Repeated Tensile Loading of Thin-Ply Pseudo-Ductile Laminates

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ABSTRACT

The loading-unloading-reloading response of thin-ply hybrid and angle-ply laminates is presented. Fibre fragmentation in 0˚ plies leads to a loss of modulus. Considerable non-linearity arises in the angle plies, with some permanent deformation. However there is little loss of initial modulus on reloading. Experimental results are presented for different configurations, and the results compared to illustrate the mechanisms controlling the cyclic behaviour and changes in modulus.

INTRODUCTION

As part of the HiPerDuCT programme on High Performance Ductile Composites Technology, thin-ply carbon/glass hybrid laminates have been investigated. It has been demonstrated that if the carbon plies are very thin, delamination can be suppressed, and progressive fragmentation of the carbon can be obtained [1,2], with a pseudo-ductile unidirectional tensile response and plateau in the stress-strain curve, as shown for example in Fig. 1. Suppression of matrix cracking and delamination has also been demonstrated in thin angle-ply laminates, leading to pseudo-ductile response [3].

In this paper the loading-unloading-reloading response of unidirectional thin-ply glass/carbon hybrid laminates is presented. This is compared against $(\pm 26_5)_s$ carbon fibre angle-ply laminates which show substantial non-linearity due to the matrix behaviour and associated fibre re-orientation. Finally results for $(\pm 26_5/0)_s$ carbon fibre laminates are presented, which combine both mechanisms of 0˚ fibre fragmentation and non-linearity in the angle plies [4,5].

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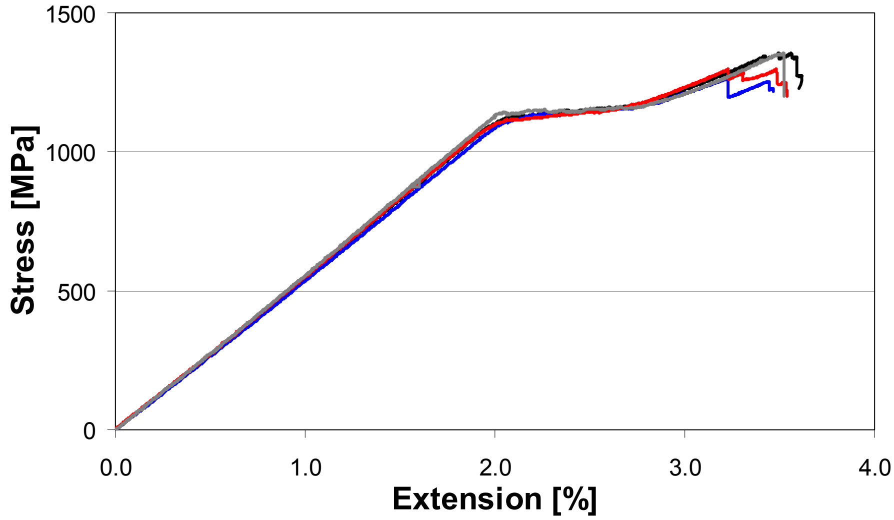

Figure 1. Pseudo-ductile response of S-glass/high strength carbon hybrid

UNIDIRECTIONAL GLASS/CARBON LAMINATES

Hybrid specimens were made with standard thickness Hexcel S-glass / 913 epoxy and thin Skyflex MR40 intermediate modulus carbon/epoxy prepregs. A single ply of 0.061 mm thick carbon was sandwiched between two 0.155mm glass plies. The fibre aerial weights of the glass and carbon were 190 g/m^2 and 50 g/m^2 and the volume fractions 50% and 45% respectively. Specimens 20 mm wide with 160 mm gauge length were tabbed and tested in tension in a servo-hydraulic test machine under displacement control at a cross-head rate of 2 mm/minute. Load was applied up to a predetermined displacement of 2.5 mm, equivalent to a strain of about 1.56%. The specimens were then unloaded at the same rate and immediately reloaded to a higher level. This was repeated for displacements increasing in 0.5 mm increments up to 5 mm (3.12%). Strains were measured accurately with a video extensometer. A total of six specimens were tested in the same way.

