HYBRID EFFECT OF CARBON/GLASS COMPOSITES AS A FUNCTION OF THE STRENGTH DISTRIBUTION OF ALIGNED SHORT CARBON FIBRES

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Abstract

This paper aims to investigate the effect of strength distribution of aligned discontinuous carbon fibre layers in carbon/glass hybrid composites on the increase of carbon fibre failure strain. The aligned discontinuous carbon layers were manufactured by the HiPerDiF (High Performance Discontinuous Fibre) method, this allows manipulating the strength distribution of carbon layers while maintaining mechanical properties comparable with continuous carbon composites. Single fibre tests were performed to obtain the statistical properties of each group of carbon fibres. Interlaminated hybrid composite specimens with aligned discontinuous carbon plies sandwiched between continuous glass plies were designed and tested in uniaxial tension. The experimental results of the hybrid effect were compared with modelling predictions.

1. Introduction

Hybrid composites consist of two or more fibre types in a common matrix and offer a balanced material in terms of mechanical properties such as modulus, strength, toughness and ductility. However the key challenge is to predict their mechanical properties because of the synergistic effects between different fibres, often termed the hybrid effect. It is defined in different ways but the crucial observation is that the failure strain of the low elongation (LE) fibres appears to be greater in hybrid than in pure-LE fibre composites. In a recent review of Swolfs et al. [1], the main mechanisms for the hybrid effect were identified to be the altered failure development due to statistical effects on formation of clusters of fibre breaks and dynamic stress concentrations.

Zweben, who was the first to develop a model for predicting the hybrid effect, showed the importance of the strength distribution of the LE fibre [2]. Swolfs et al. pointed out that fibres with large variability in fibre strength will yield a significantly larger hybrid effect [3]. However there have been limited experimental results to validate this aspect of the model as the required fibre strength distribution is difficult to control in continuous fibres.

The HiPerDiF method (High Performance Discontinuous Fibre method), which was recently invented by Yu et al. [4], is able to produce short fibre composites with high mechanical properties due to the high level of fibre alignment. This is a promising tool to study the hybrid effect because it is able to manipulate the strength distribution of carbon fibres in different ways; intimately mixing two or more types of carbon fibres with different strength but the same stiffness. It enables a direct comparison between two cases where the mean strengths of both aligned discontinuous carbon layers are the same but the shapes of the strength distributions differ.

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This research is therefore aimed at the investigation of the strength distribution effect of an aligned discontinuous carbon layer, manufactured with the HiPerDiF method, in interlaminated carbon/glass hybrid composites on the increase of carbon failure strain. Single fibre tests were performed to obtain the statistical properties of each group of carbon fibres and then provide the results as inputs for the model. Interlaminated hybrid composite specimens with aligned discontinuous carbon plies sandwiched between continuous glass plies were designed and tested in uniaxial tension. The experimental results of the hybrid effect were compared with modelling predictions.

2. Experimental

2.1 Materials

Three different types of carbon fibres were used as listed in Table 1. The mechanical properties were provided by the manufacturers except for the AS4 (Hexcel) carbon fibres that were reclaimed by Pimenta and Pinho [5] from a M56 resin composite with a pyrolysis process ("cycle B" in [5]). The moduli of all three fibre types are similar, with a difference of only ±5%.

Table 1. Fibres properties from manufacturers

Fibre properties		AS4(recycled), Hexcel	T300, Toray	C124, TohoTenax
Diameter	(μm)	6.5*	7	7
Density	(g/cm^3)	1.79	1.76	1.82
Tensile modulus	(GPa)	220*	230	225
Failure stress	(MPa)	1007*	3530	4344
Failure strain	(%)	0.46*	1.5	1.93

* Reported in Pimenta and Pinho [5].

S-glass/epoxy (SG913, Hexcel) prepreg was used as outer layers for the interlaminated carbon/glass hybrid composites.

2.2 Single fibre test

Single Fibre Tensile Tests (SFTTs) were performed to determine the tensile strength distribution of AS4(recycled, r) and T300 carbon fibre types using maximum likelihood Weibull fitting according to the BS ISO 11566 Standard [6]. A single fibre testing machine (Dia-Stron, UK) was used at a test speed of 0.015 mm/sec and the load was measured with a 20 N load cell. Individual realisations of fibre strength were calculated using the average diameter of the corresponding fibre type. The fibre length was 38 mm including the gauge length for the strain measurement of 12 mm. Plastic end tabs provided by the machine manufacturer were attached using UV light cure epoxy adhesives (Optocast3553, EMIUV). More than 20 fibres were tested for each batch.

