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HYBRID COMPOSITES WITH ALIGNED DISCONTINUOUS FIBRES

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Abstract
High performance composites can replace metals in many applications because of their exceptional strength and light weight, but brittle failure is an undesirable characteristic. Hybridisation is one of the approaches to overcome this limitation of composites because hybrid composites provide the potential for tailoring a response with desired stiffness, strength and ductility. In this paper, hybrid composites consisting of unidirectional continuous glass laminates and aligned discontinuous carbon preforms developed by the HiPerDiF (High Performance Discontinuous Fibre) method were tested in tension. The hybrid composite is designed as a layer-by-layer system to achieve pseudo-ductile response. Results are presented showing the effects of the proportion and absolute thickness of the aligned carbon preform on the failure modes. This paper also introduces the advantages of the aligned discontinuous carbon preforms produced by the HiPerDiF method in layer-by-layer hybrid composites.

1. Introduction

Hybridisation is one of the approaches to overcome the limitation of brittle failure in composite materials by introducing some pseudo-ductility into the failure process. The most common hybrid can be achieved by stacking different layers of prepregs together. Unidirectional glass/carbon hybrid composites with continuous fibres were recently designed and tested in uniaxial tension at the University of Bristol to obtain pseudo-ductility and a gradual failure process. It has been shown that if the carbon plies are sufficiently thin and the ratio of carbon to glass is low enough, multiple carbon layer fractures can occur accompanied by diffuse delamination with increasing strain whilst sustaining load without significant drops. It was also found that it is possible to suppress unstable delamination in glass-carbon hybrid laminates and create a pseudo-ductile response experimentally. Also, a numerical model to predict a failure mode was developed showing good agreement with the experimental results [1-4].

The aim of this research is to investigate the hybrid composites composed of UD continuous glass laminates and aligned discontinuous carbon fibre preforms to achieve pseudo-ductility. The idea behind this work is the same as the hybrid continuous fibre composites with a layer-by-layer system but the aligned discontinuous carbon preform takes the role of a thin carbon ply in the hybrid composites. Figure 1(a) shows the new alignment method [5, 6] schematically, which has a unique fibre orientation mechanism using the large momentum change of a fibre suspension rather than shear flow of the suspension. This method allows a high level of fibre alignment in composites even though the suspension is a low-viscosity fluid such as water. It was previously noted that tensile stiffness, strength and strain to failure of aligned discontinuous fibre composites were very close to those of continuous composites, provided the fibres are accurately aligned and of a length sufficiently long compared to the critical value. This work therefore focuses on the feasibility of manufacturing hybrid composites using aligned discontinuous carbon fibres at the layer level.

In this paper, hybrid unidirectional glass laminates with aligned discontinuous carbon preforms developed by the HiPerDiF method were tested in tension. Tensile test results showed the effects of the carbon proportion and absolute carbon thickness on the response. This paper also introduces the advantages of the aligned discontinuous carbon preforms produced by the HiPerDiF method in manufacturing layer-by-layer hybrid composites.

