University of BRISTOL
Bristol Composites Institute (ACCIS)

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The Composites Centre
for research, modelling, testing and training in advanced composites

# HiPerDuCT Programme Grant

## Final report: Angle Plies

### Ductility via fibre re-orientation

Using carbon/epoxy plies of only 0.03 mm thickness, matrix cracking and delamination can be completely suppressed in angle-ply laminates, allowing the fibres to rotate under tensile loading, creating additional strain and pseudo-ductility [1]. Angle plies of (±45) layup can produce strains of over 20% and necking behaviour despite the brittle nature of the matrix (see figure 1). There is a trade-off between the stresses and strains that can be achieved depending on the angle, and this has been investigated in modelling studies [2]. A good balance of properties has been achieved for example with thin ply (±25) carbon/epoxy laminates that gave a pseudo-ductile strain of 1.23% and a maximum stress of 927 MPa, figure 2 [1].

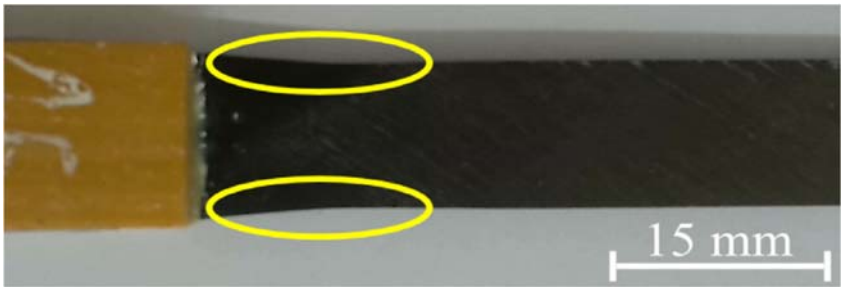


**Figure 1.** Necking of (±45) thin ply carbon/epoxy angle ply specimen

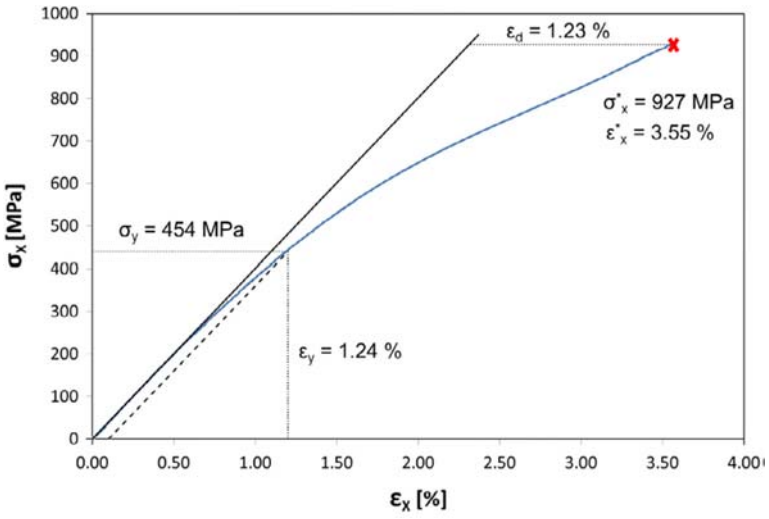


**Figure 2.** Pseudo-ductile response of thin ply (±25) carbon/epoxy laminate

Tests involving loading, unloading and then reloading have shown that the initial modulus is fully recovered, and so these laminates may be considered as ductile rather than pseudo-ductile, figure 3 [3].

