INVESTIGATING THE DAMAGE MECHANISMS AND THEIR EFFECTS ON THE NOTCH SENSITIVITIES OF CROSSPLY CFRP LAMINATES UNDER UNIAXIAL LOADING

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Abstract

Experiments have been performed to investigate the damage mechanisms and failure modes of crossply CFRP laminates under pure tensile and pure compressive loading. Unnotched and notched crossply laminates were tested. Extensive splitting was observed prior to specimen failure for both pure tension and pure compression cases. This mode of damage was seen to have a profound effect on the strength and notch sensitivities of the specimens. Although notches were observed to greatly weaken the laminate, the reduction in strength was not proportional to the inverse of the stress concentration factor presented by the notch geometry. This was explained by the damage that had developed around the notch tips that acted to reduce the stress concentration at hand, and effectively strengthen the laminate specimens.

1. Introduction

Over the past four decades, the fracture behaviour of composite laminates has been investigated extensively as composite materials become increasingly popular in the aircraft, automotive and marine industries due to their high specific stiffnesses and strengths. The notch sensitivity of carbon-fibre reinforced plastic (CFRP) laminates in particular, has for a long time been a popular research topic in the field of composite materials. This is because holes and notches exist in practical applications of laminates due to mechanical joining methods. Therefore, understanding how these stress concentrations affect the mechanical performance and strength of the material is important for improving composite laminate designs.

Considerable research has been undertaken on the subject of notched behaviour of laminates especially in the area of pure tension. A comprehensive review of the earlier work on the notched tensile strength of composite laminates was compiled by Awerbuch and Madhukar [1] in 1985. Since then, many researchers have proposed various theories and correlations regarding this subject [2-8], and indeed, work continues on this topic to the present day [9, 10]. The continued effort and work in this field demonstrates the fact that the fracture behaviour of composite laminates is a very complex problem and although much progress has been made, there are still many gaps in the literature to be filled.

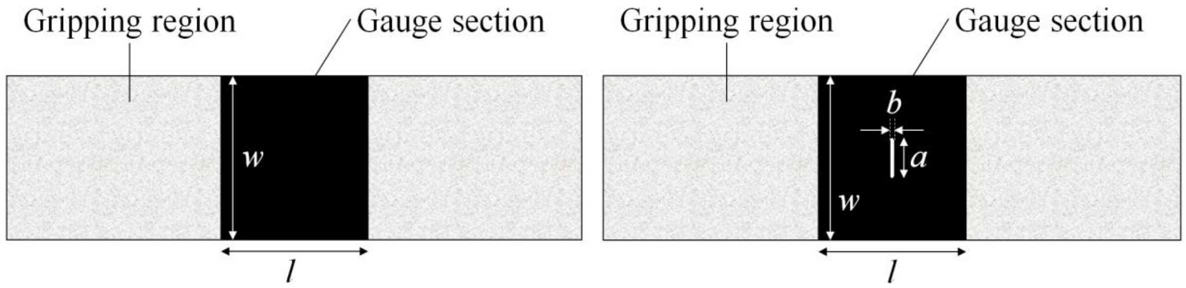
It is the purpose of the present paper to investigate and characterise the main subcritical damage mechanisms that develop in notched crossply IM7/8552 laminates under uniaxial loading (i.e.: pure tension and pure compression), and then explore how these damage mechanisms affect the strengths and notch sensitivities of the laminate, comparing the case of pure tension with pure compression where relevant.

2. Experimental procedure

2.1. Manufacturing of CFRP and specimens

The CFRP material used in this work was HexPly® IM7/8552 prepreg tape with a fibre volume fraction of approximately 60% and nominal ply thickness of 0.125mm. Crossply laminates with the stacking sequence $[(0/90)_3/0/\overline{90}]_S$ were laid-up by hand in a cleanroom, then vacuum-bagged and autoclaved according to the standard cure cycle prescribed by the manufacturer.

The cured CFRP laminate panels were then cut to size using a water-cooled diamond saw and end-tabbed with aluminium tabs. 2 types of specimens were tested in this study – unnotched and notched laminate specimens. For the notched specimens, the centre-notches were manufactured using tungsten carbide drill bits and fretsaw blades. The final geometries of the specimens are shown in the schematic diagrams in Figure 1.



