HiPerDuCT Programme Grant

Final report: Thin-ply hybrids

Pseudo-ductility in Unidirectional Tension

A new failure mechanism of fragmentation in hybrid thin-ply laminates has been demonstrated, with multiple failures of the stiffer, lower strain to failure plies and stable pull-out of the fragments, producing a pseudo-ductile stress-strain response [1]. The use of thin plies suppresses overall delamination. Figure 1 shows a typical response for two 0.029 mm plies of high strength TR30 carbon sandwiched between single 0.155 mm S-glass epoxy plies on either side [2]. The striped pattern associated with the fragmentation is also shown.

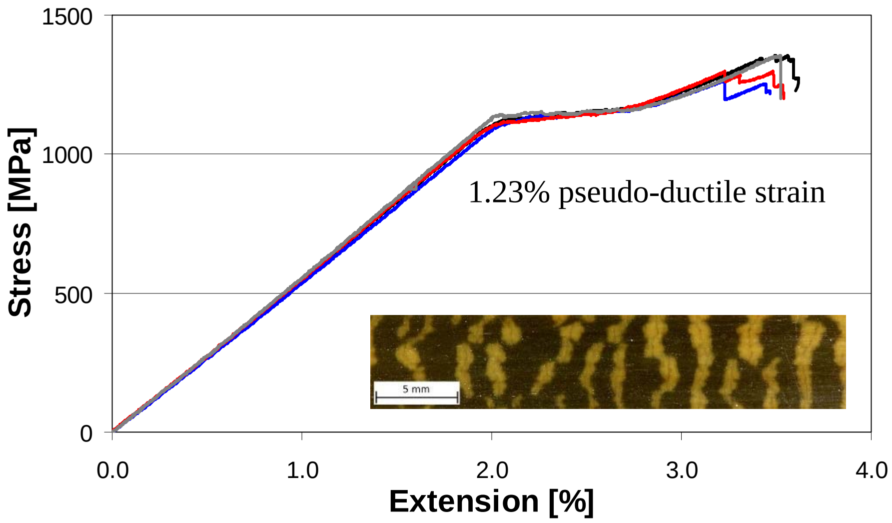


Figure 1. Pseudo-ductile response of S-glass/high strength carbon hybrid [2]

Modelling has shown that both the relative thickness (i.e. proportion of carbon) and absolute thickness of the carbon plies are important in controlling the hybrid response [3-6]. With the appropriate thicknesses, premature brittle failure of the whole hybrid specimen and catastrophic delamination can be avoided.

Damage mode maps can be produced such as Figure 2, with the different failure mode regions in this case indicated approximately based on FE analysis [3]. However analytical models allow the boundaries to be calculated explicitly [4].

There is a trade-off between pseudo-ductility and yield stress [2,5]. A range of different glass-carbon hybrid configurations has been evaluated, and pseudo-ductile strains of up to 2.66% have been obtained with a plateau stress of 520 MPa, or 0.86% pseudo-ductile strain with a plateau stress of over 1300 MPa [2].

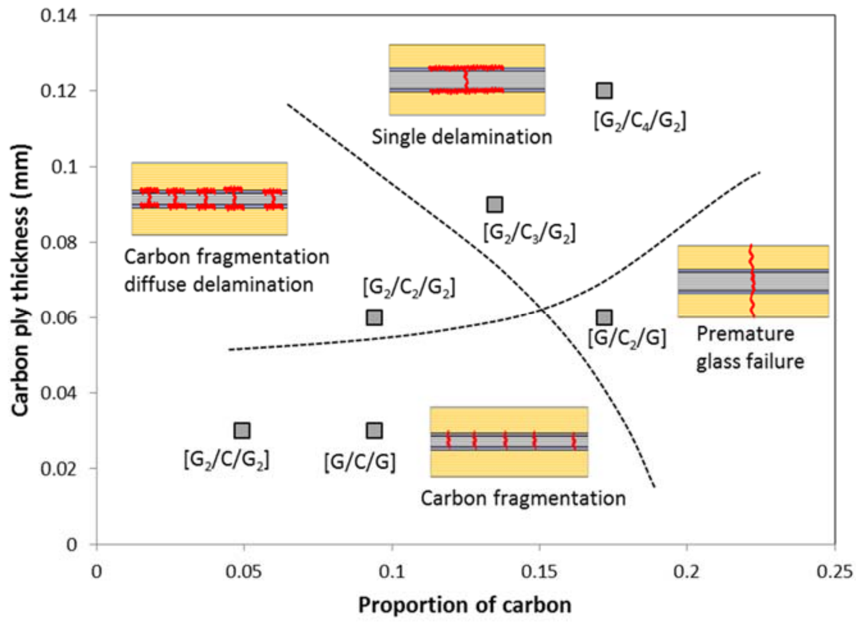


Figure 2. Damage mode map for E-glass/thin carbon hybrid composite [3]

