PSEUDO DUCTILITY IN QUASI-ISOTROPIC CFRP THROUGH PLY WEAKENING

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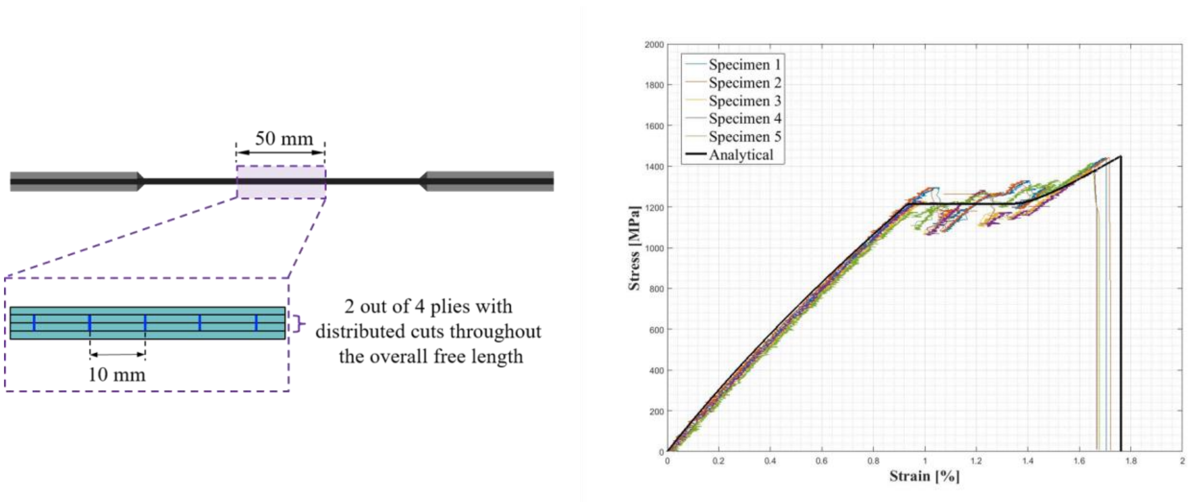
ABSTRACT

Conventional CFRP composites commonly exhibit brittle behaviour; failure is often catastrophic with little or no warning and poor residual load bearing capacity. Previous research in unidirectional (UD) carbon-epoxy composite laminates showed pseudo-ductility can be achieved through the introduction of ply cuts and this behaviour can be tailored by adjusting the position of the cuts. This paper examines the potential of implementing this cut-ply strategy in quasi-isotropic (QI) carbon-epoxy laminates. Tensile tests showed that a pseudo-ductile behaviour can be achieved in cut-ply QI laminates and open-hole specimens showed that the cut-ply architecture is notch insensitive.

1 INTRODUCTION

Several approaches have been proposed to promote a progressive or pseudo-ductile failure process. These include fibre reorientation of angled ply composites [1], hybridization at fibre and lamina levels [2-5] and wavy ply structures [6]. One approach investigated by the authors to achieve pseudo-ductility is the introduction of weakening at specific plies in a carbon fibre composite material [7]. Previous research on unidirectional (UD) laminates (see Fig. 1) has demonstrated that a pseudo-ductile tensile response can be achieved by introducing continuous ply cuts in selected plies within the laminate. A three-stage pseudo-ductile tensile response consisting of two almost linear stages separated by an intermediate plateau stage (see Fig. 1(b)) was observed in the experimentally tested 4-ply UD laminate specimens in which the internal plies were cut at 10 mm intervals. The plateau stage is related to the propagation of mode II interlaminar delamination between the cut plies and pristine (uncut) plies initiating from the ply cuts.



(a) (b)

Figure 1: Schematic of UD 4-ply CFRP laminate containing 10 mm spaced ply cuts in the two middle plies and the corresponding pseudo-ductile tensile stress-strain curves.

The current paper presents an experimental investigation of the effectiveness of the cut-ply strategy to introduce pseudo-ductility in quasi-isotropic (QI) composite laminates containing cut plies and also investigate the open hole tensile (OHT) behavior of this cut ply configuration.

