AN EXPERIMENTAL INVESTIGATION INTO THE STACKING SEQUENCE EFFECTS OF QUASI-ISOTROPIC CARBON/EPOXY LAMINATES UNDER COMPRESSIVE LOADS

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ABSTRACT

The effects of stacking sequence on the compressive strength for sharp notched carbon/epoxy quasi-isotropic laminates were studied experimentally. Two quasi-isotropic stacking sequences with and without central 0° plies were tested to understand the significance of the double 0° ply. From the experimental results, it was found that there was no significant difference in the strengths for the two quasi-isotropic stacking sequences considered. Further analysis using X-ray computed tomography (CT) scans of the two stacking sequences found there was a difference in the extent of damage of the micro-buckled and splitting regions, particularly within the blocked double 0° plies for SS1 and the single 0° ply next to the mid-plane.

1 INTRODUCTION

The compressive strength of unidirectional carbon/epoxy laminates is typically less than 60% of its tensile strength [1]. The ultimate compressive strength for composites reduces with the presence of a notch due to the stress concentrations present. Notches can arise from cut-outs, bolts, access holes or damaged surfaces making this a critical case during the design process. How these added stress concentrations contribute to the failure process is of primary importance for a designer.

Lee and Soutis [2] found that the reduction from the un-notched compressive strength for a quasi-isotropic 4mm-thick IM7/8552 open hole specimen of stacking sequence **$[45/90/-45/0]_{4s}$** was 53% for the baseline specimen shown in Figure 1. The primary failure mechanism reported was fibre micro-buckling along the plane of fracture in the vicinity of the hole. Tan et. al. [3] investigated the effects of a sharp notch under multi-axial loading for a quasi-isotropic IM7/8552 2mm-thick specimen with a stacking sequence of **$[45/0/-45/90]_{2s}$**. The primary failure mechanism dominating the response under direct compression was reported as fibre micro-buckling in the 0˚ plies, initiating at the notch tips, similar to the open-hole response but with some additional splitting. Micro-buckling was also observed in the adjacent +/-45˚ plies. However, for the pure compression case no X-ray Computed Tomography (CT) scan images were provided to show in detail the failure mechanisms occurring for different plies, but only a description of the failure mechanism.

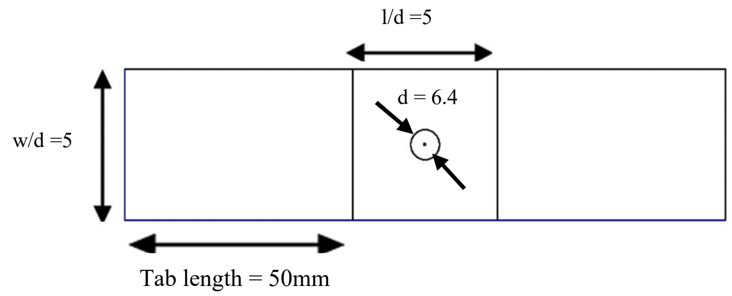


Figure 1- Schematics of the baseline open-hole specimen for compression

Quasi-isotropic laminates offer good in-plane performance in all material axes, but the effects of the differing quasi-isotropic stacking sequences on the failure process and stress is important and not fully understood from the literature. The effects of the quasi-isotropic stacking sequence under compression was investigated by Halverson and Tuttle [4] for which un-notched compressive experiments on IM7/5260 panels with a 2mm thickness were performed for differing quasi-isotropic stacking sequences. It was concluded that there is a significant difference between the **$[45/90/-45/0]_{2s}$** and the other quasi-isotropic laminates considered. However, the notched performance was not included.

This paper considers the compressive strength for sharp notched quasi-isotropic IM7/8552 carbon/epoxy laminates, measured experimentally. The effects on the failure process by changing the stacking sequence in the quasi-isotropic lay-up was analyzed. Experiments were conducted to understand the significance of the central double 0˚ plies on the strength of the sharp notched specimen. The central double plies can potentially have a key role in the failure process, depending on the specimen thickness and the proportion of the double 0˚ plies. CT scan images were compared to understand the fundamental differences in the failure mechanisms.

2 METHOD

Figure 2 shows a schematic of the sharp notched specimen used for the compressive tests, where *l* represents the gauge length, *w* the specimen width and *C* the notch length. For the baseline case, a notch length of 6.4mm was used. For compression tests a *l*/*C* ratio of 5 and a tab length of 50mm were used.