A typical loading-unloading-reloading response is shown in Fig. 2, with straight tangential lines shown in black. The initial response was linear and the first unloading came almost down the same line since the damage threshold had not been exceeded. The second loading overlaid the first, but went beyond the initial failure strain of the carbon into the plateau region of the stress-strain response. Progressive fragmentation of the carbon ply occurred, as shown in Fig. 3. By the fifth cycle the ply was fully fragmented and the load started to increase again in this and the sixth cycle. There was a small amount of hysteresis, increasing as the damage progressed, which is believed to be due to the reversed high interlaminar shear stresses in the regions near the carbon ply fractures. There was also a very small residual deformation of the specimens.

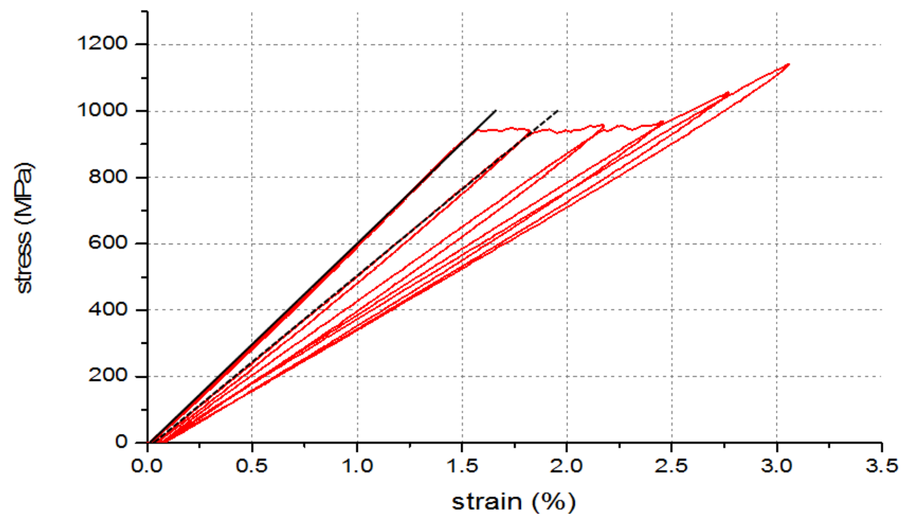

Figure 2. Loading-unloading-reloading response of S-glass/intermediate modulus carbon hybrid

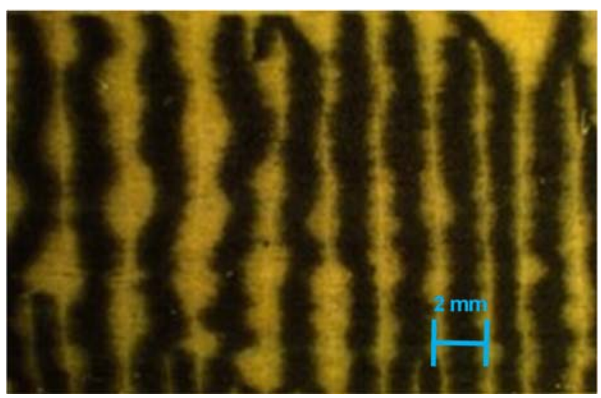

Figure 3. Ply fragmentation in S-glass/intermediate modulus carbon hybrid

The secant modulus was measured on loading between 0 and 600 MPa, and is plotted against the nominal maximum strain based on the cross-head displacement in Fig. 4. It can be seen that the modulus steadily reduces with increasing fragmentation, approaching the expected value with no contribution from the carbon at high strains.