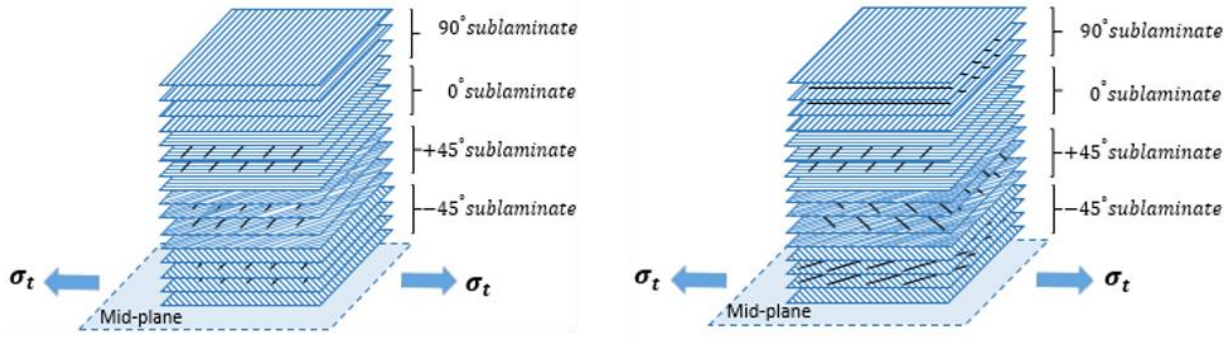
2 EXPERIMENTAL

2.1 Material

Material used in this study was M21/35%/198/T800s carbon/ epoxy UD prepregs produced by Hexcel® with nominal cured ply thickness of 0.184 mm. Key properties of this material are the elastic modulus in fibre direction of 153 GPa, tensile strength of 2800 MPa and the mode II interlaminar fracture toughness of 1.7 kJ/m2.

2.2 Specimen details

The laminate stacking sequence was designed based on the 4-ply UD laminate containing cuts in the internal plies which had previously been shown to exhibit a pseudo-ductile behavior. The stacking sequence for the QI laminates was $[90_4/0_4/+45_4/-45_4]_s$.



(a) (b)

Figure 2: QI laminate with (a) ply cuts perpendicular to the loading direction (PL) and with (b) cuts perpendicular to the fibre direction of each specific sub-laminate (PF) [Note: the distance between in-plane cuts is 10mm for both cut ply cases].

The ply cuts within the UD sub-laminates were introduced in two ways: (1) perpendicular to the loading direction (PL), in which case no cuts were made in the 90 degree sub-laminates (see Fig. 2(a)); (2) perpendicular to the fibre direction (PF) of the sub-laminate (see Fig. 2(b)). In both cases the cuts were confined to the central two plies of each four ply sub-laminate.

The tensile performance of the two types of QI cut-ply laminates was measured using plain tensile specimens (i.e. without a hole) and specimens containing a central 8 mm-diameter hole. Specimen dimension of the plain and open-hole specimens was based on the CRAG standard methods 302 and 303, respectively. The continuous cuts in specific plies were introduced by utilizing a Genesis 2300 CNC prepreg cutting machine supplied by Blackman & White. Good alignment of ply cuts in different layers was achieved by cutting holes at the 4 corners of each ply during the ply cutting process. These holes were aligned with 4 pins on the alignment fixture as shown in Fig. 3. The laminates were then consolidated on a vacuum table and cured in an autoclave according to the recommended cure cycle by prepreg manufacturer (for 2 hours at temperature of 180 °C and pressure of 0.7 MPa). Glass/epoxy (GFRP) cross-ply end tabs with a bevel edge were adhesively bonded to the laminates which were then cut with a waterjet cutter to the size shown in Fig. 4. The 8mm diameter hole was cut utilizing the waterjet cutter.

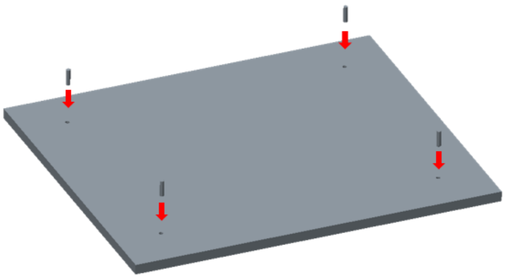


Figure 3: Schematics of an alignment fixture composed of an aluminum with four holes at each corner and 4 pins.

