TAKING ADVANTAGE OF THE HYBRID EFFECT IN THIN-PLY PSEUDO-DUCTILE LAMINATES

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Abstract
Hybrid laminates and angle-ply laminates with thin unidirectional carbon plies have been shown to give a pseudo-ductile response with more gradual failure than conventional composites. This paper shows the effect of ply thickness on tensile strength. Significant enhancements to the failure strain are demonstrated in glass-carbon hybrid composites, in hybrids with different grades of carbon fibre and in carbon fibre laminates combining 0˚ and angle plies. In addition to providing pseudo-ductility, these laminates therefore enable greater advantage to be taken of the intrinsic properties of the materials.

1. Introduction

Composite materials have excellent specific strength and stiffness, but a major drawback is their lack of ductility. The High Performance Ductile Composites Technology (HiPerDuCT) programme is a collaboration between the University of Bristol and Imperial College to address this challenge by developing new materials and architectures that give a gradual failure.

It has been shown that using thin-ply hybrid laminates, delamination can be suppressed, and progressive fragmentation of the high modulus plies can be obtained [1]. This gives a pseudo-ductile unidirectional tensile response with a plateau in the stress-strain curve, e.g. Fig. 1. A second mechanism is fibre reorientation in angle ply laminates, which can produce significant additional strain as the fibres become more aligned with the loading direction [2]. Stiffness has been shown to be recoverable, with no loss of initial modulus on reloading, and this therefore represents ductile rather than pseudo-ductile behaviour [3]. These mechanisms can be combined in angle ply laminates containing thin 0˚ plies which fragment followed by reorientation of the angle plies [4], producing a longer plateau. These laminates are pseudo-ductile, because the fragmentation leads to loss of modulus even though the fibre reorientation does not [3].

A hybrid effect can be defined as an increase in properties when one material is mixed with another compared with the same material on its own. Tests on glass-carbon laminates have confirmed that there is a hybrid effect for strength when the carbon plies are very thin, leading to a significant increase in the strain at failure [5]. The mechanism responsible for the hybrid effect is the constraint of the adjacent glass plies limiting the development of critical clusters of carbon fibre breaks, and so may also apply in other cases where constraint from adjacent plies means that fibre fracture is not catastrophic.

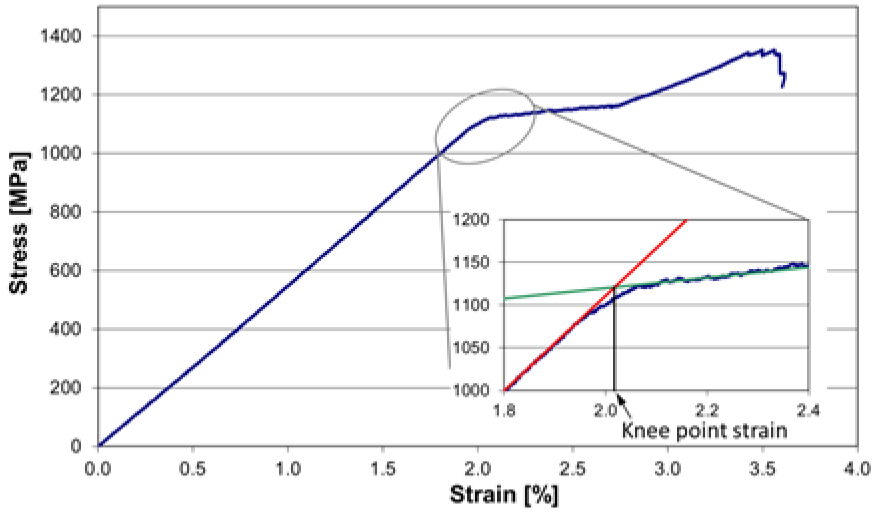

Figure 1. Typical pseudo-ductile response of (SG/$TR30_2$/SG) glass/carbon hybrid and method for defining failure strain [5]

This paper investigates various configurations of laminates, showing the magnitude of the enhancement of the failure strain that can be obtained. The results demonstrate that as well as giving a pseudo-ductile response, these laminates enable greater advantage to be taken of the mechanical properties of the basic materials by exploiting the hybrid effect.