CARBON FIBRE ANGLE PLIES

Angle-ply $(\pm 26_5)_s$ and $(\pm 27_5)_s$ laminates of thin Skyflex TR30 standard modulus carbon fibre/epoxy were manufactured [6]. The ply thickness was about 0.029 mm, with 21 g/m^2 aerial weight and a volume fraction of about 42%. Specimens with gauge length of 150 mm and 15 mm width were tabbed and tested in tension in a servo-hydraulic test machine under displacement control at a cross-head rate of 2 mm/minute. Three specimens of each type were loaded successively to displacements of 3 mm, 6 mm, 7.5 mm and 8.75 mm, with unloading and immediate reloading at the same rates. Strains were measured with a video extensometer.

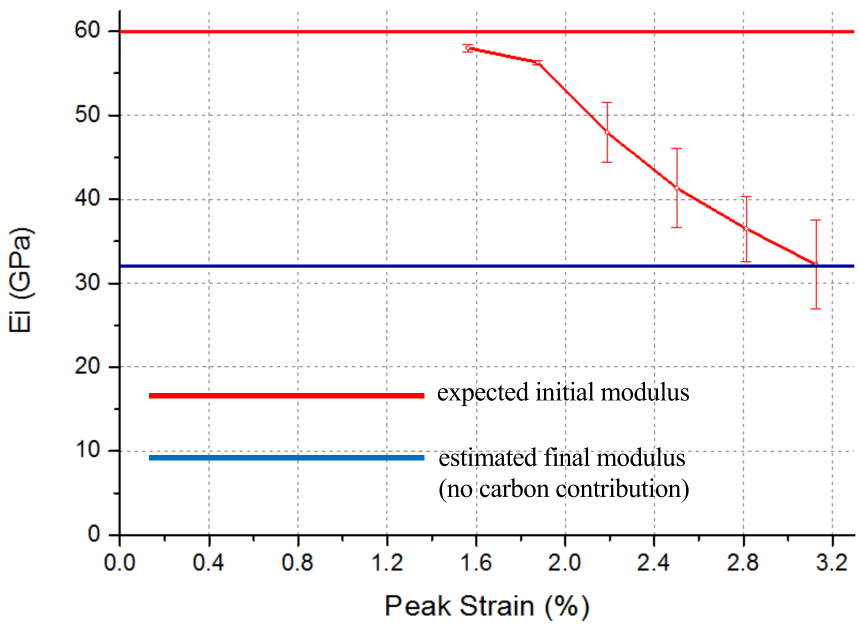

Figure 4. Change in reloading modulus of glass/carbon hybrid

Fig. 5 shows the response of the $(\pm 26_5)_s$ laminates, compared against the monotonic loading response. A considerable amount of non-linearity can be seen, and a large amount of hysteresis, due to the response of the matrix under the high shear created by the angle-ply layup. The envelope of the cyclic loading responses matches closely the monotonic response. There is also considerable residual deformation immediately after unloading, increasing substantially as the specimens were successively loaded to higher strains.

At first sight it appears that there is a substantial reduction in modulus on successive cycles. However, if the loading modulus is measured in a consistent way up to the same stress, a different picture emerges. Fig. 6 shows the modulus measured up to the same stress of 360 MPa normalised by the initial modulus, plotted against the strain at zero stress after unloading. Values for both $(\pm 26_5)_s$ and $(\pm 27_5)_s$ are included on the same plot, as the normalised results are very similar. It can be seen that there is negligible change in initial modulus. In fact the modulus slightly increases at the highest strains, due to a slight reorientation of the fibres. X-rays of the specimens showed no visible matrix cracking, delamination or other damage even after the strains of almost 4%.

