HYBRID UHMWPE/CARBON MICROBRAIDS FOR DUCTILE COMPOSITES

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Abstract
This paper presents a comprehensive series of mechanical tests performed on core-filled hybrid microbraids and composites manufactured using those microbraids as the reinforcing phase. Tensile tests performed on dry microbraids revealed the dependence of the mechanical properties on the bias angle of the fibres. During tensile loading conditions, the unidirectional core failed first, the bias yarns contained the failed core and shared the load until final failure occurred. The observed saw-tooth stress vs. strain curved can be attributed to multiple fractures of the inner core. The trends witnessed during testing the dry microbraids were very similar to those seen during tensile testing the composites.

1. Introduction

Braiding is the process of interlacing three or more threads in such way that they cross over one other, and are laid together in a diagonal formation. This is an old manufacturing technique by which it is possible to produce linear, flat, tubular or solid forms. In theory, any material in the form of strips or filaments can be braided. It has been shown that the final mechanical properties of braids depend not only on the material properties but also on the braid architecture [1–3]. Under an external axial load, the bias fibres in a dry or impregnated braided system tend to scissor to the loading direction, the braid angle and braid diameter diminish whilst straining. Braids are able to carry very little load prior to jamming point and are resisted only by the inherent yarn-to-yarn friction. After reaching the jamming point, i.e. when the bias yarns are locked, the braid angle and braid diameter will not change further and the properties of the constituent material will influence the response of the braid up to failure.

It is possible to manufacture braids having different architectures by changing the pattern and the number of working carriers in the braider (Fig. 1). For example, when a yarn is let over and above one other, the resulting braid is defined "diamond braid"; when a yarn is let over and above two others, the resulting braid is defined "regular braid". It is possible to manufacture braids over uniaxial yarns (core-filled braids), or insert axial yarns among the bias yarns (triaxial braids). The latter types of braids would be stiffer due to the off-axis reinforcement. On the other hand, it is possible to manufacture braids with different braid angles by changing the braiding take-up speed. Hence, the braiding technique offers the possibility to design engineers to modify and the tailor, to a small extent, their mechanical properties to fulfil the in-service requirements.

The mechanical properties of braid reinforced polymer composites (BRPC) will reflect those of the con-

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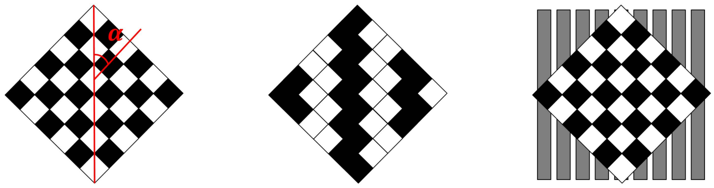


(a) (b) (c)

Figure 1. Different braid architectures: (a): Diamond braid; (b): Regular braid; (c): Core-filled diamond braid.

stituent reinforcing phase [4, 5]. An increase in the braid angle will lead to more compliant composites with lower Young's modulus and tensile strength, but a higher strain to failure.

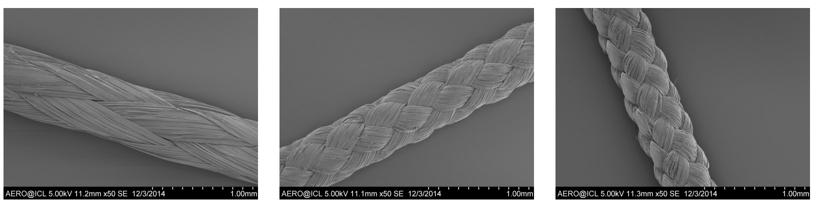
Recently, a novel class of BRPC, in which microbraids having sub-millimeter diameter are directly used as the reinforcing phase within polymer composites, have been showing promising results as far as the mechanical properties of the composites are concerned [5–7]. However, further investigations are required in order to understand the behaviour of this new class composites (which we will call microbraid reinforced polymer composites, or mBRPC).

This paper presents the manufacture and mechanical characterisation of dry microbraids and their direct use as the reinforcing phase within polymer reinforced composites. The main aim of this work is to manufacture composite materials able to undergo large deformations under tensile loading, nevertheless having stiffness and energy absorption capabilities at least similar or better with respect to "conventional" fibre reinforced polymer composites.