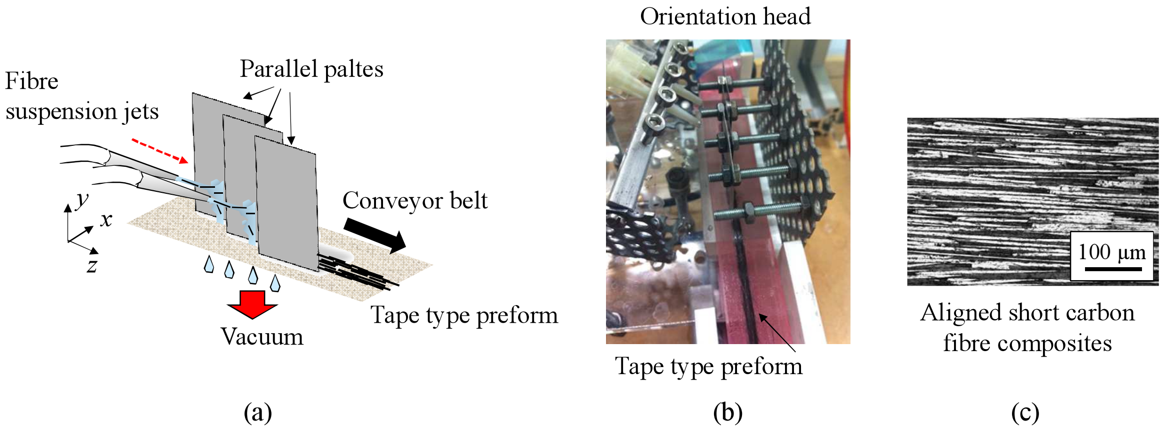


Figure 1. (a) Schematics of the HiPerDiF method, (b) Prototype device to align discontinuous fibres, (c) Microscopic image showing the alignment level of discontinuous carbon/epoxy composites [5, 6].

2. Hybrid composites model development

A continuous glass/aligned discontinuous carbon UD hybrid was designed to create a pseudo-ductile response. Unidirectional glass fibre prepreg (HexPly 913G, Hexcel) with 0.125 mm nominal cured ply thickness was used for embedding aligned discontinuous carbon fibre preforms with 3 mm long fibres (C124-High Strength grade, TohoTenax). The thickness of the carbon layer can be adjusted by setting variables such as the fibre suspension flow rate, fibre volume fraction in the suspension, and velocity of the perforated conveyor belt of the HiPerDiF method [6].

Hexcel 913/E-glass [2, 7]					MTM49/Aligned short carbon [2, 6]				
E_1 [GPa]	E_2=E_3 [GPa]	G_{12}=G_{13} [GPa]	ν_{12}=ν_{13}	S_H [MPa]	*E_1 [GPa]	E_2=E_3 [GPa]	G_{12}=G_{13} [GPa]	ν_{12}=ν_{13}	**S_L [MPa]
38.7	15.4	4.34	0.3	1350	115	6.0	2.4	0.3	1955
G_{IIc}			1.0 N/mm						

*Experimentally measured, **The strength is assumed such that the first cracking strain is 1.7%.

Table 1. The elastic material properties of Hexcel 913/E-glass and MTM49/Aligned discontinuous carbon.

The absolute and relative thickness of the carbon layer were determined according to the criteria given in [1] to avoid premature overall failure as well as ensuring that the failed layer will not pull out unstably. The damage mode map with the different potential failure modes for the continuous E-glass/aligned discontinuous carbon composites is shown in Figure 2. The details of this map can be found in [4]. According to this map the highest values of pseudo-ductile strain can be achieved if the configuration sits in region 1 [2, 4]. The parameters used in creating this map are given in Table 1. The interface toughness (G_{IIc}) of carbon composite with MTM49 resin was assumed equal to 1.0 N/mm, the same as with Hexcel 913 resin.

	Order of required stress for damage modes
1	$\sigma_{LF}<\sigma_{del}<\sigma_{HF}$
2	$\sigma_{LF}<\sigma_{HF}<\sigma_{del}$
3a	$\sigma_{del}<\sigma_{LF}<\sigma_{HF}$
3b	$\sigma_{del}<\sigma_{HF}<\sigma_{LF}$
4a	$\sigma_{HF}<\sigma_{LF}<\sigma_{del}$
4b	$\sigma_{HF}<\sigma_{del}<\sigma_{LF}$