2. Hybrid effect in glass-carbon laminates

Various configurations of glass/carbon hybrids were tested in tension [5]. The materials were S2-glass/913 epoxy prepreg supplied by Hexcel with a standard thickness of 0.155 mm, and Skyflex TR30 carbon/K50 epoxy prepreg only 0.029mm thick from SK Chemicals (designation USN020A). The resins were both 120°C cure epoxy systems, which were found to be compatible.

Laminates with the layups given in Table 1 were cured and 20 mm wide specimens with 160 mm gauge sections were cut, and end-tabbed. Tests were carried out under uniaxial tensile loading at a crosshead speed of 2 mm/min. Strains were measured using a videogauge with a nominal gauge length of 130 mm. A minimum of four specimens were tested from each configuration.

Table 1. S-glass / Carbon hybrid specimen types

Specimen Type	Fibre areal mass	Nominal thickness	Carbon layer thickness relative to full thickness	Modulus	Knee point/load drop strain corrected for residual stress (CV)
	[g/m^2]	[mm]		[GPa]	[%] [rel. %]
SG/TR30/SG	190/21/190	0.339	0.085	50.2	2.227 (1.4)
SG/$TR30_2$/SG	190/42/190	0.368	0.157	53.4	2.004 (1.6)
SG/$TR30_3$/SG	190/63/190	0.397	0.218	56.8	1.877 (1.5)
SG_2/$TR30_4$/SG_2	380/84/380	0.736	0.157	53.4	1.839 (2.1)

Specimens with 3 or 4 layers of carbon failed with a single fracture in the carbon in the gauge section, followed by delamination of the carbon from the glass. This was accompanied by a sharp load drop, and the strain at this point was recorded. Specimens with 1 or 2 layers failed by progressive fragmentation of the carbon plies with no load drop. There was a plateau on the stress-strain curve, and the failure strain was estimated from the intersection of straight lines fitted to the plateau and the initial loading response, as shown in Fig. 1. Strains were also corrected for the small effect of thermal residual stresses due to the different expansion coefficients of the glass and carbon.

Results are shown in Fig. 2. Failure strains for the 3 and 4 ply cases were similar, both close to the fibre failure strain of 1.9% quoted on the manufacturer's datasheet. Failure strains for the laminates with thinner carbon layers are higher, with values of 2.00% and 2.23% for the double and single ply cases compared with an average of 1.86% for the thicker plies, relative increases of about 8% and 20%.

It can also be seen that there is a slight slope on the plateau as progressively stronger parts of the carbon ply fail. The maximum strain in the single carbon ply at the end of the plateau when fragmentation is saturated is estimated to be 2.35% [5], a further 5% relative increase.

