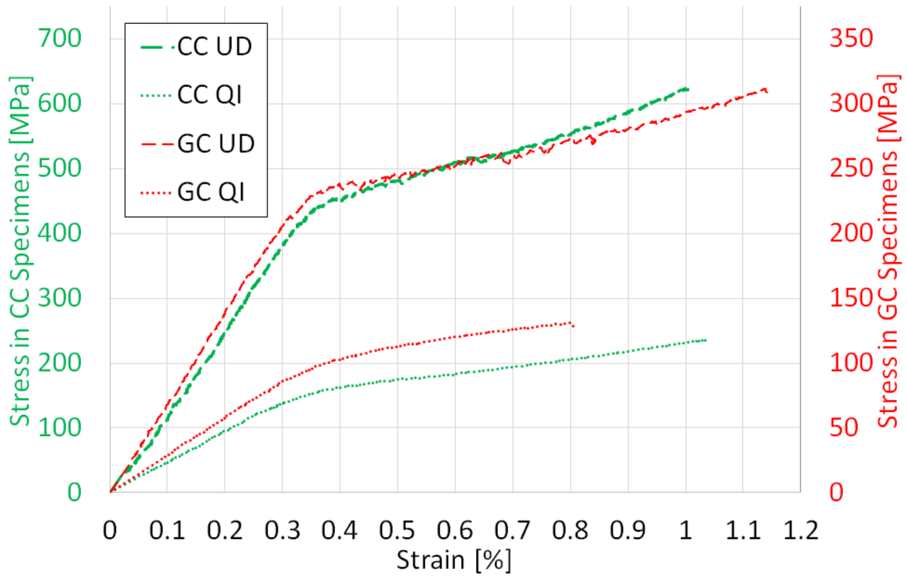

Figure 2. Representative Tensile Test Results.

The tensile response for the UD configurations, both for the CC and the GC hybrids, display a typical pseudo-ductile behaviour. The initial linear elastic response is followed by a fragmentation plateau, the inflection point coincides with the HMC fibres failure strain. The pseudo-ductile behaviour is also displayed by the QI laminates: compatibly with the lamination sequence the stiffness is reduced, however the knee point is at the same strain value as the UD laminates.

4. Conclusions

From the experimental results obtained in this study and shown in Figure 2, it can be concluded that the pseudo-ductile behaviour observed in unidirectional intermingled hybrid aligned discontinuous fibre composites is retained also in a quasi-isotropic lay-up. A previous work demonstrated the higher mechanical performance of quasi-isotropic aligned discontinuous fibre composites when compared with randomly oriented fibre composites made of identical fibres and with the same fibre volume fraction [10]. Therefore, intermingled hybrid aligned discontinuous fibre composites not only represent a superior solution when compared with randomly oriented but also offer the possibility to achieve pseudo-ductile behaviour.

The work will be continued by investigating the behaviour of QI ADFRC manufactured with different low to high elongation reinforcement fibres ratios. Moreover, the formability of QI ADFRCs, both made with a single fibre type and pseudo-ductile hybrids, will be assessed.

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