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

Larissa Sorensen, Thomas Gmür and John Botsis

Laboratory of Applied Mechanics and Reliability Analysis

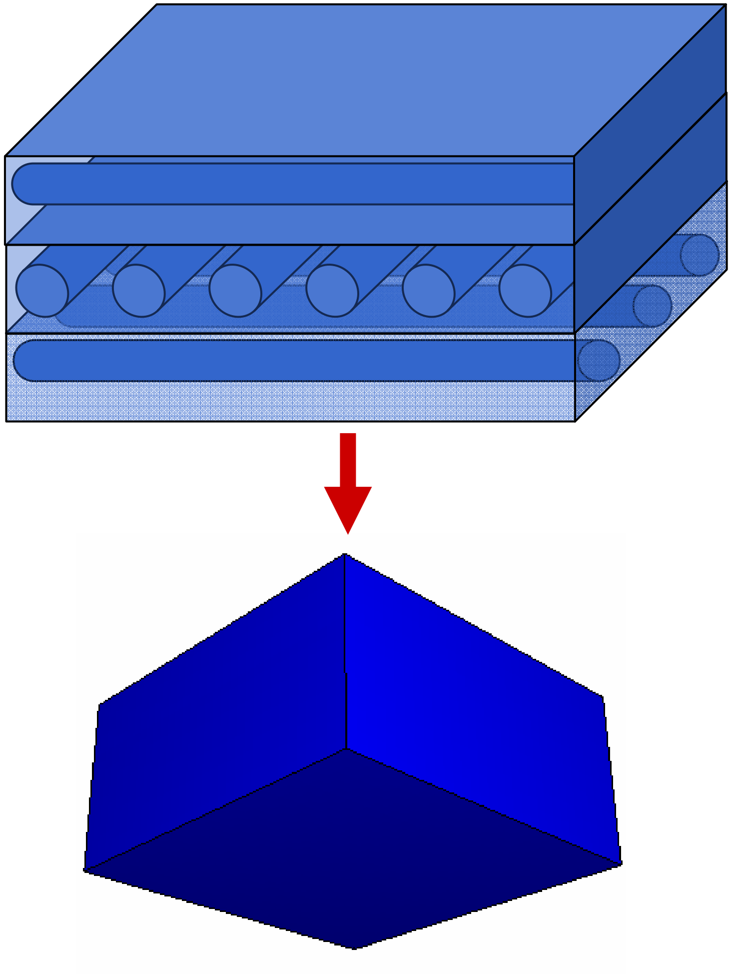
Swiss Federal Institute of Technology, Lausanne

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

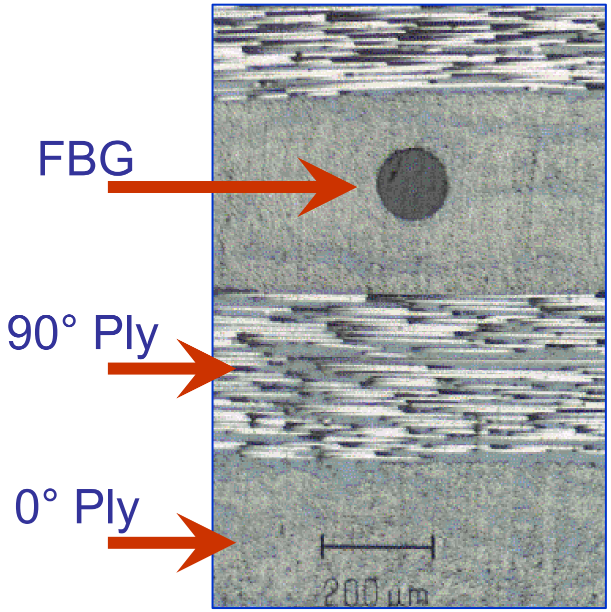
- Residual strains can be the source of damage initiation and premature failure in composites….