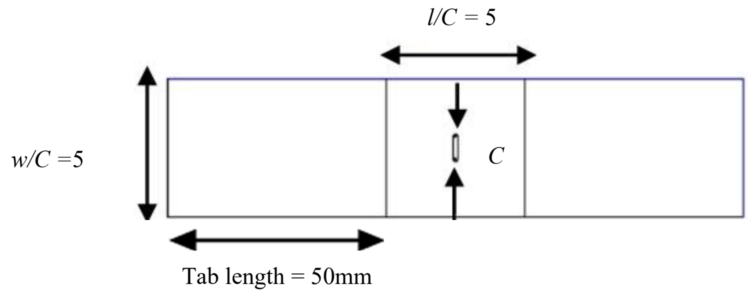


Figure 2- Schematics of the sharp notched specimen for compression

Table *1* provides details of dimensions. The two stacking sequences considered are **$[45/90/-45/0]_{4s}$** (SS1) and **$[45/0/-45/90]_{4s}$** (SS2).

Specimens	**Number of Specimens**	**Notch Length, C (mm)**	**Gauge Width (mm)**	**Gauge Length (mm)**	**End tab Length(mm)**
SS1- $[45/90/-45/0]_{4s}$	5	6.35	31.75	31.75	50.00
SS2- $[45/0/-45/90]_{4s}$	5	6.35	31.75	31.75	50.00

Table 1- Dimensions of the Specimens for SS1 and SS2 Testing

The $[45/90/-45/0]_{4s}$ (SS1) laminate has a central double 0º ply and three pairs of single 0º plies and the $[90/-45/0/45]_{4s}$ (SS2) laminate only has single 0º plies as shown in Figure *3*, where the black, white and yellow blocks represent the 0º, 90º and +/-45º plies respectively. The overall specimen thickness was fixed at 4mm.

Figure 3- Schematic of the two stacking sequences considered

The material used for testing was Hexcel Hexply IM7/8552 carbon epoxy pre-preg with a nominal ply thickness of 0.125mm. An Instron 250kN hydraulically driven machine was used for testing the sharp notched specimens, as shown in Figure 4. Anti-buckling guides were not needed for the baseline specimens as no buckling was observed during the experiments. The compression tests were conducted under displacement control at a loading rate of 0.25mm/minute.

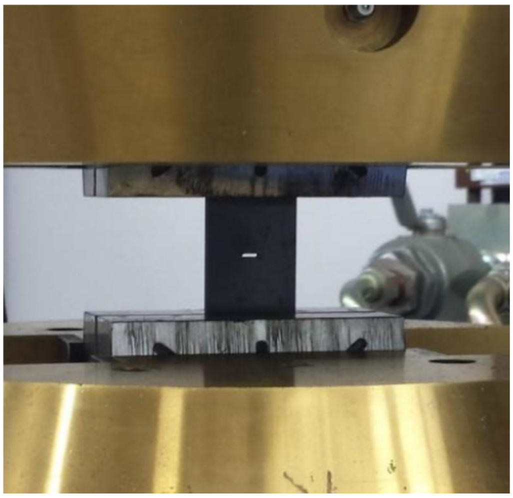


Figure 4- Experimental set-up in a typical test.

The centre notches was cut by an automated process using a computer numerical controlled (CNC) machine. The width of the notch was 1mm to avoid surface contact under compressive loading. The notch tip had a radius of 0.5mm. This was similar to the notch width used by Tan et al. [3] in which a notch width of 0.7mm was used for a similar experiment under compression. The notch width was held constant throughout the experimental process.

3 RESULTS AND DISCUSSION

3.1 Experimental Results

Table 2 provides a summary of the experimental results. The compressive strength was calculated from the gross section area using the peak failure load. Analyzing the results for SS1 and SS2 using a t-test statistical analysis showed that there was no significant difference in the compressive strength. Comparing the sharp notched result to the un-notched specimen under compression shows that there is a 47% decrease in strength when a sharp notch is present for the SS1 case considered.