Similarly pseudo-ductile response has been demonstrated with hybrids with different grades of carbon fibres. Figure 3 shows the response of hybrid specimens made from thin plies of Granoc XN80 ultra-high modulus carbon between layers of T1000 intermediate modulus carbon fibres [7].

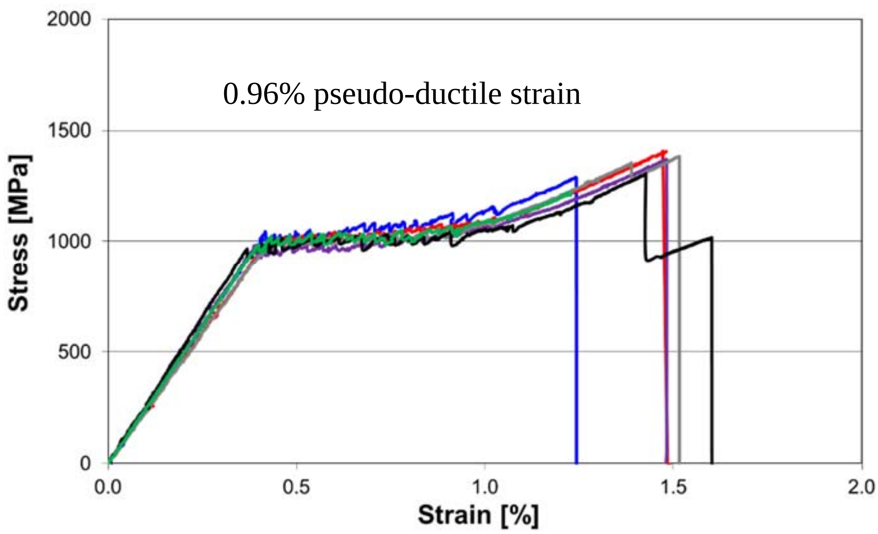


Figure 3. Stress-strain response for [$T1000_2$/$XN80_2$/$T1000_2$] carbon hybrid [7]

Loading-unloading-reloading tests show a reduction in initial modulus due to the damage, and so these laminates are pseudo-ductile rather than truly ductile [8,9].

It has been shown that acoustic emission can be used to detect fragmentation, with a direct correlation between acoustic and fragmentation events, allowing the technique to be used to detect fragmentation in opaque carbon/epoxy laminates [9,10].

Introducing cuts into the low strain plies is an alternative means of producing pseudo-ductility via controlled local delamination from the discontinuous plies before they fragment [11].

Pseudo-ductility in Multi-directional Laminates

Modelling showed how pseudo-ductile behavior could be achieved in multi-directional layups [12] and this has been demonstrated experimentally with quasi-isotropic laminates made from unidirectional carbon fibre hybrid sub-laminates [13]. An alternative concept with sublaminates formed by blocks of the same material with different ply orientations rather than blocks of different materials with the same orientation has also been shown to produce pseudo-ductile quasi-isotropic laminates whilst reducing the risk of free edge delamination [14], and giving similar response in all the fibre directions, Figure 4 [15]. Loading at small off-axis angles also produces pseudo-ductile response [16]