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

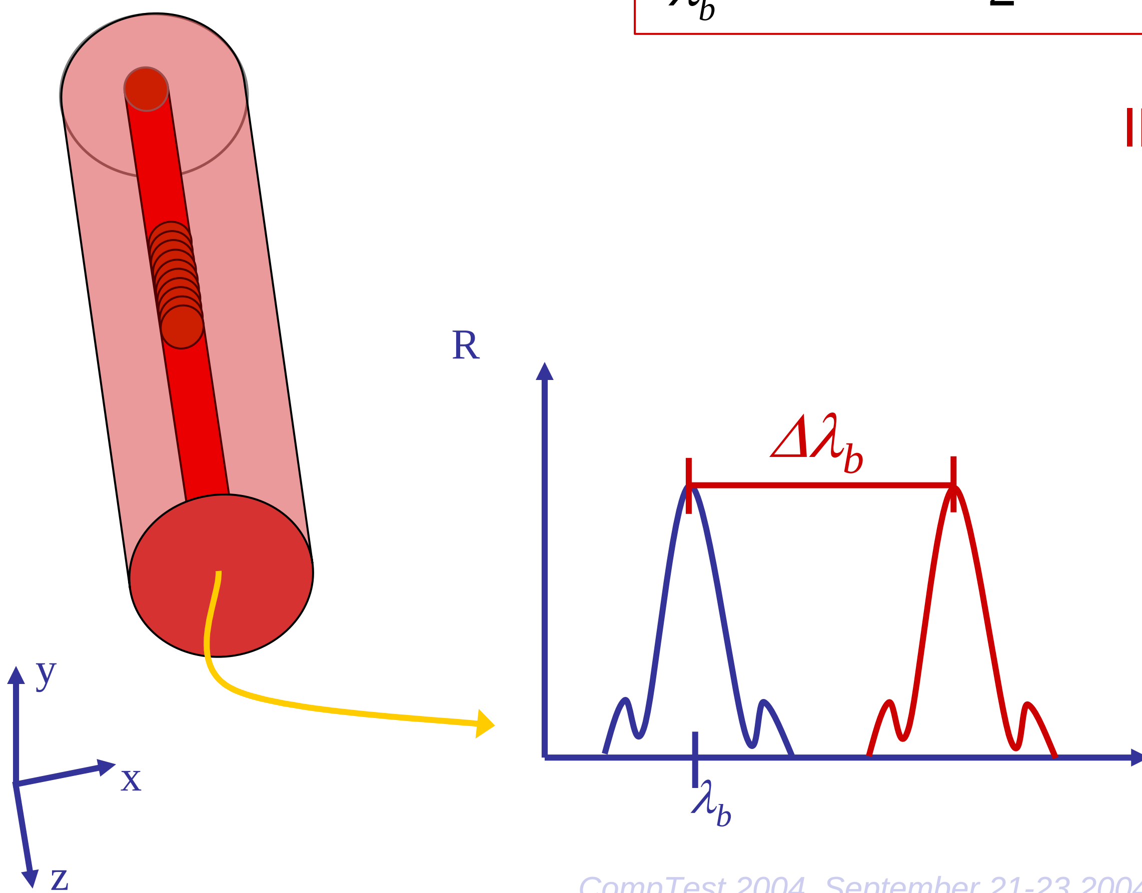
Thermomechanical-Optic Relations

Uniform Strain Field

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

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

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



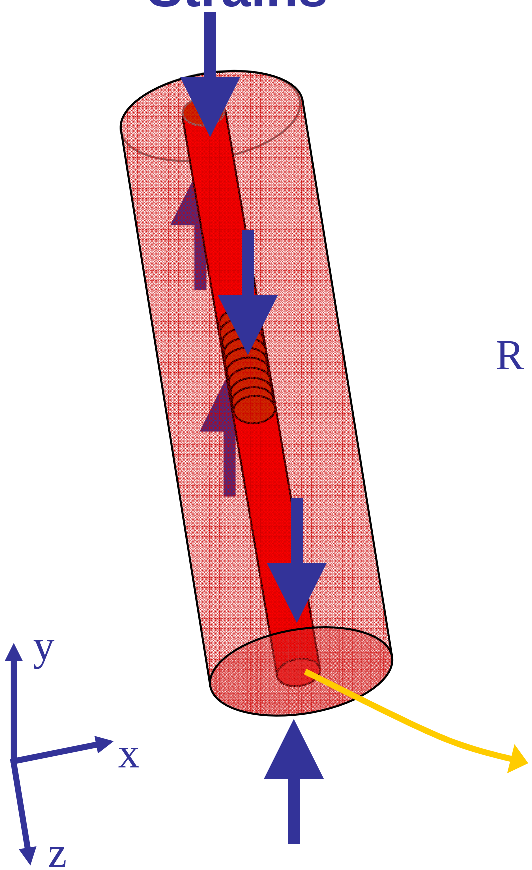
n_o	Effective Index of Refraction
ε_i	Normal Strain in i-Direction
p_{11}, p_{12}	Pockel's Constants
ξ	Thermal-Optic Coefficient
ΔT	Change in Temperature

p_e 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!