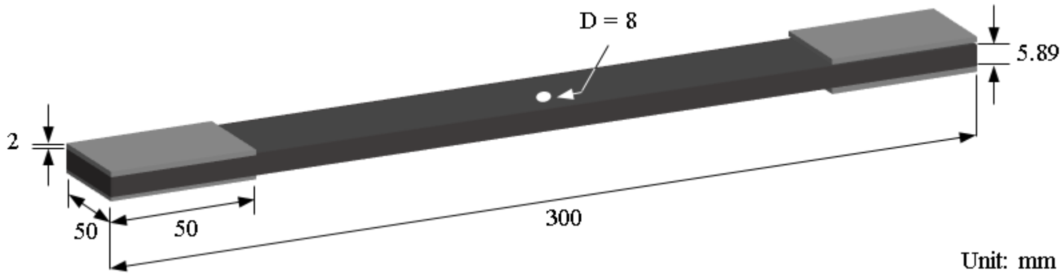


Figure 4: Schematic of a QI cut ply test-piece with an 8 mm open hole in the middle.

2.3 Experimental procedure

The mechanical tensile tests were performed in a 250kN Instron machine fitted with hydraulic wedge type grips and subjected to uniaxial tensile loading with a crosshead displacement speed of 2 mm/min. Five specimens were tested for each configuration. Four were continuously tested up to the ultimate failure load for measurement of the complete tensile stress-strain response. The test of the final specimen was interrupted at intervals to enable damage propagation to be monitored.

Each specimen was sprayed with speckle pattern on one surface (see Fig. 5) to measure the full-field strain distribution using digital image correlation (DIC). The other surface was marked with 3 pairs of white target points with a gauge length of 160 mm (see Fig. 5) to record the overall strain variation using a video gauge system. An AE unit manufactured by Physical Acoustic Corporation and two broadband (WD) sensors were used to detect any acoustic events during the test.

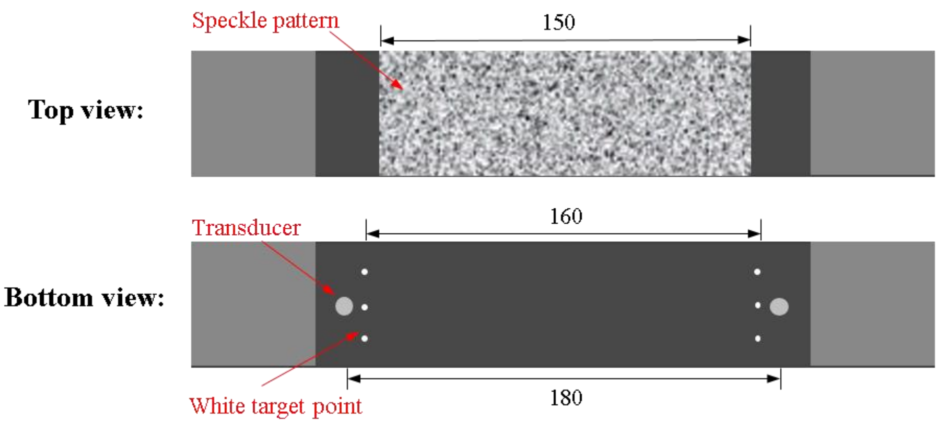


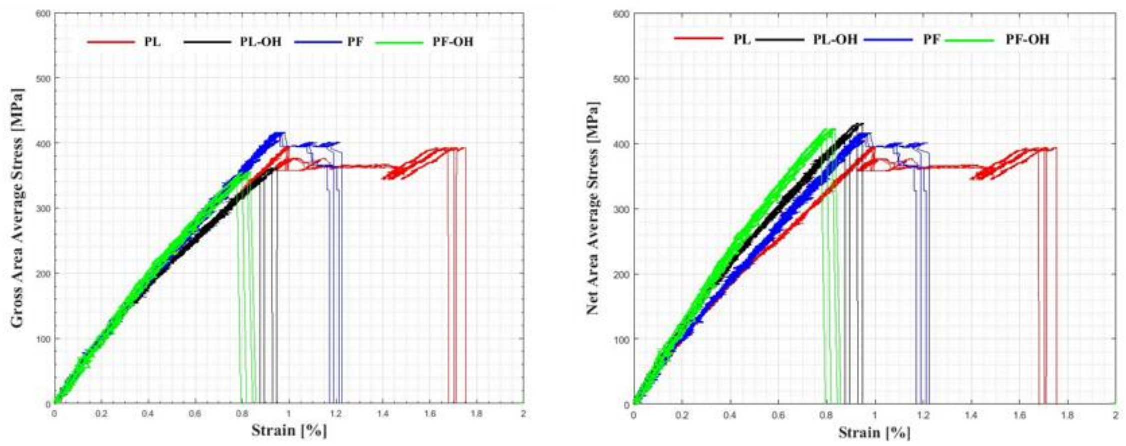
Figure 5: Schematics of speckle pattern, white target points and acoustic sesnors on a specimen.

