DEVELOPMENT OF PSEUDO-DUCTILE HYBRID COMPOSITES WITH DISCONTINUOUS CARBON- AND CONTINUOUS GLASS PREPREGS

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Abstract

Sandwich (layer-by-layer) type hybridisation is a promising method to overcome the brittle and usually catastrophic failure of conventional composites. The new concept of combining discontinuous and continuous layers to improve the performance of hybrid composites is presented. The paper reports on the pseudo-ductility demonstrated with unidirectional discontinuous carbon/continuous glass sandwich hybrid composites. The stress-strain response of the new material architecture was analysed, and the pseudo yield strains of various specimen configurations were accurately predicted using an approach based on mode II energy release rate calculations. The effect of specimen thickness and carbon platelet length on the stress-strain response was studied and presented.

1. Introduction

High performance polymer matrix composites provide exceptional specific stiffness and strength, fatigue and corrosion resistance and are therefore suitable for high-tech applications such as military and civil aerospace, spacecraft or motorsports. However, a fundamental limitation of current fibre reinforced composites is their inherent brittleness. Failure can be sudden and catastrophic, with little or no warning and usually poor residual load-carrying capacity if any. High performance ductile composites are of significant interest and could extend the scope of applications towards new fields such as automotive or construction. The present paper shows the work done within the High Performance Ductile Composites Technology (HiPerDuCT) programme grant to develop the recently demonstrated thin-ply hybrid composites ductility concept [1] further with the use of discontinuous carbon layers in a unidirectional (UD) glass/carbon sandwich (layer-by-layer) hybrid architecture. The key challenge of the work is to improve the tensile properties and extend the design envelope of the previously developed pseudo-ductile continuous glass/carbon hybrid composites. The main objective of this study was to increase the carbon/glass ratio by exceeding the previously explored energy release rate limitations due to the carbon layer thickness. In this way, the initial modulus and the pseudo-yield stress of the hybrid composites can be improved.

2. Design considerations

2.1. Ductility mechanism in tension

The specimen design is based on the novel idea of introducing periodic discontinuities (ply cuts perpendicular to the fibre direction) in the stiffer layer of UD sandwich hybrid composite plates. This technique releases the previously established carbon layer thickness limitations to assure progressive fragmentation and stable pull-out of the carbon layers in continuous carbon hybrid configurations [1]. The mode II energy release rate at the carbon layer failure strain should always be lower than the fracture toughness (G_{IIc}) in a continuous ply hybrid composite to avoid sudden delamination and load drops. But this criterion no longer has to be satisfied in the discontinuous carbon layer configurations, because stable delamination can initiate before carbon fibre failure. The cuts introduced to the carbon layer before curing the composite can trigger the stable pull-out of the carbon “platelets” at (controllable) lower strains than the strain to failure of the carbon fibres, when the energy release rate becomes equal to the critical value.

2.2. The effect of carbon platelet length

The discontinuous central carbon layer contributes to the hybrid composite stiffness in a less favourable way than a continuous one because of the presence of ineffective segments of the carbon platelets which are not fully carrying load. In order to keep the high initial stiffness of the hybrid composites, high platelet length was chosen for the first configuration, and the effect of platelet length was investigated within the study.

2.3. The effect of specimen thickness

The mode II energy release rate is determined by the elastic properties and the thicknesses of the glass and carbon layers in the hybrid composite. A thick carbon platelet increases the energy release rate and it initiates interlaminar fracture earlier than a thin one. The effect of thickness on failure type was investigated by testing scaled specimens.

2.4. Materials

The materials considered for design, and used in the experiments were E-glass/913 and S-Glass/913 epoxy prepregs supplied by Hexcel, and Sky Flex USN 020A carbon/epoxy prepreg from SK Chemicals. Material data of the three prepreg systems can be found in tables 1. and 2.

