AN INVESTIGATION INTO THE DAMAGE DEVELOPMENT OF OPEN HOLE SPECIMENS IN FATIGUE

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Abstract
An extensive experimental program was carried out to investigate and understand the sequence of damage development throughout the life of open hole composite laminates loaded in tension-tension fatigue. Two quasi isotropic carbon/epoxy laminates, with stacking sequence $[45_2/90_2/-45_2/0_2]_S$ and $[45/90/-45/0]_{2S}$ were examined. These were selected on the basis that under quasi-static loading they respectively exhibited delamination dominated and fibre dominated failure modes. Specimens were fatigue loaded at 5Hz with various amplitudes to 1E6 cycles or catastrophic failure, which ever occurred first. For both laminates failure occurred by delamination. A number of tests were interrupted at various points as the stiffness dropped with increasing cycles. The interrupted test specimens were inspected using X-ray Computed Tomography (CT) scanning in order to accurately determine a sequence of damage events leading to failure.

1 Introduction
In many applications fibre reinforced composite materials have become a replacement for more dense metals due to their excellent corrosion and fatigue properties as well as weight saving advantages. The lack of understanding of fatigue in composites can be a setback since. in terms of long-term service lifetime, failure with regards to fatigue represents the most uncertainty. Many applications, particularly rotating components, involve repeated loading cycles, which means the need to understand and evaluate fatigue is on the increase.

In previous work, Spearing and Beaumont [1] concentrated on tension-tension fatigue of notched Carbon/Epoxy (T300/914) and Carbon/Polyetheretherketone (PEEK) laminates using an R ratio of 0.1. NDT (non-destructive testing) techniques included X-radiography to produce images of the damage. It was also shown how prolonged exposure to the zinc iodide dye penetrant can accelerate the growth of damage in the specimens.

Broughton et. al. [2] carried out a study on open-hole tension-tension fatigue behaviour of a quasi-isotropic glass-fibre reinforced plastic GFRP laminate under constant amplitude and block amplitude loading. They showed that longitudinal strain, stiffness and surface temperature can be used to assess damage progression and fatigue life, and are potentially suitable for predicting notched fatigue performance. They also showed how the application of various measurement techniques such as fibre-Bragg grating (FBG) and digital image correlation (DIC) can be useful for fatigue damage assessment, and also highlighted localised

sub-critical damage at the hole edge. They did not however conduct a detailed study of the damage mechanisms and sequence of events occurring. This paper describes and compares the fatigue damage events in open hole tensile tests on two different quasi-isotropic layups on unidirectional carbon/epoxy prepreg.

2 Experimental Procedure

Two quasi isotropic carbon/epoxy laminates manufactured from Hexcel's IM7/8552 unidirectional pre-preg material system, with stacking sequence $[45_m/90_m/-45_m/0_m]_{ns}$ were used in this work. The first layup, with m=1 n=2 is defined as a dispersed ply laminate due to the repeated sublaminate units, which represents one of two ways of increasing the thickness of the laminate. The second with m=2 n=1 is defined as a blocked ply laminate due to the plies being blocked together in each orientation. From previous quasi-static testing [3], the blocked ply laminate had a delamination dominated failure, whilst the dispersed ply laminate had a fibre dominated failure. The load is applied in the 0º direction and the laminate had a central hole diameter of 3.175 mm, width of 16 mm, thickness of 2 mm, gauge length of 64 mm, and end tab length of 50 mm. For quasi-static tests, the specimens were loaded at 1mm/min until failure. A mean static failure load could then be established. Specimens were then loaded in tension-tension fatigue with R=0.1 at 5Hz at various amplitudes to 1E6 cycles or catastrophic failure (represented by a 15% drop in stiffness), which ever occurred first. A number of tests were interrupted at various points as the stiffness dropped with increasing cycles, using 60% severity tests in the blocked ply case and 80% severity tests in the dispersed ply case in order to accurately determine a sequence of damage events leading to catastrophic failure in fatigue.

The interrupted test specimens were inspected using X-ray Computed Tomography (CT) scanning in order to determine the level of damage in each specimen. CT reconstructions were carried out on each sample after scanning. This enables visualisation of a given sample as a 3D map in which features of interest such as delaminations and matrix cracking could be identified.