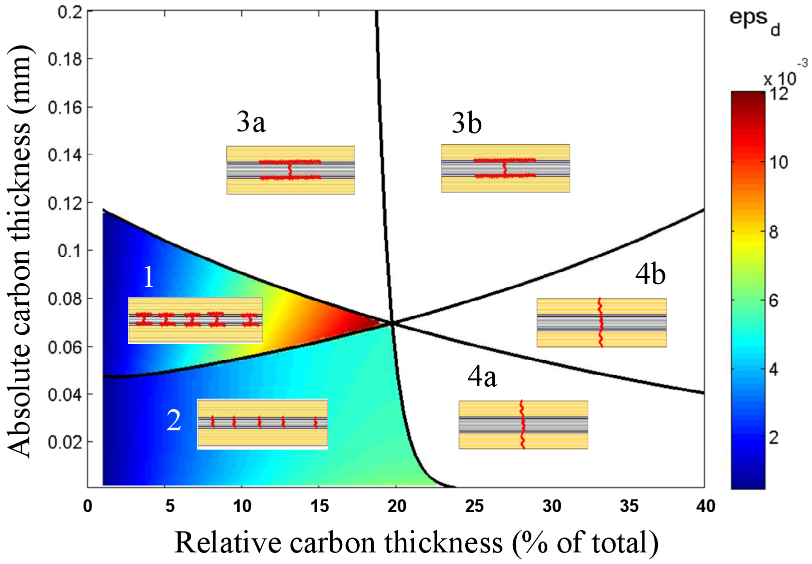


Figure 2. Map of damage modes and pseudo-ductile strain (eps_d) for continuous E-glass/aligned short carbon fibre composites. (Region 1: Fragmentation in carbon and dispersed delamination, 2: Fragmentation in carbon, 3a,b: Single delamintation, 4a,b: Failure in glass) [2, 4]

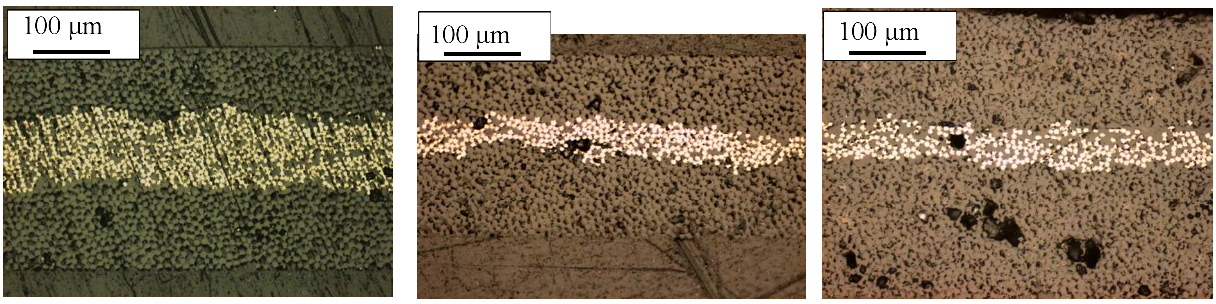
3. Experimental procedure

3.1. Fabrication

Three kinds of unidirectional laminates were laid up and cured using the dry carbon preforms manufactured by the HiPerDiF method and UD glass prepregs. The manufacturing conditions for the aligned carbon preform in this work are listed in Table 2. The dimensions for all specimens were 55×3 [mm] in length and width respectively. Since the HiPerDiF method produces aligned discontinuous fibre preforms with 1 mm width, three preform strips are put next to each other to make a 3 mm wide preform. The aligned carbon preform was placed in between two glass prepreg layers and then heat and pressure were applied so that excess resin from the glass prepreg could partially penetrate into the carbon preform. Three sets of 1)[G/C_2/G], 2)[G/C/G] and 3)[G_2/C/G_2] with different glass and carbon thicknesses were prepared and then placed in a semi-closed mould and cured by vacuum bag moulding in an autoclave. The specimens were cured at 135°C for 90 minutes. Figure 3 shows the cross section of the hybrid composite samples. The thickness of each sample was measured using a microscope and is shown in Table 3. The measured thickness of the specimens was different from the predicted one because the glass or carbon fibres were pushed out through the small gaps between the upper and bottom mould with rectangular channels when the resin was being squeezed out under the high temperature and pressure as shown in Figure 4. All specimens had burrs at both edges along the fibre direction, so the burrs were gently removed with sand paper before the tabbing process for the tensile test. Based on the measured thickness in the cured composites, the fibres escaping from the mould were mostly glass. Test set 1, set 2 and set 3 specimens were intended to be in the region 3b, 2 and 1 respectively but the real specimen thickness and condition did not give a good agreement with the original design, so the position of specimens on the failure mode map was changed as shown in Figure 5. The red symbols denote the planned hybrid specimens and the blue ones denote the hybrid specimens manufactured in reality.