Fibre type	Manufacturer	Elastic modulus [GPa]	Strain to failure [%]	Tensile strength [GPa]	Density [g/cm^3]
Pyrofil TR30 carbon	**Mitsubishi Rayon**	234	1.9	4.4	1.79
EC9 756 P109 E-glass	**Owens corning**	72	4.5	3.5	2.56
FliteStrand S ZT S-glass	**Owens Corning**	88	5.5	4.8-5.1	2.45

Table 1. Fibre properties of the applied UD prepregs (based on manufacturer’s data)

Prepreg material	Property	Fiber mass per unit area	Cured ply thickness	Fibre volume fraction	Initial elastic modulus	Strain to failure	Interlaminar shear strength
	Unit	[g/m^2]	[mm]	[%]	[GPa]	[%]	[MPa]
Carbon/ epoxy	Average	21.2[1]	0.029[1]	41[1]	101.7[2]	1.9[1]	-
	COV* [%]	4.0[1]	-	-	2.75[2]	6.76[1]	-
E-glass/ epoxy	Average	192**	0.14[1]	54[1]	40**	3.7[3]/2.8[1]***	100**
	COV [%]	-	-	-	-	-	-
S-glass/ epoxy	Average	190**	0.155	50**	45.7	3.98	-
	COV [%]	-	-	-	3	1.1	-

*Coefficient of variation, **Based on Hexcel data, ***Measured on different specimen types in tension,

Table 2. Cured ply properties of the applied UD prepregs

2.5. Prediction of pseudo-yield strain

One of the most important features of the stress-strain response of the novel pseudo-ductile thin-ply hybrid composites is the *pseudo-yield strain* which follows the strain to failure of the low strain material if it is continuous. In the case of a discontinuous low-strain layer hybrid configuration, the *pseudo-yield strain* corresponds to the *initiation of stable platelet pull-out*. The criterion for this is given by the mode II energy release rate and the fracture toughness of the interface. The mode II energy release rate in the hybrid specimens can be calculated using the approach detailed in [1] with equation (1)

$$G_{II} = \frac{\varepsilon^2 E_2 t_2 \left(E_1 (h\text{-}t_2) + E_2 t_2\right)}{4E_1 (h - t_2)} \tag{1}$$

where ε is the overall strain in the specimen, E_1 is the elastic modulus of the glass layers, E_2 is the elastic modulus of the carbon platelets, t_2 is the thickness of the carbon platelets and h is the full thickness of the hybrid plate. The ε_{ini} strain to platelet pull-out initiation can be calculated by substituting the G_{IIc} fracture toughness in equation (1) as follows:

$$\varepsilon_{ini} = \sqrt{\frac{4G_{IIc} E_1 (h - t_2)}{E_2 t_2 \left(E_1 (h\text{-}t_2) + E_2 t_2\right)}} \tag{2}$$

2.6. Fracture toughness of the hybrid composite layer interface

The fracture toughness of E-glass/carbon hybrid composites was investigated by tensile testing several series of single cut central layer type hybrid specimens of various thicknesses (with L_f =160 mm and W=20 mm) incorporating one single cut in the middle of the specimen (see figure 1.). The fracture toughness of each specimen type was calculated using equation (1) and found to be in the range of G_{IIc}=1.1-1.36 N/mm (see table 3.). Although S-glass/carbon hybrid specimens are investigated in the majority of this study, the E-glass/carbon fracture toughness data is relevant, as both glass/epoxy composites were made with the same Hexcel 913 type epoxy resin matrix, which plays the most important role in interfacial load transfer and therefore primarily determines the properties.

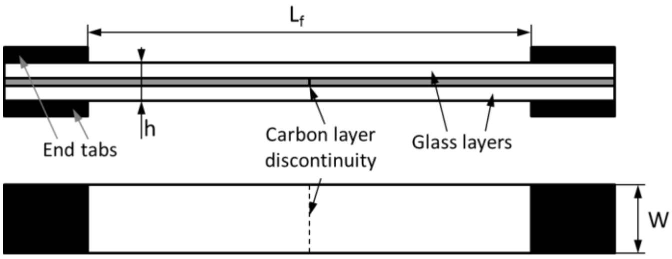

Figure 1. Single cut central layer sandwich hybrid composite specimen schematic

Figure 2. shows the test results of various specimen configurations including scaled ones. The strains to delamination (stable pull-out) initiation of each specimen type were taken from the graphs at points where the stress-strain curves started to deviate significantly from linear. The figure clearly shows that the delamination initiation strain and stress are controlled by the energy release rate of the carbon layer which ultimately depends on the thickness. Slight variation of the average moduli of the different specimen types are in line with their carbon/glass ratios.

