MEASUREMENT OF STRAIN AND STRAIN GRADIENTS WITH FIBER BRAGG GRATING SENSORS

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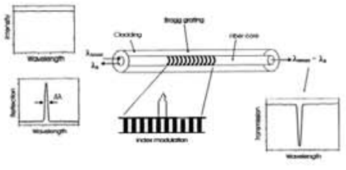
Motivation and Objectives

Fiber Optic Sensors show many advantages compared to traditional strain sensors:

- Long term stability
- Immune to electromagnetic interference
- Flexibility and small diameter ⇨ embedding in structures possible
- Strain gradients can be measured
- High temperature tolerance
- Multiplexing capabilities

The objective of this project is to develop the fundamental understanding of Bragg sensors to measure strain gradients in composite materials. The research is developing simulations and validate the models with experiments.

Fiber Bragg Grating Sensors



Schematic of a Fiber Bragg Grating (FBG) Sensor

Center wavelength of reflected signal is given by the Bragg condition:

$$\lambda_B = 2 \cdot n_{eff} \cdot \Lambda$$

Λ = *grating spacing*
n_{eff} = *effective refractive index*

- Grating area in strain field:
  - Grating spacing Λ changes
  - Refractive Index changes because of opto-elastic effect

➡ Bragg wavelength λ_B changes

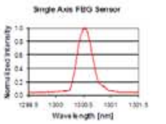
Single and Dual Axis FBG Sensor

Two different types of FBG Sensors have been used:

- Single Axis FBG Sensors:

$$\Delta\lambda = \begin{pmatrix} C_x & C_y & C_z \end{pmatrix} \cdot \begin{pmatrix} \Delta\varepsilon_x \\ \Delta\varepsilon_y \\ \Delta\varepsilon_z \end{pmatrix} + C_T \cdot \Delta T$$

$$\Delta T = 0$$
$$C_x > C_y, C_z$$



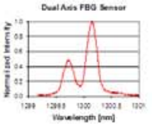
⇨ most sensitive to axial component

- Dual Axis FBG Sensors

$$\Delta\lambda_1 = \begin{pmatrix} C_{1x} & C_{1y} & C_{1z} \end{pmatrix} \cdot \begin{pmatrix} \Delta\varepsilon_x \\ \Delta\varepsilon_y \\ \Delta\varepsilon_z \end{pmatrix} + C_{1T} \cdot \Delta T$$

$$\Delta\lambda_2 = \begin{pmatrix} C_{2x} & C_{2y} & C_{2z} \end{pmatrix} \cdot \begin{pmatrix} \Delta\varepsilon_x \\ \Delta\varepsilon_y \\ \Delta\varepsilon_z \end{pmatrix} + C_{2T} \cdot \Delta T$$

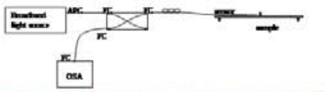
$$\Delta T = 0$$
$$C_{1y} < C_{1x} = C_{1z}$$
$$C_{2x} < C_{2y} = C_{2z}$$



⇨ most sensitive to transverse components

Experimental Setup

Schematic of waveform capture:



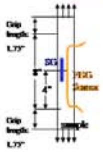
Light from a broadband light source is transmitted to the FBG sensor and the reflected signal is recorded with an optical spectrum analyzer (OSA)

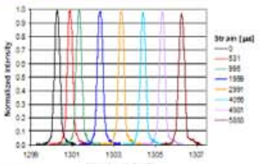
Sensor glued on surface of aluminum or titanium beam

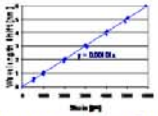
Experiments:

- ASTM standard methods generating predictable strain fields:
  - Uniform axial strain: Tension test (ASTM D3039)
  - Uniform transverse strain: Four point bending (ASTM D6272)
  - Linear strain gradient: Three point bending (ASTM D790), four point bending (ASTM D6272)

Single Axis Sensor in Uniform Axial Strain



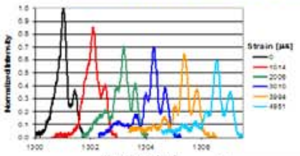




$$\Delta\lambda = \begin{pmatrix} 1010\,\frac{nm}{\varepsilon} & C_y & C_z \end{pmatrix} \cdot \begin{pmatrix} \Delta\varepsilon_x \\ \Delta\varepsilon_y \\ \Delta\varepsilon_z \end{pmatrix}$$

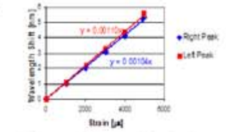
- 1000 µε causes a wavelength shift of approximately 1 nm
- For uniform strain the peak intensity and width are almost constant

Dual Axis Sensor in Uniform Axial Strain



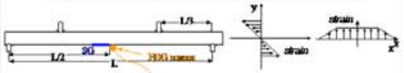
$$\Delta\lambda_1 = \begin{pmatrix} 1040\,\frac{nm}{\varepsilon} & C_{1y} & C_{1z} \end{pmatrix} \cdot \begin{pmatrix} \Delta\varepsilon_x \\ \Delta\varepsilon_y \\ \Delta\varepsilon_z \end{pmatrix}$$