(i) (ii)

Figure 1. (i) Geometry of the unnotched specimen. (ii) Geometry of the notched specimen. ($a/w = 0.25$, $w = 25$mm, $l = 23$mm, $b = 0.7$mm, thickness ≈ 1.9mm)

2.2. Test method

Tests were conducted on an Instron 5584 screw driven tensile testing machine in the room temperature/dry condition. Wedge grips were used to apply pure tensile loading to the tensile specimens and a modified Celanese test rig was used to apply pure compressive loading to the compressive specimens. In all tests, the load was applied monotonically (loading rate of 0.5mm/min) until specimen failure. At least five specimens were tested to measure the unnotched and notched failure stresses for each configuration.

Interrupted tests were also performed on the notched specimens to identify and characterise the fracture mechanisms and damage evolution for the crossply lay-up.

2.3. Damage visualization techniques

X-ray computed tomography (CT) scanning with the use of a radiopaque dye penetrant was employed during the interrupted tests to assist in visualising the subcritical damage and critical failure mechanisms in the specimens. The use of a radiopaque liquid dye penetrant was imperative in all scans as it functioned as a contrasting agent to highlight the damage sustained by the specimen. The dye used was the same as that used by Tan et al. [11] and was prepared by mixing the following components until a clear brown solution was obtained:

- Isopropyl alcohol (5ml)
- Zinc iodide powder (30g)
- Photoflow solution (5ml)
- Distilled water (5ml)

The specimens to be inspected by CT-scanning were first soaked in a bath of the dye for approximately 30 minutes. During this time, the radiopaque dye penetrant was drawn into the damage zones at the notch tips through capillary action. After the specified duration, the specimens were thoroughly wiped down to remove excess penetrant before being CT-scanned. It should be noted that this radiopaque dye penetrant (zinc iodide solution) is extremely corrosive. Therefore, extra care must be taken when handling this liquid.

CT- scanning was performed using the X-TEK HMX160 ultra-focus X-ray system. Data were collected at X-ray tube settings of 55kV and 65μA. For tomographical reconstruction, a conical X-ray beam scanned the specimen which rotated at increments of 1° for each rotation step with an average of 32 frames taken each time.

With this CT-scanning technique, the damage modes in each ply and interface were easily identified by simply slicing through the 3D tomographical reconstruction of the specimens. The interrupted tests allowed the characterisation of damage mechanisms to be done for the crossply layup loaded in pure tension and in pure compression. The damage sequence and damage evolution were also easily obtained.

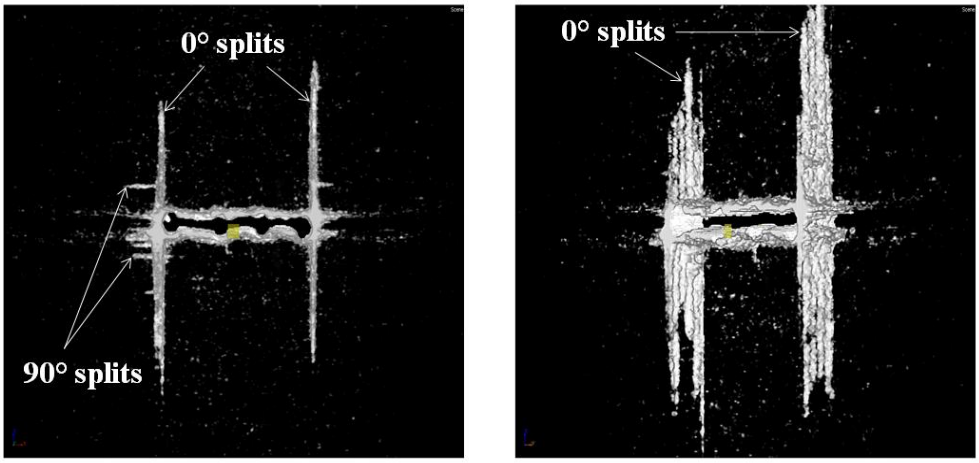
3. Results

3.1. Subcritical damage mechanisms and failure modes

3.1.1. Pure tension

Interrupted tests revealed that the notched crossply specimens under pure tensile loading developed extensive splitting (i.e.: matrix failure along the fibre direction) in each ply orientation prior to ultimate failure. Narrow delamination zones between the plies accompanied splitting near the notch tips as well. These damage mechanisms are well-demonstrated in the 3D tomographical reconstruction of the notched tensile specimen that was loaded to 90% failure load shown in Figure 2. The light regions indicate where the radiopaque dye penetrant had infiltrated and thus represent the damage sustained by the specimen.