2. Materials, manufacture and testing method

2.1. Materials and manufacture

The manufacture of 2D hybrid microbraid was performed at Imperial College London using a Herzog RU2/16-80 vertical braiding machine. The braider was set to interlace eight Dyneema®SK75 yarns in a diamond fashion over a unidirectional core of carbon fibres (Torayca® T300). Microbraids having different braid angle α were manufactured by changing the cogwheel ratio on the braiding machine. The diameter of the microbraids and their bias angles were determined by analysis of SEM images (Fig. 2). The linear density of the microbraids was determined according to the ASTM D1577-07 Standard Test Methods for Linear Density of Textile Fibers [8]. The density of the hybrid microbraids was determined by using gas pycnometry (Accupyc II 1340). Physical properties of the raw materials and of the manufactured microbraids are presented in Table 1 and Table 2, respectively.



(a) (b) (c)

Figure 2. Hybrid microbraids: (a): HMB1; (b): HMB2; (c): HMB3.

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Table 1. Physical properties of the raw materials (from [9], [10] and [11]).

Fibre	Density g/cm^3	Linear density g/10000 m	Single fibre diameter μm	Filament count
Dyneema®SK75	0.97	110	17	50
Torayca® T300	1.76	660	7	1000
Matrix	Density g/cm^3		Areal density g/m^2	Thickness μm
Rayofix TP	0.932		71.63	75

Table 2. Physical properties of the hybrid microbraids.

bID	Braid diameter mm	Braid angle °	Linear density dtex	Density g/cm^3
HMB1	0.62 ± 0.01	14.0 ± 0.6	1611 ± 27	1.271 ± 0.012
HMB2	0.61 ± 0.01	33.1 ± 0.9	1853 ± 26	1.226 ± 0.009
HMB3	0.57 ± 0.01	38.9 ± 0.6	2058 ± 46	1.181 ± 0.007

Among the manufactured microbraids, HMB2 was chosen for the manufacture of microbraid reinforced polymer composites (mBRPC). Details of the manufacturing process are presented in [5]. Physical properties of the manufactured laminates are listed in Table 3. The density of the hybrid composite was determined by using gas pycnometry.

Table 3. Physical properties of the mBRPC.

cID	No. of layers	Stacking sequence	Thickness mm	Areal density g/m^2	Density g/cm^3	V_f %
cHMB1	4	$(0/90)_s$	1.70 ± 0.03	1031 ± 14	1.135 ± 0.006	76

2.2. Testing methods

Quasi-static tensile tests on yarns and dry microbraids were performed at room temperature using an Instron 5969 universal testing machine equipped with a 50 kN load cell having an accuracy of ± 0.5% of the displayed force. It was not possible to perform tensile tests using conventional pneumatic capstan grips, recommended for yarns, chords and braids, because they promoted premature failure of the carbon fibres at the clamping area of the pneumatic grips. Therefore, Instron 2716 wedge action grips were employed to perform the tensile tests on yarns and microbraids. In order to prevent fibre damage and a possible premature failure of the carbon filaments, rubber tabs were glued on the specimen ends using two-part epoxy glue (Araldite 2011). A sketch of the tensile specimens is shown in Fig. 3(a). Up to 500 data-points per second were recorded by the acquisition system during each test. In order to study the effects of the strain rate and gauge length, tensile tests were performed with two different gauge lengths of 100 mm and 300 mm, and at two different strain rates of 0.01 s^{-1} and 0.001 s^{-1}, respectively. For each test batch, at least three valid tests (failure within gauge length) were performed and collected. Tensile

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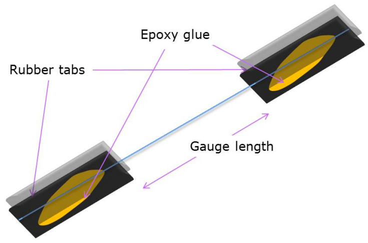
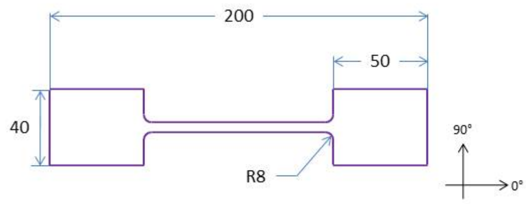
tests on mBRPC were performed at room temperature using the same testing machine and gripping system adopted for testing the dry fibres and microbraids. Testing specimens were waterjet cut from the manufactured laminates (Fig. 3(b)). All tests were performed at a constant cross-head speed of 10 mm/min.