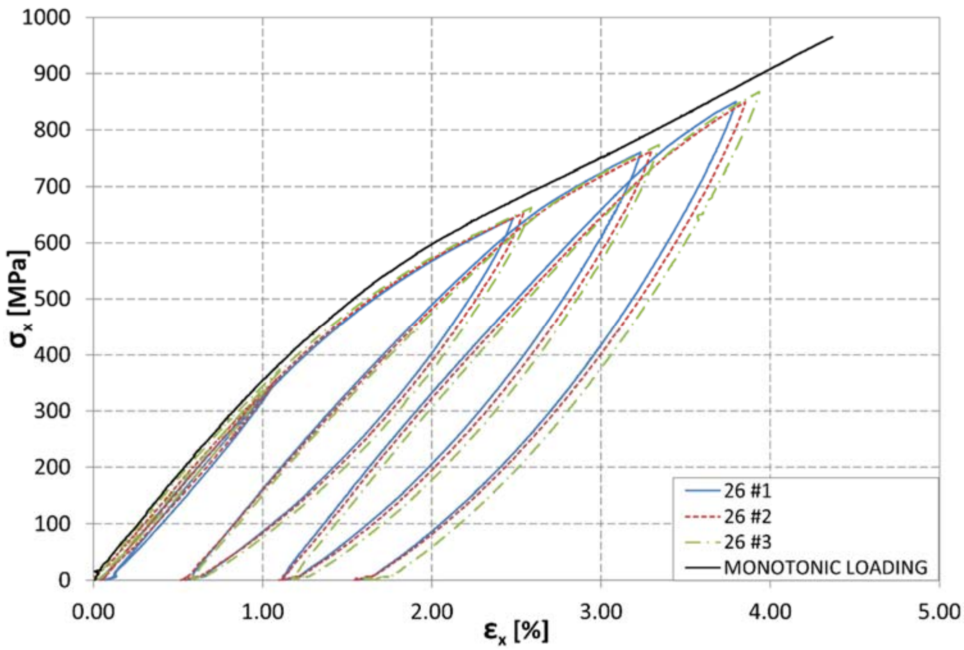

Figure 5. Loading-unloading-reloading response of $(\pm 26_5)_s$ carbon laminate. Reproduced from [6].

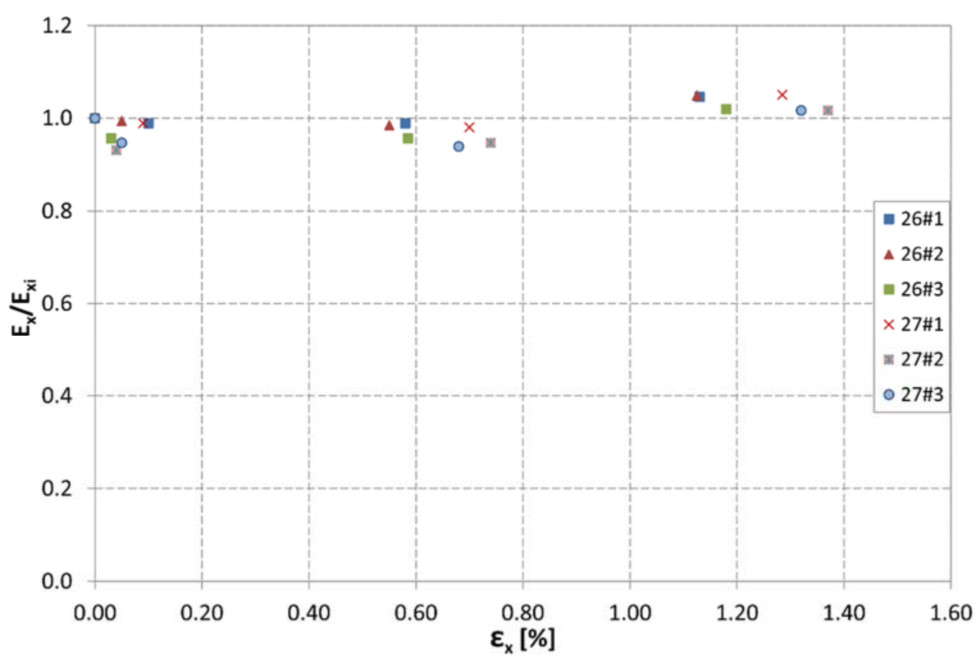

Figure 6. Change in reloading modulus to 360 MPa, $(\pm 26_5)_s$ and $(\pm 27_5)_s$ laminates. Reproduced from [6].

