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PSEUDO DUCTILITY IN UD CFRP THROUGH INTERLAMINAR AND PLY WEAKENING

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Abstract

The inherent brittleness of unidirectional (UD) carbon fibre reinforced composites means that there is often little or no warning of possible material degradation until catastrophic failure occurs for a composite structure loaded in tension. In previous research, finite element analysis showed that a more gradual tensile failure can be achieved in a UD carbon composite through the introduction of ply and interlaminar weakening and that this behaviour can be tailored by modifying the weakening parameters. This paper describes a study examining the behaviour of laminates containing continuous ply cuts. A simple analytical model has been used to predict the tensile response of these pre-weakened laminates. The predicted response is compared to experimental results of four types of specimens configured with varying locations of ply cuts and confirms that ply cuts can produce pseudo-ductile tensile behaviour in a UD carbon composite laminate. The experimental results show good agreement with the analytical model.

1. Introduction

Various strategies aimed at tailoring the architecture of composite structures have been proposed to promote ductility and a gradual failure process in composite structures. These include fibre re-orientation [1], hybridization at fibre and lamina levels [2-4] and wavy ply structures [5]. However one drawback of these techniques is the reduction in initial stiffness compared to a conventional UD composite laminate (of the high stiffness material in the case of hybrids). Finite element modelling has shown that a UD laminate of a single carbon composite system containing ply and interlaminar weakening has the potential to introduce pseudo-ductility with high initial stiffness [6]. This paper describes an analytical and experimental investigation of the pseudo-ductility that can be induced by ply cuts.

2. Analytical model

A simplified analytical prediction for the tensile stress-strain response of a cut ply laminate was performed based on the method proposed by Czél et al [4]. Fig. 1 shows a schematic of a laminate consisting of a total number of n_t plies of UD carbon prepreg of which an even number of n_p plies are

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pristine, i.e. contain no ply cut. A block of $(n_t - n_p)$ plies containing cuts is positioned at the mid-thickness of the laminate so that there are $\frac{n_p}{2}$ pristine plies above and below the cut-ply block.

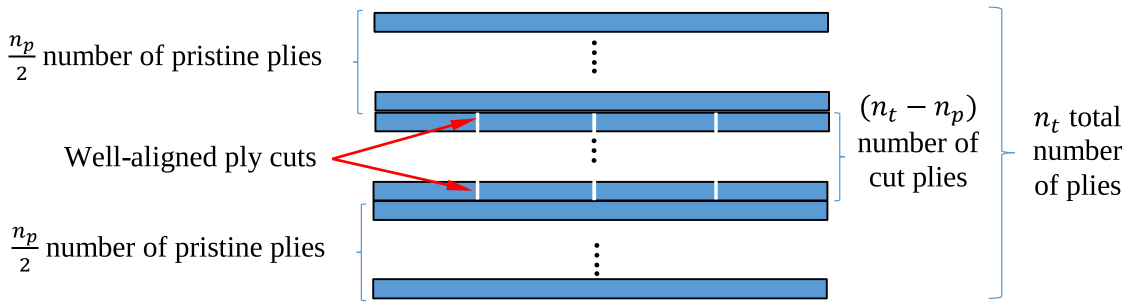

Figure 1. Schematic of the stacking sequence of a laminate comprising central cut plies enclosed by pristine plies.