3 Static Testing

Five specimens of each layup were loaded to failure using a displacement rate of 1mm/min. Failure was taken as the first significant drop on the load-displacement curve (>5%). Previous analysis of quasi-static tests after failure using various thicknesses and layups had shown three distinct failure modes [3]:

- Pull-out - a fibre dominated failure mode with extensive sub-critical damage.
- Brittle - a fibre dominated failure mode with little or no sub-critical damage.
- Delamination - a matrix dominated failure mode.

The tests from the layups in the present study represent those from the Pullout (dispersed ply) and Delamination (blocked ply) failure modes. In both cases quasi-static tests were repeated before commencing the fatigue testing programme.

For the dispersed ply case pull-out failure was consistently obtained in each of the five specimens tested. The average failure load was 572 MPa with a CV of 3.1 %. For quasi-static tests, pull-out failure occurs when the fibre failure stress is reached between full width delamination of the surface 45/90 interface and the full width delamination of the -45/0 interface. If the fibre failure stress has not been reached at the point at which there is complete delamination at the -45/0 interface then delamination failure is achieved, as in the blocked ply case. For these tests a failure load of 446.8 MPa was recorded with a CV of 4.56%.

Interupted tests of the two cases show typical damage levels at 80% and 85% of the static failure load for blocked and dispersed ply tests respectively in figures 1 and 2.

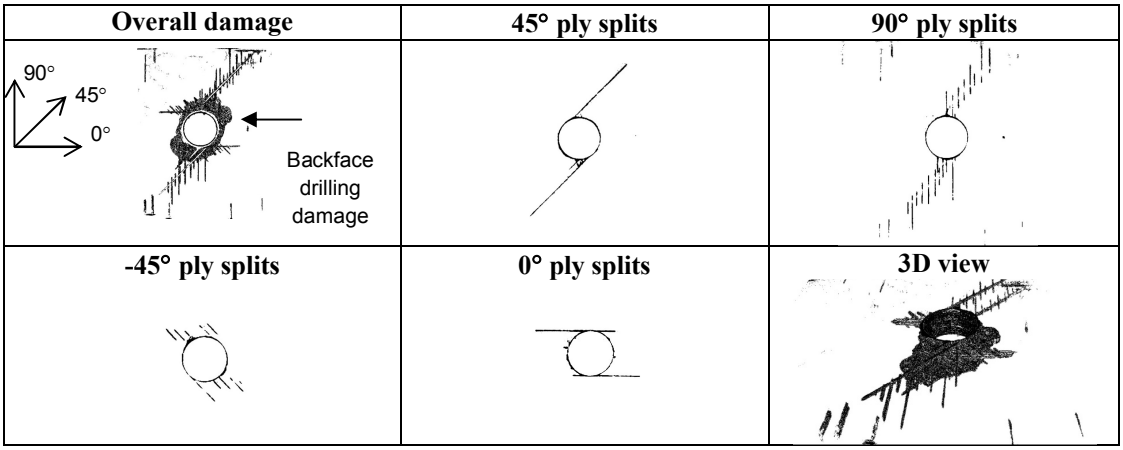

Figure 1. X-ray CT scan images from a blocked ply test interrupted at 80% static load, showing the damage initiation (from top left), the global damage pattern, +45 splits, 90 splits, -45 splits and zero splits.

