DEVELOPMENT AND CHARACTERISATION OF PSEUDO-DUCTILE HYBRID CARBON/GLASS-EPOXY COMPOSITES MADE OF THIN SPREAD CARBON TOWS

G. Czél*, J. Etches, I. P. Bond, M. R. Wisnom

Advanced Composites Centre for Innovation and Science, Department of Aerospace Engineering, University of Bristol, Queens Building, Bristol, BS8 1TR
**G.Czel@bristol.ac.uk*

Keywords: Fracture, Hybrid composite, Delamination, Ductility

Abstract

Unidirectional hybrid composites were fabricated by sandwiching single plies of two different types of thin, dry spread tow carbon fibre tapes between double plies of a conventional glass fibre-epoxy prepreg system. Tensile tests were carried out under optical video monitoring for later damage analysis. In the case of the specimens reinforced with a single layer of the thicker carbon fibre tape (68 g/m^2), the failure type of the carbon layer was sudden and catastrophic. In the case of the thinner carbon fibre tape reinforcement (40 g/m^2) a stable, pseudo-ductile damage process was observed, which was well pronounced on the stress-strain curves. Observed damage characteristics agreed well with the performed simple fracture mechanics analysis.

1 Introduction

Conventional polymer matrix composites offer high strength and stiffness combined with low density. However, a fundamental limitation of current composites is their inherent brittleness. Failure is usually sudden and catastrophic, with little warning or residual load-carrying capacity. Structures that satisfy a visual inspection, can fail suddenly at loads much lower than expected. To ensure safe operation, currently a much greater safety margin is applied for composites, than for other more ductile materials. For example, maximum allowable design strains can be as low as 0.1% for carbon fibre composites under repeated loading, despite maximum failure strains of up to 2%. These serious design limitations not only prevent engineers and operators from exploiting the performance advantages of composites, but render them unsuitable for many applications in which loading conditions are not fully predictable, but catastrophic failure cannot be tolerated. According to the explained limitations of currently available high performance composites, pseudo-ductile composites are of exceptional interest and could potentially offer a ground breaking increase in the scope of applications including automotive and civil engineering fields.

Basic strategies to achieve pseudo-ductility are either the incorporation of new ductile constituents, or modifying the structure of the composite laminates manufactured. Unfortunately, developing new constituents and introducing them for primary load carrying applications in such sensitive industries as aerospace is exceptionally difficult and can take at least a decade, as was the case for current carbon fibre reinforced plastics. Applying modified architectures of existing materials is faster and more straightforward, not only because of the availability of materials, but accumulated experience is also important. This section only highlights some of the most important fields of research in the structural aspects of damage tolerant composites. Significant research has been undertaken during the last few decades to improve the through-thickness strength of composite laminates by means of increased interlaminar fracture toughness by applying techniques such as stitching [1] or z-pinning [2]. These strategies are applied successfully e.g. in increasing impact resistance, but do not address the issue of brittleness and catastrophic failure. Ductility during manufacturing can be achieved using discontinuous, but highly aligned fibres. Research is underway to develop manufacturing technology which is adaptable for mass production (e.g. [3]). Discontinuous fibres can be introduced in hybrid composites in a less distributed way using slit, broken or laser cut/drilled prepregs. It seems that the benefits of these techniques to date have only been exploited during the manufacturing of complex shaped composite structures with unaffected or slightly reduced mechanical properties. Early work on hybrid composites [4-7] showed their potential to obtain gradual failure over a range of strains by mixing different types of fibres either on the tow or on the ply level [8-9]. Some authors have reported that thin ply composites show better mechanical properties and failure characteristics (especially in out of plane impact loading) than conventional laminates [10-13], mainly because delaminations are suppressed in the thin ply case.

The present study focuses on thin ply carbon/glass hybrid laminates designed to combine the benefits of both hybrid and thin ply approaches by exploiting the full ductility potential of these material structures. Using thin carbon plies in the hybrid laminate, a more stable damage process can be achieved, instead of the sudden drop in load typically seen when the low strain fibres fail, followed by load recovery as the high strain fibres pick up all the load. According to our fracture mechanics analysis, it is possible to achieve stable pull out of a sufficiently thin central carbon reinforced layer from thicker glass reinforced layers. This means, that a stable transition can be achieved between the stress-strain curves of the intact hybrid laminate and the delaminated layers, where only the glass plies carry load (see figure 1.).