2.3 Interlaminated carbon/glass hybrid composites test

2.3.1 The HiPerDiF process

The fibre orientation mechanism of the HiPerDiF method is simply summarised as follows [4]. Firstly fibres are dispersed in water and the fibre suspension is supplied into the fibre orientation head, which is composed of two parallel plates. Subsequently the fibre suspension jet is directed into a gap between two parallel plates at an oblique angle, this aligns the fibres by a sudden momentum change of the suspension provided that the fibre length is less than the gap distance as shown in Figure 1(a). The fibres fall onto a conveyor mesh belt where the alignment is finalised. Meanwhile, the water is removed by a vacuum suction line underneath the mesh belt, creating a dry fibre preform as shown in Figure 1(b). One of the advantages of the HiPerDiF method is that it allows manufacturing intimately intermingled hybrid composites by mixing different types of fibres in the stage where the fibre suspension is prepared [7]. 5 mm wide aligned carbon preforms were made with the prototype HiPerDiF machine for 2 cases; 1) 100% T300 carbon fibres preforms and 2) intermingled carbon preforms with 30% AS4(r) and 70%

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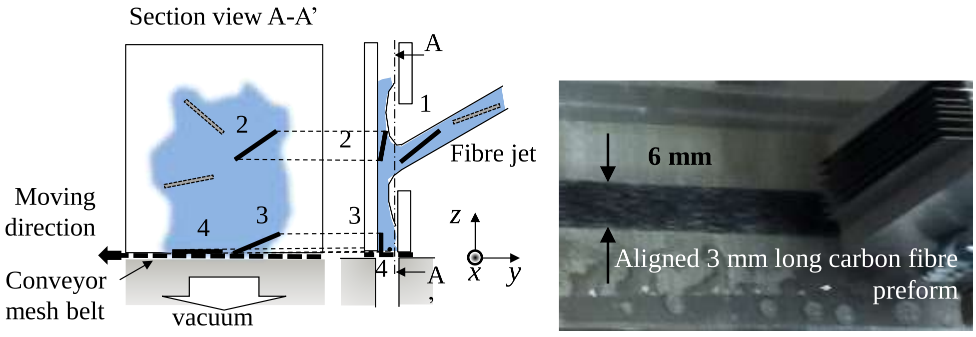
C124 carbon fibres to achieve the same mean strength but different strength distribution in this study. The nominal fibre length is 3 mm for all carbon fibre types.



(a) (b)

Figure 1. (a) Short fibre orientation mechanism of HiPerDiF method, (b) Aligned short carbon fibre preform.

2.3.2 Specimen preparation

Interlaminated hybrid composite specimens with aligned discontinuous carbon plies, manufactured by the HiPerDiF method, sandwiched between continuous UD glass plies were designed by Wisnom et al. [8, 9] (see Figure 2.). The stacking sequence of the laminates was [SG_2/ADC_2/SG_2]. Two sets of specimens with different strength distribution of carbon plies were prepared and then placed in a semi-closed mould and cured by vacuum bag moulding in an autoclave at 125°C for 105 minutes under a pressure of 6 bar. The nominal thickness of the interlaminated hybrid composites is 0.56 mm with the thickness ratio of carbon/glass being 1:4. The nominal carbon thickness is around 110 µm. The fibre volume fractions inside the carbon and glass layer were approximately 35% and 55%, respectively, estimated by taking account the areal weights of each layer in the composite specimens and the thickness measured with the microscopy images.

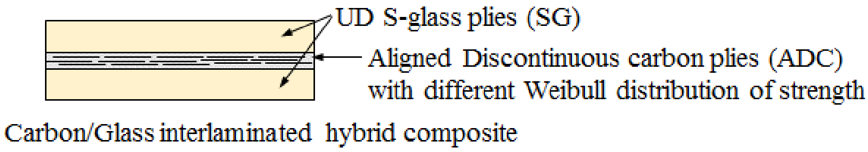


Figure 2. A schematic of interlaminated hybrid composite specimens.

