REDUCED TENSILE NOTCH-SENSITIVITY IN PSEUDO-DUCTILE THIN-PLY COMPOSITES

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Abstract
Pseudo-ductile thin-ply composites loaded in tension exhibit a non-linear stress-strain response with a plateau, analogous to yielding in a metal. This provides an alternative means for load redistribution at stress concentrations, giving reduced notch-sensitivity. The notched tensile response of both thin-ply hybrid and angle-ply laminates is presented, and the failure mechanisms described and compared with those of conventional composites to explain the reduced notch sensitivity.

1. Introduction

Continuous fibre composites are normally notch sensitive. Significant stress concentrations arise at discontinuities, which due to the linear-elastic behaviour of the material cannot be relieved by stress redistribution. Damage in the form of splits and delamination at the notch can blunt the stress concentrations under tensile loading, especially for small notches, reducing notch sensitivity, and giving rise to the hole size effect. Nevertheless conventional laminates tend to fail catastrophically from stress concentrations, with large reductions in strength compared to unnotched specimens.

One of the mechanisms that has been demonstrated to achieve pseudo-ductile response is the fragmentation of thin carbon plies in interlayer hybrid composites. Unidirectional carbon plies can be added to unidirectional glass, and if they are thin enough and the ratio of constituents is appropriate, the carbon plies will fragment and delaminate stably without catastrophic failure [1].

This creates a plateau on the stress-strain curve analogous to yielding in a metal as shown in Fig. 1. The response can be tailored based on the strain to failure and modulus of the fibres and the absolute and relative thickness of the plies [2]. Similar response can also be achieved with hybrids consisting of different grades of carbon fibres [3].

Another mechanism for creating pseudo-ductility is by rotation in angle-ply laminates. If the plies are thin, then delamination and matrix cracking are suppressed, and very large strains can be achieved [4]. This can be combined with ply fragmentation by including thin 0° plies within the angle ply laminate, and has been shown to give a plateau on the stress-strain curve, with very high strains [5].This paper shows the behaviour of notched specimens of both thin-ply hybrid and angle-ply pseudo-ductile laminates. The notch sensitivity and failure mechanisms are described and compared with those of conventional composites.

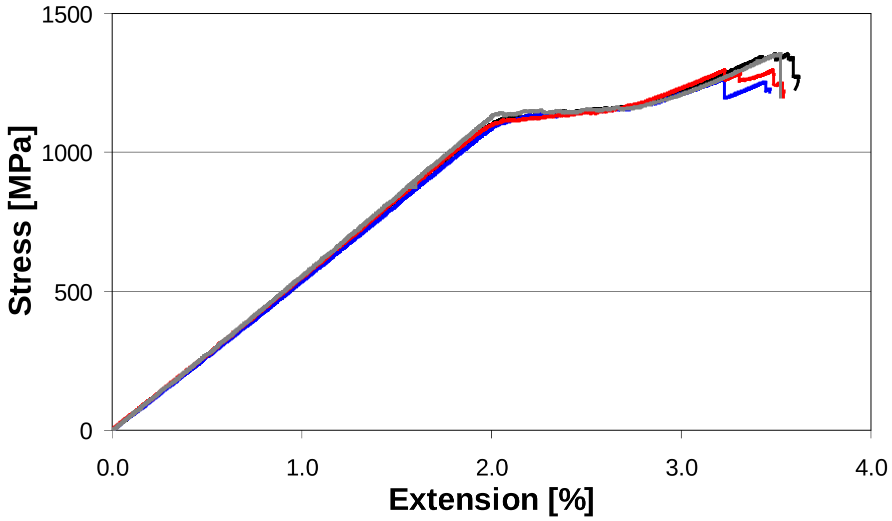

Figure 1. Pseudo-ductile response of S-glass/high strength carbon hybrid [1].