$(\pm 26_5/0)_s$ CARBON FIBRE LAMINATES

Similar tests were undertaken on angle-ply laminates of the same material with two additional 0˚ plies at the centre of the layup [4-6]. This configuration is analagous to the carbon/glass hybrids, with the lower modulus carbon fibre angle plies playing a similar role to the glass. The 0˚ plies fragment in a similar way, and this is combined with the non-linear response of the angle plies presented in the previous section.

The overall response is shown in Fig. 7 compared against the monotonic response of the same specimens. The non-linearity and hysteresis is clearly seen, although less pronounced than before, as a result of the increased stiffness from the 0˚ plies. There is now a plateau as the centre plies fragment. The reloading modulus is plotted against residual strain in Fig. 8. The modulus is measured to the same stress in each cycle, although the value of 400 MPa is slightly higher than in the previous tests. This time there is a reduction in modulus, approaching the calculated value without the contribution of the 0˚ plies as the fragmentation progresses. Ultrasound C-scans of these specimens show a similar pattern of ply fractures and delamination as seen in the hybrid tests, although at an angle to the loading direction, Fig. 9.

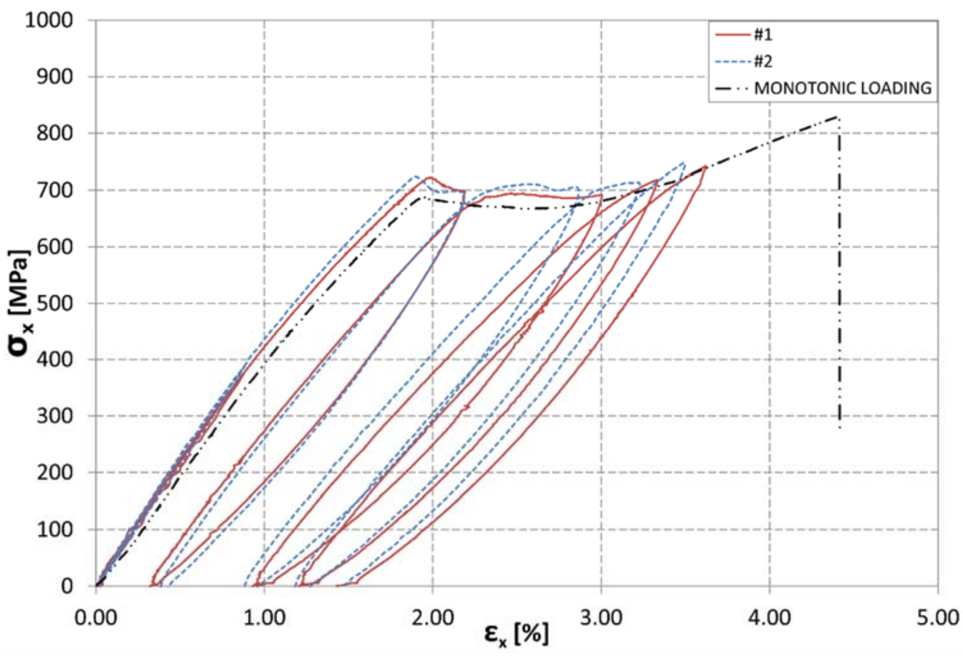

Figure 7. Loading-unloading-reloading response of $(\pm 26_5/0)_s$ carbon laminate. Reproduced from [6].

