3D-woven composite - Defect detection

Depth 0.1 mm below the surface

Extract a Unit cell

FE modelled data
Cross-correlate with unit cell

Maximum of the cross-correlation (red) corresponds to the centre location of the unit cells.
Create benchmark scan using a unit cell at each peak in the cross-correlation…

Then subtract benchmark scan from measured scan…

Original scan  Benchmark scan  Subtraction result
3D-woven composite - Defect detection

Real specimen: 1.7 mm thick (5-layers). FVF≈50%

- Sticker placed to check orientation of sample
- Resin columns allowing light through
- Resin block from infusion
- Tape around the edges showing delimitation of the scanned regions
- Real specimen top view (and back-lit)
Single unit cell extraction

C-Scan 0.1mm below the surface (showing the unit cell chosen)

Unit cell dimension
3D-woven composite - Defect detection

Benchmark scan vs Original scan

Original scan

Benchmark scan

Then subtract benchmark scan from measured scan...

Subtraction result
3D-woven composite - Defect detection

- Extension to 3D
  - Same process performed for each in-plane layer in the 3D data.
  - Six different depths below surface...

Depth: 0.14 mm
Depth: 0.42 mm
Depth: 0.70 mm

Depth: 0.99 mm
Depth: 1.27 mm
Depth: 1.7 mm
2D Woven Composites
• Warp and Weft angles and spacing – plain weave

These lines have Miller indices (01) and (10) (indistinguishable)

But also truly identical ‘pattern’ lines at twice this spacing (0½)
• Lattice lines are described this way...

• ...and weave-characteristic lines using fractional indices
Image Transformation

- Radon Transform & FFT gives: spatial-frequency vs angle

N=5 for 5-harness satin weave

Lattice lines

Weave Characteristic lines

$\left( \frac{1}{5} - \frac{3}{5} \right) \quad \left( \frac{2}{5} - \frac{1}{5} \right) \quad \left( \frac{3}{5} \frac{1}{5} \right) \quad \left( 1 \frac{2}{5} \right)$
Weave Classification

\[ \frac{1}{2} - \frac{1}{2} \quad \frac{1}{3} \quad \frac{1}{3} \]
• Map $\delta$ - the angle between warp and weft
• In this case, $\delta = 110^\circ$ between warp and weft
Simulated 5-harness satin weave with sine-wave in-plane waviness.

0/90 and +45/-45 plies are shown.

Colour is shear angle measurement.
Transitioning academic algorithms to multiple supply-chain partners

- Transition software-engineering documents, not actual software.
- Allows customisation within pre-existing commercial software packages.
• Manufacturing Technology Centre (MTC), UK
  • New programme to ease transition of academic public-domain algorithms into industry
• Algorithm Deployment Support Service (ADSS)
• Manufacturing Technology Centre (MTC), UK
  • New programme to ease transition of academic public-domain algorithms into industry

• Algorithm Deployment Support Service (ADSS)

Process flow:

1. Generation of software specification: requirements, design & test documents
   - University
   - MTC
   - OEMs

2. Collection of test data inputs (Optional)
   - MTC
   - Supplier(s)

3. Implementation of software produced to specification
   - Supplier(s)

4. Implementation tested and certified to specification
   - MTC
   - Supplier(s)
• Some industries insist on multiple suppliers
  • A new design strategy based on NDT requires confidence in long-term support
  • Sole-supplier is often unable to provide that.
• Publish science, algorithms, validation
• Enable implementation with multiple suppliers
  • University prepares software engineering documents
  • Supports implementation
  • BUT end-users require confidence in implementation
Pilot scheme - NDT Algorithms

- Ultrasonic 3D imaging of composites
  - EPSRC Fellowship in Manufacturing 2013-2018
  - End-user-funded collaborative project (9 partners)...

<table>
<thead>
<tr>
<th>Academic Research</th>
<th>End users</th>
<th>NDT Supply Chain</th>
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<tbody>
<tr>
<td>University of Bristol</td>
<td>Rolls Royce</td>
<td>Ultrasonic Sciences Ltd</td>
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<td>BAE Systems</td>
<td>DolphiTech</td>
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<td><strong>Software engineering &amp; testing</strong></td>
<td>Dstl (MoD)</td>
<td>Wavelength NDT / UTEX</td>
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<tr>
<td>Manufacturing Technology Centre</td>
<td>GKN/Fokker Aerospace</td>
<td>+ 1 other</td>
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<td></td>
<td>Wind turbine company</td>
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- Deployment of novel algorithms in industry (MTC)
  - Algorithm Deployment Support Service
    - Software-engineering document generation
    - Validation tests
Ultrasonic 3D imaging of composites

- Ultimate aim is to underpin lighter designs:
  - Full 3D inversion of material properties and defects
  - NDT-based performance prediction of as-manufactured, or damaged components
Ultimate aim is to underpin lighter designs:
- Full 3D inversion of material properties and defects
- NDT-based performance prediction of as-manufactured, or damaged components

‘Chicken and Egg’ problem
- NDT implementation requires ‘pull’ from OEMs
- Aircraft design ‘pull’ requires established NDT technology.

Preliminary phase: solve a current problem
- Better-informed concessions – enhanced ‘imaging’
Advantages of MTC approach

• Offers traceability of requirements to implementation
• Offers 3D perspective to documentation
• HTML enables documents to be easily transferred and hosted on site
• Offers an intuitive way that a user can control the level of information they want to see
<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Development and testing of Software Engineering Documents</td>
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<tr>
<td>Stage 1</td>
<td>Nov 2018</td>
<td>Jan 2019</td>
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<td>2nd Supplier implementation</td>
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<tr>
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<td>Sep 2019</td>
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<tr>
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</tr>
<tr>
<td>Stage 3</td>
<td>Oct 2019</td>
<td>Nov 2019</td>
<td>Dec 2019</td>
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Conclusions

• Analytic Signal formulation separates phase (ply spacing) effects from amplitude (resin layer thickness).
• Ply tracking uses phase to track resin layers.
• Out-of-plane wrinkles can be measured using structure tensor applied to phase data.
• In-plane waviness measured using Radon transform on amplitude data.
• 3D weaves characterised and defects detected using cross-correlation of amplitude data vs benchmark.
• 2D weaves classified using image transformation of amplitude data, Miller indices, and distortions mapped.
Publications (presentation code: 44999)

Analytic signals and ply tracking:

Out-of-plane ply orientation and wrinkle measurement:

In-plane fibre direction and stacking sequence:
Ply Wrinkle Measurement

• Structure-tensor method

• 2D or 3D gradients in data

Rock strata imaging – Geological sciences

\[ S = \begin{bmatrix} I_x^2 & I_x I_y \\ I_x I_y & I_y^2 \end{bmatrix} \]

Eigenvectors of the tensor indicate orientation at that pixel location.

\[ \lambda_1 = \lambda_2 = \lambda_3 \quad \lambda_1 \gg \lambda_2 = \lambda_3 \quad \lambda_1 = \lambda_2 >> \lambda_3 \]

Fig. 3. Examples of three classes of structure in 3D data (above) and the corresponding structure-tensor shape when viewed as an ellipsoid (below). (For
In-plane fibre orientation

- Fibre angle measurement: Radon Transform

Radon Transform example projections at $0^\circ$ and $90^\circ$

Radon Transform from $0^\circ$ to $179^\circ$

Measure of contrast at each projection angle

Angular distribution from $0^\circ$ to $179^\circ$