Thermography for full-field stress and damage analysis of composite components

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Cunningham
Summary

• TSA overview
• Motivation
• Validation of FEA – case studies
• Damage Analysis
• Non crimp and woven materials
Motivation

• Accurate definition of material/structural behaviour – large variations in values in literature for nominally identical materials

• Particularly important in composite materials – variations depend on manufacturing process etc

• Essential to accurately validate FEA using full-field experimental mechanics techniques

• Tools for damage analysis and NDE
Thermoelastic stress analysis

\[ \Delta T = -\frac{T}{\rho C_p} \left( \alpha_1 \Delta \sigma_1 + \alpha_2 \Delta \sigma_2 \right) \]


Coefficient of thermal expansion

Harwood and Cummings 1991

Vacuum infused Fruehmann et al JSA 2008

Daniel and Ishai 1994
Derivation of stresses from TSA-calibration

\[
\Delta T = K_2 T \Delta \sigma_1 + K_2 T \Delta \sigma_2
\]

\[
K_1 = \frac{\alpha_1}{\rho C_p} \quad K_2 = \frac{\alpha_2}{\rho C_p}
\]

\[
\frac{\Delta T}{K_1 T} = \Delta \sigma_1 + \frac{K_2}{K_1} \Delta \sigma_2
\]

### Sandwich structures and core junctions

<table>
<thead>
<tr>
<th>Type</th>
<th>Face Material</th>
<th>$t_f$ [mm]</th>
<th>width [mm]</th>
<th>Core Material 1</th>
<th>Core Material 2</th>
<th>Core Material 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Aluminium alloy</td>
<td>1.0</td>
<td>45.6</td>
<td>Aluminium alloy</td>
<td>Rohacell 51WF</td>
<td>Rohacell 200WF</td>
</tr>
<tr>
<td>2</td>
<td>PMMA</td>
<td>1.5</td>
<td>47.2</td>
<td>PMMA</td>
<td>Dynathane 1000</td>
<td>Rohacell 51WF</td>
</tr>
<tr>
<td>3</td>
<td>GFRP-CSM</td>
<td>1.2</td>
<td>46.8</td>
<td>PMMA</td>
<td>Dynathane 1000</td>
<td>Rohacell 51WF</td>
</tr>
<tr>
<td>4</td>
<td>GFRP-NCF</td>
<td>2.8</td>
<td>49.0</td>
<td>Aluminium alloy</td>
<td>Rohacell 51WF</td>
<td>Rohacell 200WF</td>
</tr>
</tbody>
</table>
Sandwich structures and core junctions

Section A-A
(the left support is not shown)
Experiment
Calibration of the face sheet material

Isotropic CSM material \[ \Delta T = KT \Delta (\sigma_1 + \sigma_2) \]

Orthotropic NCF material \[ \Delta T = K_1 T \Delta \sigma_1 + K_2 T \Delta \sigma_2 \]
## Material properties and calibration constants

<table>
<thead>
<tr>
<th>Material</th>
<th>Young’s modulus [MPa]</th>
<th>Poisson’s ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium alloy 7075-T6</td>
<td>71700</td>
<td>0.32</td>
</tr>
<tr>
<td>PMMA (Degussa Plexiglas XT)</td>
<td>3100</td>
<td>0.41</td>
</tr>
<tr>
<td>GFRP-CSM</td>
<td>13000</td>
<td>0.30</td>
</tr>
<tr>
<td>GFRP-NCF, [0/+45/90/-45 / +45/90/-45/0]₂</td>
<td>19200</td>
<td>0.29</td>
</tr>
<tr>
<td>Rohacell 51WF</td>
<td>75 [10]</td>
<td>0.32 [11]</td>
</tr>
<tr>
<td>Dynathane 1000 (PU rubber foam)</td>
<td>5.5</td>
<td>0.22</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium alloy 20.0, 40.0</td>
<td>10.0, 20.0</td>
<td>10, 30, 50</td>
<td>20.0, 40.0</td>
<td>6.06 (5.3%)</td>
<td>6.45 (2.5%)</td>
</tr>
<tr>
<td>PMMA 5.4, 10.8</td>
<td>3.2, 6.4</td>
<td>6, 10</td>
<td>1.31 (6.1%)</td>
<td>1.33 (3.8%)</td>
<td></td>
</tr>
<tr>
<td>GFRP-NCF 10.0, 20.0</td>
<td>5.0, 10.0</td>
<td>6, 10</td>
<td>5.63 (11.2%)</td>
<td>5.35 (9.9%)</td>
<td></td>
</tr>
<tr>
<td>GFRP-CSM 10.0, 20.0</td>
<td>5.0, 10.0</td>
<td>6, 10</td>
<td>3.74 (3.7%)</td>
<td>3.87 (6.7%)</td>
<td></td>
</tr>
</tbody>
</table>
Results from CSM face sheet
Results from NCF face sheet