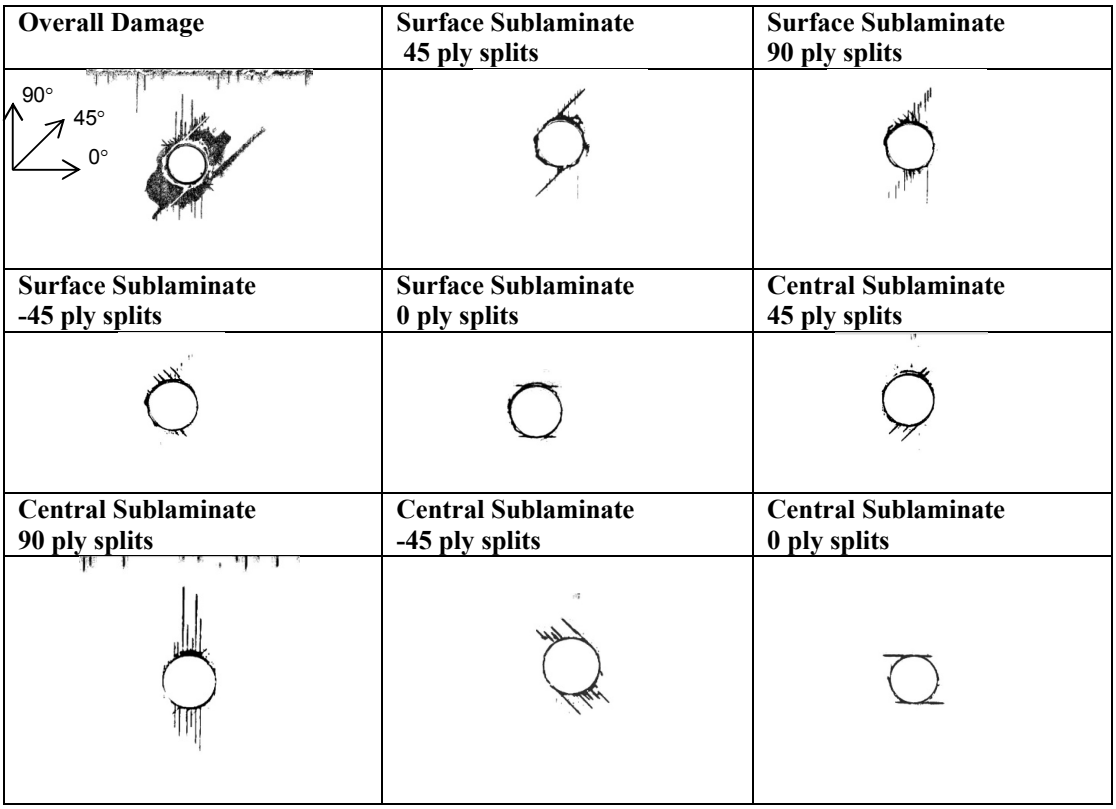

Figure 2. X-ray CT scan images from a dispersed ply test interrupted at 85% static load, showing the damage initiation (from top left), the global damage pattern, +45 splits, 90 splits, -45 splits and zero splits.

4 Fatigue Testing

For the ply blocked specimens the damage in general follows a similar pattern to the quasi-static failure and occurs in the following order:-

- Isolated damage around the hole and free edge of the specimen.
- Damage around the hole at inner delamination regions and damage that is localised around the free edge resulting from full width matrix cracks.
- Damage propagates across the full specimen width from the hole.
- Extensive delamination back to the grips at the -45/0 interface which was the cause of the catastrophic failure.

For the dispersed ply specimens, failure appeared to follow a very similar trend with delamination dominating in all but the very highest severities (>90%). It is notable that this differed significantly from the quasi-static failure which was dominated by fibre failure with no delamination progressing along the length of the specimen. It can thus be seen how the role of delamination is critical in the case of fatigue loading, even when it does not dominate in static tests.

As the fatigue severity decreases from 90% to 80% there is a transition from pullout to delamination failure for the dispersed ply specimens. At lower loads the fibre-failure stress is not reached during the development of damage prior to delamination across the full width of specimens. This explains why the fatigue results at 90% tend to shift the SN curve (figure 3) to the left as pullout failure occurs before delamination in the overall damage development sequence. In all severities lower than 90% we initially see subcritical damage mainly being confined to the outer sublaminate down to a normalised effective modulus of around 0.6 (figure 4). Then in the latter part of the stiffness drops the damage crosses over into the inner sublaminate regions, this can be shown as a kink in the stiffness curves (figure 4). There is a significant amount of free-edge delamination in comparison to the blocked ply interrupted tests. All of the splits and cracks are accompanied by small local delaminations in the adjacent interfaces and have a similar size to that of the ply thickness.

Figures 4 and 5 show the loss in stiffness, characterised as normalised effective modulus, for typical tests at each severity for both blocked and dispersed ply testing. Failure was taken as a 15% reduction in the normalised stiffness when plotting the SN curve (figure 3). The significant loss of stiffness relates to the accumulation of damage which is best characterised through interrupted testing as described in the next section.