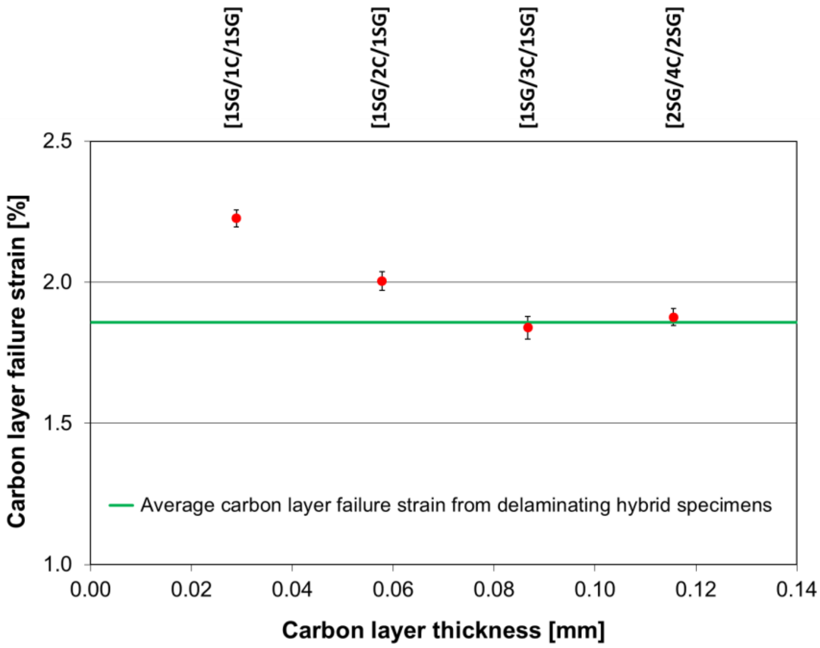

Figure 2. Hybrid effect for thin carbon layers [5]

3. Hybrid effect in carbon-carbon laminates

A hybrid effect was also observed in tests on similar specimens made from all carbon/epoxy laminates including ultra high modulus fibres. Materials were North Thin Ply Technology ThinPreg 120 EPHTg-402 with T1000 intermediate modulus and XN80 ultra high modulus carbon fibres, with ply thicknesses 0.032 mm and 0.047 mm respectively, and layups shown in Table 2. The ratio of layer thicknesses is lower than for ply weights due to the higher density of the XN80 fibres. Specimen dimensions, manufacturing and test procedures were the same as for the glass/carbon hybrids.

Stress-strain curves of the [$T1000_2$/$XN80_2$/$T1000_2$] laminate are shown in Fig. 3. Failure strains were estimated using the same method as before based on the intersection of straight lines fitted to the plateau and initial response, and corrected for the small compressive strain of 0.005% due to residual thermal stresses. Six specimens of each type were tested. These results are also shown in Table 2.

Table 2. Carbon hybrid specimen types and failure strains

Specimen Type	Fibre aereal mass	Nominal thickness	Low strain layer thickness relative to full thickness	Modulus	Knee point strain corrected for residual stress (CV)
	[g/m^2]	[mm]		[GPa]	[%] [rel. %]
[T1000$_1$/XN80$_1$/T1000$_1$]$_S$	[28/50/28]$_S$	0.112x2	0.425	242.5	0.422 (1.6)
[T1000$_2$/XN80$_2$/T1000$_2$]	56/100/56	0.223	0.425	244.8	0.398 (4.8)

The single ply gave a strain of 0.422% compared with 0.398% for the double ply, a relative increase of 6%, similar to the increase obtained with the slightly thicker double TR30 ply case. The strains in the XN80 at the end of the plateau for the single ply case are estimated using the same approach as in [5] to be 0.467%, a further relative 11% higher. The two sets of results are compared in Fig. 4 showing straight lines between the knee points based on the averages of all the experimental results, clearly showing the hybrid effect.

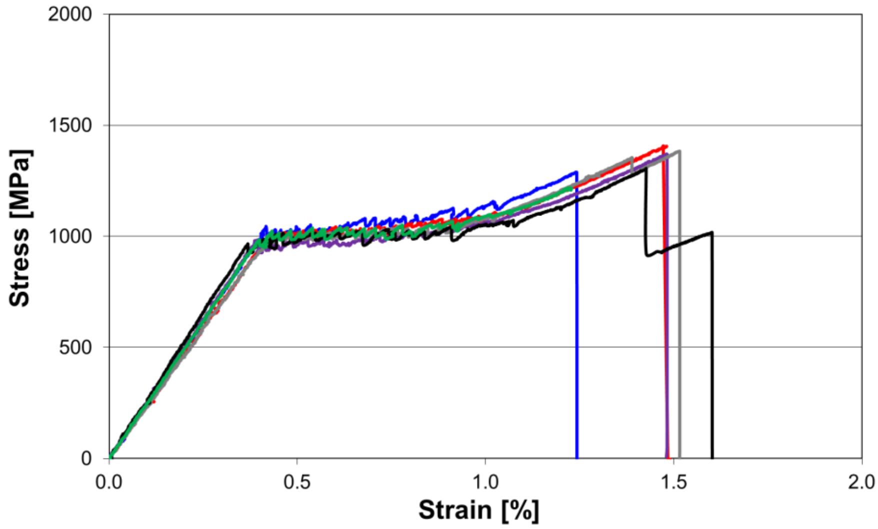

Figure 3. Stress-strain response for [T1000$_2$/XN80$_2$/T1000$_2$] carbon hybrid [6]