The speckle patterns were monitored with a GOM DIC system fitted with a 150 mm camera frame and two ARAMIS® 3D stereo camera lenses capable of acquiring 3D image data from a measuring volume of 150 mm $\times$120 mm $\times$ 90 mm and measuring distance of 350 mm. The target points were tracked by an Imetrum optical strain gauge system. The internal damage evolution was investigated by evaluating the acoustic energy levels associated with damage events using a non-destructive testing (NDT) system supplied by AEwin.

For the interrupted tests, the acoustic emission results from the specimens were used to determine the load levels at which to stop the tests. After each interruption, structural integrity (especially for the internal crack detection) was inspected by scanning a specimen, previously soaked in x-ray opaque penetrant, in an Xpert-80 X-ray scanner supplied by Elekron technology and fitted with a 5-45 micro focal spot. Ultrasonic inspection was also performed with a focused 5 MHz transducer and a TecniTest® scanning machine in a water tank.

3 RESULTS AND DISCUSSION

Fig. 6 shows the experimental tensile stress-strain curves for the 2 types of QI cut-ply laminates and the corresponding open-hole configurations.

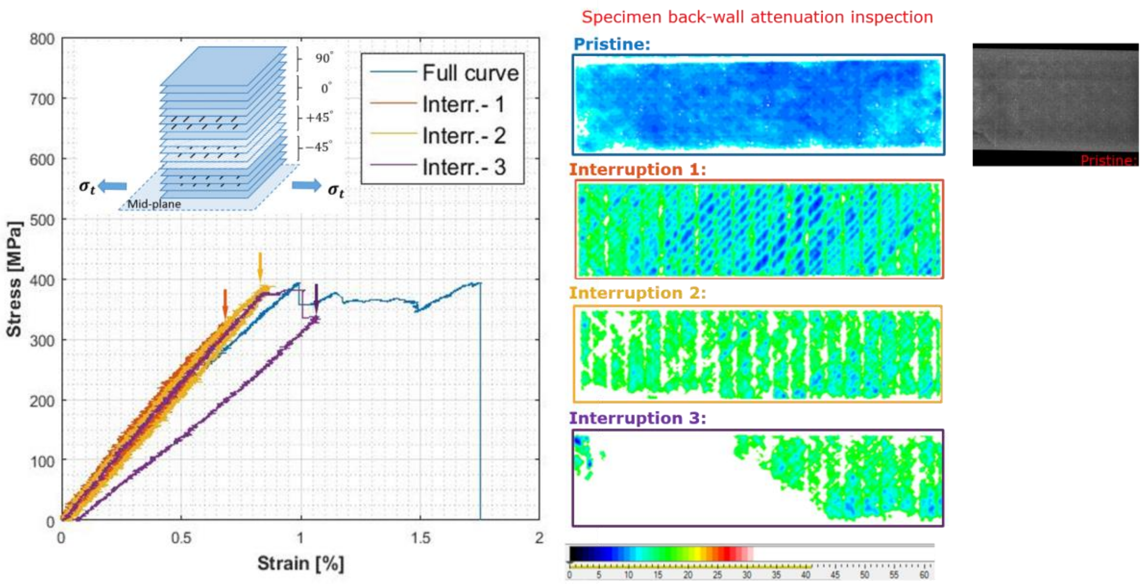


(a) (b)