2. Notched Behaviour of Pseudo-Ductile Thin-Ply Hybrids

Quasi-isotropic (QI) pseudo-ductile carbon/epoxy laminates with layup $[45/90/-45/0]_s$ were manufactured in which each "ply" consisted of a hybrid sublaminate of two different types of carbon [6]. Single plies of high modulus XN-80 fibres of 63 g/m^2 were sandwiched between two plies of intermediate modulus T1000 fibres of 28 g/m^2 on either side to create a $[\text{T1000}_2/\text{XN-80}_1/\text{T1000}_2]$ with a total fibre areal weight of 175 g/m^2 and "ply" thickness of 0.192 mm similar to one typical thickness ply. All materials were supplied by North Thin-Ply Technology.

Specimens with a gauge length of 64 mm and width 16 mm had holes of 3.2 mm drilled and were tested in tension. Fig. 2 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 of the same size [6].

An alternative material combination of multi-directional glass/carbon hybrids was also investigated. Quasi-isotropic sublaminates of Skyflex T300 carbon fibre/epoxy were sandwiched between quasi-isotropic sublaminates of Hexcel S-glass/913 epoxy. Each single carbon ply was 22 g/m^2 with a thickness of 0.029 mm, and the glass was 190 g/m^2 with a ply thickess of 0.155 mm. The layup was $[60_{\text{S-glass}}/-60_{\text{S-glass}}/0_{\text{S-glass}}/0_{\text{T300-carbon}}/60_{\text{T300-carbon}}/-60_{\text{T300-carbon}}]_s$ with an overall thickness of 1.10 mm. This arrangement of blocking together plies of the same material rather than plies of the same orientation has been shown to be less susceptible to free edge delamination [7].

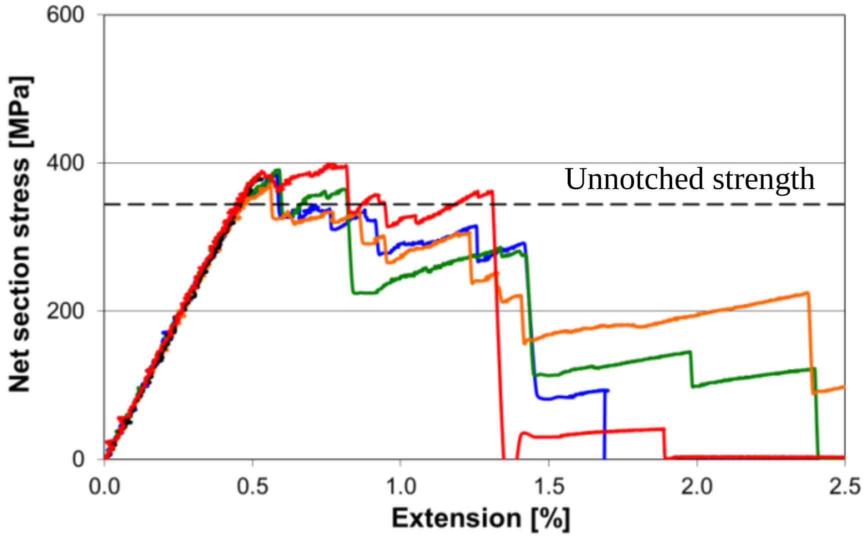

Figure 2. Open-hole tension of QI hybrid carbon specimens.

Specimens with guage length 64 mm and width 16 mm had holes of 3 mm diameter and sharp notches of the same width machined, and were tested in tension. Fig. 3 shows the response. Both the open hole and sharp notched specimens failed at almost the same gross-section stress as the plateau stress for the unnotched specimens. It should be noted that the unnotched failure stress was reached much earlier, causing damage, load redistribution and slight non-linearity of the overall response.