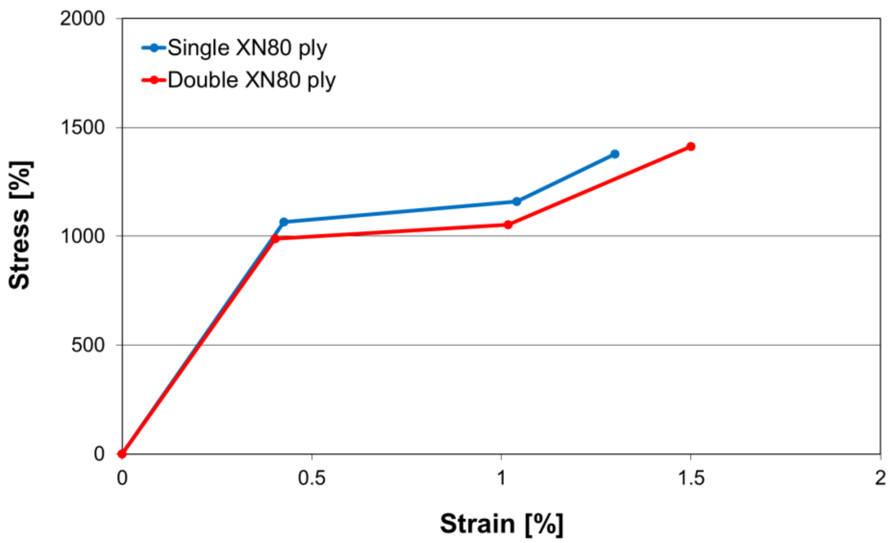

Figure 4. Hybrid effect from averaged T1000/XN80 carbon laminate responses

4. Hybrid effect in carbon angle-ply laminates

Two sets of carbon angle-ply laminates with different 0° ply thicknesses were tested. The first was made of the same Skyflex TR30 carbon/epoxy prepreg used in the previous carbon/glass hybrid specimens, with layups containing 0° and (26/-26)° plies, as shown in Table 3.

Table 3. USN020 Carbon/epoxy angle-ply laminates and failure strains

Specimen Type	Nominal thickness	0° layer thickness relative to full thickness	Modulus	0° failure strain corrected for residual stress (CV)
	[mm]		[GPa]	[%] [rel. %]
$[(26/-26)_3/0/(-26/26)_3]$	0.377	0.077	44.0	2.024 (2.7)
$[(26/-26)_5/0_2/(-26/26)_5]$	0.638	0.091	41.1	1.895 (2.0)

The second set of specimens were made with North TPT YSH-70A 0° plies between angle plies of either SK USN020A carbon epoxy used previously, or UIN020A, a similar prepreg but with intermediate modulus fibres and higher volume fraction, giving a unidirectional composite modulus of 146 GPa compared with the 102 GPa of the USN020A. Cured ply thicknesses were 0.024 mm and 0.03 mm for the UIN020 and YSH-70A respectively. Different combinations of angle plies were used as shown in Table 4.

Table 4. YSH-70A Carbon/epoxy angle-ply laminates and failure strains.

Layup	Materials	Nominal thickness	0° layer thickness relative to full thickness	Modulus	0° failure strain corrected for residual stress (CV)
		[mm]		[GPa]	[%] [rel. %]
[(22.5/-22.5)/0/(-22.5/22.5)]	USN/YSH/USN	0.146	0.205	108.0	0.551 (5.5)
[(26/-26)/0/(-26/26)]	USN/YSH/USN	0.146	0.205	98.8	0.510 (3.1)
Average for single 0° plies					0.530
$[(25/-25)_2/0_2/(-25/25)_2]$	UIN/YSH/UIN	0.252	0.238	134.5	0.480 (1.5)