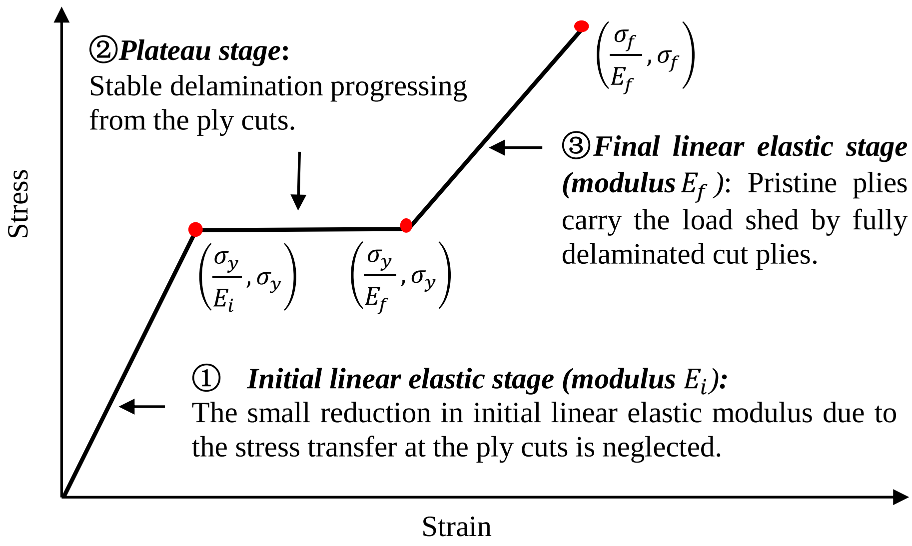

Figure 2. Schematic of the predicted tensile stress-strain response of cut-ply UD carbon composite laminate with coordinates of transition points.

The stages in the failure process that must be represented in the analysis are illustrated in Fig. 2**.** These stages were modelled as follows:

(1) The initial elastic modulus, E_i, was approximated to that of the pristine UD composite. This neglected the small effect of the stress transfer at the ends of the ply at a cut. The error due to this approximation will be small provided that the spacing of the cuts is large compared to the length of the stress transfer zone.

(2) The stress, σ_y, to initiate delamination growth from a cut was determined from the mode II interlaminar fracture toughness, G_{IIC}, to be:

$$\sigma_y = 2\sqrt{\frac{E_i\, n_p G_{IIC}}{t\, n_t\, (n_t - n_p)}} \tag{1}$$

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where t is the ply thickness of a composite ply.

(3) The elastic modulus, E_f, in the final linear stage and the ultimate tensile failure strength, σ_f , were determined by assuming the block of cut plies was fully delaminated. Therefore the modulus and the strength are given by:

$$E_f = \frac{n_p}{n_t} E_i \tag{2}$$

$$\sigma_f = \frac{n_p}{n_t} \sigma_0 \tag{3}$$

where σ_0 is the tensile strength of the UD carbon composite in fibre direction.

3. Experimental

3.1. Material

Material used in this study was M21/35%/198/T800s carbon/ epoxy produced by Hexcel® with cured ply thickness of 0.184 mm. Key properties of this material, as required for the analytical model are the elastic modulus in fibre direction of 153 GPa, tensile strength of 2800 MPa and the mode II interlaminar fracture toughness of 1.68 $\mathrm{kJ/m^2}$.

3.2. Specimen details

Four cut-ply configurations which exhibited promising pseudo-ductile performances, according to the earlier analysis, were selected for manufacture. Schematic side views of these four configurations are shown in Fig. 3.