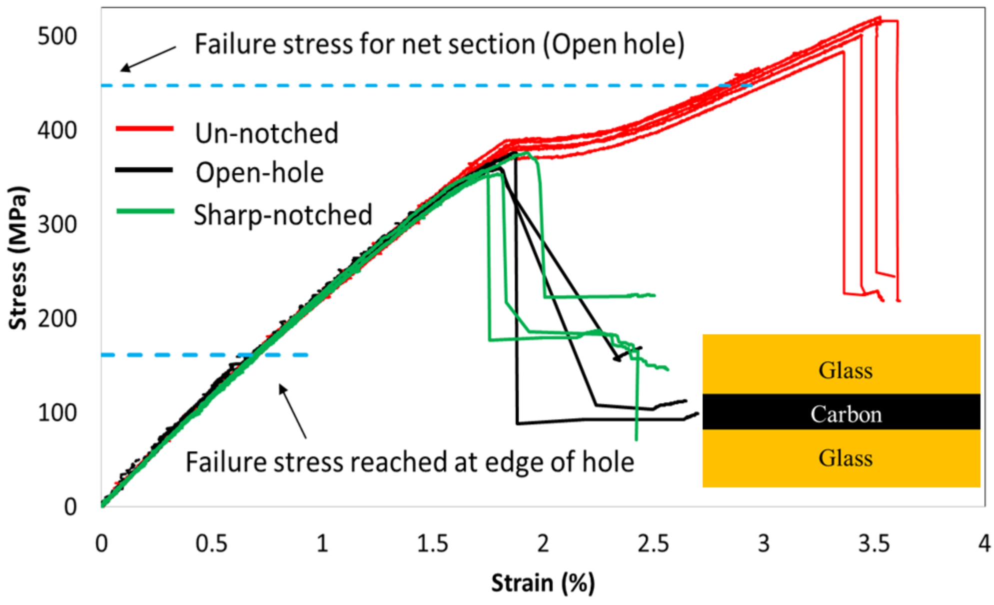

Figure 3. Open hole, sharp notched and unnotched response of QI ±60/0 glass/carbon laminates [7].

3. Notched Behaviour of Thin-Ply Angle-Ply Laminates

Laminates were made with layup $[\pm25_2/0]_{s4}$ with the angle plies made of Skyflex MR60 intermediate modulus carbon/epoxy 0.028 mm thick and the 0^0 plies of North YSH-70A ultra high modulus carbon/epoxy 0.032 mm thick [8]. Specimens with gauge length 64 by 16 mm with 3.2 mm holes were machined and tested in tension.

Specimens failed at a net section stress very similar to that at the start of the pseudo-ductile plateau on the unnotched specimens, Fig. 4.

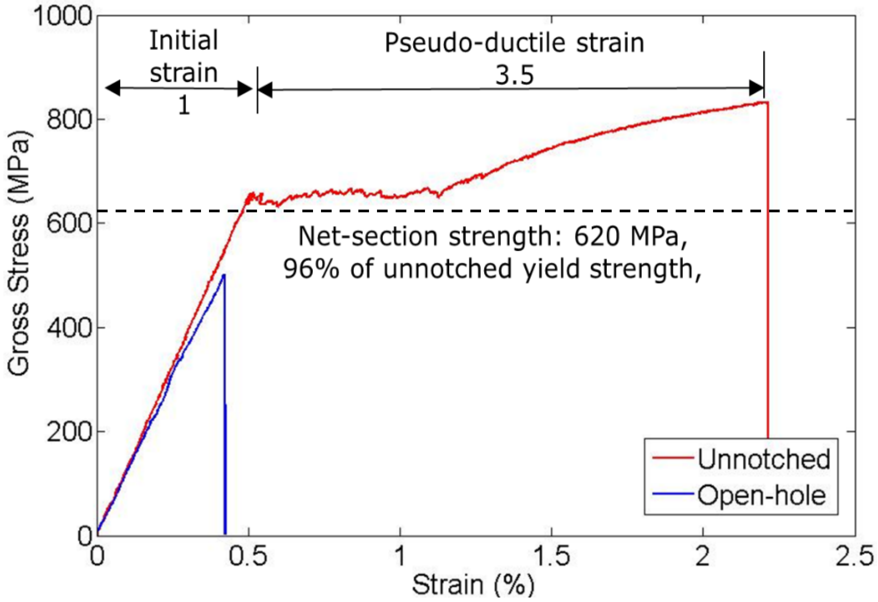

Figure 4. Open-hole response of $[\pm25_2/0]_{s4}$ IM-HM carbon/epoxy laminates.