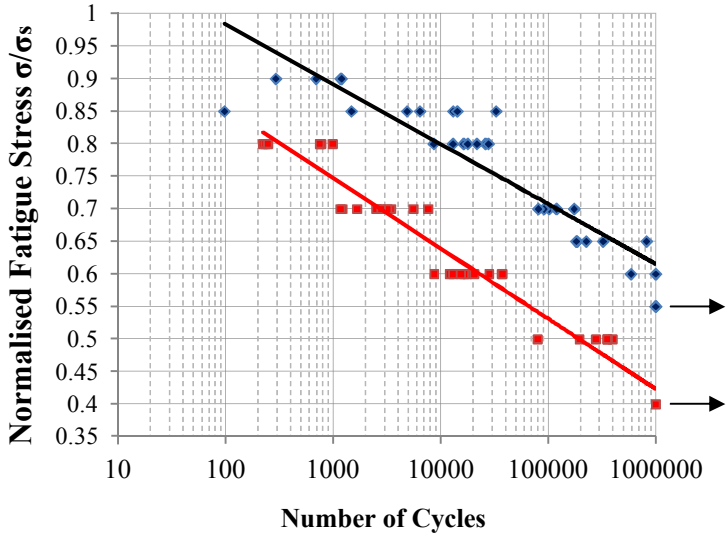

Figure 3. Plot showing both blocked and dispersed ply SN curves with runouts indicated using arrows.

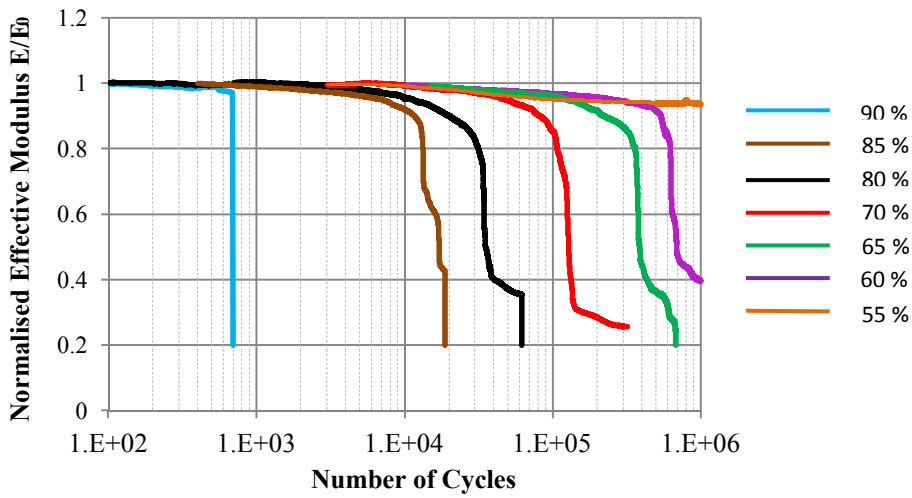

Figure 4. Typical fatigue stiffness curves at each severity for the dispersed ply test program.

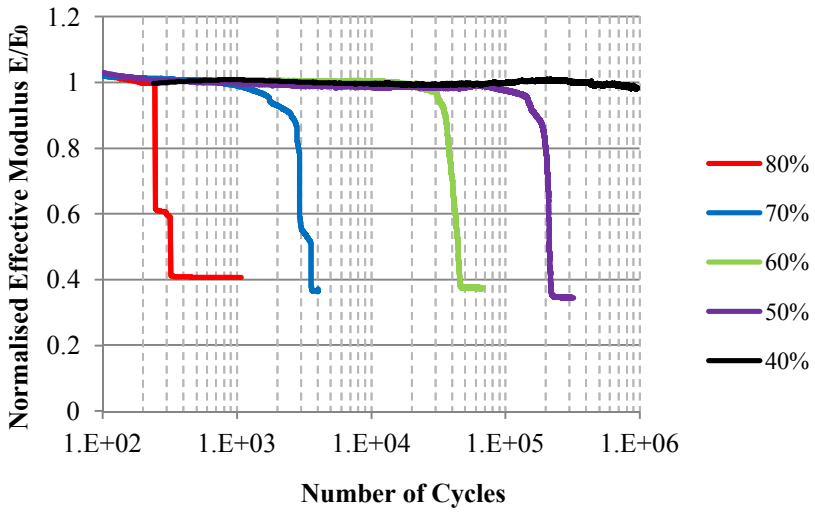

Figure 5. Typical fatigue stiffness curves at each severity for the blocked ply test program.