Lay-up sequence	Property	Modulus	Delamination initiation strain	G_{IIc}
	Unit	[GPa]	[%]	[N/mm]
2EG/4C/2EG	Average	53.1	1.6	1.10
	COV [%]	2.37	-	-
2EG/5C/2EG	Average	53.6	1.4	1.13
	COV [%]	0.50	-	-
4EG/6C/4EG	Average	47.3	1.52	1.34
	COV [%]	1.50	-	-
4EG/8C/4EG	Average	50.2	1.26	1.35
	COV [%]	1.64	1.42	-
4EG/10C/4EG	Average	52.1	1.09	1.36
	COV [%]	1.51	1.79	-

Table 3. Results of mode II fracture tests (Designation: EG- E-glass, C- carbon, with numbers corresponding to the number of plies of the constituent prepregs)

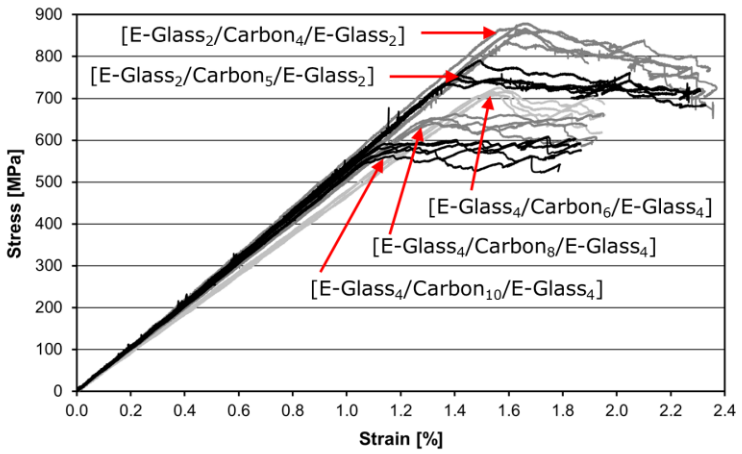

Figure 2. Tensile test results summary of single cut central layer E-glass/carbon hybrid composites

2.3. Specimen design

The specimens tested within the main part of the study were parallel edge tensile specimens with glass/epoxy tabs at the ends. Nominal specimen dimensions were 280/160/20/h mm-overall length/L_f-free length/W-width/h-variable thickness respectively. Another important geometric parameter of the discontinuous carbon layer was the L_p- platelet length (or cut spacing). Figure 3. shows the geometric parameters on the side and top view schematics of a tensile specimen. Table 4. shows the configurations of the specimen types. Some calculated and predicted values are also included in the table. Please note, that the fracture toughness values used for pull-out initiation strain predictions were different for thinner and thicker specimen types according to table 3. (G_{IIc}=1.35 N/mm for 4SG/8C/4SG type and G_{IIc}=1.1 N/mm for the others). The calculated energy release rates at the carbon fibre strain to failure being higher than the fracture toughness of the corresponding specimen configurations indicate that the platelets will be pulled out before carbon fibre failure.