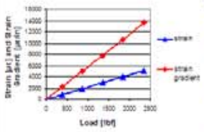
$$\Delta\lambda_2 = \begin{pmatrix} 1100\,\frac{nm}{\varepsilon} & C_{2y} & C_{2z} \end{pmatrix} \cdot \begin{pmatrix} \Delta\varepsilon_x \\ \Delta\varepsilon_y \\ \Delta\varepsilon_z \end{pmatrix}$$



- Both peaks shift parallel in uniform axial strain
- 1000 µε causes a wavelength shift of 1 nm
- Problem: Area below peaks is not constant

Four-Point Bending Transverse Strain Method





Beam center deflection:

$$\delta_{max} = \frac{\varepsilon_{max} \cdot L^2}{4.7 \cdot h}$$

Strain gradient:

$$grad\ (\varepsilon) = \frac{9.4 \cdot \delta_{max}}{L^2}$$

h = sample depth (thickness)

L = span

ε_{max} = strain measured by strain gauge

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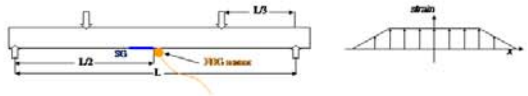
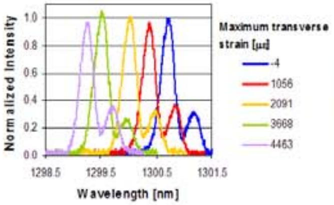
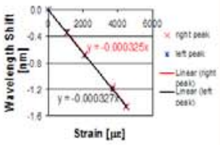
Dual Axis FBG Sensor in Uniform Transverse Strain

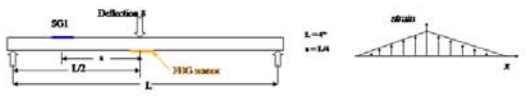


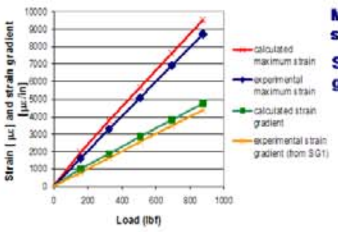




- ♦ Both peaks move parallel, instead of peak separation
- ♦ Intensity almost constant, no broadening

Three-Point Bending Axial Strain and Strain Gradient Method





Maximum strain: $\varepsilon_{max} = \frac{6 \cdot \delta \cdot h}{L^2}$

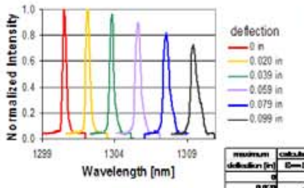
Strain gradient: $grad(\varepsilon) = \frac{12 \cdot \delta \cdot h}{L^3}$

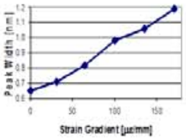
d = deflection

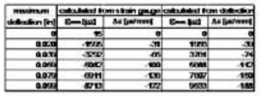
h = sample depth (thickness)

L = span

Single Axis FBG Sensor under Tensile Strain and Strain Gradient

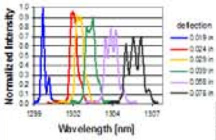


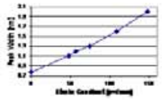


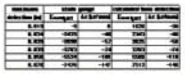


- ♦ Axial strain causes waveform shift
- ♦ Strain gradient causes only slight broadening

Dual Axis FBG Sensor under Tensile Strain and Strain Gradient

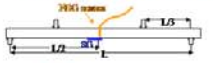


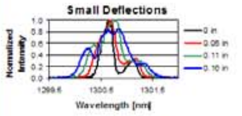


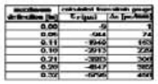


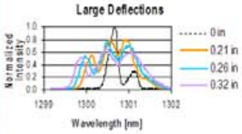
- ♦ Waveform is moving to longer wavelength and broadens
- ♦ Multiple peaks are forming with increasing strain and strain gradient
- ♦ The used polarization tools are not capable to suppress one peak completely, so it is not possible to separate both peaks

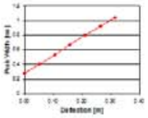
Dual Axis FBG Sensor in Transverse Strain Gradient











- ♦ Waveform is not shifting: average strain is zero
- ♦ Waveform is broadening: strain gradient

Conclusions

- ♦ **Conclusions**
  - ⬥ Uniform strain causes waveform shift
  - ⬥ Strain gradient causes slight peak broadening in single axis sensor
  - ⬥ Strain gradient causes intense peak broadening in dual axis sensor. Additionally multiple peak development was observed

- ♦ **Challenges**
  - ⬥ Exact location of the grating area is difficult to locate
  - ⬥ Area below peak is not constant
  - ⬥ Polarization tools were not good enough to suppress one of the dual axis sensor peaks completely

Future Work

- ♦ New polarization tool at 1550 nm wavelength will suppress left and right peak and improve measurement method
- ♦ Validation of FEM model with the recorded results
- ♦ Embedding FBG Sensors in Composites to understand strain gradients in 3-D preforms
  - ⬥ Influence of defects and unit cell dimensions

Acknowledgements

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