	Test set 1	**Test set 2, 3**
Using two peristaltic pumps		
Total fibre suspension flow rate (ml/s)	4.46	4.46
Fibre volume fraction in the suspension	0.003%	0.003%
Width of preform (mm)	1	1
Perforated weave velocity (mm/s)	5.1	4.5
Fibre preform areal density (gsm)	47.74	54.06
Using fibre preforms (tape type) for one composite sample		
# of fibre preforms in thickness direction	2	1
Total preform areal density (gsm)	95.48	54.06

Table 2. Process variables in manufacturing discontinuous preforms.



(a) (b) (c)

Figure 3. Cross section images of (a) Test set 1[G/C_2/G], (b) Test set 2 [G/C/G], and (c) Test set 3 [G_2/C/G_2].

	Test set 1		**Test set 2**		**Test set 3**	
	Predicted	Measured	Predicted	Measured	Predicted	Measured
Stacking sequence	[G/C_2/G]		[G/C/G]		[G_2/C/G_2]	
Specimen thickness (μm)	346	300	304	260	554	380
Absolute carbon thickness (μm)	96	94.5	54	62.5	54	68.4
Carbon ratio	0.27	0.31	0.18	0.24	0.10	0.18

Table 3. Specifications of hybrid specimens.

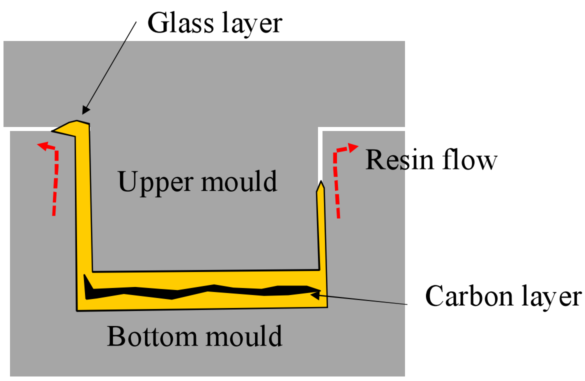


Figure 4. Schematic diagram showing semi-closed mould induces thickness reduction in the samples.

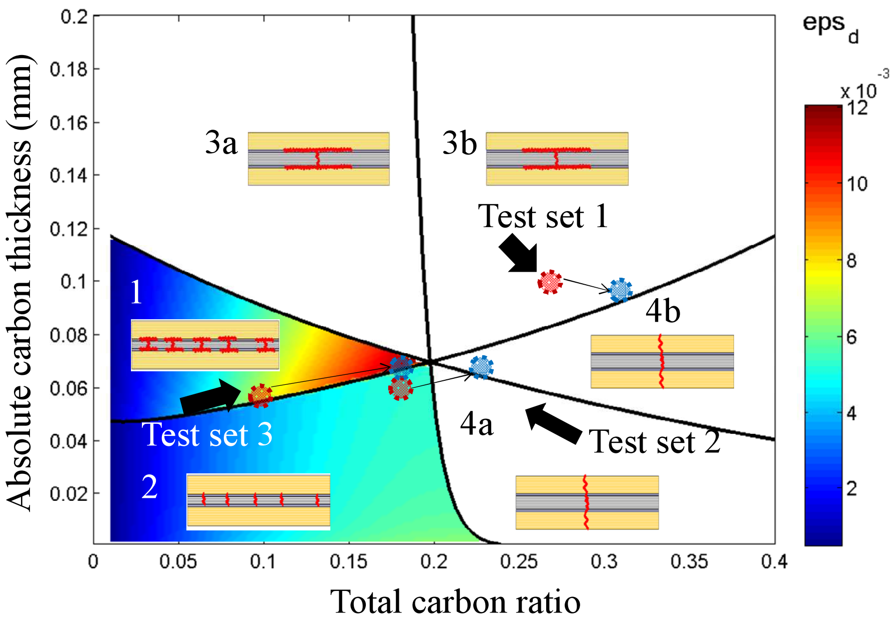


Figure 5. Damage mode map of the continuous glass/aligned discontinuous carbon hybrid with the intended and measured experimental specimens (red and blue symbols respectively).