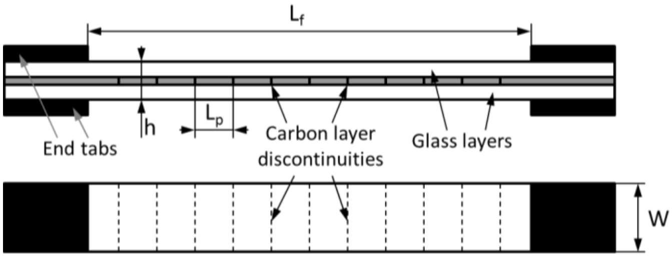

Figure 3. Periodically cut central layer sandwich hybrid specimen schematic

Lay-up sequence	Platelet length	Nominal thickness	Nominal carbon/ glass volume ratio	Predicted pull-out initiation strain	Calculated G_{II} at carbon strain to failure	Measured G_{IIc} for thickness
	[mm]	[mm]	[-]	[%]	[N/mm]	[N/mm]
2SG/4C/2SG	continuous baseline	0.736	0.16	-	1.43	1.10
2SG/4C/2SG	25	0.736	0.16	1.66	1.43	1.10
4SG/8C/4SG	25	1.472	0.16	1.31	2.86	1.35
2SG/4C/2SG	13	0.736	0.16	1.66	1.43	1.10

Table 4. Tested specimen configurations (Designation: SG- S-glass, C- carbon, with numbers corresponding to the number of plies of the constituent prepregs)

3. Experimental

3.1. Specimen manufacturing

The new type composites involving discontinuous prepreg plies needed new manufacturing procedures, especially to make sure the performance of the fibres around the discontinuities in the prepreg is not affected by the cutting technique and that the platelets are aligned accurately during lay-up. A 25 mm diameter "pizza wheel" blade was found to be suitable to reduce the shearing of the uncured prepreg when fabricating the sensitive internal cuts (see figure 4.). The less important circumferential cuts around the outside edges of the plies were made with a standard V-shape blade which cuts faster and is easier to set up, but introduces more shear deformation to the prepreg.

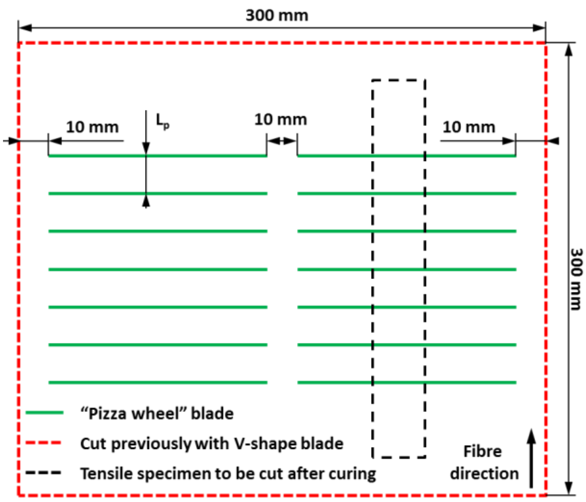

Figure 4. Cut pattern for the central carbon layers of the hybrid composite plates showing position where a typical specimen is cut out

The steps of the manufacturing route for the cut blocked ply specimens were the following:
1. Cutting the carbon prepreg to the size of the panel to be manufactured (see figure 4.);
2. Laying-up the thin carbon plies to make the central layer of the sandwich hybrid;
3. Creating the periodic internal cuts in the uncured carbon prepreg ply block with a 25 mm diameter "pizza wheel" blade leaving uncut sections in the middle to retain the alignment of the platelets during the next layer assembly step (see figure 4.);
4. Attaching the central carbon layer to the outer glass ones and consolidating under vacuum;
5. Bagging the composite plate up in the usual way using a silicone sheet on top of the prepreg plies to promote uniform pressure distribution and good surface finish;
6. Curing the composite plate in an autoclave using the recommended cure cycle;
7. Fabrication of individual specimens with a diamond cutting wheel.

3.2. Test procedure

Testing of the continuous glass/discontinuous carbon hybrid composite specimens was executed under uniaxial tensile loading and displacement control using a crosshead speed of 2 mm/min on a computer controlled Instron 8801 type 100 kN rated universal hydraulic test machine with wedge type hydraulic grips. Strains were measured using an Imetrum videogauge system with a nominal gauge length of 130 mm.