(a)



(b)

Figure 3. (a): Sketch of a specimen for tensile testing yarns and microbraids; (b): Specimen geometry for tensile tests. All dimensions in mm.

- The tensile strength of dry yarns and microbraids was calculated dividing the recorded force by the specimen cross section area A, where $A = \mu/\rho$, μ= linear density, ρ = density;
- The tenacity of dry yarns and microbraids was calculated dividing the recorded force by the specimen linear density;
- The strain to failure ε was calculated using a high speed camera: two points were marked along the gauge length of the specimen and their relative displacement measured via a motion tracking software developed in-house;
- The normalised energy absorption was calculated as the area under the tenacity vs. strain curves, and would represent the energy of the tested specimen normalised with respect to its mass;
- The tensile strength of the mBRPC was calculated dividing the recorded force by the specimen cross section area;

3. Results

Fig. 4 shows the typical tensile response of the investigated yarns and microbraids having a gauge length of 100 mm and tested at a strain rate of 0.001 s^{-1}. Similar trends are observed for the specimens tested at a 0.01 s^{-1} and 300 mm gauge length. Engineering properties are summarised in Fig. 6[1].

The tensile tests performed on microbraids HMB1 were unsuccessful. The microbraid ends debonded from the rubber tabs and slippage occurred. Amongst the investigated materials, the Dyneema®SK75 yarn had the highest tensile strength, followed by the Torayca® T300, HMB2 and HMB3, respectively. It should be noted that the tensile strength of the tested dry carbon fibres was about three times smaller with respect to the value provided by the manufacturer [10]. The mismatch can be attributed to the different testing conditions (in this study, the fibres were tested as-received, whilst the manufacturer provides data for epoxy-impregnated fibres). Hybrid microbraids HMB2 and HMB3 had the lowest tensile strength amongst the investigated materials. The higher the braid angle α, the lower the initial modulus E_i, initial and final tensile strength σ_{ic} and σ_f, the higher the strain to failure ε.

[1]The engineering properties for the "Ideal UD" are calculated as a weighted average of eight Dyneema®SK75 yarns and one Torayca® T300 yarn.

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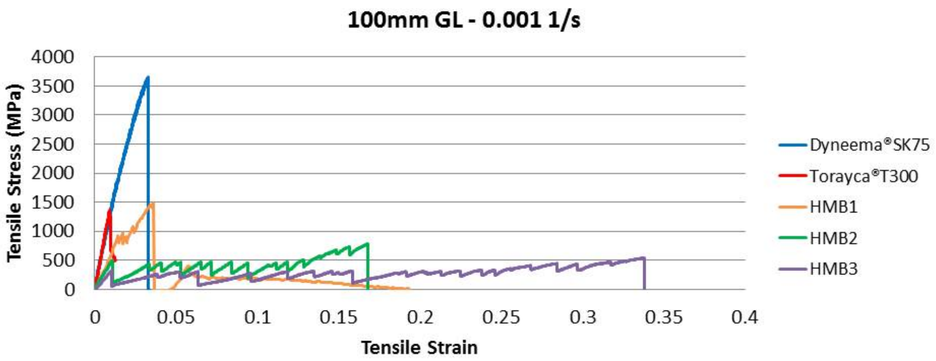
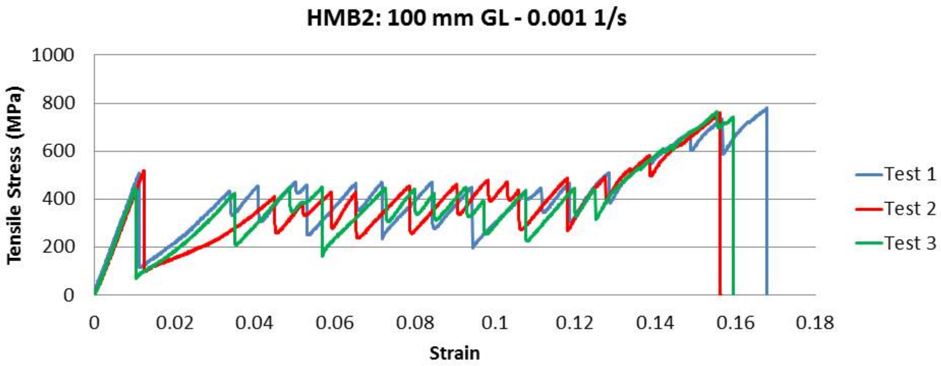


(a)



(b)

Figure 4. Tensile stress vs. tensile strain for: (a): Yarns and microbraids; (b): Close up for HBM2.