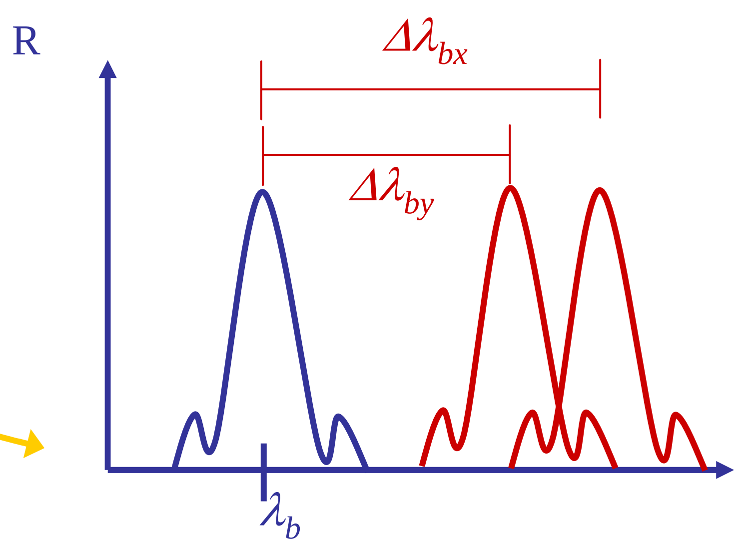
Complete 3D Solution

Unequal Transverse Strains



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

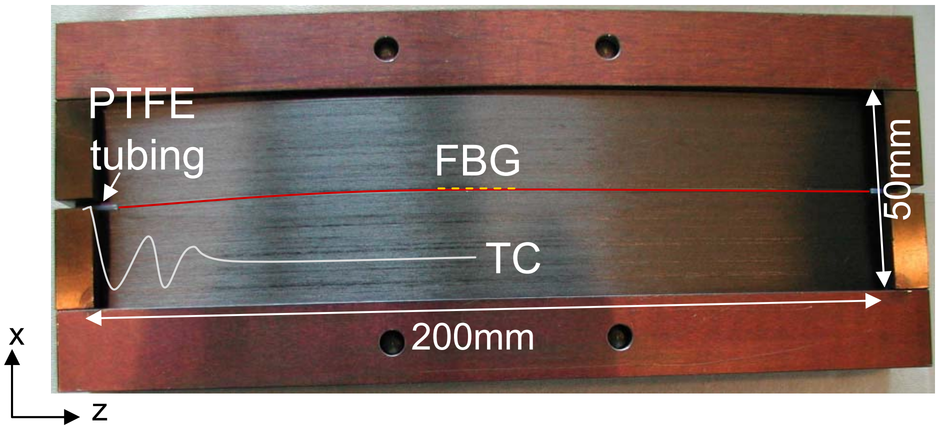
$$\frac{\Delta\lambda_{by}}{\lambda_b} = \varepsilon_z - \frac{n_0^2}{2}\left[p_{11}\varepsilon_y + p_{12}(\varepsilon_z + \varepsilon_x)\right] + \xi\Delta T$$