3.3. Results and discussion

The tensile test results of the tested specimen series are discussed here in details. Figure 5. shows the stress-strain graphs of the 2SG/4C/2SG type S-glass/carbon hybrid specimens made with 25 mm long carbon platelets, along with the corresponding continuous baseline. The platelets in this configuration are expected to be long enough to give a good contribution to the stiffness resulting in similar hybrid modulus to that of the baseline specimens. The figure shows that the special discontinuous carbon layer design improved the tensile failure character of the delaminating continuous hybrid configuration by replacing the significant (~15%) stress drop with a very smooth and gradual degradation of the tangent specimen stiffness which can be referred to as *pseudo-yielding*. The accurately predicted *pseudo-yield strain* of the discontinuous hybrid type corresponding to the initiation of stable carbon platelet pull-out is lower than the strain to carbon failure clearly marked by a stress drop in the continuous specimens. The *pseudo-yield* or plateau *stress* is also slightly lower than that of the baseline type but there is no initial stress drop present.

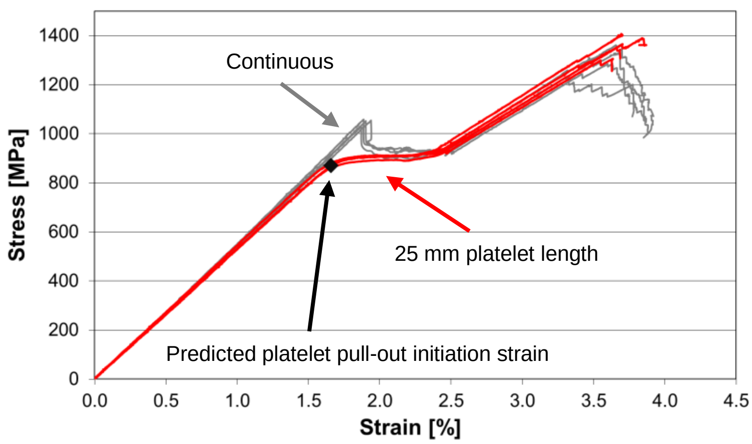

Figure 5. Tensile test results of 2SG/4C/2SG continuous and discontinuous 25 mm carbon platelet specimens

Figure 6. shows the effect of specimen thickness on the failure process through tensile test results of two scaled specimen types with the same carbon platelet length. The primary difference between the responses of the specimen types is that in the thick case, the mode II energy release rate is higher so it exceeds the fracture toughness of the interface earlier and therefore initiates the stable platelet pull-out at a lower strain. The *pseudo-yield strain* prediction applying the fracture toughness measured for the higher thickness 4G/8C/4G specimens was very accurate. A marginal effect- the slight reduction in the stiffness due to scaling- was also observed. It was also expected as the length of the platelets was not scaled for practical reasons (only three 50 mm platelets would have fitted in the gauge length of the specimens).

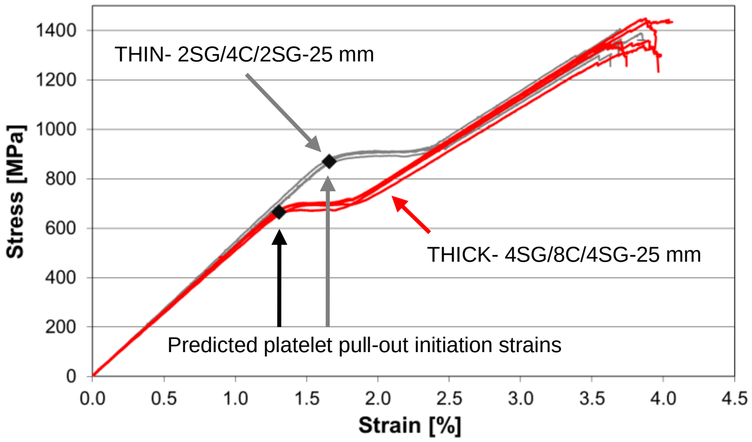

Figure 6. Tensile test results of discontinuous 2SG/4C/2SG-25 mm and 4SG/8C/4SG-25 mm type specimens

Figure 7. highlights the effect of the platelet length on the failure character of the sandwich hybrid configurations by plotting the tensile stress-strain curves of two specimen types with the same stacking sequence but various carbon platelet lengths. Please note that the stress-strain plots of the 2SG/4C/2SG-13 mm type specimens were offset by 0.1% strain for the sake of clearer comparison. The plots of figure 7. show only a small reduction in initial stiffness due to decrease in the length of the carbon platelets. This indicates that there may be scope for further reduction of the platelet length to make the new material architecture more suitable for real components and structural applications.