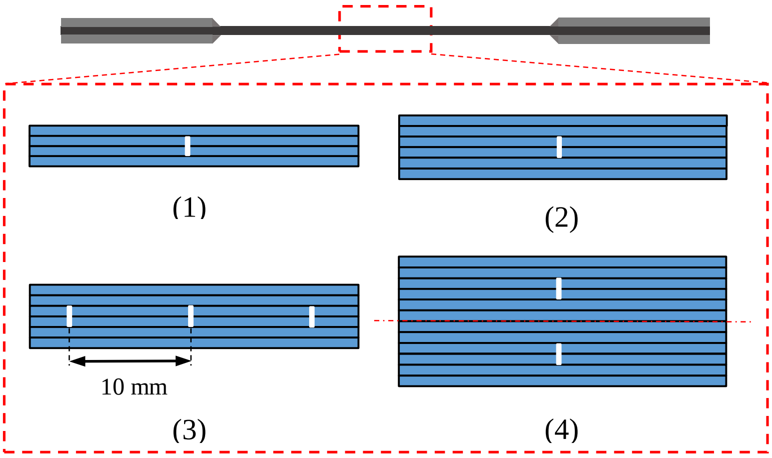

Figure 3. Schematics of the side views of four cut-ply configurations: (1) 4 ply specimen with aligned through-width single cuts in 2 central plies; (2) 6 ply specimen with aligned through-width single cuts in 2 central plies; (3) 6 ply specimen with three equally spaced and aligned lines of cuts in the two central plies; (4) 12 ply specimen containing 2 sublaminates each with the same pattern of ply cuts as the type (2) specimen.

The continuous cuts in specific plies were introduced by utilizing a CNC prepreg cutter. All four types of carbon composite laminates were laid up with fibre in longitudinal direction. The laminates were then

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consolidated in vacuum and cured in an autoclave for 2 hours at 180 C° and 0.7 MPa according to the manufacturer's recommended procedure. Glass/epoxy end tabs with 45° bevel angle were adhesively bonded to the laminates which were then cut with a waterjet cutter to the size as shown in Fig. 4.

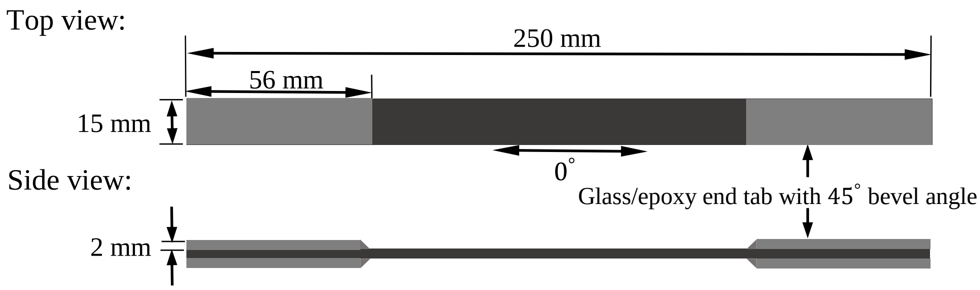

Figure 4. Schematics of the top and side views of a UD carbon fibre composite specimen for mechanical tensile test.

3.3. Experimental procedure

The mechanical tensile test was performed based on the ASTM D3039 standard in a 250 kN Instron 5985 machine fitted with a 100kN load cell. Specimens were held using wedge type grips and subjected to uniaxial tensile loading with a crosshead speed of 2mm/min. An Imetrum® video gauge system and strain gauges were used to monitor the strain variation of specimens. Bullseye self-adhesive targets provided by Imetrum® were applied as shown in Fig. 5. Fig. 5 (a) and (b) show the location of the video extensometer targets and strain gauges on specimens with single and three continuous cuts, respectively. Strains were measured between targets 1-2, 2-3 and 3-4 with the video gauge.

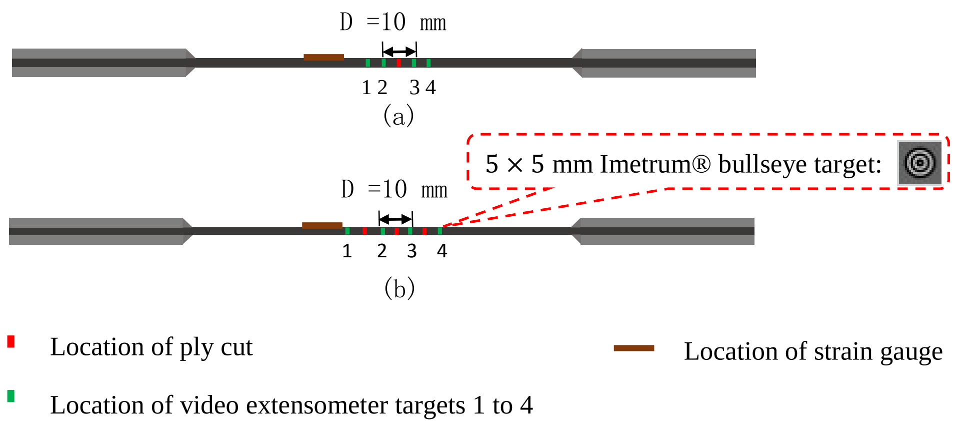

Figure 5. Schematic diagram of the side views of the specimens with (a) single cut and (b) three cuts and the locations for the strain gauge and optical video gauge targets.