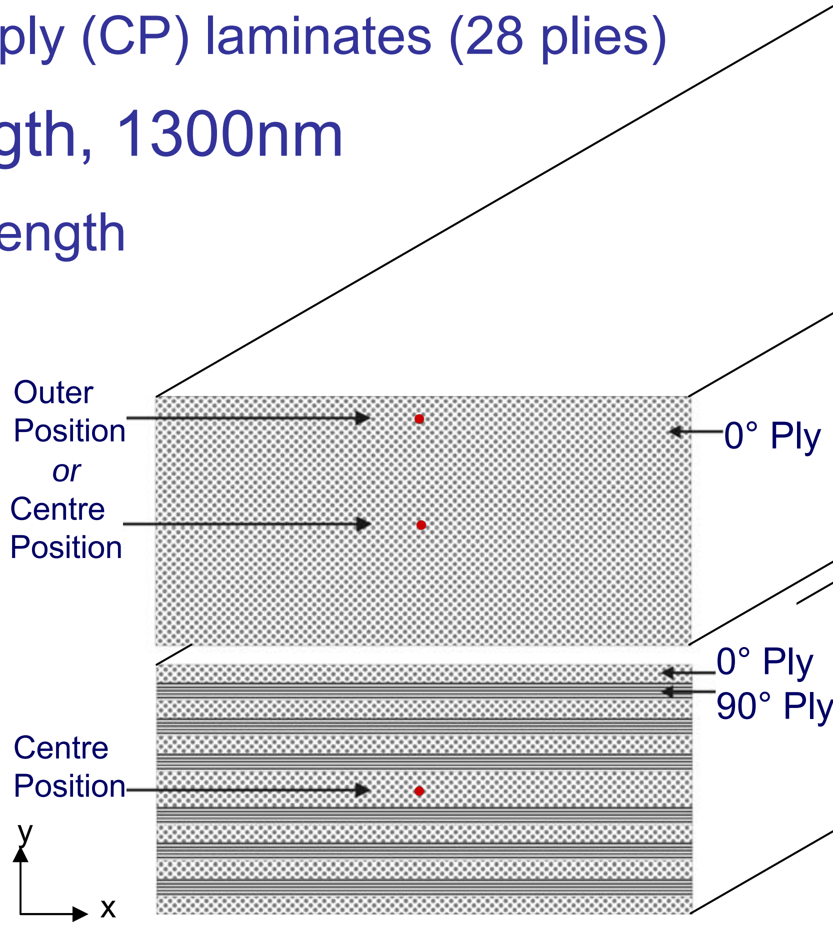


2 Equations,
3 Unknowns!

Composite Specimens

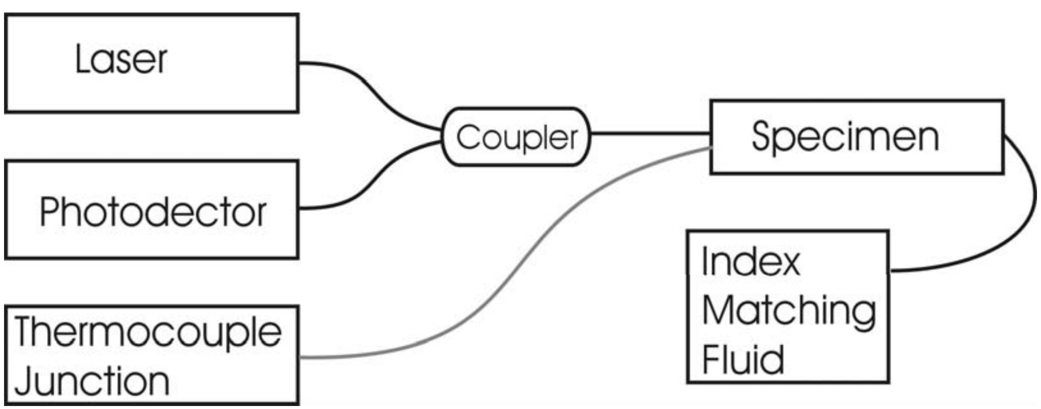
- AS4/PPS prepreg
  - Unidirectional (UD) and Cross-ply (CP) laminates (28 plies)
- FBG sensors: 22mm gauge length, 1300nm
  - Coating removed past sensor length
- 250µm diameter thermocouple





Consolidation Process

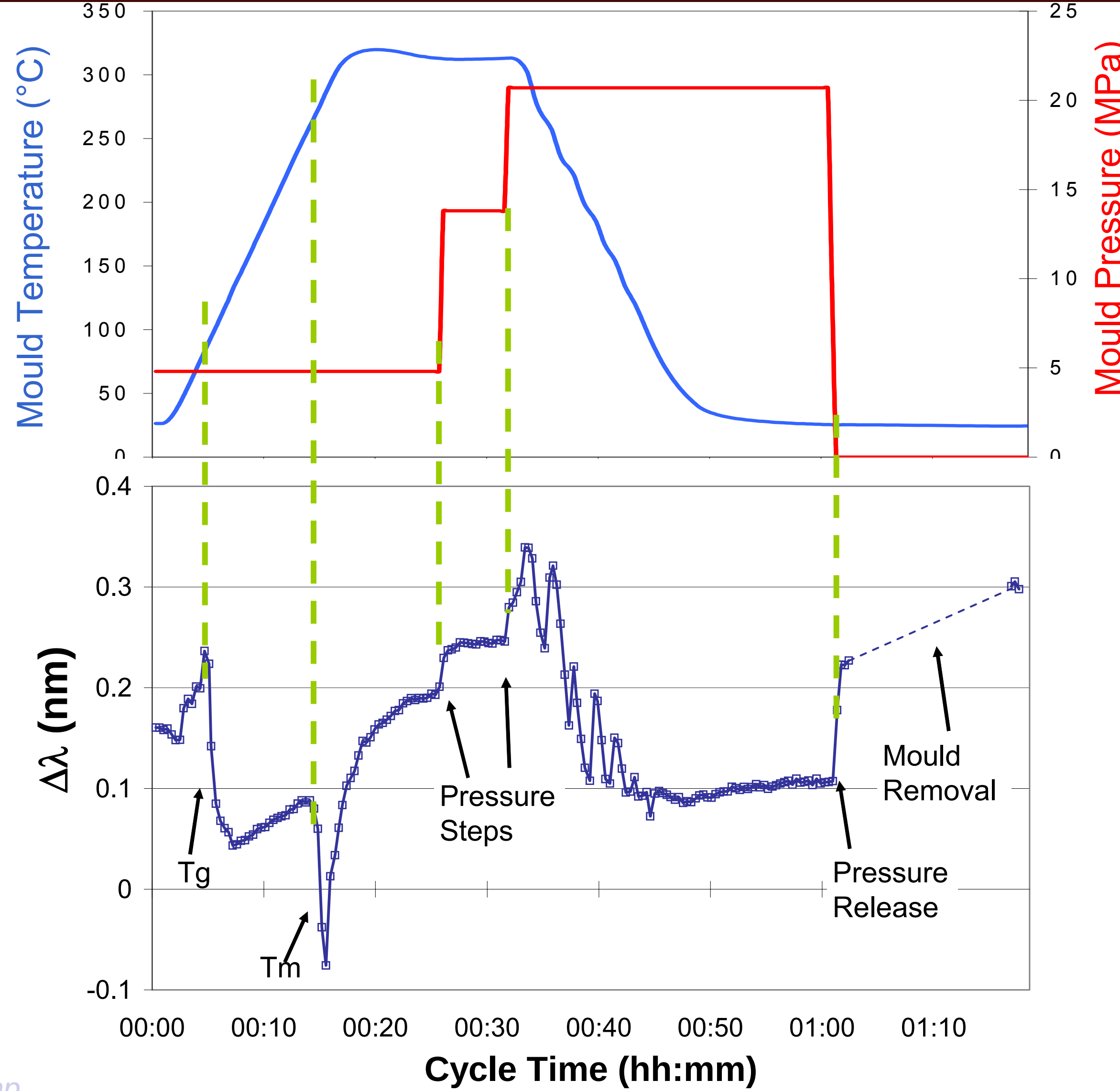
- Plies are compressed in hot press
- A polarized tunable laser probes the FBG
- Photodetector retrieves reflected spectra
- Thermocouple & FBG readings