As can be observed from Figure 2, extensive intra-ply splitting had formed in the specimen prior to catastrophic failure. Further interrupted testing revealed that intra-ply splitting in the 0° plies and 90° plies had started to grow at as early as 40% failure load. And once initiated, they were seen to grow in a self-similar manner until failure. The evolution of damage in each ply orientation and interface of the crossply tensile specimen is neatly represented in the damage evolution chart in Figure 3. The damage local to each ply orientation and interface was obtained simply by slicing through the 3D tomographical reconstruction of the specimen at various stages of loading. Here, the damage is represented by the darker regions.



(a) (b)

Figure 2. 3D tomographical reconstruction of a notched crossply tensile specimen at 90% failure load. (a) Front view, (b) Angled view. For scale purposes, the notch length is approximately 6.25mm.

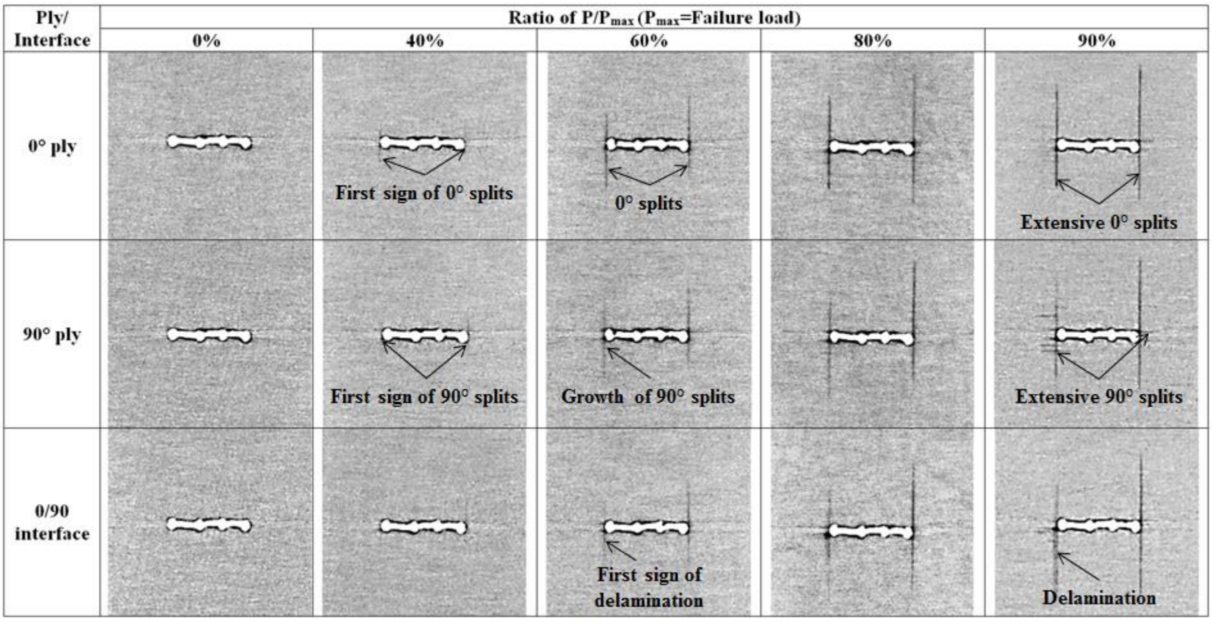


Figure 3. Damage evolution chart for the notched crossply tensile specimen. Notch length ≈ 6.25mm.