3.3. Tensile test

Tensile tests were performed on an electro-mechanical testing machine at a test speed of 1 mm/min and the load was measured with a 10 kN load cell (Shimadzu, Japan). White dots were painted on the specimens to enable the strain to be measured by tracking the target pixels with a video extensometer (IMETRUM, UK). The gauge length for the strain measurement was 5 mm. Glass fibre/epoxy end tabs were attached using epoxy adhesives (Redux®, Hexcel) for all the specimens.

4. Results

The top views of specimens of Test set 1 and 2 were examined via microscopy after the tests as shown in Figure 6. In the case of Test set 1, all stress-strain curves look straight and all specimens were broken around 1.6% tensile strain which was slightly larger than that of aligned discontinuous carbon composites (1.4%). Based on the failure surface of the specimens (Figure 6), a crack in the carbon layer had arisen and then an instantaneous delamination followed, and eventually the glass layers were broken. According to Figure 5, the position of Test set 1 is close to the boundary line between 3b and 4b on the failure mode map, where either delamination or glass failure occurs first suggesting that the glass layers were broken just after the delamination. This is the reason why the stress-strain curves were all straight with no extra pseudo-ductile strain. As shown in Figure 6(a), a single delamination between the carbon and glass can be observed, since the glass lamina is opaque and the black carbon can no longer be seen through it once delamination occurs. The specimens of Test set 2 also showed straight stress-strain curves although they could carry the load partly after the first big load drop due to splitting during the test. They did not show an instantaneous delamination because they were in the region 4b on the failure mode map where the high strain material (E-glass composite) fails first. The failure of glass and carbon therefore occurred at about the same time with several splits as shown in Figure 6(b). The averaged tensile properties of Test set 1 and 2 are listed in Table 4.

