Delamination Propagation Measurement In AS4/PPS Using Long Gauge-Length FBG Sensors

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Objectives

- Demonstrate the ability of the FBG sensor and OLCR technique to locate damage
- Determine fibre bridging stresses using
  - FBG readings
  - Inverse numerical identification method
Outline

- Methods
  - mechanical
  - optical

- Experimental Results

- Modelling and Analysis
  - bridging identification
  - comparison with experimental

- Conclusions and Perspectives
Methods

Specimen and materials
- Double cantilever beam
- AS4/PPS unidirectional composite

Sensor
- Optical – Fibre Bragg grating
  - Embeds easily into polymer matrix composites
  - Can monitor production and structural response
  - Measures non-uniform internal strains
Experimental setup

- Mode I delamination

Timed image acquisition for crack measurement
Load-displacement data
Embedding FBG sensors

FBG

Bridging Fibres
FBG sensors

- are sensitive to temperature ($T$) and 3D strain states ($\varepsilon_{x,y,z}$)

\[ \varepsilon_x = \varepsilon_y \]

\[ \varepsilon_x \neq \varepsilon_y \]

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

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

$\varepsilon_i$ Normal Strain in i-Direction

$p_{11}, p_{12}$ Pockel’s Constants

$n_0$ Effective Index of Refraction

$K_t$ Thermal Coefficient

$\Delta T$ Change in Temperature
Birefringence & distributed strains

How do we interpret this???
How to measure distributed strains

- Assumptions
  - Polarization axes do not change
    - only measure one at a time
  - Isothermal
  - Applied transverse strains follow $\varepsilon_x = \varepsilon_y = -\nu \varepsilon_z$

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

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

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

Measure local wavelength via coupling coefficient phase,

\[
\lambda_b(z) = \left\{ \frac{1}{\lambda_{b,\text{ref}}} + \frac{1}{4\pi n_{\text{eff}}} \cdot \frac{d\phi_q(z)}{dz} \right\}^{-1} \quad \Delta \lambda_b(z) = \frac{\lambda_b(z)}{\lambda_b} = (1 - p_e)\epsilon_z(z)
\]

OLCR system:

Test Arm

Reference Arm

Polarization Control

Data Acquisition

\[ |q| e^{i\phi_q} \]

Time-domain

Spatial-domain

translating stage

mirror
OLCR output – specimen B

Position From Applied Displacement (mm)

Bragg Wavelength Shift (nm)
OLCR output – specimen B

Position From Applied Displacement (mm)

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Position From Applied Displacement (mm)

Bragg Wavelength Shift (nm)
OLCR output – specimen B

Bragg Wavelength Shift (nm)

Position From Applied Displacement (mm)
**Numerical model description**

- **Plane strain**
- **Linear elements**
- **Orthotropic material**

**Bridging Stress Distribution**

- Input $\Delta/2$, $a$
- Inverse numerical identification
- Optimize bridging stresses (and moment) to match FBG strain data

\[ \sigma_{Bridging} = e^{-\frac{L}{\bar{x}}} \left( A_1 + A_2 \bar{x} \right) \]
Optimization of bridging stresses

Strain Distributions

Bridging Stress Distribution

- Initial Guess
- Second Iteration
- Ninth Iteration

Crack Tip

Distance From Specimen End (mm)

Output from Model
Analytical Applied Stress

pre-crack tip
delam. crack tip
Comparison of models

- For a 113 mm crack length

![Graph showing strain vs. distance from specimen end for different models: No Bridging, Bridging, Bridging with Moment, and FBG Strain.](image-url)
Specimen A

\[ \sigma_{\text{Bridging}} = e^{-\frac{\bar{x}}{l}} \left( A_1 + A_2 \bar{x} \right) \]
Specimen B

\[ \sigma_{\text{Bridging}} = e^{-\frac{x}{l}} (A_1 + A_2 \bar{x}) \]
Conclusions

Strain Measurements

- The current OLCR-FBG system is capable of measuring distributed strains due to delamination.
- It is possible to account for constant sources of birefringence.

Numerical Identification

- The strain distribution measured with an FBG allows for the determination of the bridging stress distribution across the delamination.
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References

- **Specimen Preparation and FBG measurements**

- **OLCR technique and applications**


- **Optical relations**