4. Comparison of Failure Mechanisms

In conventional laminates, the main damage mechanism is splitting at the notch due to the high stress concentration, accompanied by delaminations stepping through ply cracks in the laminate thickness. Fig. 5 shows an X-ray of typical splits just before failure [9], which can be very long compared with the notch size, and cause significant load redistribution. However, catastrophic fibre failure still normally occurs at the notch at a much lower stress than the unnotched strength. The damage modes in the pseudo-ductile laminates are different, with much less splitting, and stable fibre fragementation at the notch well before final failure.

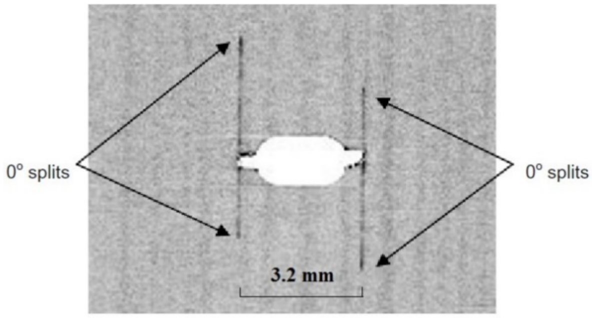

Figure 5. Typical splits at the centre of a $[45/90/-45/0]_{4s}$ IM7/8552 carbon/epoxy laminate [9].

Fig. 6 shows the results of DIC on the surface of the notched hybrid carbon specimens at 0.55% overall extension, just before the initial load peak. Very high strains occurred adjacent to the hole, well beyond that expected from the elastic stress concentration factor of 3.13 at that strain level (1.7%) and far in excess of the fibre failure strain. X-ray CT scans revealed localized delaminations through the thickness associated with ply fragmentation, although it was quite hard to actually see the fibre fractures. Nevertheless, at these high strain levels, fragmentation must have occurred, as has been seen more clearly in unnotched tests.

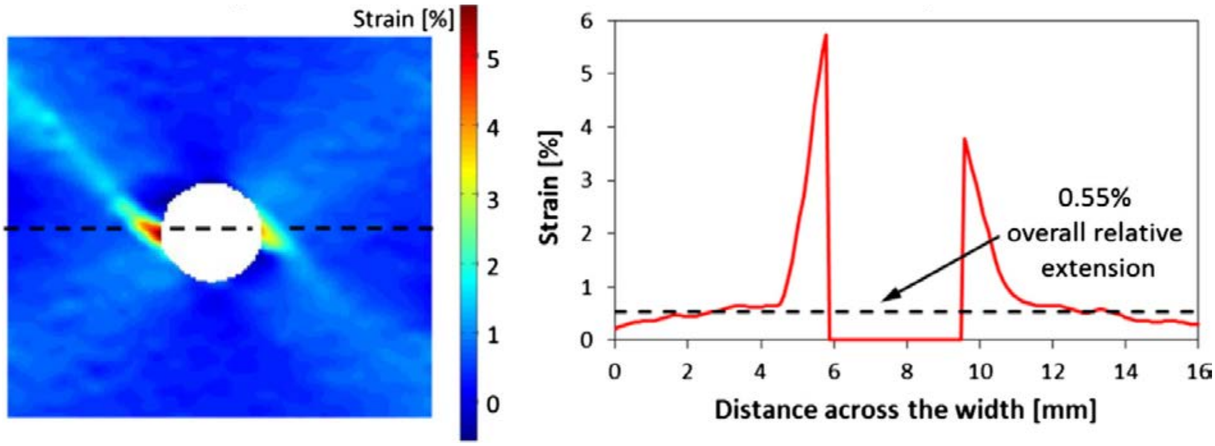

Figure 6. Strains in the loading direction (vertical) on carbon/carbon hybrids [6].