These results on the subcritical damage mechanisms are consistent with what was reported by Kortschot and Beaumont [5]. The tensile specimen generally exhibits three main forms of damage when loaded in pure tension:

(1) Splits in the 0° plies
(2) Transverse ply cracks in the 90° plies (essentially 90° splits), and
(3) Delamination zones at the 0/90 interfaces

It was found that the critical failure mechanism for the tensile specimens was always fibre tensile failure of the 0° plies. Additionally, the failure was always sudden and catastrophic, with the specimen unable to carry any load after it had failed. Inspection of the fracture plane revealed an average fibre pull-out length of approximately 20μm (see Figure 4 and Table 1).

With the fibre diameters being approximately 5μm, the average pull-out length recorded in this study is about 4 times the diameter of the carbon fibre. This is consistent with the literature – the average fibre pull-out length is somewhere between 3 to 6 times the diameter of the carbon fibre [12].

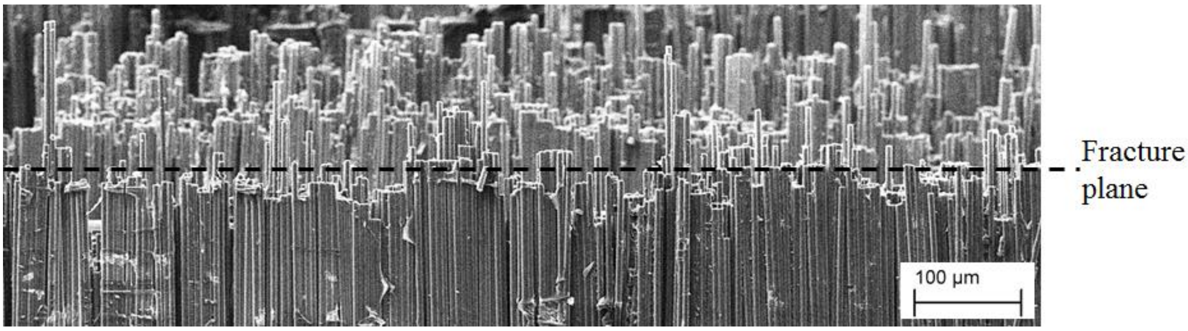


Figure 4. SEM micrograph of the fracture plane in the 0° plies of the crossply specimen

Pull-out Lengths (μm)	
Average	19.70
Max	137.20
Min	0.25

Table 1. Fibre pull-out lengths in the 0° plies of the crossply tensile specimen.

3.1.2. Pure compression

The main subcritical damage mechanisms that developed in the notched crossply specimens when loaded in pure compression were:

1. Splits in the 0° plies
2. Microbuckling in the 0° plies
3. Splits in the 90° plies
4. Small delamination zones near the microbuckles

These damage modes are mostly illustrated in the CT-scans shown in Figure 5. It is interesting to note that the splits at the notch tips in the 0° plies are noticeably shorter and less prominent than those seen in the tensile specimens. This has a notable effect on the notch sensitivities as will be explained in a later section. Also, the microbuckles that form at the notch tips occur at approximately 80% failure load.

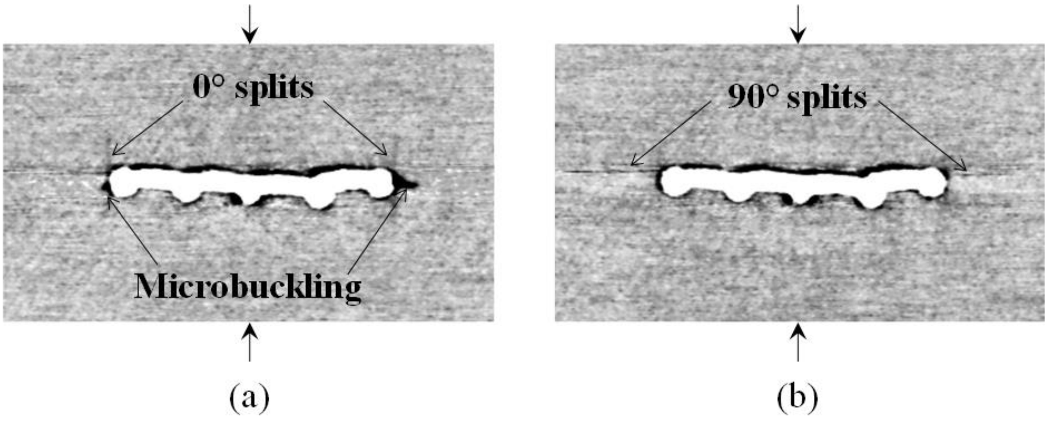


Figure 5. CT-scans of the (a) 0° ply and (b) 90° ply of the crossply specimen loaded in pure compression. These CT-scans were taken after the specimen was loaded to 90% failure load. Notch length ≈ 6.25mm.