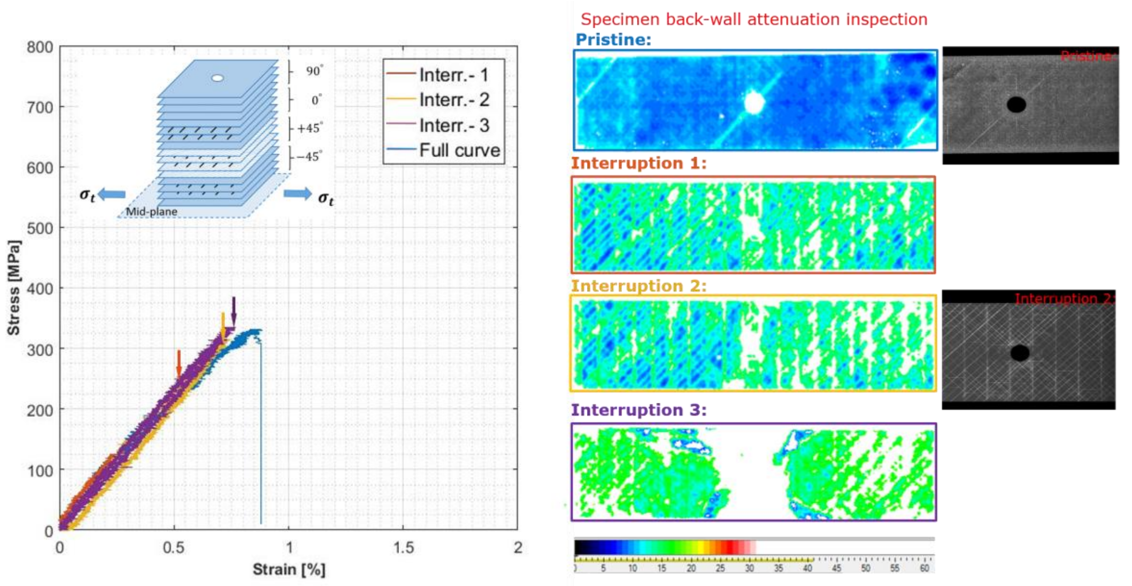
Figure 6: (a) Gross area average stress and (b) net area average stress vs. strain curvess for QI panels containing PL and PF ply cuts and the corresponding configurations with an 8 mm open hole.

The plots show that the pseudo-ductile behavior observed in the UD samples (see Fig. 1(b)) can be achieved in QI laminates but depends on the orientation of ply cuts (i.e. either perpendicular to the loading or to the fibre direction of the sub-laminate). The PL ply cuts result in a strain range in the plateau stage which is over twice that for the case of PF ply cuts. However, the PL ply cut pattern results in lower stiffness after initial ‘yielding’. In addition, from Fig. 6 (b), which plots net section stress, it is observed that both PL and PF cut-ply QI laminates are almost notch insensitive.

Fig. 7 presents the stress-strain curves for the loading-unloading processes in the interrupted tests and the corresponding full stress-strain response of each type of configuration. These figures also include ultrasonic C-scans acquired after each interruption and some x-ray images. Delamination initiates and propagates from the ply cuts was observed for the configurations without an open-hole (Fig. 7(a) & 7(c)). For the open-hole cases (Fig. 7(b) & 7(d)), the delamination damage is focused around the open-hole. The x-ray images also recorded dense ply cracking around the holes, but there is still some delamination growth from the ply cuts.

