An extensive experimental program has been carried out to understand the sequence of damage events throughout the life of notched composite laminates loaded in tension-tension fatigue.

Several tests were interrupted during the decrease in stiffness for both ply and sublaminate configurations.

X-ray CT scans were carried out for all interrupted tests to determine the level of damage in each specimen.
Open Hole Test Program

- Specimens were loaded to failure in static tests.
- Based fatigue load levels both experimentally and numerically on the average of their respective static failure loads.
- Fatigue tests were ran at various load levels at 5Hz up to 1E6 cycles or until failure.
- Each test is at constant amplitude with an R ratio of 0.1.
- Failure is taken as a 15% reduction in stiffness.

Figure 1. Specimen Geometry
Ply Scaled Testing

- Hole size of 3.175 mm, ply level scaling, symmetric quasi-isotropic layup with ply orientations $[45_2, 90_2, -45_2, 0_2]_s$

- Tests were carried out in fatigue at 40%, 50%, 60%, 70% and 80% of the static failure load for ply level laminates.

- The same mode of failure is observed for specimens in fatigue to that of the static specimens which is delamination dominated. Dominant failure mode is the delamination at the $0/-45$ interface.

- Runouts to 1E6 cycles are observed at 40% severity.

Figure 2. shows SN Curve for ply scaled Specimens
Ply Scaled Interrupted Testing

<table>
<thead>
<tr>
<th>45° ply splits</th>
<th>45°/90° delaminations</th>
<th>90° ply splits</th>
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<td><img src="image2.png" alt="Image" /></td>
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<table>
<thead>
<tr>
<th>90°/-45° delaminations</th>
<th>-45° ply splits</th>
<th>-45°/0° delaminations</th>
<th>0° ply splits</th>
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<tbody>
<tr>
<td><img src="image4.png" alt="Image" /></td>
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<td><img src="image6.png" alt="Image" /></td>
<td><img src="image7.png" alt="Image" /></td>
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</tbody>
</table>

Figure 3. Shows Interrupted test (b) sample 033, X-Ray CT Images.

Figure 4. Showing the progression of the delamination at the 0/-45 interface for several interrupted tests of increasing levels of damage.
Sublaminate Scaled Testing

- Hole size of 3.175 mm, sublaminate level scaling, symmetric quasi-isotropic layup with ply orientations [45, 90, -45, 0]$_2$s

- Tests were carried out in fatigue at 55%, 60%, 65%, 70%, 80%, 85% and 90% of the static failure load for sublaminate level laminates.

- Mode of failure in static tests defined as ‘pullout’, a fibre dominated failure mode. However for specimens in fatigue there is a change to a delamination dominated failure mode.

- Runouts to 1E6 cycles is observed consistently at 55% severity.

Figure 5. show SN Curve for sublaminate scaled Specimens

Figure 6. X-ray CT image of the 0/-45 delamination of an interrupted test specimen from the fatigue sublaminate scaled program.
FE Modelling

• Fully integrated solid interface elements were placed between coincident nodes in order to predict the initiation and propagation of subcritical damage.

• Previous experimental observations had shown that these were the major splits that are significantly involved in specimen failure.

• Quasi-static numerical failure loads agree well with static experimental failure loads.

• A half model through thickness is used as the layup under investigation is symmetric about the centreline.

• Thermal residual stresses were included in the model to simulate cool-down from the $180^\circ$C processing temperature to room temperature.

Figure 7 showing location of inserted splits within the model and loading condition.
FE Modelling

- The model is mode I and II maximum interfacial strength dominated where mode I strength is 60 MPa and mode II strength is 90 MPa.

- A crack tip tracking formulation is used for accurate determination of crack fronts.

- The fatigue FE Modelling results also agree well to that of the experimental results (figure 8).

![Graph showing Normalised Fatigue Stress vs Number of Cycles](image)

**Figure 8** Shows FE results for the ply scaled program with the experimental results superimposed.

**Figure 9.** Progression of the delamination at the 0/-45 interface in the FE model.
Conclusions and Further Work

- Ply-level Specimens failed with a delamination dominated mode in both quasi-static and fatigue tests.

- Sublaminate Specimens failed with a fibre dominated mode in quasi-static tests, but in fatigue testing a delamination dominated failure mode is observed.

- The location and sequence of failure events from FE modelling agreed well with those of the experimental results.

- Future objectives includes a pilot study recently started on a new sublaminate configuration which is shown to give a brittle failure mode in static tests.

- Residual strength testing for runouts on recent sublaminate study plus the new configuration.
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Any questions?