The Effect of Ply Thickness and Notch Size in CFRP Tension Specimens

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Abstract

With the increasing application of fibre-reinforced composites into aircraft structures, understanding the effect of material and structural parameters on their damage behaviour is critical. An experimental investigation was conducted to study the effect of ply thickness and notch size on the damage of carbon fibre-reinforced composite specimens. Open hole tension and ply drop specimens in a range of configurations were tested quasi-statically until ultimate failure or the onset of detectable damage. The load response, damage modes and strain field development were experimentally recorded. The results demonstrated that changing the ply thickness and specimen dimensions markedly affected the damage modes and specimen behaviour. This key insight into the nature of composite behaviour is critical for the development and validation of analysis methodologies capturing damage initiation and progression.

Keywords: composites; scale effects; experimental testing; open hole tension; ply drop.

Introduction

Fibre-reinforced polymer (FRP) composites are finding increasing application in aerospace, and other industries due their advantages in performance, structural efficiency and cost. However, despite many years of research, an accurate and validated methodology for predicting the behaviour of composite structures including the effects of damage has not yet been fully adopted by industry as a design or material certification and qualification tool. One aspect that remains critical for composite materials is the issue of scale effects, where damage initiation and progression can be significantly influenced by the relative size of the specimen, any notches or structural details, and the thickness of the composite plies.

In this work, an experimental investigation was conducted into the damage modes, notched performance and scale effects of carbon fibre-reinforced polymer (CFRP) composite coupons. Notched coupons were tested in quasi-static tension loading until ultimate failure or the onset of detectable damage. The goal of the study was to experimentally characterise the damage modes and scale effects, and investigate the relationship between damage progression and the surface strains. This output is critical for the development and validation of analysis methodologies, such as those described in a companion paper [1]. The results in this work are part of a broader collaborative research project investigating an energy-based multi-axial material characterisation methodology for composite materials, which is capable of incorporating length scale effects [2-4].
Specimen Design and Test Procedure

Two tension specimens were tested: Open hole (OH) specimens (Fig. 1) and specimens incorporating a ply drop (PD) region as a ‘notch’ (Fig. 2). Varying lay-ups were used, where the ply thickness was effectively increased by using multiple plies in the same orientation, whilst keeping the overall thickness and ply angle proportions constant. The lay-ups were classified as “single-ply”, “two-ply” or “four-ply”, depending on the number of repeated plies. The OH specimens used single-ply and four-ply lay-ups, whilst the PD specimens used single-ply and two-ply configurations. The coupons were manufactured from AS4/3501-6 carbon/epoxy uni-directional prepreg, with nominal ply thickness 0.13 mm.

Strain gauges (SGs) were applied in the far-field region and adjacent to the notch on one side of the specimen, as shown in Fig. 3. Both SGs were in the loading direction, or 0° direction as shown in Fig. 1 and Fig. 2. On the other side of the specimen an optical full-field strain measurement system was applied with screen printing, which tracked the movement during the test of dots screen printed onto the specimen surface. The processing of the test images was conducted using the REMDIS2D software package, from the Computational Multiphysics Systems Laboratory of the U.S. Naval Research Laboratory [6].

OH specimens were tested in un-notched (OH-00), 0.5” hole (OH-05) and 1.0” hole (OH-10) configurations. For the specimens with holes, the in-plane dimensions were scaled with the hole diameter. In a previous study, OH specimens of similar configuration but shorter gauge length were investigated [5]. However, there were some issues found with hole drilling generating back face delamination. In this study, the holes were manufactured with diamond-tip drill bits and sacrificial plates on the front and back surface to prevent delamination.

The PD specimens were designed with three 12-ply sublaminates on one side and the 12 centre sublaminates sequentially terminated in a stepped pattern, leaving two 12-ply sublaminates on the other side. The thinner end was tabbed so that both ends had the same thickness in the grips.