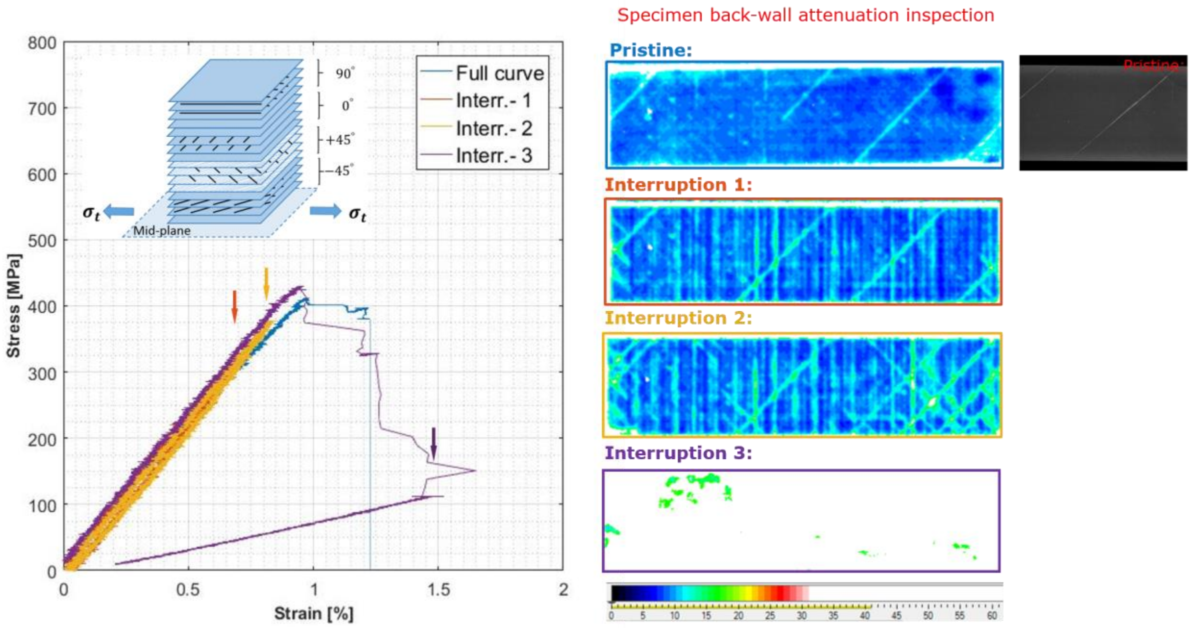


(a) PL

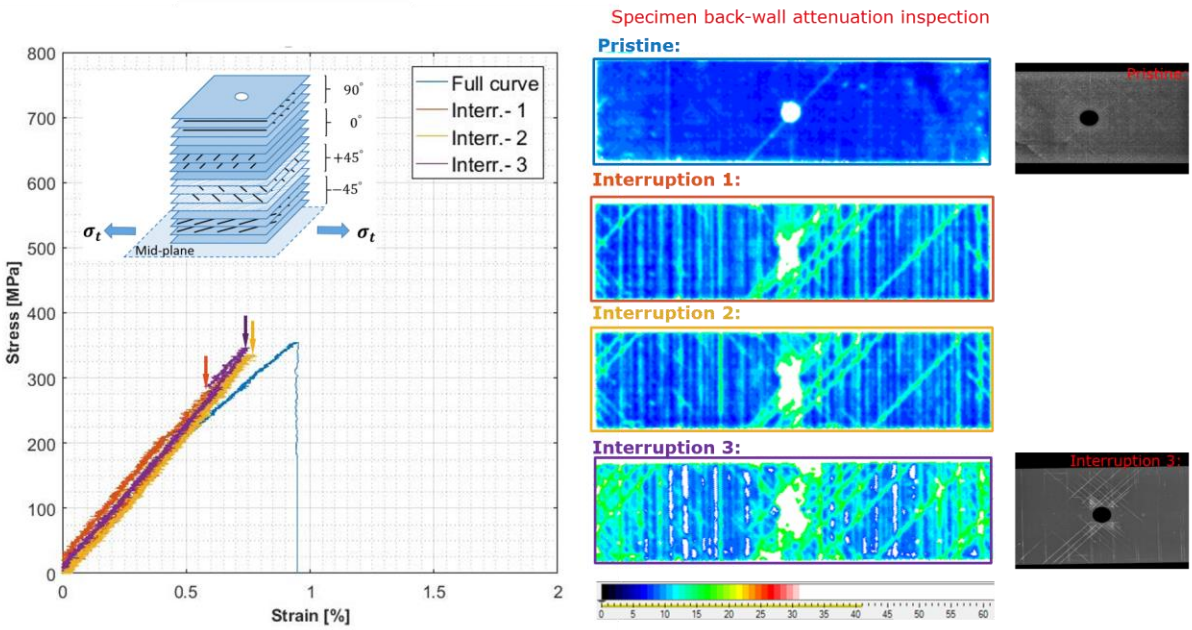


(b) PL open-hole

Figure 7: Tensile stress-strain curves of the interrupted tests and the corresponding ultrasonic C-scanning and X-ray scanning diagrams for PL, PL open-hole, PF, PF open-hole configurations. (The darkness of inspected section in x-ray scanning diagrams is affected by the amount of penetrant left in the specimen during scanning)