The critical failure mechanism observed was 0° fibre microbuckling that grew catastrophically once the critical peak load was reached. This observation is consistent with what has been reported in the literature [13].

3.2. Unnotched and notched strengths

The average peak loads recorded in the tests were converted into net-section failure stresses and are plotted in Figure 6. Failure was taken as being the first significant load-drop on the load-crosshead displacement curve. All notched specimens failed in their gauge sections in a sudden catastrophic manner. Unnotched specimens mostly failed within the gauge section, but in some cases, failed near the grips.

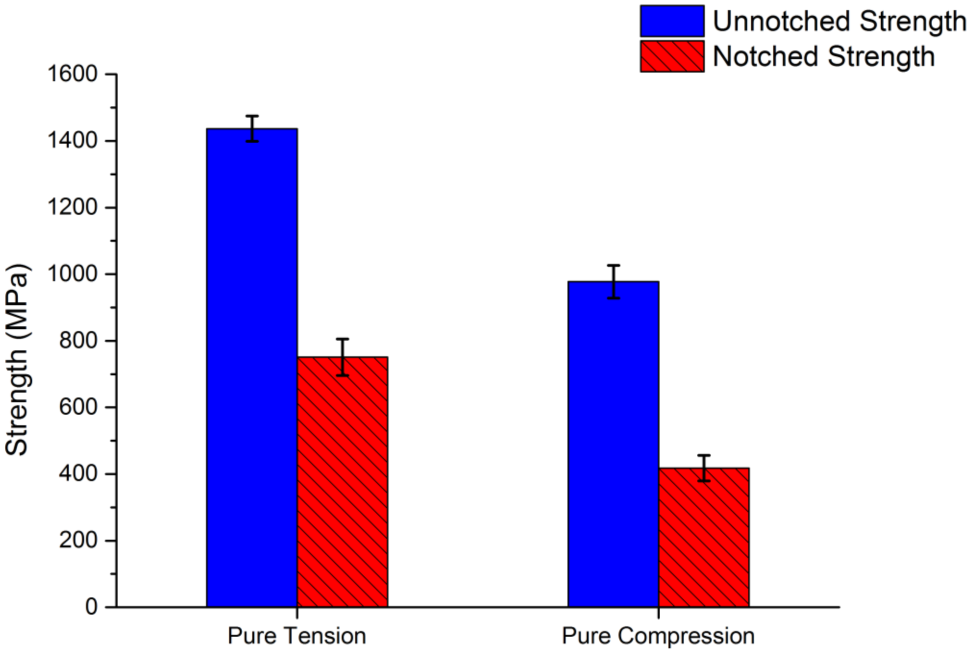


Figure 6. Unnotched and notched strengths of the crossply specimens for pure tensile loading and pure compressive loading.

As can be seen in Figure 6, the presence of a notch reduces the net section strengths of the laminate rather significantly. The notched strength of the crossply specimens is approximately half of its unnotched strength for both loading modes. Also, the compressive strength of the laminate is approximately 70% of the tensile strength.

4. Analysis

Experimental data have shown that the tensile and compressive strengths of composite laminates are severely reduced by the presence of a stress concentration. However, the reduction in strength is actually much less severe than the full effect of the stress concentration factor in an ideally brittle material as predicted by elastic theory. This contention is well-illustrated by the notch sensitivity chart devised in Figure 7. The notch sensitive line given by $1/k_T$ (where k_T is the stress concentration factor) represents the highest possible knockdown in specimen strength due to the presence of the notch. Conversely, the horizontal notch insensitive line represents the other extreme whereby the presence of the notch does not alter the net section strength of the specimen at all. The specimen strengths measured by the tests lie somewhere in between these two extremes.