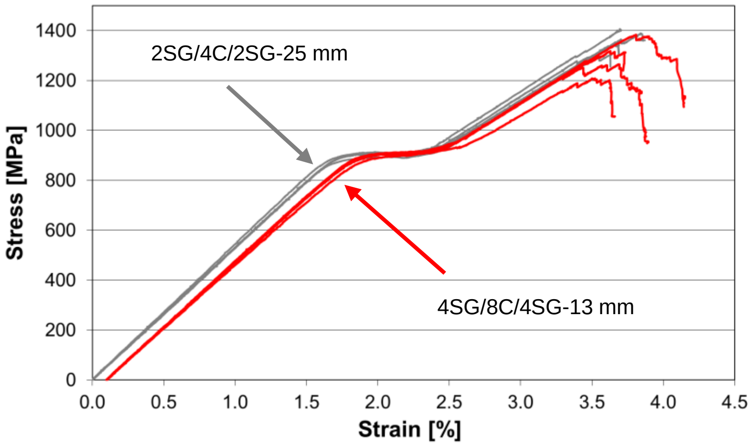

Figure 7. Tensile test results of discontinuous 2SG/4C/2SG 25 mm and 4SG/8C/4SG 13 mm type specimens

Table 5. summarizes the tensile test results for all specimen types. The evaluation of the measured initial modulus was based on the nominal thickness of the specimens. The *pseudo-*

yield points were defined as the intersection of the test curve with a straight line parallel to the initial slope of the stress-strain graph with an offset of 0.1% strain (similar to the offset yield point or proof stress in metals terminology). The *pseudo-ductile strain* was defined between the strain of a point on the initial slope line at the *failure stress* (defined at the point where a 5% fall in stress after the maximum has occurred) and the *strain at the failure stress*. The correlation between the predicted *platelet pull-out initiation strains* (table 4.) and the evaluated *pseudo-yield strains* (table 5.) is excellent, especially if we consider that the latter should be 0.1% higher because of the definition adopted.

Lay-up sequence	Platelet length	Nominal thickness	Elastic modulus	Modulus increase to pure S-glass	Pseudo-yield/ drop strain	Pseudo-yield/ plateau stress	Pseudo-ductile strain
	[mm]	[mm]	[GPa]	[%]	[%]	[MPa]	[%]
2SG/4C/2SG	continuous baseline	0.736	54.4	19.1	1.88	928	-
2SG/4C/2SG	25	0.736	53.4	17.1	1.77	893	1.36
4SG/8C/4SG	25	1.472	51.9	13.5	1.42	687	1.31
2SG/4C/2SG	13	0.736	52.2	14.4	1.82	891	1.32

Table 5. Test result summary

4. Conclusions

The following conclusions were drawn from the study of continuous glass/ discontinuous carbon UD sandwich hybrid laminates:

- A stable, pseudo-ductile failure type showing significant warning and margin before final failure has been demonstrated with the developed continuous S-glass/ discontinuous carbon UD sandwich hybrid architecture.
- The best tested specimen type generated 17.1% modulus increase (to pure S-glass/epoxy), a respectable 893 MPa high and 1% strain long stress plateau with very smooth transitions between the linear and the plateau strain regimes.
- The pseudo-yield strains of the tested specimen configurations were predicted accurately successfully accounting for the effect of variable energy release rates for various specimen thicknesses.
- The study on the effect of carbon platelet length on the modulus of the hybrid composite revealed that there is scope for further length reduction to make the new material architecture more suitable for various applications.

Acknowledgement

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