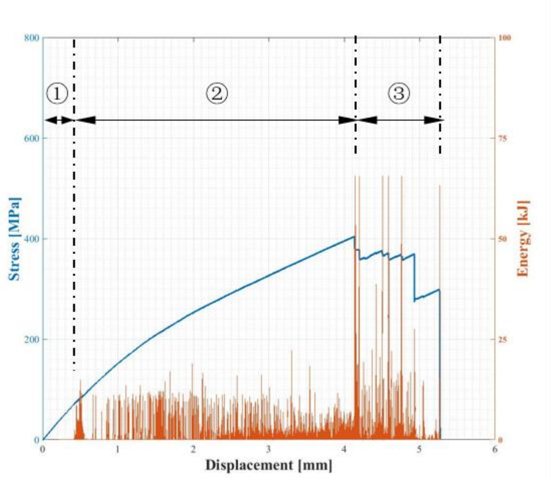
(c) PF



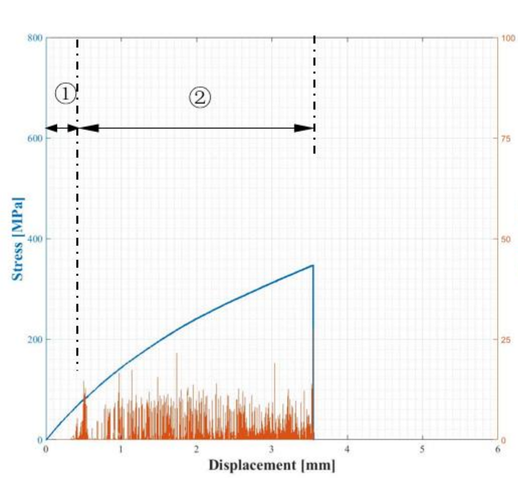
(d) PF open-hole

Figure 7 (Cont.): Tensile stress-strain curves of the interrupted tests and the corresponding ultrasonic C-scanning and X-ray scanning diagrams for PL, PL open-hole, PF, PF open-hole configurations. (The darkness of inspected section in x-ray scanning diagrams is affected by the amount of penetrant left in the specimen during scanning)

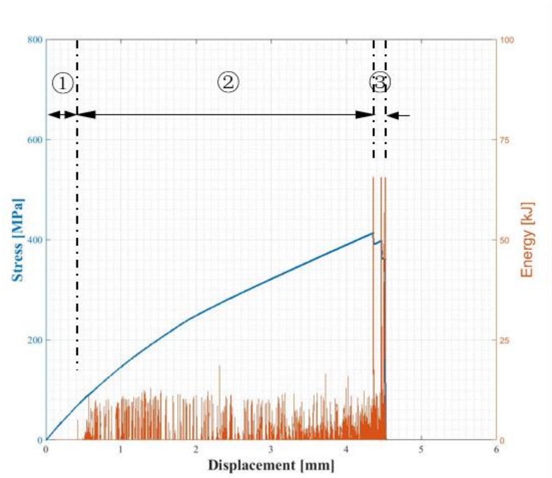
Fig. 8 shows the energy levels of acoustic events recorded during the test synchronized with the corresponding gross tensile stress - displacement diagram for each configuration. The diagrams shown in Fig. 8 can be divided into three segments depending on the failure modes. No internal damage occurred in section ①. Section ② is related to transverse crack formation mainly in the outer 90-degree sub-laminate together with the onset of some local delamination initiated from the ply cuts. Significant interlaminar delamination propagation, further formation of transverse cracks in 90-degree sub-laminate and internal breakage in other sub-laminates were detected in section ③. Detailed analysis of the failure modes in each section is under investigation.