Similar high strains and fragmentation in the 0° plies was seen in the angle ply laminates. Fig. 7 shows the results from DIC at increasing stresses where the white corresponds to the areas that have exceeded the fibre failure strain and which therefore must have fragmented. It is seen that fragmentation starts at the notch at relatively low stresses and spreads to cover a large area corresponding to pseudo-yielding across most of the width of the specimen.

5. Conclusions

Pseudo-ductile thin-ply laminates have been shown to be relatively notch insensitive. Thin-ply glass/carbon and carbon/carbon hybrids showed similar net section strengths to the pseudo-yield stress of unnotched specimens for both holes and sharp notches. Thin-ply angle-ply laminates also showed similar net section open hole and unnotched strengths. The mechanism by which this occurs is fragmentation of the lower strain to failure plies in the vicinity of the notch leading to load redistribution, in contrast to the long splits at the notch which are characteristic of conventional notched laminates.

Acknowledgements

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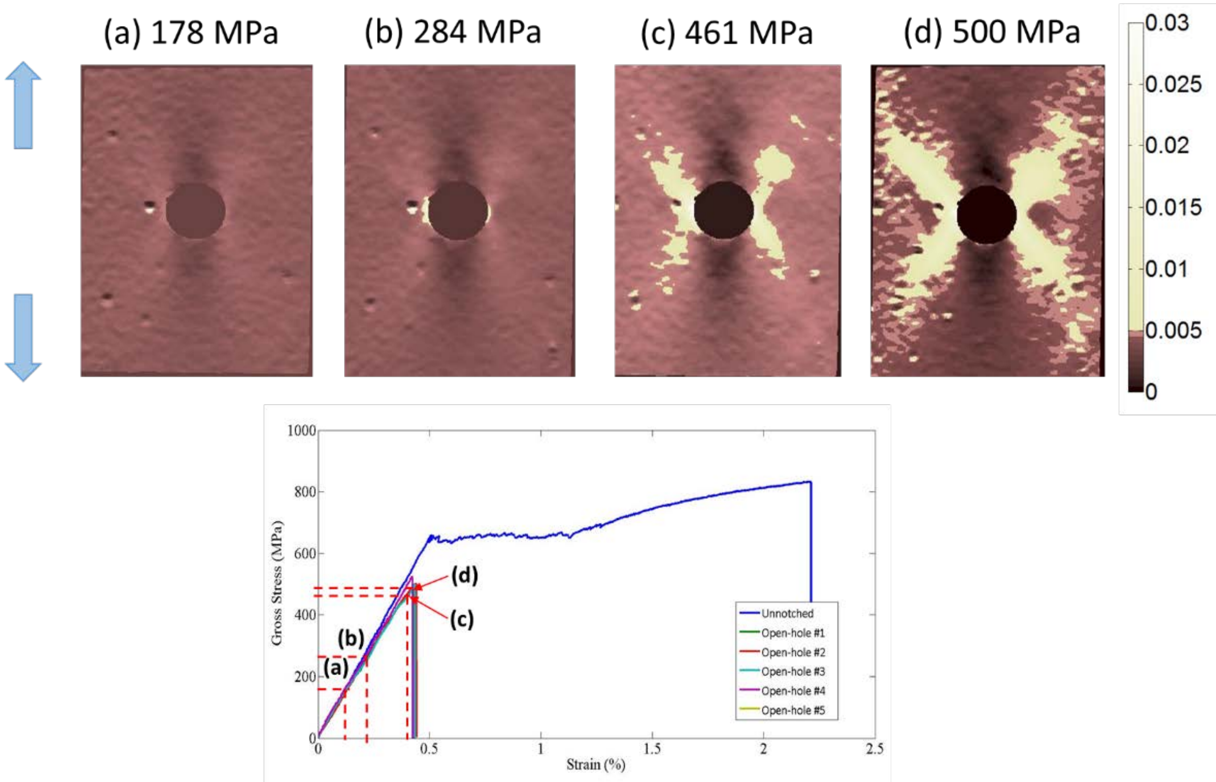

Figure 7. Spread of fragmentation in $[\pm25_2/0]_{s4}$ IM-HM carbon/epoxy laminates [8].

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