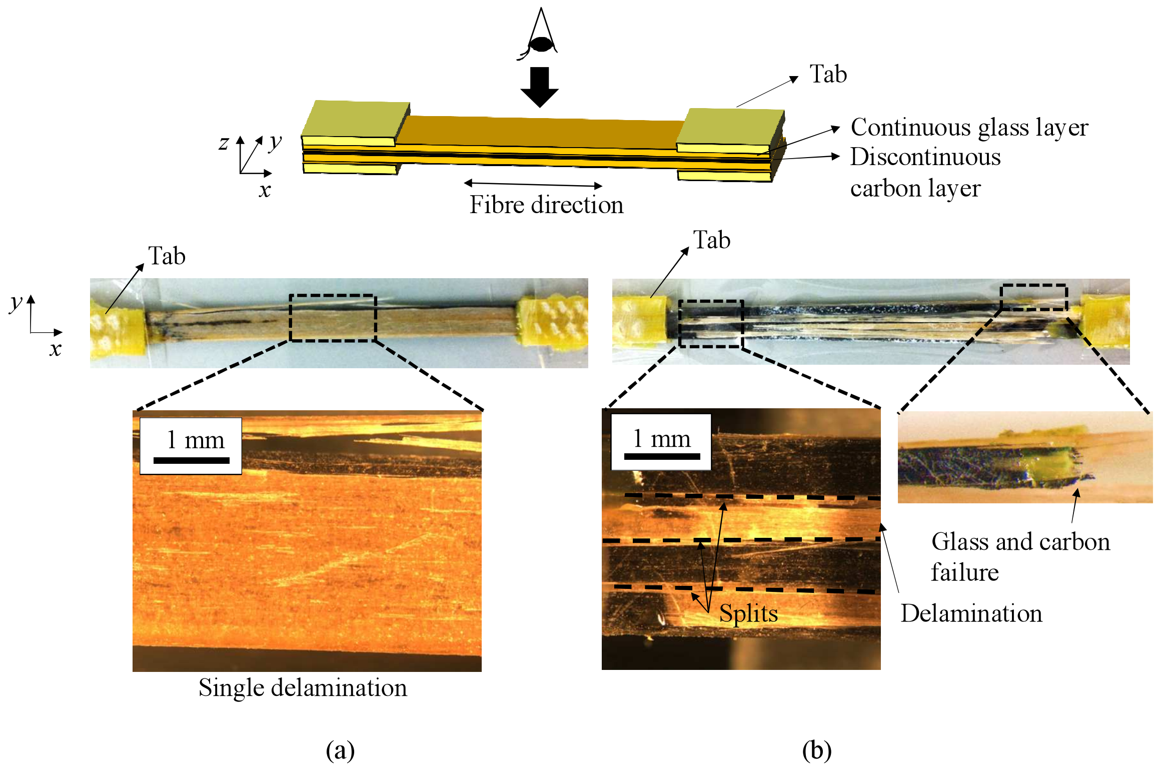


Figure 6. Failure surfaces of hybrid composite specimens; (a) Test set 1, (b) Test set 2.

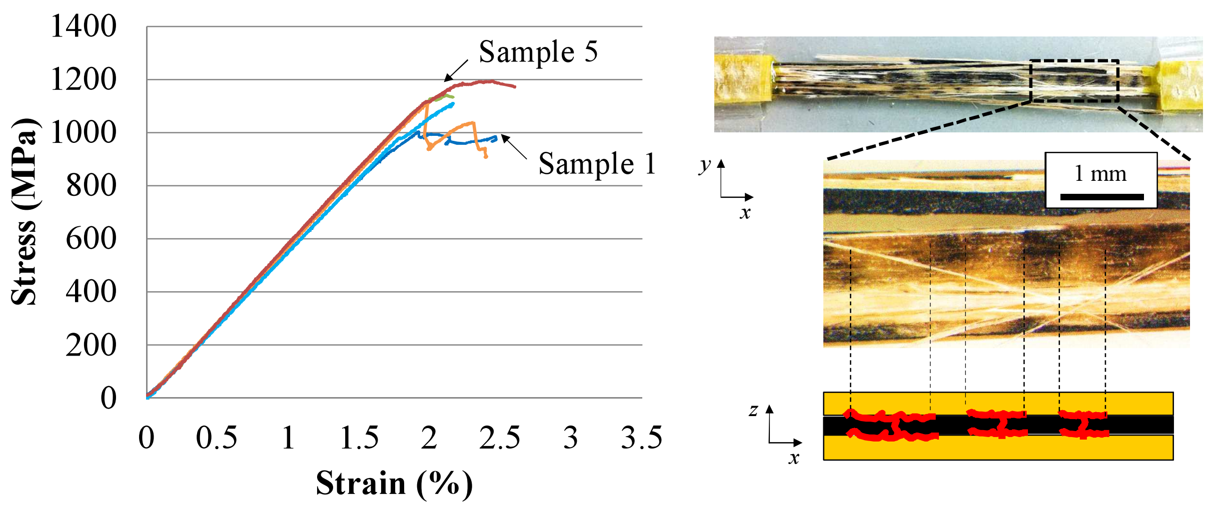
	Test set 1			Test set 2		
	E [GPa]	**σ_U [MPa]**	**ε [%]**	**E [GPa]**	**σ_U [MPa]**	**ε [%]**
Mean	66.9	1057	1.58	60.6	1035	1.71
SD	3.09	46.6	0.12	2.61	26.3	0.06
CV(%)	4.61	4.40	7.41	4.31	2.54	3.52

Table 4. Experimental results of Test set 1 and Test set 2.