	Sharp Notched Compression-SS1	Sharp Notched Compression - SS2	Compression un-notched-SS1
Baseline Strength (MPa) [C.V. %]	358 (3.4%)	364 (3.0%)	675 (6.6%) [5]

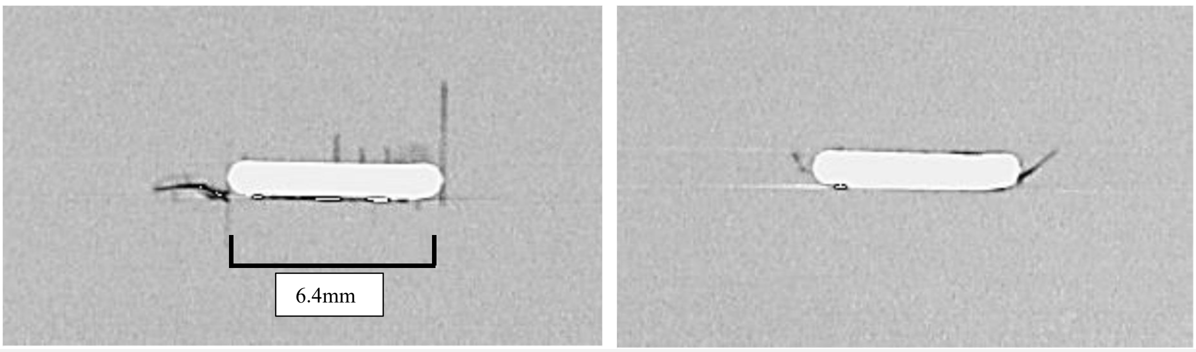
Table 2: Experimental test results under compression

3.2 CT Scan

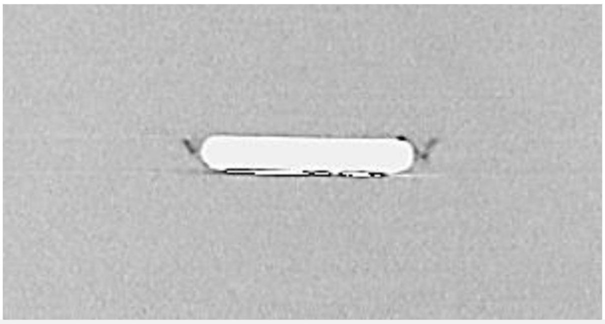
To further understand the damage state within the plies, X-ray computed tomography (CT) scans were conducted from the interrupted tests. This gives an accurate representation of the size of the damage zone relative to the notch and details of the damage states close to ultimate failure. An interrupted test for each of SS1 and SS2 was conducted at 95% of the average failure stress. A Nikon XTH225ST CT scanner was used. It has a 3 µm focal spot size and 225 kV, 225W micro focus X-ray source. Before CT scanning, the interrupted specimens were soaked in a bath of zinc iodide penetrant for 3 days. From the CT scanned images, the areas where zinc iodide penetrant is present result in dark regions, which represent defects within the sample. Figure 5 and - SS1 CT scan images for individual pliesFigure *6* show the typical CT scan images for different plies of quasi-isotropic laminates SS1 and SS2 respectively.

3.2.1 SS1

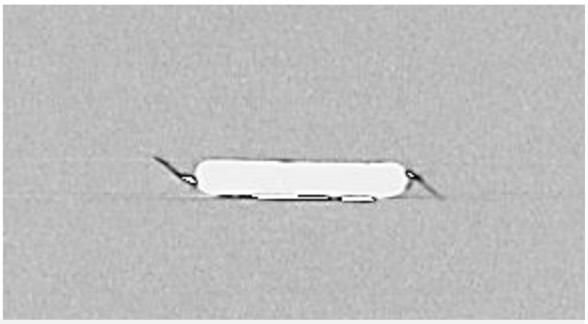
Figure 5a represents CT scans of the central blocked 0° plies for SS1. The dark regions parallel to the notch, i.e. perpendicular to the 0° ply represent the micro-buckled zone whereas the dark regions parallel to the 0° ply represent matrix splits. Analyzing SS1, it can be seen that fibre micro-buckling is the main failure mechanism observed as shown in Figure 5a, with a measured absolute length of 2.1mm for the blocked central 0° plies. This type of failure mechanism is consistent with the observation from Tan. et. al. [3] for sharp notches and Soutis et. al. [2] for open hole specimens under compression. The asymmetrical failure that was observed, i.e. fibre micro-buckling only on one side is due to the presence of 0° matrix splits. These matrix splits blunt the stress concentration at the tip of the sharp notch, therefore for SS1 stopping the micro-buckling propagation on one side. A small presence of micro-buckling can be observed in the 90° and -45° plies, with slight matrix splitting in the 45° and -45° plies, but is not thought to influence the failure process. The single 0° plies outboard show fibre micro-buckling, but the length of this micro-buckled zone is smaller than in the central blocked 0° plies. The mean of the micro-buckling length for all the 0° plies through the specimen was 1.2mm with a C.V. of 50%.