All tests were conducted at the Defence Science and Technology Organisation (DSTO), Melbourne. OH tests were conducted on a 250 kN Instron hydraulic test machines, whilst PD specimens were tested on a 100 kN MTS hydraulic test machine. OH specimens were loaded in tension quasi-statically until ultimate failure. One OH specimen of each configuration was tested in a sequential manner, to attempt to identify the onset of damage. For these sequential loading tests, the specimens were loaded to a pre-set level, then unloaded and inspected with a hand-held ultrasonic (US) A-scan. This was continued until damage was detected, or ultimate failure occurred. An example of damage detection is shown in Fig. 4, where the US signal showed peaks at the front and back faces and any delaminations. The PD specimens were loaded until a cumulative load drop of more than 5% was visible relative to the initial linear behaviour, which occurred at a clear damage event. This event was referred to as “failure”.

From each test, a range of output was generated. For the OH specimens, the ultimate load for each specimen corresponded to the maximum load in the test, and was used to calculate the maximum stress, $\sigma_{\text{max}}$, using the nominal undeformed cross-sectional area. For failure initiation, the strain history at the notch gauge (or far-field gauge for the un-notched specimens) was used. A 5% non-linearity (5% NL) point was determined, taken as a deviation of 5% from a linear fit to the initial load-strain results. At this load, the stress, $\sigma_{\text{NL}}$, was recorded.
Fig. 1: OH specimen details, dimension in mm (not to scale)

<table>
<thead>
<tr>
<th></th>
<th>d</th>
<th>w</th>
<th>l</th>
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<tbody>
<tr>
<td>OH-00</td>
<td>0.0</td>
<td>25</td>
<td>170</td>
</tr>
<tr>
<td>OH-05</td>
<td>12.7</td>
<td>50</td>
<td>170</td>
</tr>
<tr>
<td>OH-10</td>
<td>25.4</td>
<td>100</td>
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Number of specimens

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<tr>
<th></th>
<th>OH-00</th>
<th>OH-05</th>
<th>OH-10</th>
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</thead>
<tbody>
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<td>3</td>
<td>3</td>
</tr>
<tr>
<td>B: [+45, 0, -45]_{S}</td>
<td>3</td>
<td>3</td>
<td>3</td>
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</table>

Fig. 2: PD specimen details, dimension in mm (not to scale)

Number of specimens

<table>
<thead>
<tr>
<th></th>
<th>A: [+45, 0, -45]_{4S}</th>
<th>A, B</th>
</tr>
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<tbody>
<tr>
<td>A</td>
<td>3</td>
<td>A, B</td>
</tr>
<tr>
<td>B</td>
<td>3</td>
<td>A, B</td>
</tr>
</tbody>
</table>

Fig. 3: SG locations, dimension in mm (not to scale)

s = 50 (OH-05)/100 (OH-10)

Fig. 4: OH four-ply specimen, interface labelling and example US scan
Experimental Results

OH specimens

The results of the OH tests are summarised below, where Fig. 5 gives the average stress results for damage initiation and ultimate failure, Fig. 6 summarises the damage modes seen in the tests after ultimate load, and Fig. 7 summarises the results of the sequential loading with US scanning. Fig. 7 only contains results for the four-ply laminates, as no damage was detected during sequential loading of the single-ply laminates.

For the un-notched specimens, no significant non-linearity was seen prior to ultimate load. Increasing the ply thickness by four for these specimens decreased the laminate strength by around 26%. For the 0.5” hole specimens, 5% non-linearity was seen prior to ultimate load for both specimens. For the single-ply 0.5” hole, 5% non-linearity was seen at 78% of the ultimate strength, and the ultimate strength was 40% of the un-notched laminate. On the other hand, the four-ply 0.5” hole specimen showed earlier onset of non-linearity at 38% of ultimate strength, but an ultimate strength that was higher than the single-ply specimen and 66% of the un-notched strength. This difference was attributed to the failure mode (Fig. 6), where the single-ply specimens showed tension failure dominated by fibre fracture spreading from the hole edge perpendicular to the loading direction. The four-ply laminates showed significant delamination damage, which indicated that the development and progression of delamination throughout the laminate absorbed considerable energy and delayed the onset of fibre fracture. The US scanning procedure (Fig. 7) revealed that the four-ply specimens developed damage at four locations around the hole, corresponding to the fibre direction of the 45° and -45° plies. Delamination damage was seen to match at diagonally opposite locations. For the 1.0” hole specimens similar results were seen with regards to failure mode and comparison to the un-notched laminates. Doubling the notch size to 1.0” led to an 8% reduction in ultimate strength but a 17% increase in the load for 5% non-linearity, such that the single-ply specimens did not show any significant non-linearity prior to ultimate failure.