2.3.3 Tensile testing

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 40 mm. Glass fibre/epoxy end tabs were attached using epoxy adhesives (Araldite 2014-1, Huntsman) for all the specimens. The specimen dimensions are shown in Figure 3.

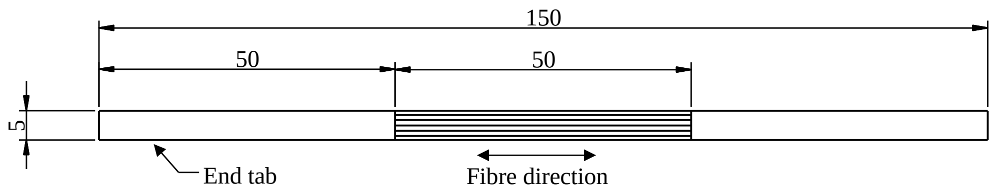


Figure 3. Specimen dimension for tensile test [mm].

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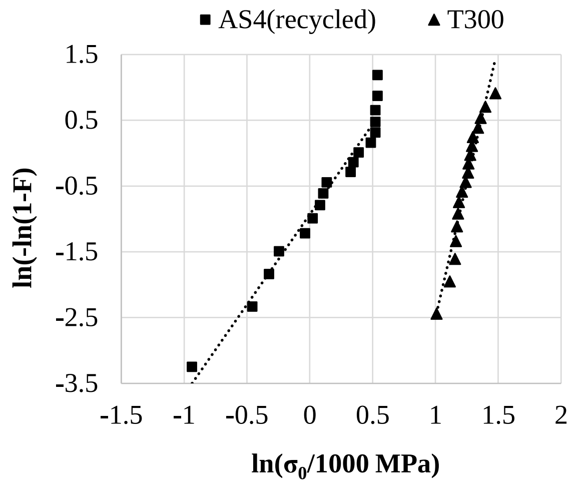
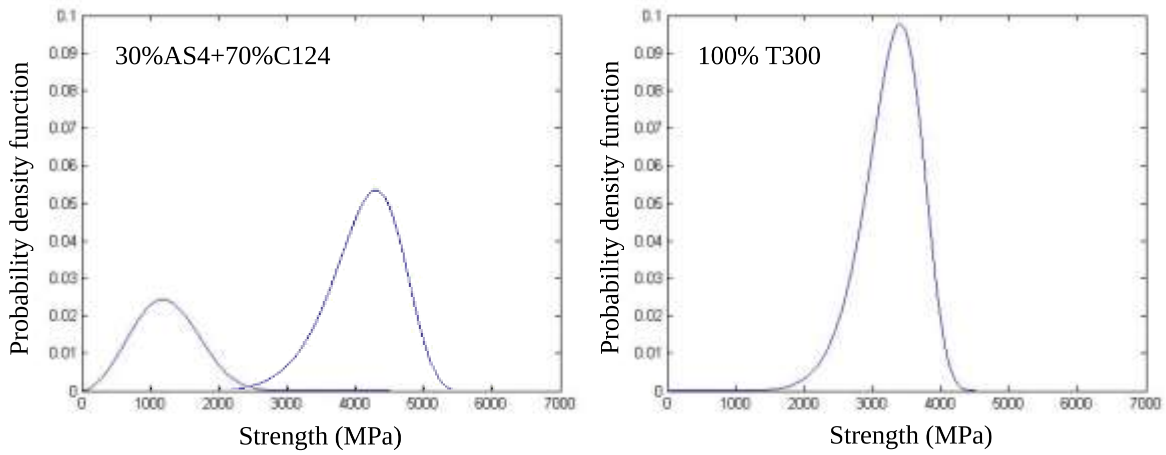
3. Results

3.1 Statistical analysis of single fibre properties

Figure. 4(a) shows the Weibull plots with experimental and fitted single fibre strengths for AS4(r) and T300 carbon fibre types measured by SFTTs. The Weibull parameters (shape parameter, m, and scale parameter, σ_0) of the fitted distributions are shown in Table 2, as well as the corresponding mean strength value, σ_m, and Coefficient of Variation (CoV). C124 carbon fibres were available in chopped form only from the manufacturer. Its shape parameter was hence assumed to be the same as virgin carbon fibres (High strength grade-AS4, Hexcel), m = 9 [5].