Specimens 15 mm wide with a gauge length of 150 mm were tabbed and tested in tension under displacement control at a loading rate of 2 mm/min. The knee point strains were calculated from the intersection of lines along the plateau and the slope before fragmentation, consistent with the approach used for the UD hybrid specimens. However the double 0° ply USN020 specimens behaved slightly differently, showing a small load drop before the start of the plateau, as shown in Fig. 5. For this case the strain at the peak load was taken, since in the absence of a gradual start to the plateau this was a more accurate estimate of the start of fragmentation. Averages are based on a minimum of 6 specimens except for the double 0° ply USN020 case, where only 4 specimens showed a load drop, but with very consistent strains (CV only 2.0%).

Results are also shown in Tables 3 and 4, including the corrections for thermal residual stresses from laminate plate theory. The USN020 specimens with a single 0° ply showed a 7% relative increase in failure strain from 1.90% to 2.02%. The increase in strain is similar to the 8% increase obtained with the carbon/glass hybrids for the two-ply compared with the thicker specimens. The strain values are also similar. However the higher strains previously measured for the single carbon ply hybrids were

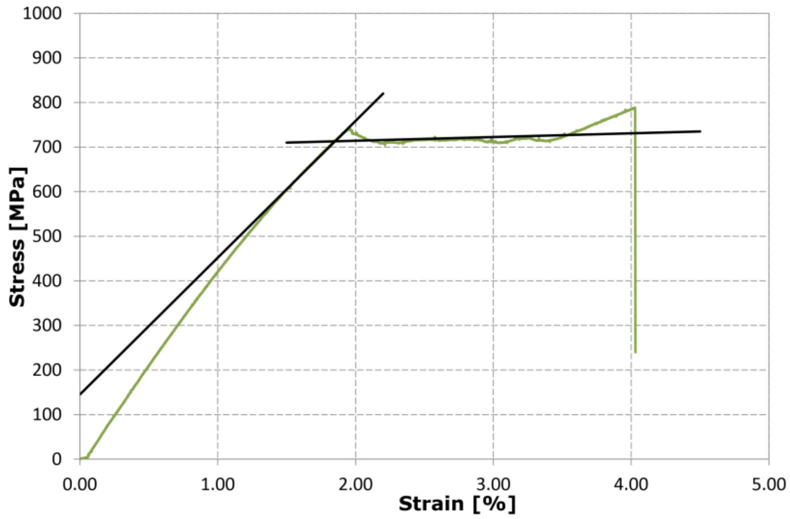

Figure 5. Typical stress-strain response for $[(26/\text{-}26)_4/0]_s$ USN020 carbon laminate

not reached with the angle ply laminates with a single 0° ply of the same material. Both the single ply YSH specimens showed higher strains than the double ply case, but there was more variability in the results. Although the angle ply orientations are different, to compare the effect of ply thickness the two cases can be averaged. This gives a mean of 0.53% for the single ply case compared with 0.48% for the double ply case, an increase of 10%.

5. Conclusions

Significant enhancements in strain at failure were measured for laminates with thin carbon plies compared with similar specimens with thicker ply blocks, demonstrating the importance of ply thickness on tensile failure. Carbon/glass hybrids showed increases of 8% and 20% for specimens with double and single thin carbon plies compared to thicker specimens. A hybrid effect was also found in carbon/carbon hybrids, with a 6% relative increase in strain at failure for single XN80 plies compared with double plies. Similar enhancements in strain at failure were observed in the 0° plies of carbon fibre laminates with angle plies, with relative increases in strain at failure of 10% and 7% for single compared with double plies of YSH-70 and TR30 fibres respectively. The results with different combinations of materials can be interpreted as a hybrid effect. However the latter increase was obtained with a single material, suggesting that the key factor is the constraint on the formation of critical clusters of fibre breaks, rather than the effect of hybridising different materials. Even higher strains were obtained further along the plateau as progressively stronger parts of the carbon plies fracture. The results show that in addition to providing pseudo-ductility, these laminates enable greater advantage to be taken of the intrinsic properties of the carbon fibre materials.

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