![Fig. 5: OH specimen, average stress results for 5% non-linearity and maximum stress](image-url)
**Fig. 6: OH specimen, failure mode after ultimate load**

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Dominant failure mode</th>
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<tbody>
<tr>
<td></td>
<td>0.0” hole</td>
</tr>
<tr>
<td>single ply</td>
<td>grip / tension</td>
</tr>
<tr>
<td>four ply</td>
<td>grip / tension</td>
</tr>
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</table>

Tension failure (single ply, 0.0” hole)

Tension failure (single ply, 0.5” hole)

Delamination failure (four-ply, 0.5” hole)

Tension failure (single ply, 1.0” hole)

Delamination failure (four-ply, 1.0” hole)
Fig. 7: OH specimen, damage detected from sequential loading and US scanning, with lengths of damage from the hole edge measured in the radius direction

**PD specimens**

The results of the PD tests are summarised in Fig. 8 to Fig. 10, where Fig. 8 shows the average results for stress and strain for the “failure” point (more than 5% load non-linearity), Fig. 9 shows simplified schematics of the damage pattern seen on the specimen edges following failure, and Fig. 10 is an example of edge damage for a single ply laminate. For both laminate types, failure was seen as a combination of delamination and through-thickness cracking, as shown in Fig. 9 and Fig. 10. This event was detected by a clear drop in load and was accompanied by a cracking noise. The damage pattern was inspected with microscopy on both edges of all specimens following failure, and it was seen that interlaminar cracks tended to propagate mainly along interfaces between $0^\circ$ and $\pm 45^\circ$ plies. Interlaminar cracks were rarely seen at a $45^\circ/-45^\circ$ interface (though there were not many of these), and never between plies of the same orientation. As shown in Fig. 9 and Fig. 10, cracks spread throughout the specimen between plies (interlaminar) and through plies (intralaminar), and appeared to initiate at the first $0/45$ interface of the ply drop region on the thinner side of the specimen. Generally, interlaminar cracks spread from the notch region all the way to the grip regions. As evident in Fig. 10, there was significantly more intralaminar cracking than shown in the simple patterns in Fig. 9, as well as interlaminar cracks along interfaces other than those shown. More intralaminar cracking was seen in the single-ply specimens than two-ply specimens. The damage patterns were also not identical on both edges of the same specimen.
Fig. 8: PD specimen, average results for stress and strain at failure

Fig. 9: PD specimen, simplified edge damage pattern
From Fig. 8, doubling the ply thickness led to reductions in the stress, ply drop strain and far-field strain at failure of 4%, 6% and 3% respectively, though these reductions were all within the range of experimental scatter. For one of the single-ply specimens, slipping of the specimen in the grips led to laminate failure at the grips, and this specimen was excluded from the results in Fig. 8. During testing, a clearly audible cracking noise was heard for one of the single-ply specimens at 70% of the failure stress, and for two of the two-ply specimens at an average of 50% of the ultimate failure load. This cracking was not always accompanied by any noticeable change in the load or strain behaviour.

**Discussion**

**Effect of ply thickness**

For the OH specimens, the results demonstrated that the effect of increasing ply thickness was reduced ply strength. This was seen as a lower ultimate strength and strain for the un-notched specimens, where a 26% reduction in strength was seen between the single-ply and four-ply laminates. This was thought to be caused by the way in which matrix cracks initiate and extend to cover the total ply thickness. As such, matrix cracks that initiate in thicker plies involve larger cracks, and as further matrix cracks accumulate these larger cracks have a lower strength than if they were dispersed through thinner plies. Such behaviour also explains why a series of fibres have far superior properties than the same volume of material in a single block.

More importantly, the change in ply thickness had a critical influence on the specimen behaviour, as the failure mode changed. Matrix cracking at the hole edge for the thicker ply specimens was shown to lead to the occurrence of delamination between plies. It is not exactly clear why matrix cracks in thicker plies promoted much more delamination than in thinner plies. However, this is likely related to similar discussions as above, where a matrix crack in a thicker ply produces a much larger crack, which would have larger crack opening displacement and as such promote more delamination. The occurrence of delamination in the four-ply laminates led to a more diffuse damage progression, so that whilst damage initiated earlier in the four-ply specimens, these specimens actually had an increased ultimate strength. These results demonstrate the link between matrix cracking and delamination, and the energy-absorbing characteristics of delamination growth.