Figure 7(a) shows the overall stress-strain curves according to the average stress calculated from the measured mean specimen thickness. The carbon layer fracture started around 1.7~1.9% strain, higher than the failure strain of the aligned short carbon composite of 1.4%.

This is because the glass layers distribute the load, reducing stress concentrations in the carbon layer near the tabs [1]. Two of the [$G_2/C/G_2$] samples (number 1 and 5) gave nonlinear stress-strain curves having a plateau region without a significant load drop although the other 3 specimens had a very narrow plateau region or big load drops due to splitting. Thickness variation of the carbon layer in the width (*y*) and length (*x*) direction is believed to be the main cause of the high variation (stress-strain curves). As another possible reason, the specimen condition on the failure mode map was very close to the apex which means that any slight variation in the material properties or configuration can result in a significant damage mode change.

From the top view of sample number 5, as shown in Figure 7(b), carbon layer fragmentation and diffuse delamination can be distinguished. The pseudo-ductile properties of each specimen are summarised in Table 5. The yield stress, σ_y, was defined in terms of a strain offset (0.1%), which is equivalent to the definition of proof stress in metals. ε_{max} is the strain at which either the specimen loses its integrity or the stress drops by more than 5% of the maximum value. The pseudo-ductile strain is the difference between ε_{max} and the elastic strain at the same stress based on the initial modulus.



(a) (b)

Figure 7. (a) Experimental stress-strain curves of different sample of Test set 3 [$G_2/C/G_2$], (b) Top view of sample number 5 and its schematics side view.

Test set 3	Yield stress [MPa]	Initial modulus [GPa]	Max. strain [%]	Pseudo-ductile strain [%]	Failure
Sample 1 (Blue)	**1017**	**55.0**	**2.44**	**0.65**	**Gradual failure**
Sample 2 (Green)	1122	57.9	2.12	0.21	Gradual failure
Sample 3 (Orange)	1113*	57.2	1.99	0.06	Splitting+gradual failure
Sample 4 (Deep green)	1070	55.4	2.16	0.15	Gradual failure
Sample 5 (Red)	**1143**	**57.8**	**2.60**	**0.55**	**Gradual failure**

*This value is for the maximum strength. (Since the pseudo-ductile strain is less than the strain offset 0.1%, the yield stress cannot be defined in the sample 3.)

Table 5. Pseudo-ductile properties of Test set 3.

This study has shown that it is possible to produce pseudo-ductility by utilizing aligned discontinuous carbon fibre preforms manufactured by the HiPerDiF method, although there are minor difficulties in manufacturing specimens. On the other hand, the continuous glass/aligned discontinuous carbon hybrid composite has a higher initial modulus compared with the continuous glass/continuous thin carbon layer hybrid composite, having the same level of pseudo-ductility. This is mainly because higher carbon ratios can be used due to the lower strength of the aligned discontinuous carbon composite, which results in a higher initial modulus with the same level of pseudo-ductility in the hybrid composites. Moreover, there are two additional key advantages over continuous-fibre hybrids: 1) the HiPerDiF method allows adjusting the thickness of the preform readily to achieve a more accurate configuration and 2) the aligned discontinuous carbon fibre preforms can be made out of recycled carbon fibres which means that recycled fibres can be applied for the improvement of the initial modulus and suppression of brittle failure in glass/epoxy composites.

5. Conclusion

In this paper, different hybrid composites made with unidirectional glass layers and aligned discontinuous carbon preforms were designed to achieve pseudo-ductility. The hybrid composites were tested in tension and their results were presented showing the effects of the carbon thickness and carbon ratio on the failure modes. Samples of Test set 3 with 68.4 μm absolute carbon thickness and 18% total carbon volume ratio showed pseudo-ductile response; the sample number 1 had 0.65% pseudo-ductile strain. This opens up a new way of using aligned discontinuous carbon fibre preforms developed by the HiPerDiF method in order to introduce pseudo-ductility to glass composites.

Acknowledgement

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