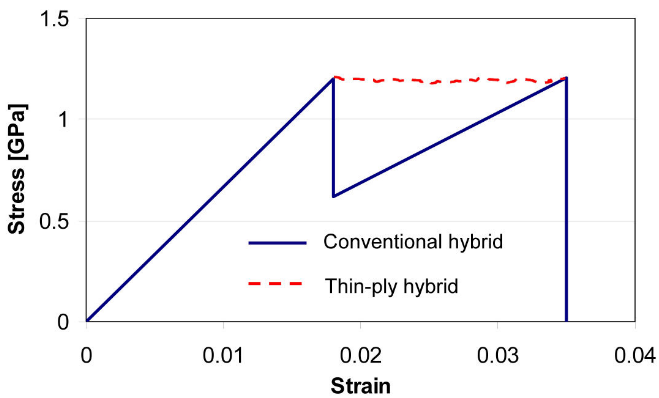

Figure 1. Schematic of the stress-strain graph of a conventional and a thin ply hybrid composite laminate

2 Experimental

Preliminary fracture mechanics analysis was performed based on the energy release rate of a thin carbon fibre reinforced ply compared to the mode II delamination fracture toughness of the interface between the central carbon and outer glass layers. These calculations showed that the limit of suitable ply thickness for stable pull-out of the carbon ply is around 60 μm depending on the material properties and overall thickness of the hybrid laminate. Calculations also indicated that double plies of standard (0.125 mm thick) glass prepreg should provide enough strength to withstand the load shed to them after carbon ply failure. Tensile tests were executed therefore on specimens with thin carbon reinforcements embedded in thicker glass plies.

2.1 Materials

Hybrid specimens were manufactured using conventional E-glass reinforced epoxy matrix unidirectional (UD) prepreg (HexPly 913G-E-5-30% supplied by Hexcel) with 0.125 mm nominal cured thickness, 192 g/m^2 glass fibre mass per unit area and 30 m% (~40 V%) cured resin content. Carbon reinforcements applied were thin, dry UD spread tow tapes from two different manufacturers. Manufacturer's data and results of the characterisation of the carbon reinforcements can be found in tables 1. and 2. Characterisation was undertaken on three rectangular pieces for each type, greater than 4000 mm^2 in area, cut from the reinforcement tapes, using weight measurements before and after burning the binder and/or sizing off the fibres. Burn off was executed in an atmospheric furnace (60 min@500°C).

Manufacturer	Type	Carbon fibre type	Tape width [mm]	Nominal mass per unit area [g/m^2]
Sigmatex	DP 0060150	IMS65 E23	86	68
Oxeon	TeXtreme® 40 UD WO	UTS50 F22S	20	40

Table 1. Factory data for dry spread tow carbon reinforcements

Manufacturer	Property Unit	Spread tow tape mass per unit area [g/m^2]	Fibre mass fraction [%]	Fibre mass per unit area [g/m^2]	Binder/sizing mass fraction [%]
Sigmatex	Average	79.1	95.8	75.8	4.2
	St. dev. (%)	0.25	0.63	0.42	14.2
Oxeon	Average	46.6	87.2	40.6	12.8
	St. dev. (%)	0.19	0.76	0.93	5.21

Table 2. Results of characterisation of dry spread tow carbon reinforcements

According to the above tables it can be stated that the actual mass per unit area of the Sigmatex tow is higher than the manufacturer's data, and the Oxeon tape contains a notable amount (13%) of combustible substances. Optical microscopy was executed on the cured composites to observe the structure and geometric properties of the new type materials (see figure 2.). Central carbon ply thicknesses of the Sigmatex and the Oxeon tapes were 67.2±7.6 μm and 36.5±12.5 μm respectively, both measured at more than 20 points along polished cross sectional samples.