5 Fatigue Interrupted Testing

A range of tests were interrupted during the stiffness loss/damage accumulation process. Figures used in this section are typically from tests interrupted at around 0.85 normalised effective modulus as this was used as the failure criterion to generate the SN curves in the previous section.

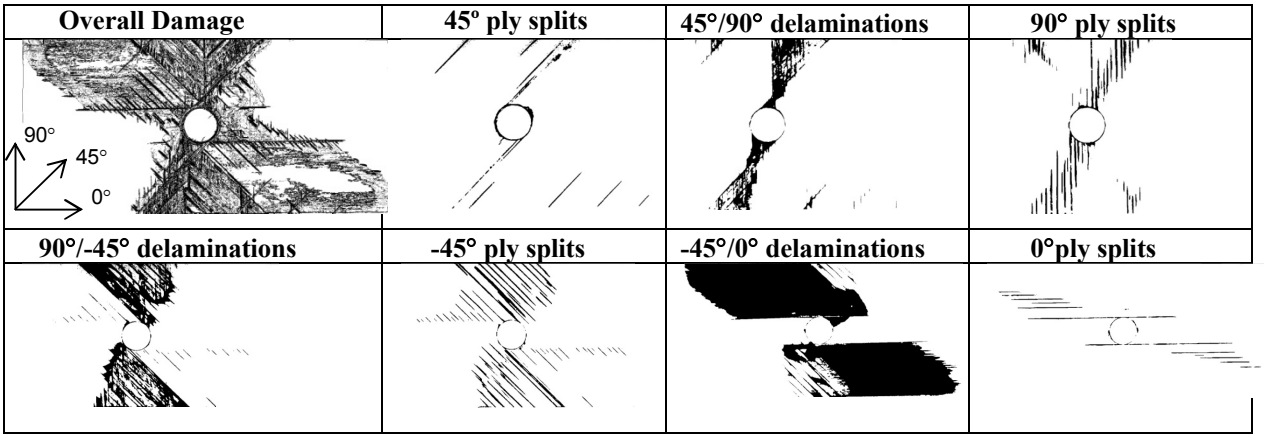

Figure 6. X-ray CT images from an interrupted test for a blocked ply laminate at 60 % severity.

In the blocked ply test shown in figure 6 which is from a test at 60% severity there is clear evidence of the delamination propagating at the 0/-45 interface. No delamination at this interface is observed in the static interrupted test at 80% of static load (figure 1). This is the most dominant damage process responsible for the sudden drop in the load in static failure and therefore this isn't observed until catastrophic failure which in fatigue is more of a gradual process.

For the dispersed ply fatigue interrupted test, there is extensive delamination at the surface 0/-45 interface and also in between the long zero splits at the lower interface to the +45 ply. This occurs relatively early in the drop in stiffness. The delamination eventually crosses over into the areas between the zero splits seen in the most severely damaged interrupted tests. This effect is shown by the x ray damage of the -45/0 and 0/+45 delaminations (Figure 7).

In the dispersed ply specimens, there is a greater degree of global matrix cracking that can initiate delamination damage at the interface.