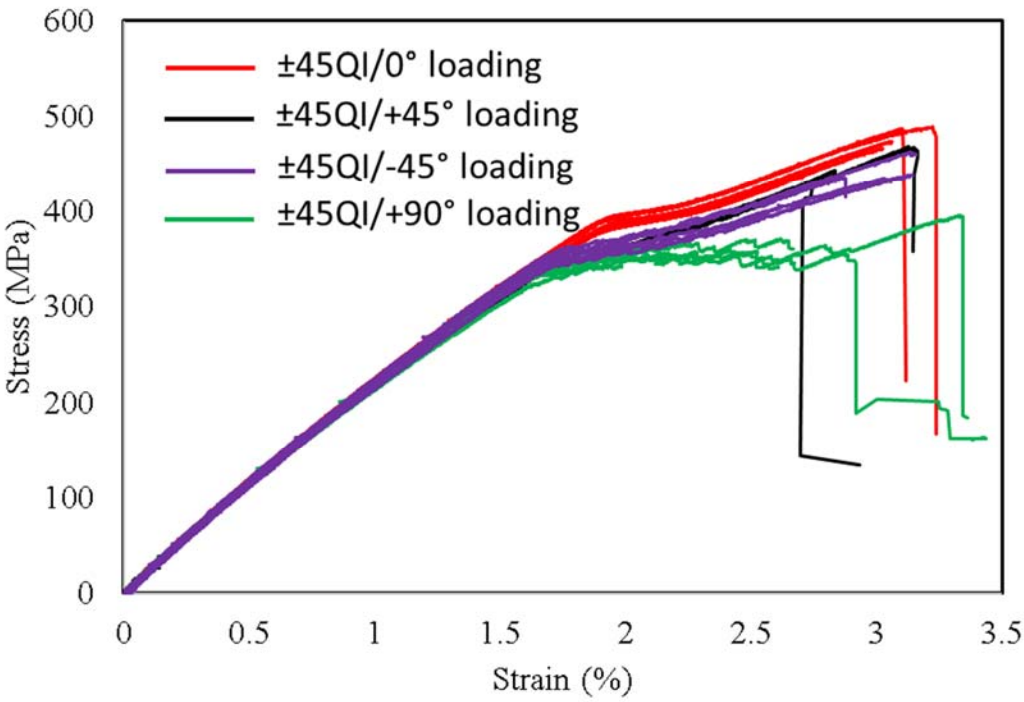


Figure 4. Pseudo-ductile response of glass/carbon hybrid loaded in four fibre directions

Notched Response of Pseudo-ductile Hybrids

The pseudo-ductility produced due to fragmentation and the associated non-linearity allow load redistribution to occur at stress concentrations, resulting in notch-insensitive response in a similar way to stress redistribution due to plasticity in ductile metals. This was investigated by modelling, which showed that the ratio of pseudo-ductile strain to failure initiation strain is a key parameter [17].

Notched quasi-isotropic pseudo-ductile laminates made from hybrid carbon sub-laminates similar to those shown in Figure 3 were tested with 3.2 mm holes [13]. Figure 5 shows the response, indicating that the failure stress of the specimens at the ligaments (net section stress) has actually exceeded the un-notched strength of the laminate. In addition, after the net section strength had been reached, they did not immediately fail catastrophically, but still showed some residual load carrying capacity, gradually reducing with further increasing strain. A similar notch-insensitive response was obtained with sharp notches [13]. Material blocked multi-directional glass/carbon hybrids were also shown not to be sensitive to sharp notches or open holes [18]. Gradual failure has also been found in bearing and bearing-bypass tests [19] and in compact tension tests as well [20].