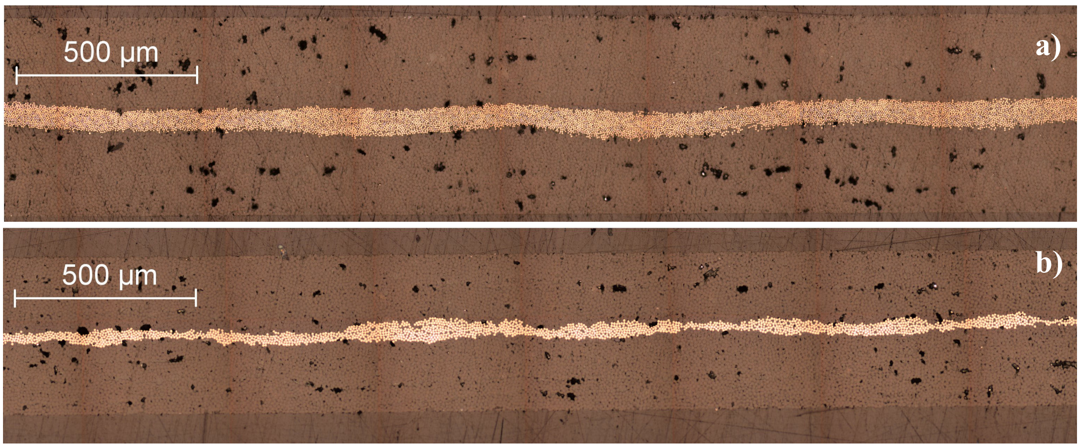

Figure 2. Micrographs of polished cross sectional samples cut from thin ply hybrid composites with a) Sigmatex, b) Oxeon central carbon ply

It is obvious from the micrograph in figure 2. b) that the Oxeon tape shows a significant fluctuation in thickness (also reflected by the 30% relative standard deviation) and in both cases the thin ply is not completely flat, caused by the double glass prepreg plies on the top and bottom.

Unidirectional laminates were laid up and cured using both types of thin carbon tapes in the following sequence: [G_2/C/G_2], where G stands for glass plies and C for a carbon ply. The manufacturing of the hybrid composite laminates was similar to the conventional process for prepregs, except that the thin, dry tow tapes were placed on the glass prepreg layers in the middle of the laminate. Exceptional attention was paid to place the tapes so no gaps or overlaps were present. No additional resin was applied to wet out the dry spread carbon tows; there was sufficient excess resin from the glass prepreg plies for this purpose. This way uniform matrix properties throughout the whole thickness of the laminate and high fibre volume fraction were ensured. Laminates were cured at the recommended cure temperature and pressure cycle for Hexcel 913 resin (60 min@125°C, 0.7 MPa). A flat aluminium tool plate and caul plates were used during the bagging process and resin bleed out was not blocked. Machining of the specimens was done using a diamond cutting wheel. Glass fibre reinforced end tabs with 2 mm thickness were bonded to the specimens using Redux® 810 epoxy supplied by Hexcel, cured for 60 min@70°C.

2.2 Test procedure

Testing of hybrid carbon/glass composite specimens was executed under uniaxial tensile loading and displacement control using a crosshead speed of 2 mm/min on a computer controlled Instron MJ6283 type 100 kN rated universal hydraulic test machine with wedge type hydraulic grips. Nominal specimen dimensions were 280/160/20/0.6 mm overall length/gauge length/width/thickness respectively. Strains were measured using an Imetrum video gauge system with a Sony XCD-SX910 type CCD camera at a nominal gauge length of 100 mm. Videos were recorded to be used for failure type and process characterisation.

2.3 Results and discussion

Specimens were marked according to the manufacturer of the single carbon ply in the middle of the laminate. Figures 3. and 4. show the overall tensile stress-strain graphs obtained from the tests, based on the average stress through the specimen thickness. Arrows and numbers in brackets refer to characteristic points of the graphs, used for data representation. Point (4) was determined for each specimen tested, using the intersection point of two straight lines laid on surrounding sections of the graphs. Final strain values (5) were determined at a 15% drop in stress towards the end of the failure process. In the case of the Sigmatex type specimens conventional hybrid composite failure was observed as the lower strain carbon ply fractured at about 2.1% strain and immediate delamination of the whole specimen took place. After this significant drop in the overall stress, the glass plies started to take up the whole load until the final failure of the specimens. This two stage failure process cannot be called pseudo-ductile although it is more gradual than the usual sudden death type failure of single fibre composite. Oxeon type specimens failed in a favourable, pseudo-ductile way. Multiple cracks appeared in the carbon ply around 2.3% strain, in a distributed pattern along the gauge length. Localized delaminations initiated around the carbon ply cracks in parallel, and developed stably until almost linking up. The observed pseudo-yielding provided a stable failure process until the final failure at around 3% strain on average. Tables 3. and 4. show the results of the tensile tests on the thin dry carbon tow reinforced hybrid specimens.