4. Results and discussion

Fig. 6 shows analytical and experimental tensile stress-strain curves for the type (1) 4-ply specimens. The experimental behaviour of a 3-ply UD pristine specimen is also shown for comparison. The experimentally tested cut-ply specimens achieved high initial moduli almost identical to that of the pristine specimen. The slopes of the final linear stage for the experimentally tested cut-ply specimens were also close to the analytically predicted values.

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The mode II interlaminar toughness was in fact determined from tensile tests on cut ply specimens of types 1 and 2 and therefore as expected the stress at initiation of delamination is in good agreement with the analytical model. There is however a significant drop in stress almost immediately after initiation of delamination for one experimentally tested specimen and after a small amount of strain for the other specimen. This stress drop is not predicted by the simple analytical model. Fig. 6 also shows small differences between the pseudo-ductile strains (as defined in [3]) achieved in the experiment and the analytical prediction.

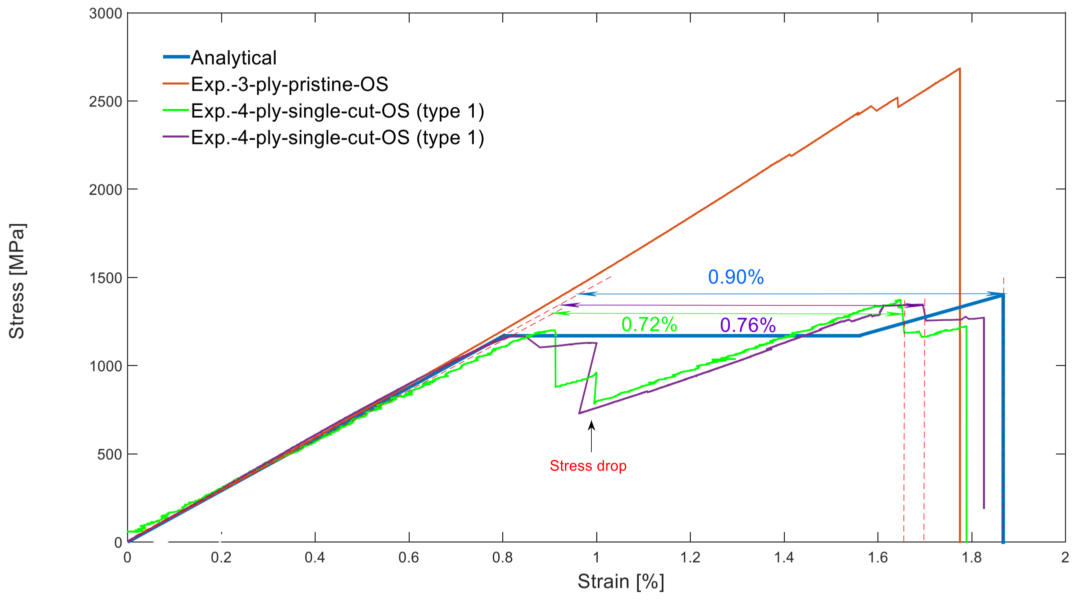

Figure 6. Tensile stress-strain curves for analytically and experimentally investigated 4-ply specimens with single though-width cut at the two central plies. [OS refers to the Imetrum video gauge measurement for strain]

Fig. 7 shows the tensile stress-strain response of the experimentally tested 6- and 12-ply specimens with ply cuts and the analytically predicted behaviour. The experimental results again show good agreement with the initial modulus of the pristine specimen and with the analytically predicted delamination stress and slope of the final linear stage. There is again a stress drop associated with unstable propagation of delamination from the cuts but in this case the stress drops are lower than for the thinner 4 ply (type 1) specimens.