For the PD specimens, the effect of ply thickness was not obvious from the failure or edge damage patterns. As mentioned, audible cracks were heard at 70% of the failure load for one single-ply specimen, and 50% of the failure load for two of the two-ply specimens. This suggests an early initiation of failure for thicker plies, which agrees with the OH results. The cracking was not heard for all specimens, which may have been due to the difficulty in detecting aural events in a laboratory environment without specialist equipment. Regardless, the difference in early initiation between single-ply and two-ply laminates did not translate to a
difference in failure load or damage pattern. In other words, whether or not some form of damage initiated at 50% or 70% of the failure load, a difference of only 4% in failure stress was seen. This may have been related to use of the same ply drop stepped pattern for both laminates, where plies were stepped individually. As such, matrix cracks that initiated at the end of plies in the two-ply laminates would only have extended to cover one ply. Further, for the multi-path failure process involving intralaminar and interlaminar cracks and including cracking along the stepped region, the ply drop steps may have acted in essence as an initial flaw. In this respect, the onset of failure would not have been influenced by any difference in matrix crack initiation, or whether the first 0/45 interface was offset by one ply thickness.

With regards to damage patterns for OH and PD specimens, there were differences between the laminates that were related to the fact that for the two-ply and four-ply laminates there were fewer interfaces that cracks could propagate along, as cracks never propagated between plies of the same orientation. This led to reduced intralaminar cracking for the two-ply and four-ply laminates, though there was no indication that any reduction in intralaminar cracking led to any change in the amount of interlaminar cracking.

Effect of notch size

For the OH specimens with holes, the results showed that doubling the notch size (and in-plane dimensions) led to an 8% decrease in the ultimate strength for both the single-ply and four-ply specimens. This shows that regardless of failure mode, increasing the hole size, and as such the size of the stress concentration and length of the high stress region away from the hole, caused failure at lower loads. On the other hand, doubling the notch size led to an increase in the stress at 5% non-linearity of 18% and 17% for the single-ply and four-ply specimens. Furthermore, inspection of the strain gauge data showed that for the four-ply specimens, the onset of delamination around the hole could be correlated to a clear slope change in the load-strain history. Whilst the onset of delamination increased the rate of strain accumulation for the 0.5” hole specimens, for the 1.0” four-ply specimens a decrease in strain was seen. Both the increase in non-linearity onset and the different load-strain character indicated differences in the damage behaviour between the 0.5” and 1.0” holes. However, these differences may be related to the fact that the damage occurred at the 45° locations around the hole, as shown in Fig. 7, whereas the strain gauge was located at the 90° location. Further work is continuing on studying the full-field strain data, to more accurately identify non-linearity and more closely associate this with the damage behaviour.

Conclusion

An experimental investigation was conducted into the ply thickness and notch size effects of open hole and ply drop specimens. The following conclusions were made:

- For un-notched specimens, increasing the ply thickness by a factor of 4 led to a 26% reduction in the ultimate tensile strength, demonstrating the reduced strength associated with thicker plies.
- For OH specimens, the change in ply thickness led to a clear change in damage mode, from fibre-dominated damage in the single-ply laminates with 40% of the un-notched strength to delamination-dominated damage in the four-ply laminates with 66% of the un-notched strength.
- For the OH specimens, doubling the notch size and in-plane dimensions led to an 8% reduction in the ultimate strength, regardless of failure mode.
For the PD specimens, the first major failure event involved a complex combination of multiple intralaminar and interlaminar cracks, which appeared to originate at the end of the ply drop region on the thinner side of the specimen.

For the PD specimens, doubling the ply thickness led to only a 4% reduction in failure load. Cracking heard during testing suggested damage initiation prior to failure at 70% and 50% of the failure load for the single-ply and two-ply specimens.

The results of this investigation are important for further understanding composite material behaviour and developing robust predictive tools for capturing progressive laminate damage.

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References