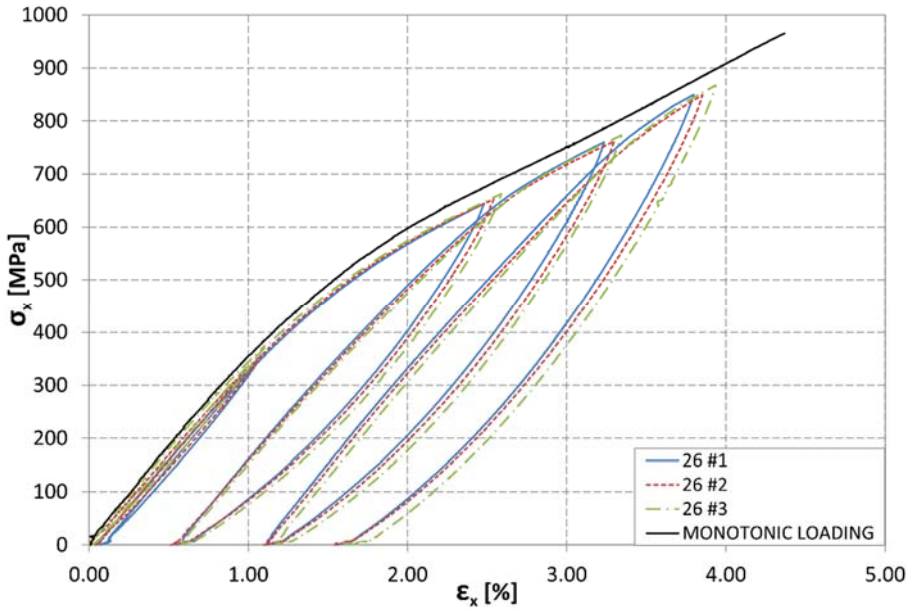


**Figure 3.** Cyclic loading of $(\pm 26_5)_s$ carbon/epoxy laminate

## Fragmentation in thin-ply angle-plies with 0˚ plies

Introducing thin 0˚ plies allows fragmentation to occur in these plies which together with the fibre rotation of the angle plies gives a highly non-linear response, as shown in figure 4, with a pseudo-ductile strain of 2.2% in this case [4]. On reloading, these laminates do show some loss of initial modulus due to the fragmentation of the 0˚ plies, and so are pseudo-ductile rather than fully ductile [3]. Gradual failure is maintained when loaded at small angles to the 0˚ plies, although with reduced pseudo-ductile strain. High strain rate testing has demonstrated that pseudo-ductile behaviour can be retained, with modified response [5]. The effects of different temperatures on response have also been assessed [6]

Different materials can be used for the 0˚ and angle plies. For example a (25/-25/0/-25/25) layup using thin ultra-high modulus carbon for the 0˚ ply but standard modulus thin carbon for the angle plies allows a pseudo-ductile sub-laminate to be produced which is only 0.15 mm thick and has a modulus of 135 GPa [5]. Multi-directional laminates of these pseudo-ductile plies can then be created. Modelling has shown that they give a pseudo-ductile response [7] and this has also been demonstrated experimentally.

Fragmentation of the 0˚ plies can also occur under compression, giving an analogous pseudo-ductile response to that in tension, although with lower strength [8].