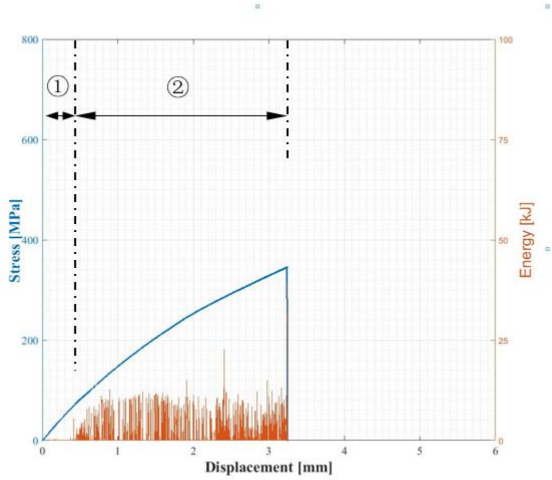
(a) PL



(b) PL open-hole (Net area stress)



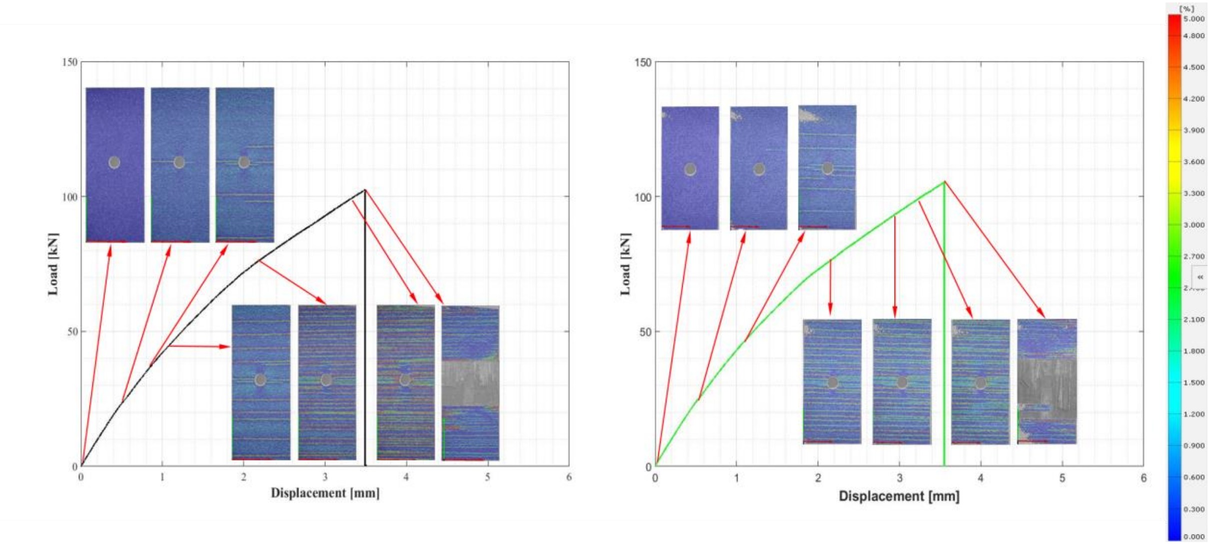
(c) PF



(d) PF open-hole (Net area stress)

Figure 8: Tensile stress - displacement and acoustic energy - displacement diagrams for the cut-ply and corresponding open-hole configurations.

The strain distribution in the surface ply (90 degree) measured with the GOM DIC system at intervals for the two types of open-hole cut ply configurations is shown in Fig. 9. Strain concentration along the cracks in 90-degree surface ply and strain concentration around the holes can be observed as the tensile load increases.



(a) (b)

Figure 9: Full field strain maps for (a) PL open-hole and (b) PF open-hole cut-ply configurations at intervals.

4 CONCLUSIONS

This study investigated the potential of achieving pseudo-ductility in QI carbon composite laminates by introducing ply cuts. The experimental results have shown that ply cuts perpendicular to loading direction, promotes more significant pseudo-ductility compared with that of the configuration containing ply cuts perpendicular to the direction of fibres in sub-laminates. Non-destructive inspection results showed that delamination and cracks are the dominant failure modes in promoting pseudo-ductility. Open-hole tension tests on the two types of cut ply configurations showed that both configurations are notch-insensitive. Denser cracks and more severe delamination were observed around the open-hole due to the stress concentration effect.

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