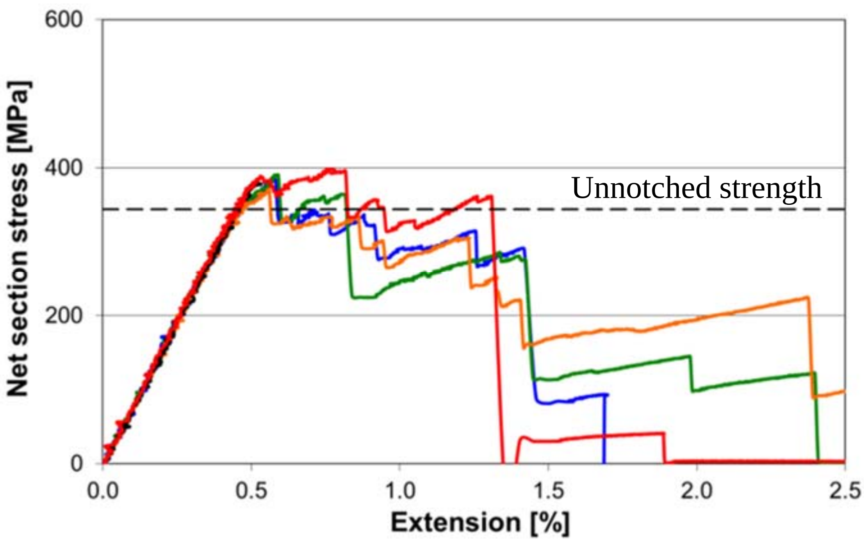
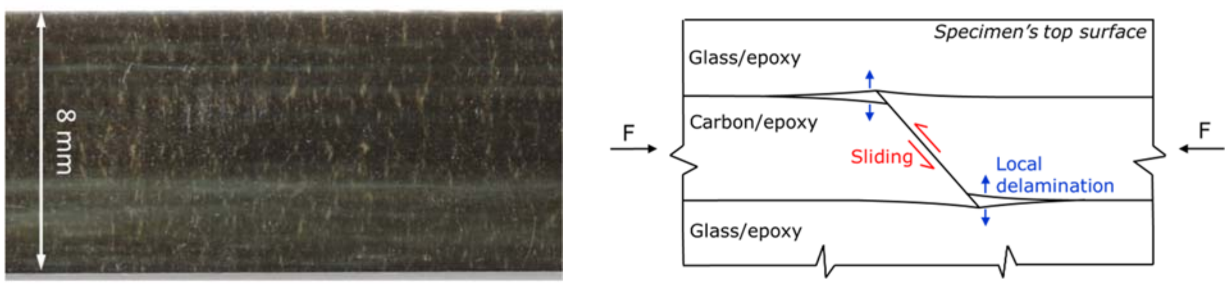


Figure 5. Open-hole tension of QI hybrid carbon specimens

Pseudo-ductility in Other Loading Modes

Fragmentation can also occur in compression, for example in thin ply M55 carbon/ S glass laminates on the surface of specimens loaded in bending [21]. The carbon fibres break, and then some relative movement between the fracture surfaces allows further loading and failure elsewhere, leading to a similar fragmentation behaviour and associated change in stiffness to that observed in tension. The visually observable fragmentation pattern and a schematic of the failure mechanism is shown in Figure 6 [22]. Similar behaviour has also been obtained in direct compression tests, giving a significantly non-linear response [23].

In hybrids with higher strain carbon fibres near the surface loaded in bending, fragmentation occurred in tension before sudden failure in compression, but compressive strains as high as 2.5% were obtained in the carbon plies [21]. Specimens of this type which were fragmented first in tension and then loaded in compression, failed earlier, but still exhibited compressive strains in excess of 1%. Specimens hybridised all through the thickness similarly fragmented in tension before failing in compression [24].



a) Top view of fragmentation pattern   b) Side view schematic of micro-deformations

Figure 6. Fragmentation of S-glass/ M55 carbon hybrid in compression [22]

Tension fatigue testing on glass/carbon hybrids at 90% of the knee point strain which showed no fibre failure on first loading sustained no damage after 74000 cycles [25].

Specimens that were loaded statically until initiation of fragmentation and then fatigued at 80% of the knee point stress showed gradual growth of damage until they were fully delaminated after around 6000 cycles.

Tensile tests at high loading rates have shown that fragmentation and pseudo-ductility still occur [26]. Initial results under static indentation [27] and impact [28] show promising behaviour, with the ability to tailor the response and modify the failure mechanisms.

Overload Sensing

When fragmentation occurs in glass/carbon hybrids it causes a visible change in appearance on the surface with a striped pattern emerging as the strain increases, Figure 7. This can be calibrated and used as a simple overload detector, either forming the surface load bearing layer of the structure, or as a separate bonded-on sensor for composite or metallic structures [29-31]. It can also be incorporated into a smart self-warning repair patch [32].

