Full-field curvature measurements to assess impact damage in composite plates using an indicator based on mechanical equilibrium

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Introduction - 1

- Impact damage on composites
  - Complex: matrix cracking, delamination, fibre breakage

- Impact damage simulation accessible
  - Many parameters (matrix and interface strength, cohesive models)
  - Global force/displacement not enough to validate model

- Detailed evaluation of impact damage
  - Validation of FE models

X-ray CT scan, courtesy of D. Bull/I. Sinclair, University of Southampton

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Introduction - 2

- Why curvatures?
  - 3D FE model of cantilever beam with mid-plane delamination (Devivier et al, Composites A, 2012)
Deflectometry - 1

- Principle

\[ d = 2h \cdot \delta \alpha \]
Deflectometry - 2

- Experimental set-up

Pitch: 1 mm

h=1.34 m

2048 x 2048 8-bit CCD camera
Deflectometry - 3

Unloaded state
- Longitudinal
- Transverse

Loaded state
- Longitudinal
- Transverse

Spatial phase shifting (windowed discrete Fourier transform)

Unloaded state subtracted to loaded state

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Deflectometry - 4

Unwrapping with custom made algorithm.

\[ p: \text{grid pitch} \]
\[ h: \text{distance grid-sample point to point differentiation} \]
\[ \varepsilon = \frac{t}{2} \]

"Equivalent strains"

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Deflectometry - 5

- **Performances**
  - Recording of ‘two’ static images of the grid (average of 40 images)
  - Calculation of the standard deviation
  - Typically, for 5 pixels/period

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase</td>
<td>$\sigma_\varphi \approx 9 \text{ mrad}$</td>
</tr>
<tr>
<td>Slope</td>
<td>$\sigma_\theta \approx 0.5 \text{ mm.km}^{-1}$</td>
</tr>
<tr>
<td>Curvature</td>
<td>$\sigma_k \approx 1.5 \text{ km}^{-1}$</td>
</tr>
<tr>
<td>Strain</td>
<td>$\sigma_\varepsilon \approx 2 \text{ \mu m.m}^{-1}$</td>
</tr>
</tbody>
</table>
Experimental set-up

- Loading: different points
Experimental set-up

- **Material**
  - IM7/8552 carbon/epoxy
  - \([0/45/-45/90]_3S\)

- **Typical plate dimensions:**
  - 140 x 200 x 3 mm

- **Reflective coating**
  - Gel coat + carbon black particles (opaque)
  - Moulded against glass panel
Experimental set-up

- Impact configurations

C1
- Diameter: 40 mm
- Energy: 15 J
- Distance: 100 mm

C2
- Diameter: 125 mm
- Energy: 20 J
- Distance: 75 mm
Results – Equivalent strain maps

- Undamaged, strain in (µm/m)
Results – Equivalent strain maps

- C1 (20J)
Results – Equivalent strain maps

- C1 (20J)
Equilibrium Gap indicator - 1

- How to detect the presence of the damage?
  - Equilibrium
    \[-\int_{V} \sigma : \varepsilon^* \, dV + \int_{\partial V} T.u^* \, dS = 0\]
  - Thin plate theory
    \[-\int_{S} \left\{ k^T \right\} \left[ D \right] \left\{ k^* \right\} \, dS + \int_{\partial V} T.n^* \, dS = 0\]

measured  known  selected

\[ EG = -\int_{S} \left\{ k^T \right\} \left[ D \right] \left\{ k^* \right\} \, dS \]

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Equilibrium Gap indicator – 2

- Choice of the virtual field
  - Piecewise functions
  - 4 Hermite 16 elements

- What is detected?
  - Curvatures are not strains
  - Departure from thin plate theory!

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Results: EG maps - 1

- C1 (20J)
Results: EG maps - 2

- C1 (15J)
Results: EG maps - 3

- **C1 (15J)**

C-SCAN
Results: EG maps - 4

- C2 (20J)
Results: EG maps - 5

- C2 (20J)

C-SCAN

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Conclusion

- Deflectometry
  - Slope fields on flat reflective plates
  - Inexpensive, very sensitive

- Curvature: a good delamination damage indicator for composites

- ‘Reading’ the curvature maps for damage
  - equilibrium gap indicator based on principle of virtual work

- Next step: FE model development/validation