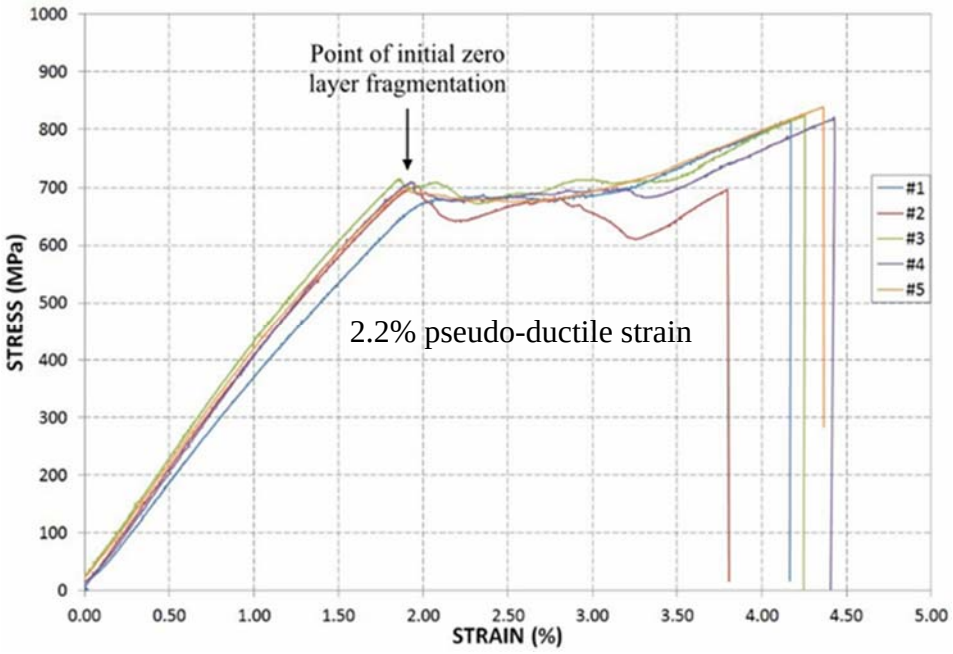


**Figure 4.** Pseudo-ductile response of $[\pm 26_5/0]_S$ laminate

## Notch Insensitivity

The pseudo-ductility produced due to fragmentation and the associated non-linear response allows load redistribution to occur at stress concentrations, in a similar way to stress redistribution due to plasticity in ductile metals. Modelling has shown that a notch-insensitive response should be obtained provided the ratio of pseudo-ductile strain to pseudo-yield strain is sufficiently high [9].

Figure 5 shows the response of a $[\pm 25_2/0]_{s4}$ laminate with Intermediate modulus angle plies and high modulus 0˚ plies. The unnotched behaviour is compared with that of a specimen with a 16 mm wide specimen with a 3.2mm hole, showing that the open hole strength is similar to the net-section pseudo-yield stress [10].

Gradual failure with load redistribution has also been demonstrated in bolt bearing tests [11].

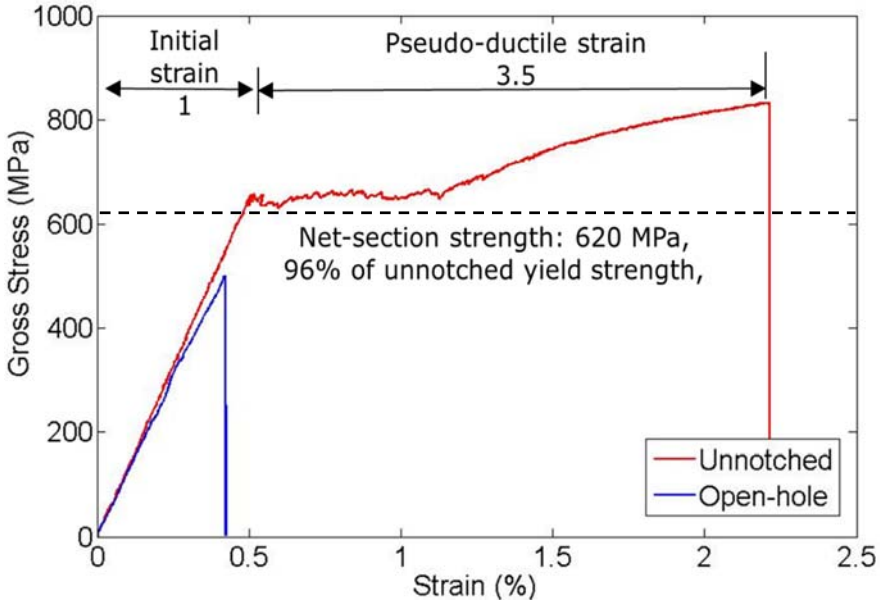


**Figure 5.** Open-hole tension response of $[\pm 25_2/0]_{s4}$ IM-HM carbon/epoxy laminates

## Fatigue Behaviour

Cyclic loading of $[\pm 25_2/\underline{0}]_s$ carbon/epoxy laminates with intermediate modulus angle plies and ultra high modulus 0˚ plies has shown no damage up until 100,000 cycles at 80% of the pseudo-yield stress and up to 1000 cycles at 95%, Figure 6 [12].