The stress-strain curves of 6-ply single cut (type 2) and the 12-ply 2 aligned cuts (type 4) specimens are very similar except for the premature failure of the 12-ply specimens (indicated by the vertical portion of the stress-strain plot). Further testing is underway to investigate this low failure stress.

The difference in the stress at the initiation of delamination and in the pseudo-ductile strain between the 4 ply (type 1) specimen and the 6 ply and 12 ply (type 2, 3 and 4) specimens confirms that the pseudo-ductile behaviour can be controlled by selecting the proportion of cut plies.

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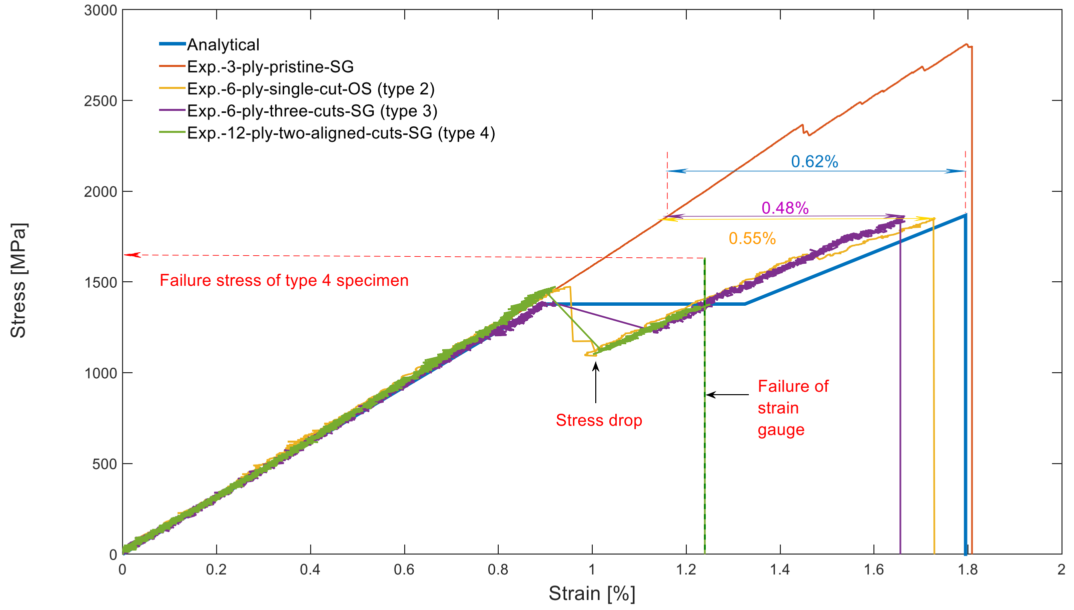

Figure 7. Tensile stress-strain curves for analytically and experimentally investigated 6- and 12-ply specimens with single though-width cut and 6-ply specimen with 3-cuts at the two central plies. [SG and OS refer to the strain gauge and Imetrum video gauge measurements for strain respectively]

5. Conclusions

The potential of using ply cuts as a means of introducing pseudo-ductility in UD composite material of a single carbon fibre type was investigated through analytical modelling and experiment. The investigation confirmed that composite configurations with continuous ply cuts as proposed in this study have the potential to promote pseudo-ductility. All the experimental tensile responses shown in this paper exhibit an intermediate unstable delamination stage between the initially linear elastic and the later 'strain-hardening' stage. Further work is being conducted on the use of ply and interlaminar weakening to reduce this tendency for unstable delamination growth so as to produce a more progressive pseudo-ductile response.

Acknowledgements

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