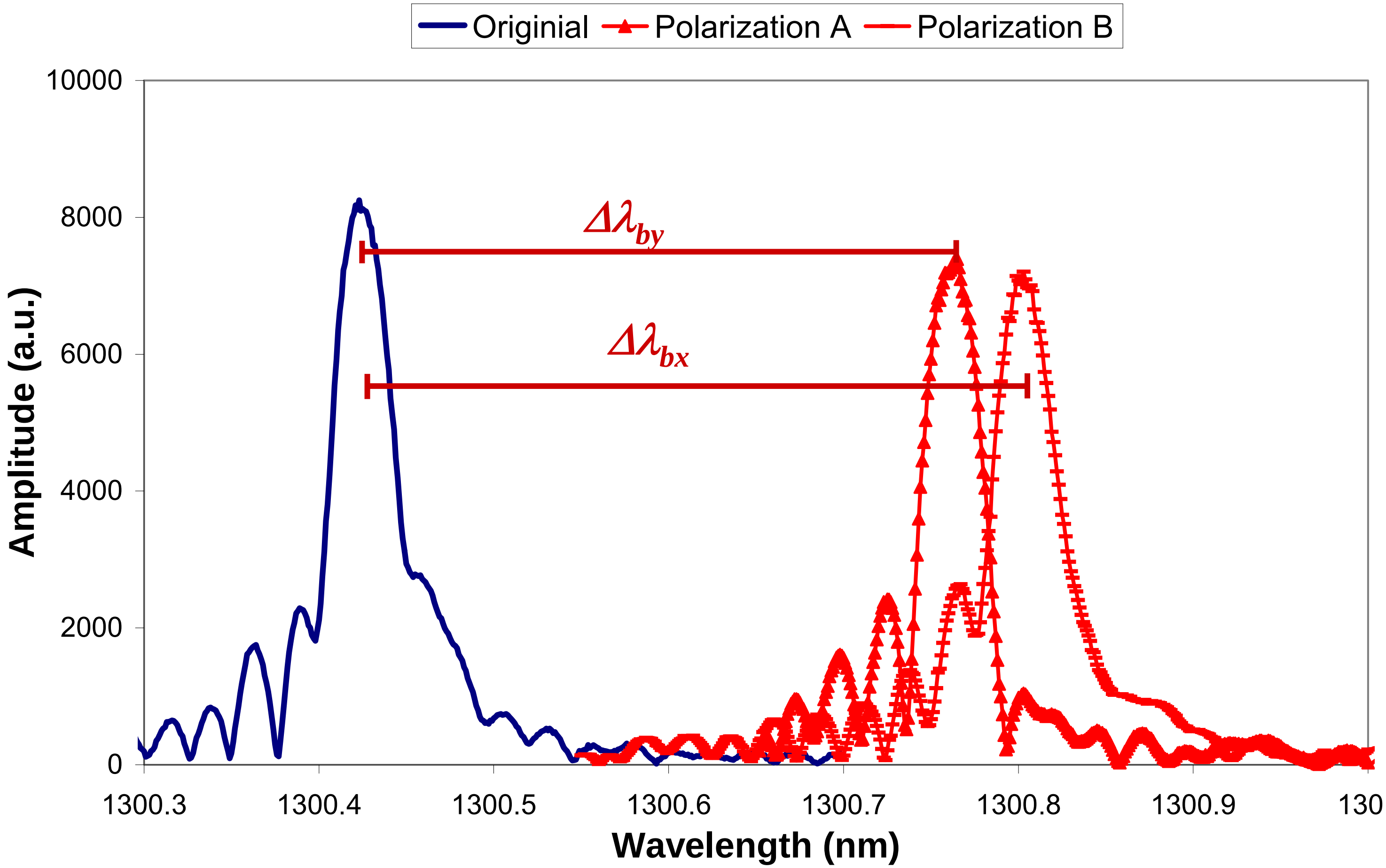
Consolidation Process

- FBG responds to
  - Pressure changes
  - Material changes

Temperature Compensated Bragg Wavelenth Changes



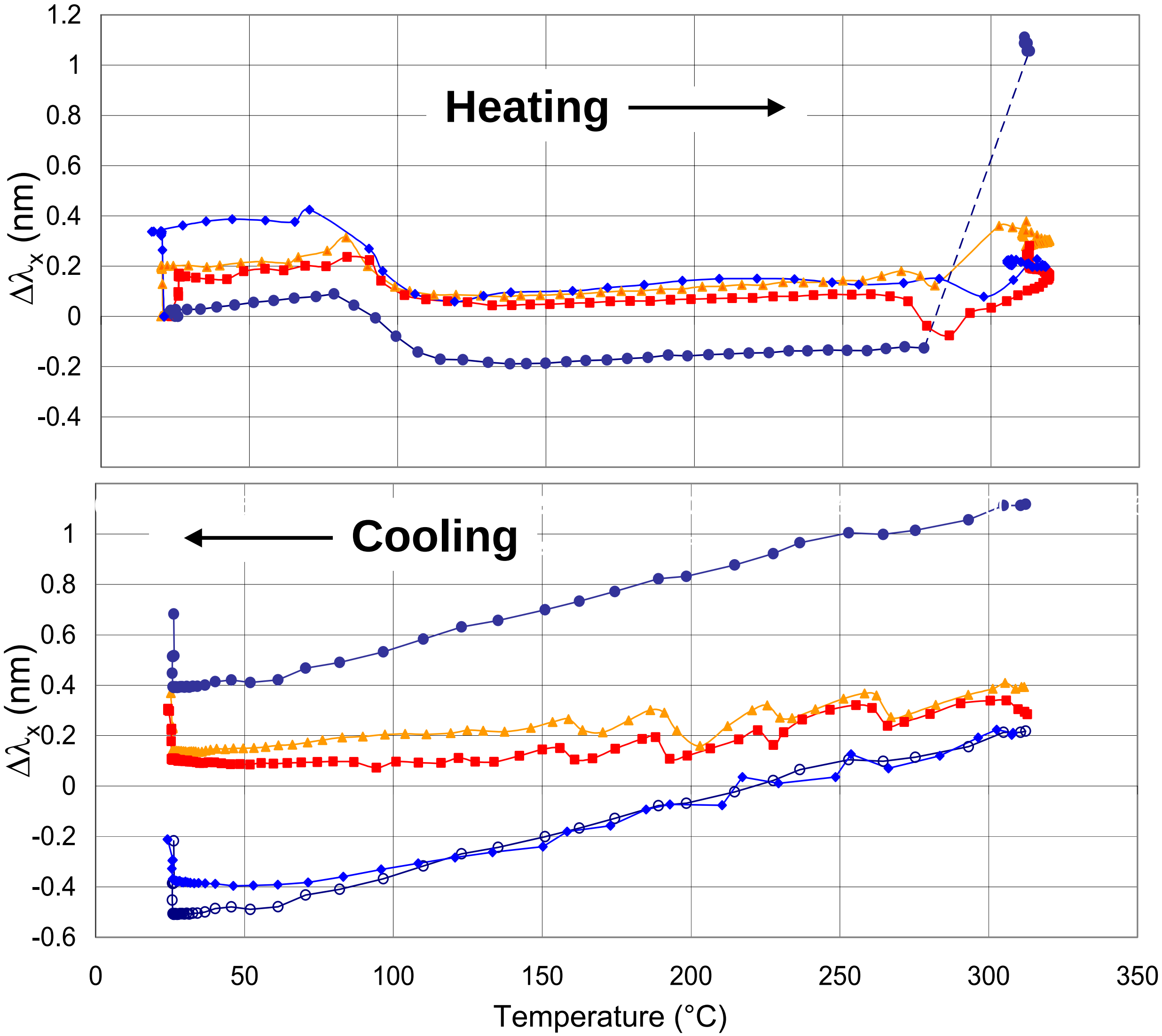
Final Residual Strains – room temp



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