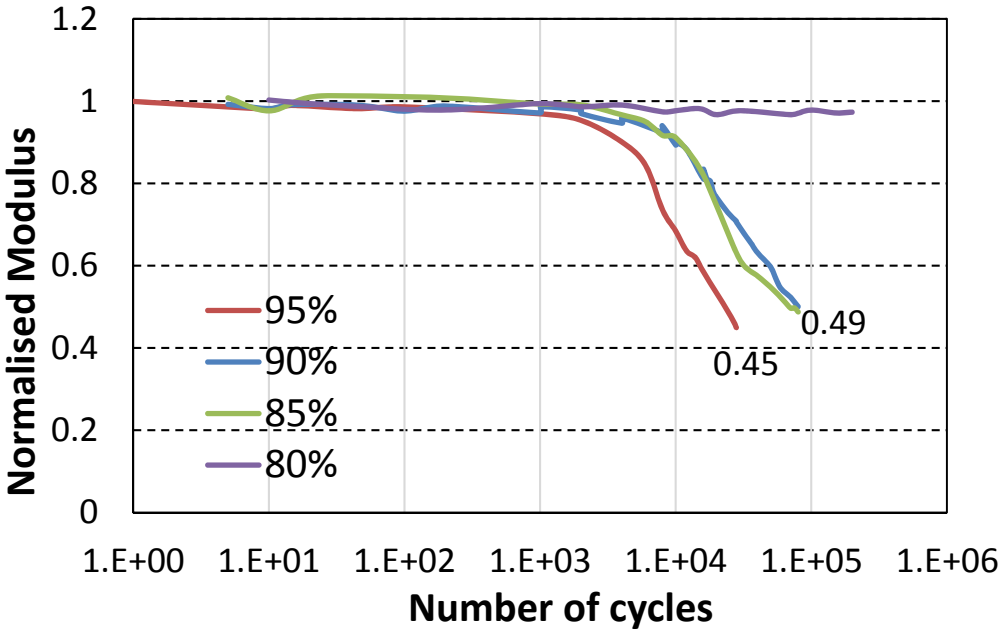


**Figure 6.** Fatigue response of IM-HM $[\pm 25_2/0]_s$ laminates

## Demonstrators

A number of demonstrators have been manufactured and tested showing that the concept can be applied to real components [13] including a skateboard [video] and a tubular tension member that successfully carried nearly 90kN with pseudo-ductile failure, Figure 7.

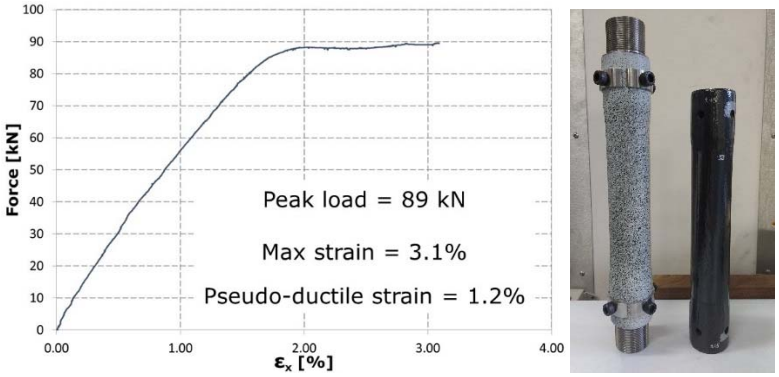


**Figure 7.** Pseudo-ductile response of tubular tension member

## References


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[3] Fuller JD and Wisnom MR 2016 Ductility and pseudo-ductility of thin ply angle-ply CFRP laminates under quasi-static cyclic loading *Composites Part A,* in press.

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