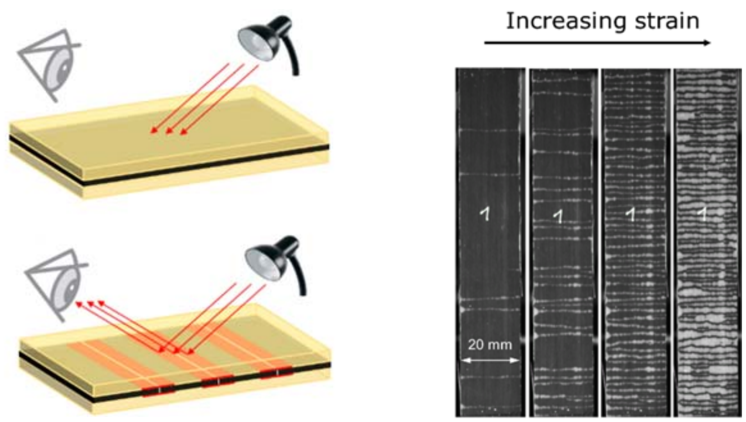


Figure 7. Visualisation of overstrain in glass-carbon hybrid

By incorporating a pre-cut, the clearly visible extent of delamination can be used to estimate the number of fatigue cycles the structure has undergone, as shown in Figure 8 [33].

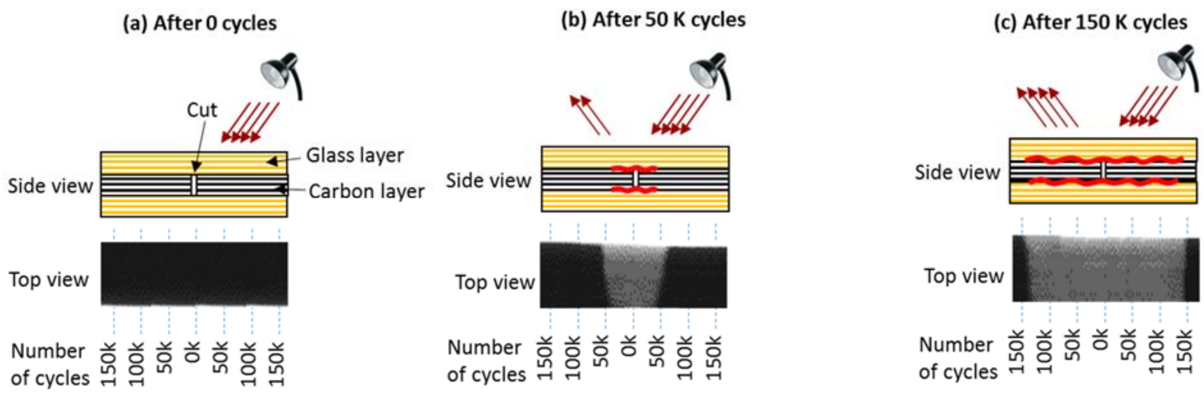


Figure 8. Fatigue sensor

Improved Testing and Understanding of Failure

Hybrid specimens allow improved tensile testing. The glass plies on the surface of glass/carbon hybrids can completely eliminate the stress concentration where the specimen is gripped, producing consistent gauge length failures [21]. This gives higher results than other test methods, and allows some fundamental effects to be explored that could otherwise be obscured by variability and premature failure.

When the low strain plies in the hybrid laminates are very thin, it has been shown that there is an enhancement in the strain to failure referred to as a hybrid effect [34]. This only occurs for plies less than 0.1 mm thick, and can be as high as 20% for a single 0.03 mm ply. The effect can be modelled, and has been shown to be due to the constraint on forming critical clusters of fibre breaks [34]. This means that as well as producing pseudo-ductile response, these hybrid laminates are able to take greater advantage of the intrinsic properties of the carbon fibres. Similar enhancements in the failure strain have also been measured with thin high modulus carbon sandwiched between intermediate modulus carbon plies [35].

Scaled hybrid specimens can be used to determine the size effect, whereby the tensile strain at failure decreases with increasing specimen volume [36]. Study of progressive ply fragmentation tests can be used to estimate the intrinsic variability of the material and deduce the Weibull modulus [36]. Hybrid specimens can also be used to study the delamination behaviour at the interface, and to deduce the mode II traction-displacement relation for use in cohesive finite element analysis [37,38].

Since thin plies suppress delamination, and tab failures can be avoided, hybrid specimens allow some innovative methods of investigating the interaction of different stress components on failure. For example, thin carbon-fibre angle plies sandwiched between glass have shown very limited effect of high in-plane shear stresses on fibre direction tensile failure [39]. Angle plies have also been used to investigate the interaction of large transverse compressive stresses on tensile failure of unidirectional plies [40].

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