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

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

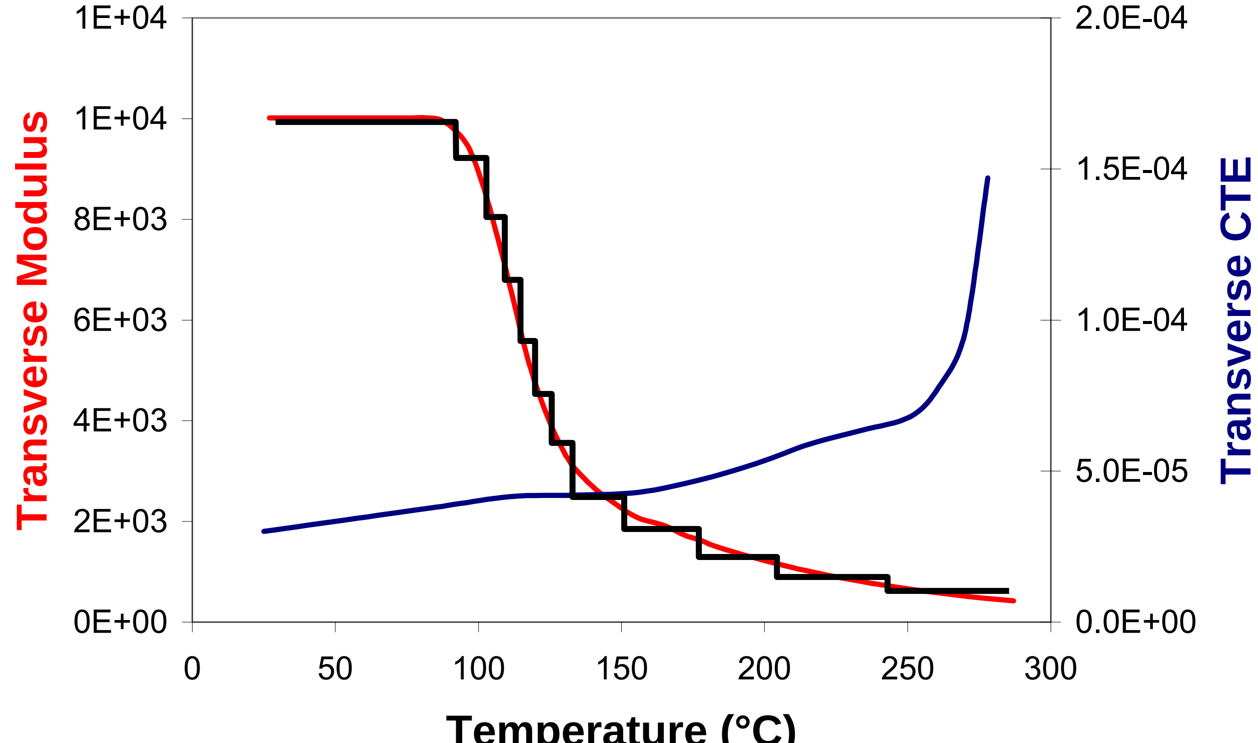
- Assumptions for a simplified model:
  - Generalized plane strain
  - Thermal contraction dominates
    - i.e. neglect crystallization effects
  - Negligible thermal gradients