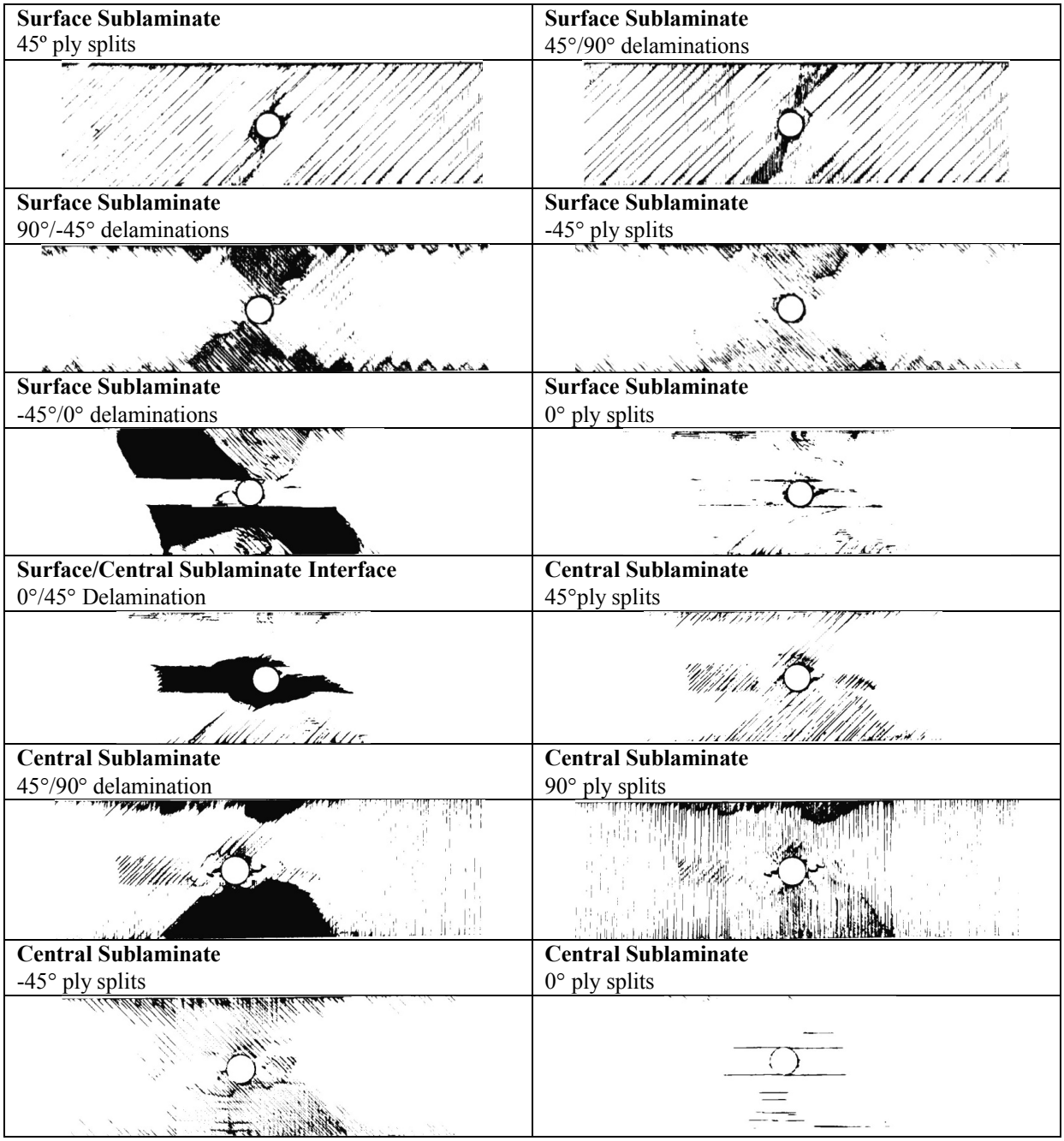

Figure 7. X-Ray CT Images from an interrupted test for a dispersed ply laminate at 80% severity with an approximate load drop of 15%.

Conclusions

Carbon fibre epoxy laminates of thickness of 2 mm, width of 16 mm, gauge length of 64 mm, with a central hole diameter of 3.175 mm were loaded in static and fatigue for dispersed and blocked ply configurations. In the static tests the two layups used had different failure modes. In fatigue however both were shown to be dominated by delamination. X-ray computed tomography (CT) data of the interrupted tests showed that, initially damage starts to propagate out from the hole edge in terms of matrix cracks and delamination. Asymmetric 0/-45 delaminations cause a large drop in effective modulus. This is the dominant failure event for the blocked ply specimens. For the dispersed ply specimens damage occurs in the outer

sublaminates first and then passes through into the central sublaminates with a greater degree of distributed matrix cracking.

References

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