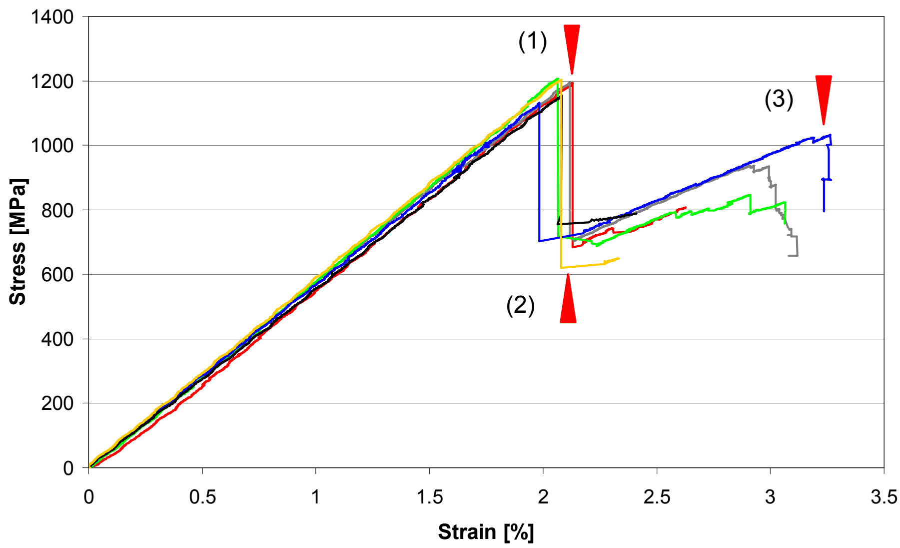

Figure 3. Results of tensile tests on carbon/glass hybrid specimens with Sigmatex type carbon ply in the middle

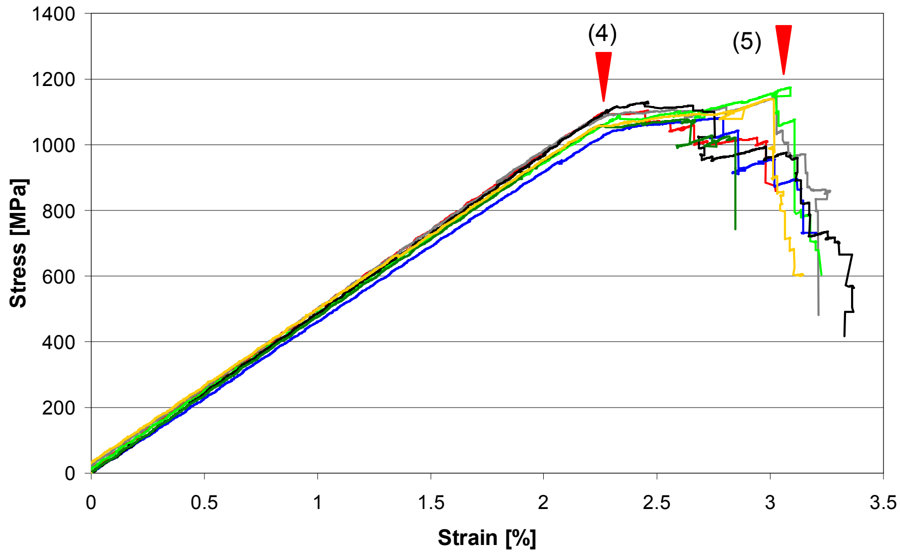

Figure 4. Results of tensile tests on carbon/glass hybrid specimens with Oxeon type carbon ply in the middle

Sigmatex type	Specimen geometry		Stress drop				Final	Initial	Approx. final
Property	Width	Thickness	Strain (1)	Upper stress (1)	Lower Stress (2)	Decrease in stress	Strain (3)	Elastic modulus	
Unit	[mm]	[mm]	[%]	[MPa]	[MPa]	[%] upper	[%]	[GPa]	[GPa]
Average	19.55	0.63	2.1	1180	693.2	58.81	3.11	61.11	30.76
Standard deviation [%]	1.32	2.01	4.64	2.6	6.37	8.09	4.13	3.32	-