  - Temp dependent polymer moduli and CTE
  - Stresses/strains accumulation can be divided into steps that will be summed

Elastic Step Model

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

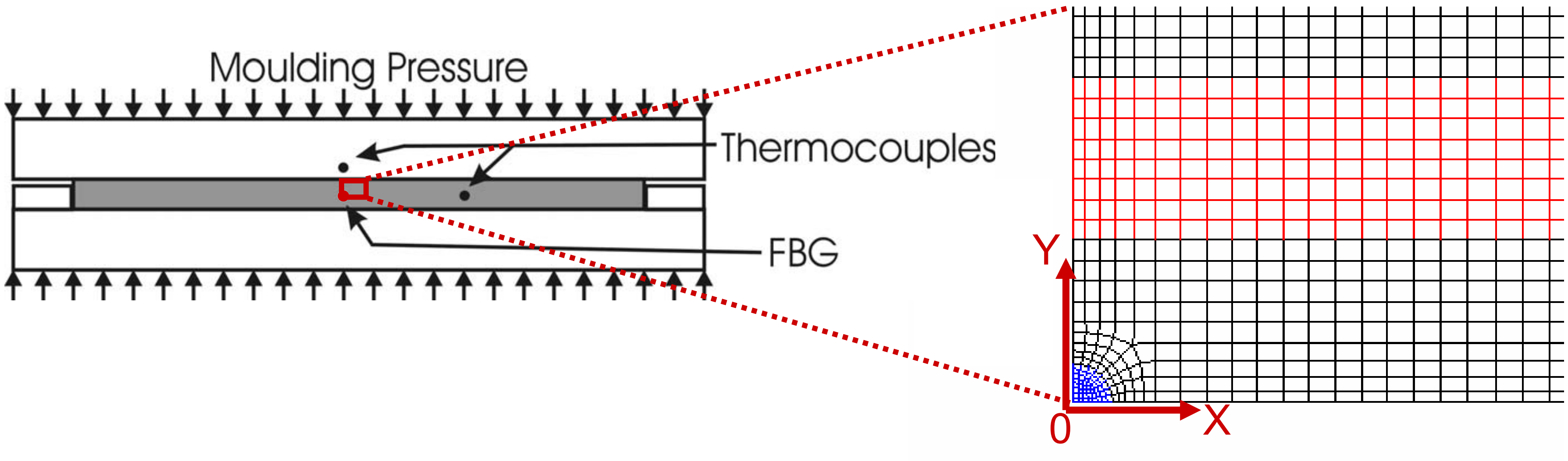
$$\varepsilon_{total_{ij}} = \sum_{k=1}^{13} \varepsilon_{ij}^{k}(T)$$