This is explained by the subcritical damage mechanisms that develop around the notch tips as the specimens are being loaded. In particular, the 0° splits act to relax the stress concentration presented by the notch, which consequently increases the specimen strengths away from the notch sensitive line and reduces the notch sensitivity of the specimens for both loading cases. This effect however, is seen to be slightly larger for the pure tension case, probably because of the larger splits observed prior to failure in the tensile specimens. But generally, the notch sensitivities of the laminate specimens for both loading modes are of similar values and this can largely be explained by the fact that the 0° plies serve as the dominant load bearing plies in both cases.

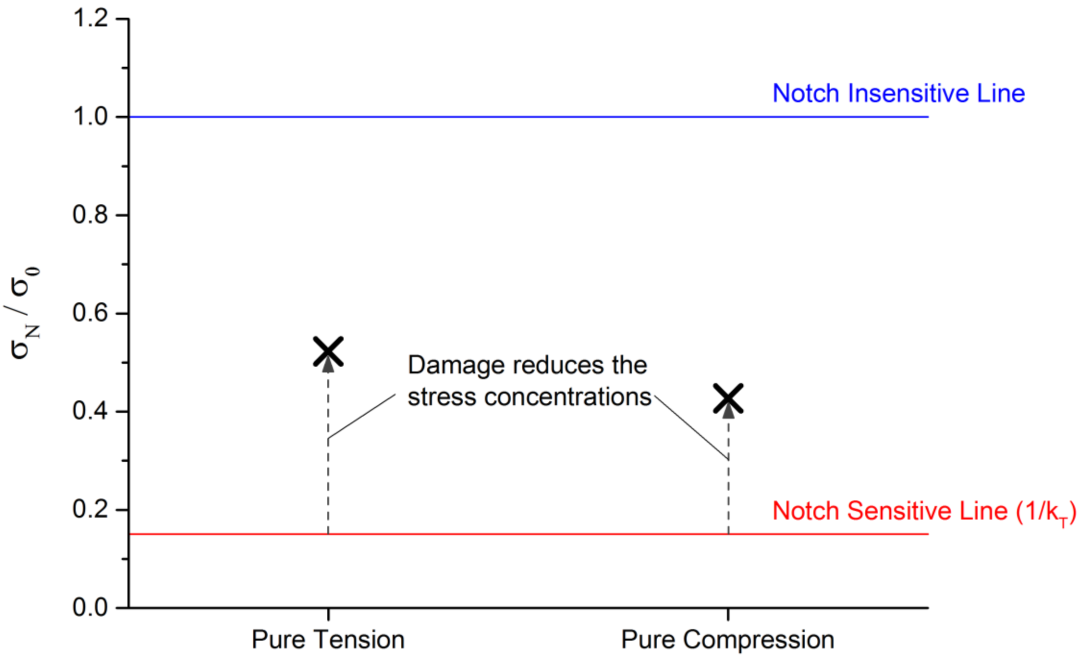


Figure 7. Notch sensitivity chart for pure tension and pure compression. σ_N is the net section mode I strength of the notched specimen, σ_0 is the unnotched mode I strength, k_T is the stress concentration factor.

In this context, it is interesting to note that the development of damage during loading of the laminate specimens has a profound effect on laminate strengths and notch sensitivities, regardless of loading mode. In fact, this relationship between the extent of damage prior to catastrophic failure and specimen strength has also been reported by researchers such as Kortschot and Beaumont [5, 6] as well as Wisnom and Chang [14].

5. Conclusions

Based on the results of this study, the following conclusions may be drawn; Composite laminates are greatly weakened by the presence of a stress concentration. However, this reduction in strength is not proportional to the inverse of the stress concentration factor because of the damage that develops around the stress concentration prior to ultimate failure. For the crossply lay-up, the 0° splits that form at the notch tips act to “blunt” the notch and reduce the stress concentration. This consequently increases the strength of the specimens away from the notch sensitive line to become less notch sensitive as otherwise would be analytically predicted. This effect is seen to be true for both the pure tension case and pure compression case. The tensile fracture behaviour is however, slightly more notch insensitive than the compressive response due to the more extensive splitting observed prior to ultimate failure.

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