The mechanical behaviour of core-filled microbraid can be idealised as shown in Fig. 5. It is possible to identify three distinctive regions: Region 1: Elastic region; Region 2: Saw-tooth region; Region 3: Hardening region. In Region 1, the tensile behaviour of the hybrid microbraids was mainly governed by the unidirectional core fibres and, to a lesser extent, by the bias fibres. The UD core eliminated the initial long plateau commonly seen when tensile testing coreless braids. The tensile stress increased in a linear fashion with increasing the load. The Young's modulus E_i and the strength at the first failure of the carbon fibres σ_{ic} decreased with increasing braid angle. When the strain reached the strain to failure of the carbon fibres, failure of the inner core occurred. The bias fibres not only contained the failed carbon fibres in the core of the braid, but also carried the load after failure of the core. In Region 2, a series of peaks in the tensile stress was observed. As the bias fibres tended to scissor to the loading direction, the diameter of the microbraid reduced, squeezing and containing the failed core. The load was taken by the bias fibres and transferred to the inner fibres via friction. Although fractured, the carbon core was able to absorb the load until a subsequent failure occurred. In Region 3, the bias fibres reached the jamming point and the tensile stress increased until a final catastrophic failure occurred. Even in this region it is possible to identify further ruptures of the carbon fibres in the core.

It is also worth noting that the number of breakages of the carbon core br_i was directly proportional to the gauge length, independent on the strain rate and only dependant on the braid angle. The higher α, the higher br_i. Hence, it is possible to control and tailor the number of breakages of the inner core by changing the braid angle α. Table 4 lists the number of breakages of the inner core for microbraids having different gauge length and tested at different strain rates. The length of the fragmented carbon

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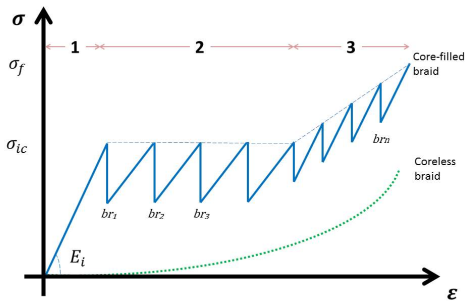

Figure 5. Tensile behaviour of dry microbraids.

fibres was not determined. Further characterisations on failed specimens, such as x-ray or microscopy, are required to determine the length of the fragmented core.

Table 4. Number of breakages of the UD core

	100 mm GL		300 mm GL	
	0.001 s^{-1}	0.01 s^{-1}	0.001 s^{-1}	0.01 s^{-1}
HMB2	13 ± 1	13 ± 1	34 ± 2	37 ± 3
HMB3	22 ± 1	23 ± 3	64 ± 4	67 ± 3

From Figure 6, it is possible to observe that the tensile strength and tenacity of the microbraids were lower with respect to the aforementioned properties calculated for the precursor materials, and fairly independent on the investigated gauge lengths and strain rates. However, the strain to failure was up to ten times higher with respect to the ε of the UHMwPE fibres. Normalising the energy absorption with respect to the linear density of the respective materials, the ability of absorbing energy of the microbraids is comparable with that of unidirectional Dyneema®SK75 fibres.

Figure 7 shows the engineering stress vs. strain curves for mBRPC specimens tested in tension.

The tensile response of the tested specimens was linear up to failure of the unidirectional carbon fibres, marked by a sudden drop in the tensile stress. The Young's modulus was calculated to be 13 ± 1 GPa. Thus, the stress started to increase again in a saw-tooth fashion up to final catastrophic failure of the specimen. The trend observed during testing the composites reflected those observed during tensile testing the dry microbraids. The composite strain to failure matched with the ε_f of the reinforcing microbraids.

4. Conclusion

In the present study, the mechanical behaviour of hybrid microbraids and their composites have been investigates. Hybrid microbraids having different braid angles were manufactured by overbraiding a unidirectional core of carbon fibres with eight UHMwPE yarns.