Stresses in secondary aircraft structure

- Increased use of composite materials in aircraft structure
  - weight saving
  - improved life time
- Development of new manufacturing techniques and new materials

Generic panel
Face sheet material characterisation

UD prepreg/autoclaved

NCF RFI Oven cure
### Thermoelastic Constants

<table>
<thead>
<tr>
<th></th>
<th>M1, $K_L$</th>
<th>M1, $K_T$</th>
<th>M2, $K_L$</th>
<th>M2, $K_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>1.592 ± 0.83</td>
<td>3.112 ± 1.19</td>
<td>1.58 ± 0.81</td>
<td>2.837 ± 1.55</td>
</tr>
</tbody>
</table>

- **Thermoelastic Constant**
  - **MPa$^{-1}$ (x 10$^{-6}$)**

The table above summarizes the thermoelastic constants for different materials. The values indicate the material's response to thermal and mechanical stresses.
Representative loading

- Allow full scale pressure load applied to generic panel
- Panel is pulled over water filled cushion
- Applied to standard test machine
- Allows cyclic loading
- Allows optical access
Full scale testing of a generic panel

Results

• Standard autoclaved prepreg offered a panel with a maximum deflection of 6.3 mm whilst RFI, NCF panel deformed by 4.6 mm.

• The measured stress response indicated a reduction in stress peak when using RFI and NCF.
Comparison of TSA and FEA

Experimental Result:

FE Result:
Autoclaved

\[ \sigma_x + \frac{\alpha_T}{\alpha_L} \sigma_y \] (MPa)

\[ \begin{align*}
\text{Position (mm)} \\
0 & \quad 50 & \quad 100 & \quad 150 & \quad 200 & \quad 250
\end{align*} \]

- FE
- TSA
NCF - RFI

\[ \sigma_x + \frac{\alpha_T}{\alpha_L} \sigma_y \] (MPa)

Position (mm)
Damage studies in Cross ply laminate

\[ [(0/90)_3, 0, (90/0)_3] \]
Cross ply

$\Delta \varepsilon_l + \Delta \varepsilon_r$

Legend:
- 0.000
- 0.002
- 0.004
- 0.006
Damage indicator

Thermography data-damage analysis

\[ \Delta T = -\frac{T}{\rho C_p} \left( \alpha_1 \Delta \sigma_1 + \alpha_2 \Delta \sigma_2 \right) \]

\[ \frac{\Delta T}{T} \]
Application of TSA to woven composites

- It is possible to correlate the thermoelastic response to the weave pattern.
- The thermoelastic response changed with repeated testing at loads below 30% of the failure stress.

Global thermoelastic response

- The effect of stacking sequence is visible in the global TSA data.
Meso-scale thermoelastic response

• Thermoelastic signal decay is concentrated in the weft cells.

• Cracks are found to form along the centre of the weft cells.

Time history of the thermoelastic response from a typical warp and weft yarn

Macroscope image (x 10 magnification) of the WRE581T single ply material after 184000 cycles at 15% loading.
Data processing

\[
\left( \frac{\Delta T}{T} \right)_{\text{Damaged}} - \left( \frac{\Delta T}{T} \right)_{\text{Undamaged}}
\]
Damage identification

- The thermoelastic response was examined at the scale of the yarn.
- ‘Virgin’ data was subtracted to identify changes in the local thermoelastic response.
Overview

• Damage in textile composites can occur at very low stress levels, < 20 % of $\sigma_f$.

• Damage can be identified using TSA despite the heterogeneous thermoelastic material response.

• Phase data provides a means for damage identification without *a priori* knowledge of the thermoelastic field.

Complete set of high resolution TSA data from the WRE581T specimen loaded at 10 % of the failure stress

This work was supported by the UK Engineering and Physical Sciences Research Council -EPSRC

Field studies – transient loading

Conclusions

- Demonstrated the necessity of accurate measured material property values for composite materials
- Shown how full-field experimental mechanics techniques can be used to validate FEA
- Presented convincing case studies that demonstrate the applicability and ease of using TSA
- Shown that TSA can be used over a range of scales for stress analysis and damage studies