$$\sigma_{total_{ij}} = \sum_{k=1}^{13} \sigma_{ij}^{k}(T)$$



FEM Model – Elastic Step Method

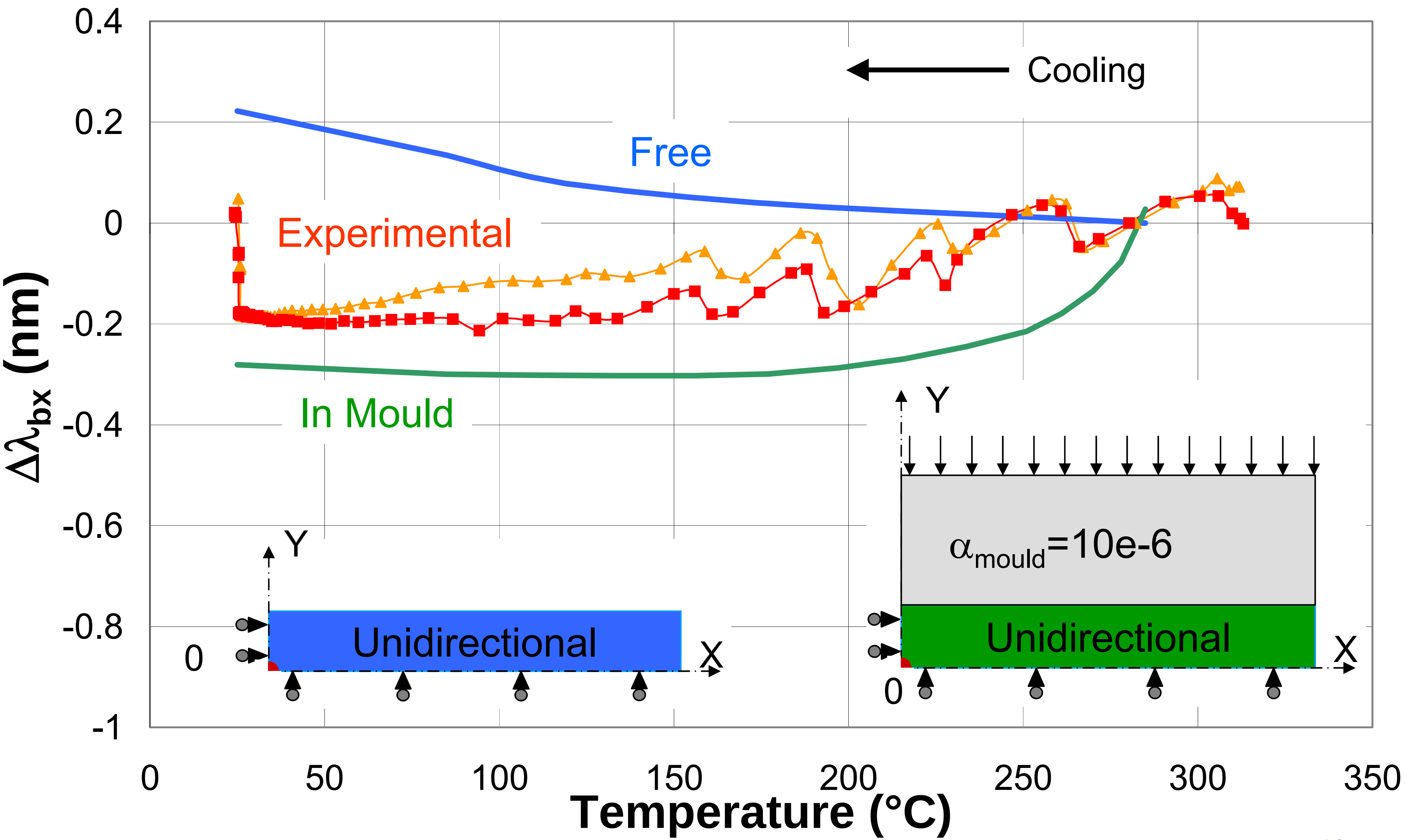
Example Cross-Ply Mesh



- ε_x, ε_y, ε_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)



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

Acknowledgements

The authors would like to acknowledge:

The financial support of the Swiss National Science Foundation, Grant no. 20-68279.02/1

&

Composite prepreg from Cytec Industries Inc.