- Tensile tests performed on dry microbraids revealed a dependency of the tensile properties with

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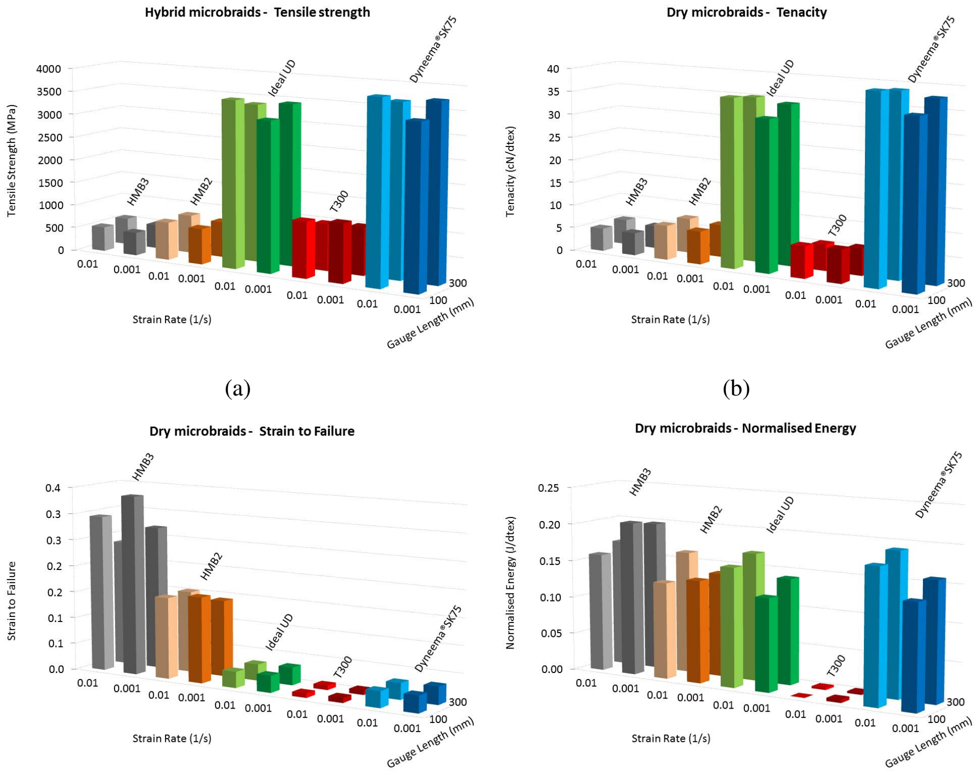

(a) (b)

(c) (d)

Figure 6. Tensile properties of hybrid microbraids with respect to the gauge lengths and strain rates: (a): Tensile strength; (b): Tenacity; (c): Strain to failure; (d): Normalised energy absorption.

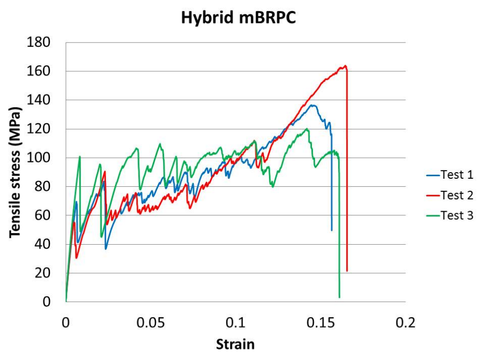

Figure 7. Tensile stress vs. strain curves of mBRPC.

respect to the braid angle. The higher the braid angle, the lower E_i, σ_{ic} and σ_f, the higher the strain to failure. During tensile loading conditions, the UD carbon core failed first but its failure was contained by the bias yarns. The scissoring of the bias fibres to the loading direction compressed and transferred the load via friction to the broken core fibres. Successive fragmentation of the carbon fibres was observed during tensile testing, and the number of fragmentation was directly proportional to the specimen gauge length and only dependant of the braid angle.

- Composite materials were manufactured using selected hybrid microbraids embedded in a thermoplastic resin film. The tensile behaviour of those composites reflected the trends observed while testing the dry microbraids.

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It is possible to tailor the mechanical performance of the microbraids and mBRPC by optimising the materials, geometry and architecture of the reinforcing phase, and stacking sequence of the laminate.

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