(a)



(b)

Figure 4. (a) Weibull plots for AS4(r) and T300 carbon fibres, (b) Weibull probability density functions for 30% AS4+70% C124 (Left) and 100% T300 carbon fibres (Right).

Table 2. Maximum likelihood Weibull fitting to SFTT strength

Fibre type	m	σ_0 (MPa)	σ_m (MPa)	CoV (%)
AS4(r)	2.85	1386	1237	33.3
T300	9.11	3451	3497	12.9
C124	9*	4344*	4344	-

*Assumed value

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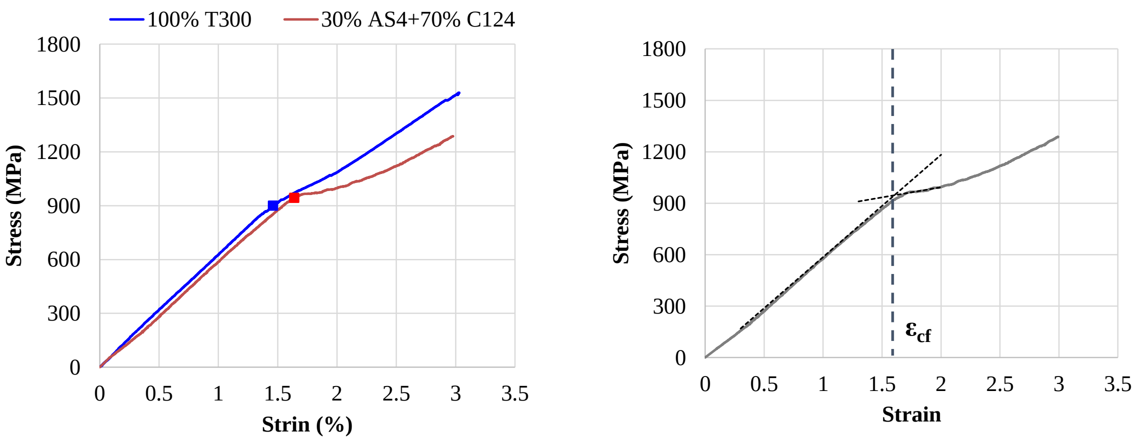
As reported in [5], the fibre reclamation process decreased the strength of AS4 carbon fibres significantly and broadened the distribution while the modulus remained the same as the virgin one. Therefore, the intermingled carbon layer with AS4(r) and C124 carbon fibres would lead to a bimodal Weibull distribution as a function of the ratio of the two types of fibres, as shown in Figure 4(b) (Left). The intermingled carbon layer with 30% of AS4(r) and 70% of C124 carbon fibres was chosen to match its mean strength and modulus to those of the 100% T300 carbon layer to exploit the direct strength distribution effect on the carbon failure strain in the carbon/glass hybrid composites (σ_m = 3400~3500 MPa, E = 220~230 GPa). The values in Table 2 were used as inputs for the prediction of hybrid effect in the model in section 4.1.

3.2 Carbon/glass hybrid composite properties

The representative stress-strain curves obtained from the tensile tests up to a strain of 3% are shown in Figure 5(a), this is because the test was interrupted before the whole rupture of the specimens, allowing further observation of the carbon failure crack pattern on the surface. Tensile properties of interlaminated hybrid composites are summarised in Table 3 and the carbon failure strain was calculated from the intersection of straight lines along the slope and the plateau as shown in Figure 5(b).

Table 3. Tensile properties of interlaminated hybrid composites, [$SG_2/ADC_2/SG_2$]

ADC_2	Initial modulus, E_0 (GPa) (CoV, %) (ε=0.3-1%)	Carbon failure strain, ε_{cf} (%) (CoV, %)	Stress at ε_{cf}, $\sigma_{@\varepsilon cf}$ (MPa) (CoV, %)
100% T300	62.3 (1.13)	1.46 (1.80)	901 (0.79)
30% AS4+70% C124	59.8 (1.45)	1.64 (1.74)	944 (1.72)



(a) (b)

Figure 5. (a) Representative stress-strain curves of interlaminated hybrid composites with carbon failure strains (Marked), (b) First carbon failure strain, ε_{cf}, defined.

