Residual Strain Development in Laminated Thermoplastic Composites Measured using Fibre Bragg Grating Sensors

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Outline

- Residual Strains in TP Composites
- FBG’s for Residual Strain Measurements
- Fabrication and Measurement Procedures
- Experimental Results
- Modeling
- Conclusions and Perspectives
Residual Strains in TP Composites

- CTE matrix ≠ CTE reinforcing fibres
  - Micromechanical strains
- Anisotropic plies
  - Interlaminar strains
- Moulding pressure, temperature gradients
  - Global strains

Stresses During Cooling
Motivation & Direction

- Residual strains can be the source of damage initiation and premature failure in composites….

**Objective:**

- Develop a method for direct internal strain measurements:
  - (residual stresses, process monitoring)
Measuring the Internal Strain State

- How can we best measure internal residual strains?

**Fibre Bragg Grating Sensors**
- Minimal disruption of surroundings
- Precise location in given layers
- Sensitive to multi-dimensional and non-uniform strain fields
Thermomechanical-Optic Relations

\[
\frac{\Delta \lambda_b}{\lambda_b} = \varepsilon_z - \frac{n_0^2}{2} \left[ p_{11} \varepsilon_x + p_{12} (\varepsilon_z + \varepsilon_y) \right] + \xi \Delta T
\]

IF \( \varepsilon_x = \varepsilon_y = -\nu \varepsilon_z \) and \( \Delta T = 0 \)

\[
\frac{\Delta \lambda_b}{\lambda_b} = (1 - p_e) \varepsilon_z
\]

- \( n_0 \): Effective Index of Refraction
- \( \varepsilon_i \): Normal Strain in i-Direction
- \( p_{11}, p_{12} \): Pockel’s Constants
- \( \xi \): Thermal-Optic Coefficient
- \( \Delta T \): Change in Temperature

Uniform Strain Field

CompTest 2004, September 21-23 2004
Pe Simplification Limitations

Consider the following cases:

- Plane Strain \((\varepsilon_z = 0)\)

- Thermal Contractions \((\varepsilon_x = \varepsilon_y \neq -\nu \varepsilon_z)\)

- Birefringence \((\varepsilon_x \neq \varepsilon_y)\)

Error depends on 3D strain state!
Unequal Transverse Strains

\[
\begin{align*}
\Delta \lambda_{bx} &= \varepsilon - \frac{n_0^2}{2} \left[ p_{11} \varepsilon_x + p_{12} (\varepsilon_z + \varepsilon_y) \right] + \xi \Delta T \\
\Delta \lambda_{by} &= \varepsilon - \frac{n_0^2}{2} \left[ p_{11} \varepsilon_y + p_{12} (\varepsilon_z + \varepsilon_x) \right] + \xi \Delta T
\end{align*}
\]

2 Equations, 3 Unknowns!
Composite Specimens

- AS4/PPS prepreg
  - Unidirectional (UD) and Cross-ply (CP) laminates (28 plies)
- FBG sensors: 22mm gauge length, 1300nm
  - Coating removed past sensor length
- 250µm diameter thermocouple
Consolidation Process

- Plies are compressed in hot press
- A polarized tunable laser probes the FBG
- Photodetector retrieves reflected spectra
- Thermocouple & FBG readings
Consolidation Process

- FBG responds to
  - Pressure changes
  - Material changes

Temperature Compensated Bragg Wavelength Changes
\[
\frac{\Delta \lambda_{by}}{\lambda_b} = \varepsilon_z - \frac{n_0^2}{2} \left[ p_{11} \varepsilon_x + p_{12} (\varepsilon_z + \varepsilon_y) \right]
\]

\[
\frac{\Delta \lambda_{bx}}{\lambda_b} = \varepsilon_z - \frac{n_0^2}{2} \left[ p_{11} \varepsilon_y + p_{12} (\varepsilon_z + \varepsilon_x) \right]
\]
Changes in Bragg Wavelengths

- Temperature compensated changes in $\Delta \lambda_x$ during consolidation process
- Slopes of X-ply > UD
Modeling Considerations

What factors affect the internal strain state in the composite during consolidation?

- Thermal expansion/contraction
- Thermal gradients
- Crystallization
- Hot Press/ Mould forces frozen into laminate
- Relaxation

Material properties depend on local temperature!!
Simplified Consolidation Model

Assumptions for a simplified model:

- Generalized plane strain
- Thermal contraction dominates
  - i.e. neglect crystallization effects
- Negligible thermal gradients
- Temp dependent polymer moduli and CTE
- Stresses/strains accumulation can be divided into steps that will be summed
Elastic Step Model

- Divide the cooling process into 13 steps
- Steps represent temperature ranges where material properties are piecewise constant

\[
\varepsilon_{\text{total}_{ij}} = \sum_{k=1}^{13} \varepsilon_{ij}^k (T)
\]

\[
\sigma_{\text{total}_{ij}} = \sum_{k=1}^{13} \sigma_{ij}^k (T)
\]
FEM Model – Elastic Step Method

$\varepsilon_x, \varepsilon_y, \varepsilon_z$ from fibre core are inserted into optomechanical equations

$\Delta \lambda_b(\varepsilon_x, \varepsilon_y, \varepsilon_z)$
Evolution of $\Delta \lambda_{bx}$ During Cooling (Uni)

Temperature (°C)

Free

In Mould

Experimental

Unidirectional

$\alpha_{mould} = 10^{-6}$
Conclusions

- FBG’s are capable of registering changes in material state and moulding pressure.

- During consolidation, residual strains accumulate at different rates according to lay-up.

- Consolidation pressure & mould contact cause birefringence in FBG sensors.

- Complete opto-mechanical relationships are required to use FBG measurements.
Future Perspectives

- Improve the consolidation model that relates strains in the FBG with strains in composite

- Continue to improve methods to account for polarization/birefringence effects
  - Including a method to decouple non-uniform longitudinal strains from transverse strains
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