Table 3. Tensile test results of Sigmatex carbon tape reinforced glass fibre hybrid specimens

Oxeon type	Specimen geometry		"Yield"		Final	Initial
Property	Width	Thickness	Strain (4)	Stress (4)	Strain (5)	Elastic modulus
Unit	[mm]	[mm]	[%]	[MPa]	[%]	[GPa]
Average	19.35	0.60	2.3	1078	3.04	47.58
St. deviation [%]	0.97	0.68	1.17	2.49	3.46	1.93

Table 4. Geometry and tensile test results of Oxeon carbon tape reinforced glass fibre hybrid specimens

I is worth noting, that the final strain of Sigmatex type specimens was determined from only 3 specimens, because the video gauge system lost the targets for the rest of the specimens before the end of the test. This was because the paint pattern applied to aid full-field strain capture can be detached from the specimen surface due to extensive failure (e.g. splitting parallel to UD fibres). The term “yield” in table 4. refers to a pseudo-yielding effect only, because no true plastic deformation can take place in either of the constituents of the hybrid laminates tested. Stable horizontal plateaus on the stress-strain graphs of the Oxeon type specimens are the result of multiple failures of the carbon layers, and stable pull out of the fractured carbon ply segments from the glass plies.

3 Conclusions

- Stable failure to high strains has been successfully demonstrated on thin dry spread tow tape reinforced hybrid composite materials.
- Carbon plies 67 μm thick delaminated from the glass whereas ones of 36 μm showed stable pull-out, consistent with the expected transition in behaviour at about 60 μm.
- A novel and advantageous composite material structure has been developed that exhibits pseudo-ductile failure characteristics.

Acknowledgement

This work was funded under the EPSRC Programme Grant EP/I02946X/1 on High Performance Ductile Composite Technology in collaboration with Imperial College, London.

References

[1] Mouritz A.P., Leong K.H. Herszberg I. A review of the effect of stitching on the in-plane mechanical properties of fibre-reinforced polymer composites. *Composites: Part A,* **28**, pp. 979-99 (1997).

[2] Mouritz A.P. Review of z-pinned composite laminates. *Composites: Part A,* **38**, pp. 2383-2397 (2007).

[3] Harper L.T., Turner T.A., Martin J.R.B., Warrior N.A.: Fiber alignment in directed carbon fiber preforms – A feasibility study. *Journal of Composite Materials*, **43**, pp. 57-74 (2009).

[4] Bunsell A.R., Harris B. Hybrid carbon and glass fibre composites. *Composites,* **5**, pp. 157-164 (1974).

[5] Summerscales J., Short D. Carbon fibre and glass fibre hybrid reinforced plastics. *Composites,* **9**, pp. 157-166 (1978).

[6] Hancox N.L. *Fibre composite hybrid materials.* Applied Science Publishers Ltd., London (1981).

[7] Kretsis G. A review of the tensile, compressive, flexural and shear properties of hybrid fibre-reinforced plastics. *Composites,* **18**, pp. 13-23 (1987).

[8] Short D., Summerscales J. Hybrids - a review Part 1. Techniques design and construction. *Composites,* **10**, pp. 215-221 (1979).
[9] Short D., Summerscales J. Hybrids - a review Part 2. Physical properties. *Composites,* **11**, pp. 33-38 (1979).
[10] Sihn S., Kim R.Y., Kawabe K., Tsai S.W. Experimental studies of thin-ply laminated composites. *Composites Science and Technology*, **67**, pp. 996–1008 (2007).
[11] Yokozeki T., Aoki Y., Ogasawara T. Experimental characterization of strength and damage resistance properties of thin-ply carbon fiber/toughened epoxy laminates. *Composite Structures*, **82**, pp. 382–389 (2008).
[12] Saito H., Morita M., Kawabe K., Kanesaki M., Takeuchi H., Tanaka M., Kimpara I. Effect of ply-thickness on impact damage morphology in CFRP laminates. *Journal of Reinforced Plastics and Composites*, **30**, pp. 1097–1106 (2011).
[13] Yokozeki T., Kuroda A., Yoshimura A., Ogasawara T., Aoki T. Damage characterization in thin-ply composite laminates under out-of-plane transverse loadings. *Composite Structures*, **93**, pp. 49–57 (2010).