An Inverse Method for Determining the Stiffness of Impact Damage in Laminated Composites

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Presentation Layout

- Impact Damage
- Inverse Method
- Tensile Characterisation
- Compressive Characterisation
- Advanced Issues
Impact Damage
Composites and Impact

AIRBUS A350

Hail stones

Ground collision

Bird strike

Hail stones

Bird strike

Dropped tools

BOEING 787
Problem of Impact Damage

- Impact happens accidentally
- Impact often causes damage
- Damage reduces strength
- Damage affects buckling
- How much???
- STIFFNESS DISTRIBUTION IS KEY!!!
Inverse Method
Inverse Method

Iterative updating of constitutive material parameters in Finite Element model - ABAQUS

![Flowchart of the approach]

Displacement fields measured by Digital Image Correlation - ARAMIS

Sztefek & Olsson (2008), Composites Part A.
**Aim**

Seeking minimum of displacement error function by updating material parameters

**Approach**

Gradient method *Steepest Descent* combined with *Davies, Swann, and Campey’s algorithm*

**Description**

Mean squared error function:

\[ f(x) = \frac{1}{N} \sum_{i=1}^{N} \left( \frac{\Delta u_i}{u_{\text{max}}} \right)^2 + \left( \frac{\Delta v_i}{v_{\text{max}}} \right)^2 \]

Gradient and Search direction:

\[ g_k = \Delta f / \Delta P_k \quad u_k = g_k / |g_k| \]

Parameter vector:

\[ x_{k+1} = x_k + \lambda_k u_k \]
Experiments
Digital Image Correlation System

Non-contact optical 3D deformation measuring system ARAMIS from GOM

<table>
<thead>
<tr>
<th>System type</th>
<th>GOM ARAMIS 1.3 M</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DIC Principle</strong></td>
<td><strong>Speckle pattern</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Before deformation</strong></td>
</tr>
<tr>
<td></td>
<td><strong>During deformation</strong></td>
</tr>
<tr>
<td>4 cameras in master and slave mode</td>
<td></td>
</tr>
<tr>
<td>Camera resolution</td>
<td>1280 x 1024 pixels</td>
</tr>
<tr>
<td>Measuring volume</td>
<td>10 x 8 x 8 mm$^3$ to</td>
</tr>
<tr>
<td></td>
<td>1.7 x 1.4 x 1.4 m$^3$</td>
</tr>
<tr>
<td>Max. frame rate</td>
<td>12 Hz</td>
</tr>
<tr>
<td>Strain range</td>
<td>0.05% up to &lt;100%</td>
</tr>
<tr>
<td>Strain accuracy</td>
<td>up to 0.02%</td>
</tr>
</tbody>
</table>
Overview of Experiments

Impact testing

Quasi-isotropic Carbon/epoxy

Impactor

Boeing rig

Field of DIC measurement

Tensile loading

Fractographic findings

4 mm thickness

14 J

4 mm

14 mm

32 mm

Compressive loading

Heterogeneous properties

Apparent properties
Tensile Characterisation
Experimental Setup

Static jaw

Control unit

Loading jaw

CCD cameras

Specimen

Mechanical clamps

Speckle pattern

Sand paper

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Aeronautics
London

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Inverse Analysis

**ABAQUS analysis**

- Homogeneous isotropic thin shell
- Full-field boundary conditions

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**Figure:**

- Normalised strain, $\varepsilon_x$, vs. y-coordinate (mm)
- Graph showing strain values: 0.30%, 0.40%, 0.85%
- Diagrams illustrating material properties and boundary conditions.

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**Materials:**

- Diameter: 18 mm
- Thickness: 2 mm
- Energy absorption: 7 J
Heterogeneous Material Parameters

- For 2 mm, 5 J:
  - Young's Modulus: 2 mm, 5 J
  - Poisson's Ratio: 2 mm, 5 J
- For 2 mm, 7 J:
  - Young's Modulus: 2 mm, 7 J
  - Poisson's Ratio: 2 mm, 7 J
- For 4 mm, 10 J:
  - Young's Modulus: 4 mm, 10 J
  - Poisson's Ratio: 4 mm, 10 J
- For 4 mm, 14 J:
  - Young's Modulus: 4 mm, 14 J
  - Poisson's Ratio: 4 mm, 14 J

Dimensions:
- 2 mm, 5 J: Ø 14 mm
- 2 mm, 7 J: Ø 18 mm
- 4 mm, 10 J: Ø 26 mm
- 4 mm, 14 J: Ø 32 mm
Nonlinear Material Behaviour

Strain concentrations at different applied (far-field) strains

Heterogeneous nonlinearity
Compressive Characterisation
Experimental and Optical Setup

Specimen & Boeing rig

Fluorescent lights

Perspex setup panel

Characteristic features

Seeing from front

FRONT SIDE

BACK SIDE

Boeing antibuckling rig

From FRONT SIDE

From BACK SIDE

90 mm

70 mm

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Full-field Benefits

Strain concentration

Post-impact deflections

Delamination opening
Full-field Buckling Patterns

Local and global buckling development
Finite Element Model

**ABAQUS analysis**

- Homogeneous isotropic thin shell
- Geometrically nonlinear analysis
- Full-field boundary conditions

In-plane and out-of-plane BCs

Out-of-plane BCs only

- 4 mm 10 J
- 4 mm 14 J
- 4 mm 20 J

∅ 26 mm
∅ 32 mm
∅ 36 mm
Apparent Material Parameters

Buckling patterns at different applied strains
Apparent Material Nonlinearity

Buckling patterns at different applied strains

Comparison of apparent material behaviours
Advanced Issues
Arbitrary and Multiple Damage Location

Numerically damaged plate

Severe damage

Light damage

6 concentric rings model

5 × 5 grid model

Damage localisation from strain map
Stiffness Reconstruction

Using 6 concentric rings

Using 5x5 grid
Orthotropic Materials

**Findings to date**

- Load dependent material identification
- Geometry dependent material identification

**Numerical test**

<table>
<thead>
<tr>
<th>Material set</th>
<th>$E_1$</th>
<th>$E_2$</th>
<th>$G_{12}$</th>
<th>$\nu_{12}$</th>
<th>Error in $E_1$</th>
<th>Error in $E_2$</th>
<th>Error in $G_{12}$</th>
<th>Error in $\nu_{12}$</th>
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</thead>
<tbody>
<tr>
<td>Inner square</td>
<td>25 GPa</td>
<td>5 GPa</td>
<td>3 GPa</td>
<td>0.35</td>
<td>0.2%</td>
<td>0.1%</td>
<td>2.9%</td>
<td>2.8%</td>
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<tr>
<td>Middle square</td>
<td>35 GPa</td>
<td>10 GPa</td>
<td>4 GPa</td>
<td>0.2</td>
<td>9.4%</td>
<td>12.6%</td>
<td>4.3%</td>
<td>65%</td>
</tr>
<tr>
<td>Outer square</td>
<td>50 GPa</td>
<td>20 GPa</td>
<td>5.5 GPa</td>
<td>0.3</td>
<td>8.1%</td>
<td>8.9%</td>
<td>1.5%</td>
<td>40%</td>
</tr>
</tbody>
</table>
Conclusions

• Inverse method using FEM coupled with DIC
• Applied to impact damage in laminates
• In-plane stiffness reduction in damage zone
• Material nonlinearity described

On-going Work

• Arbitrary and multiple damage location
• Impact damage in orthotropic laminates

Possible Future Applications

• Biomechanics
• Hot objects
• Aircraft inspection
Thank you for your attention

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