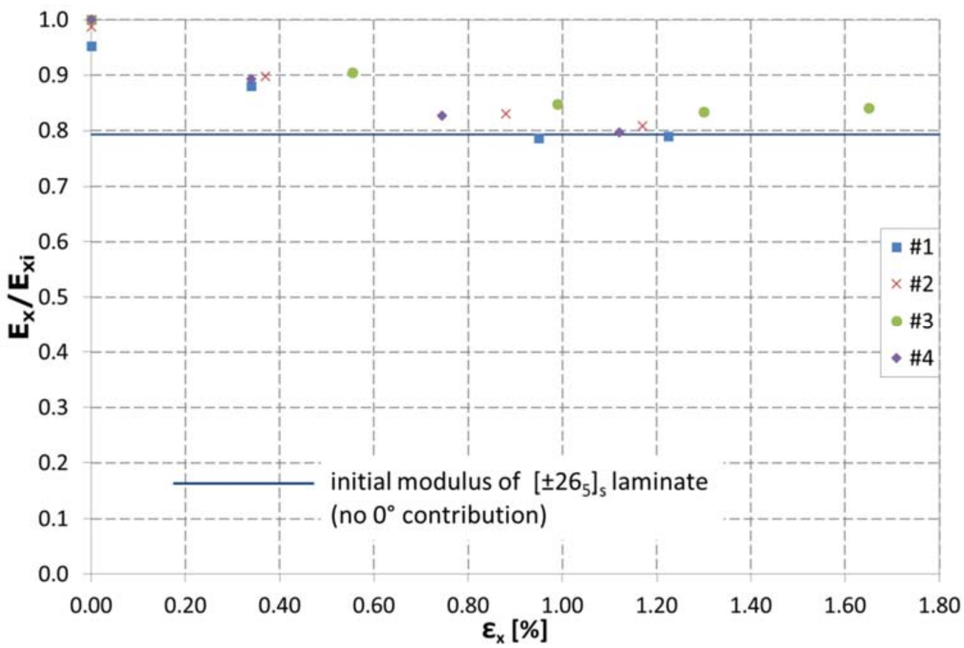

Figure 8. Change in reloading modulus to 400 MPa of (±26$_5$/0)$_s$ carbon laminate [6].

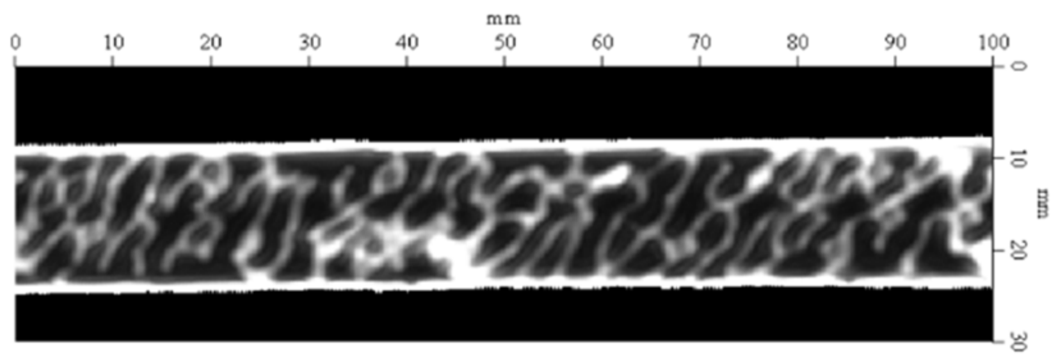

Figure 9. Ply fragmentation in (±26$_5$/0)$_s$ carbon laminate [4]

CONCLUSIONS

The loading-unloading-reloading response of thin ply hybrid and angle-ply laminates has been established. The non-linearity in the angle-ply laminates is due to the matrix response and results in hysteresis and residual deformation. There is no loss of modulus and so the response can be considered as ductile. Damage in the glass/carbon hybrids consists primarily of ply fragmentation and localized delamination, and this does lead to a loss in modulus as the fragmenting ply gradually contributes less and less to the overall stiffness of the laminate. There is little residual deformation, and this response should be considered as pseudo-ductile. Thin angle-ply laminates with 0˚ plies show both 0˚ ply fragmentation and matrix dominated non-linear response. There is still residual deformation, but less hysteresis than with the pure angle plies. There is a loss of modulus due to the fragmentation and so these laminates should still be classified as pseudo-ductile.

ACKNOWLEDGEMENT

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