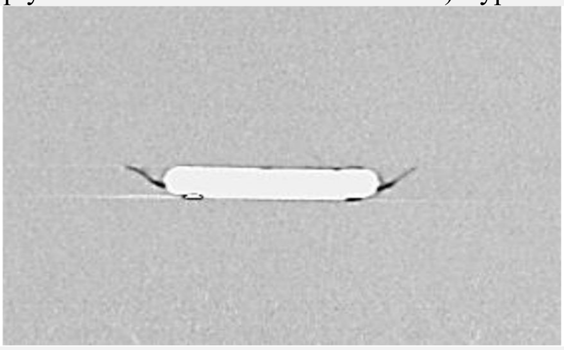
a) Central double 0º ply block b) Typical 45º ply



c) Typical 90º ply



d) Typical -45º ply



e) Single 0 º outboard ply

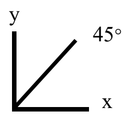
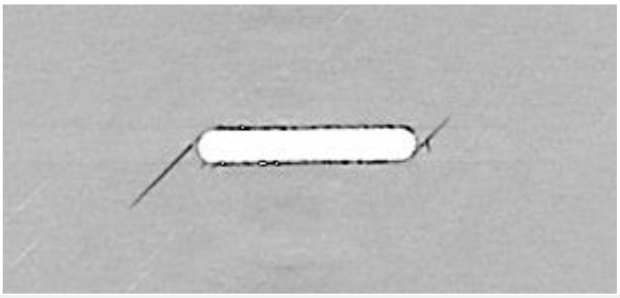


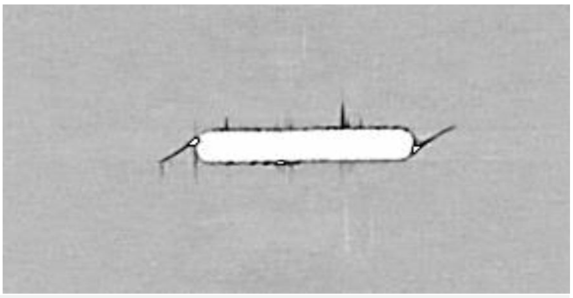
Figure 5- SS1 CT scan images for individual plies

3.2.2 SS2

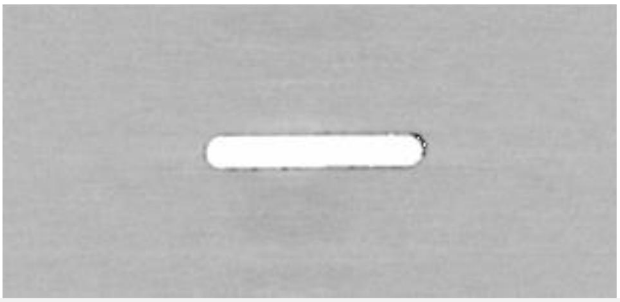
Figure 6 shows the CT scan images for SS2. Comparing the central blocked 0° plies for SS1 to the 0° plies closest to the mid-plane for SS2 there are some key differences. Micro-buckling initiates from both ends as seen in Figure 6b. The measured value for the 0° plies closest to the mid-plane was 1.55mm either side of the sharp notch, smaller than the measured micro-buckling length for the blocked central 0° plies in SS1. The kink angle, β, was defined by the angle at which the micro-buckling propagates from the reference x axis for the 0° ply close to mid-plane. For SS2 this was measured at 43.5°, which is different to SS1 for which the micro-buckling was almost parallel to the reference x axis. It is likely that the presence of the central double 45° adjacent to the 0° ply can have an influence on the kink angle of the specimen. Slight matrix splitting is also visible on the left side of Fig.7b, however not as long as observed in SS1. A small amount of delamination was present on the outer 0° plies for the SS2 specimens. The mean of the micro-buckling length for all the 0° plies was 1.50mm with a C.V. of 50%.