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4. Discussion

4.1 Hybrid effect prediction

The failure strain of the composites was predicted using the tensile failure model of Swolfs et al. [10-13]. The finite element (FE) model [13, 14] used to predict the stress concentrations assumed a longitudinal fibre stiffness and an elastoplastic matrix with no matrix cracking. This FE data has been previously described elsewhere [13] and the same data was used for all fibre types. The strength model contained 1000 fibres, and preferential cluster formation at the edge was prevented by including boundary fibres [15]. These fibres were arranged in a random packing with a circular boundary and all fibres had a 7 µm diameter. The fibre volume fraction was 50%, which is higher than in the experiments. This however has a negligible effect on the outcome of the predictions.

The presence of the continuous glass fibres was ignored, as previous modelling results [10] proved that the layer thickness in the experiments was sufficient to prevent any hybrid effect due to their presence. The model was 20 mm long with element lengths equal to 3.5 µm. The fibres were made discontinuous by including fibre breaks prior to each simulation. While the distance between each of the fibre breaks within the same fibre was always 3 mm, their location in different fibres was randomly varied. The end of the model corresponded to the first occurrence of a critical cluster growing, and hence did not include any subsequent multiple failures or fragmentation.

Table 4. Carbon layer failure values

ADC_2	Experimental, ε_{cf} (%) (CoV, %)	Modelling prediction, ε_{cf} (%) (CoV, %)
100% T300	1.46 (1.80)	1.50 (1.31)
30% AS4+70% C124	1.64 (1.74)	1.71 (1.82)
Relative increase	12%	14%

4.2 Strength distribution effect of low elongation (Carbon) fibres layer on hybrid effect

Since any other parameters known to affect the hybrid effect, i.e. absolute or relative carbon thickness in interlaminated hybrids and thermal coefficient factor, were designed to be the same, the experimental data between the intermingled carbon layer with AS4(r) and C124 fibres and the T300 carbon layer allows a direct comparison for the strength distribution effect on the increase of failure strain in the hybrid composites. As expected, both interlaminated carbon/glass hybrids show the same initial modulus with less than 5% difference. The intermingled 30% AS4(r) and 70% C124 carbon layer yielded an experimental failure strain, ε_{cf}, of 1.64% compared to 1.46% for the 100% T300 carbon layer, a relative increase of 12%. As shown in Table 4, the modelling predicted ε_{cf} of 1.71% and 1.50% for the intermingled carbon layer and single carbon layer, respectively, showing a relative increase of 14%. The modelling values are slightly higher than the results from the experiments. This is likely to be due to small errors in the Weibull distributions, which are known to have an effect on the model predictions [15]. The experimental results agreed with the fact that large variability in strength distribution in low strain material leads to delay of failure in hybrid composites.

However, in order to confirm the hybrid effect from the strength distribution variability quantitatively, much additional experimental work will be required including more extensive SFTT's results and hybrid composites testing as a function of mixture ratio in the intermingled low strain material layer. Intermingling does not only lead to different strength distributions but also to a hybrid effect inside the layer due to the interactions between the two different fibre types. Such effects also need to be clarified. Nevertheless, this preliminary experimental study shows potential that the HiPerDiF method would be a good tool to investigate the strength distribution effect on the increase of failure strain of low strain materials in hybrid composites. In addition, since recycled carbon fibres usually have broad strength distributions, highly aligned recycled carbon fibre preforms would allow maximising the hybrid effect in the interlaminated carbon/glass hybrid composites with comparable strength and failure strain to those with continuous carbon prepregs.

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5. Conclusions and Future Work

The effect of the strength distribution of carbon layers on the enhancement in strain at failure in interlaminated carbon/glass hybrid composites was investigated experimentally, and compared with an analytical model. A 12% relative increase in strain at failure was obtained for the intermingled carbon layer with AS4(recycled) and C124 fibres, which has a bimodal Weibull distribution in strength, compared with the T300 carbon layer. In addition, the experimental results show a good agreement with the modelling results, a relative increase of 14%.

The preliminary study shows the potential of the HiPerDiF method as a promising tool to investigate the strength distribution hybrid effect. Moreover, despite the significant reduction in recycled fibre strength, the HiPerDiF method could offer a way to recover much of that lost strength in a hybrid laminate thanks to the hybrid effect due to the broad strength distribution.

Acknowledgments

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