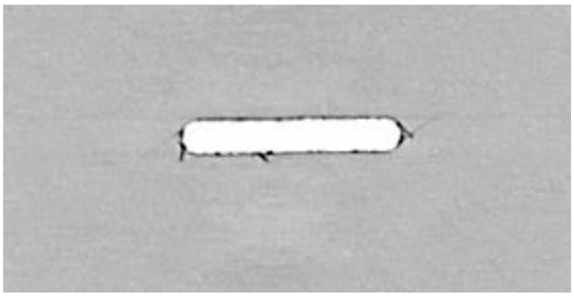
a) Central double 45° ply block



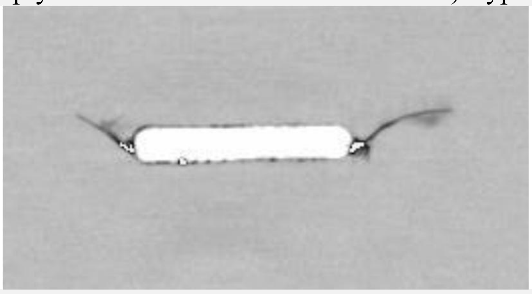
b) Single 0° ply close to the midplane



c) Typical 90° ply



d) Typical -45° ply



e) Single 0° outboard ply

Figure 6- SS2 CT scan images for individual plies

4 DISCUSSION

From the analysis of the CT scan images of SS1 and SS2 it can be concluded that there is a difference in the extent of damage when comparing the central blocked 0° plies for SS1 and the single 0° ply close to the mid-plane for SS2. However, there is no significant difference between the average micro-buckling lengths for SS1 and SS2 as it was within the high C.V. in the reported lengths. Figure 7 shows the error bars obtained from the scatter during testing of the different specimens. The reported C.V.s for the SS1 and SS2 experimental tests are good for composite testing, however the scatter present means that the small differences in the failure stress were inconclusive.

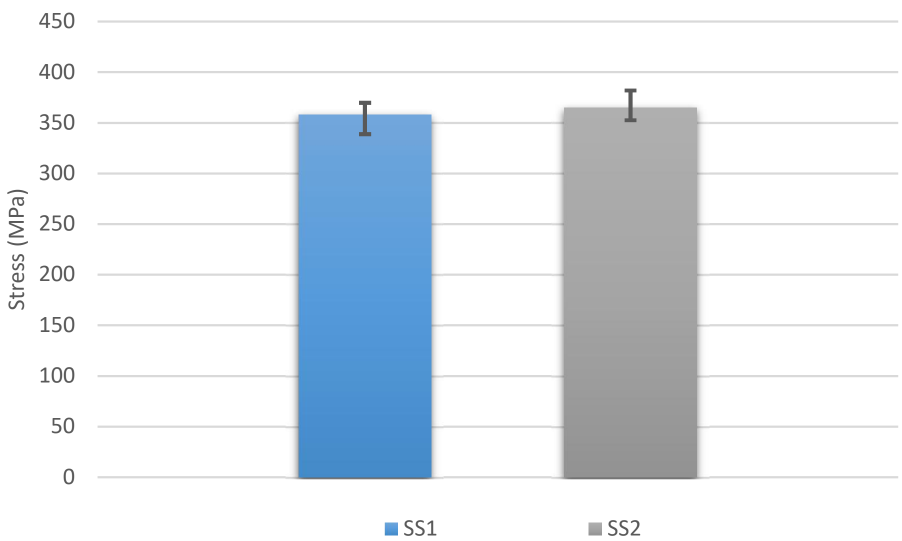


Figure 7- SS1 vs SS2 experimental results

4 CONCLUSIONS AND FUTURE WORK

Two sharp notched quasi-isotropic stacking sequences of $[45/90/-45/0]_{4s}$ (SS1) and $[90/-45/0/45]_{4s}$ (SS2) was tested under compression. For SS1, it was found that the sharp notched strength of composite laminates was about 53% of its un-notched strength for the baseline case. Similar failure stresses were found for both SS1 and SS2. Comparing the CT scans, a difference in the extent of damage was found between outboard single 0˚ plies and the central double 0˚ ply, but the average micro-buckled lengths for all plies were similar. Future work will consider experiments with 2mm sharp notched specimens of SS1 and SS2 to find whether the increased % of 0˚ plies affects the compressive strengths.

5 REFERENCES

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