# Effects of moisture on ageing and debonding in a single fiber composite using a long FBG sensor and numerical modeling

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# Outline

- Motivation - objective
- Fibre Bragg Grating (FBG) working principles

- Residual strains & Physical Characteristics in a single fiber composite (SFC)
- Hygrothermal studies on a SFC
- Conclusions

# Motivation - objectives

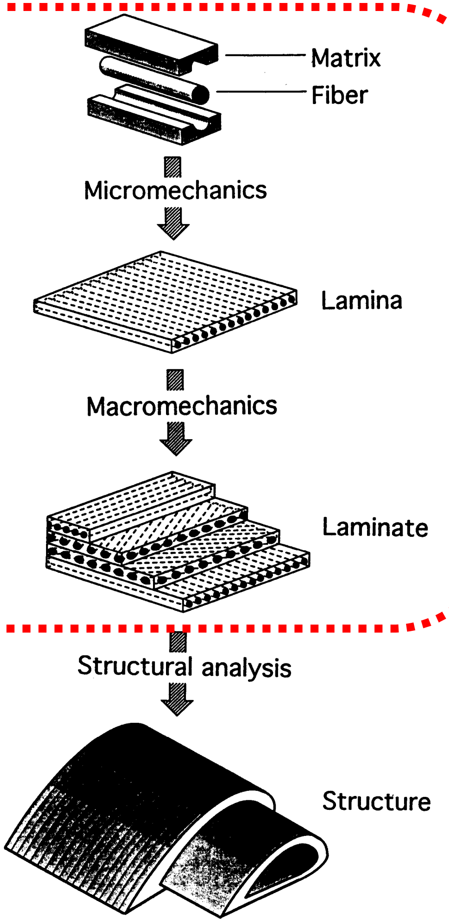
## composite materials: relevant length scales

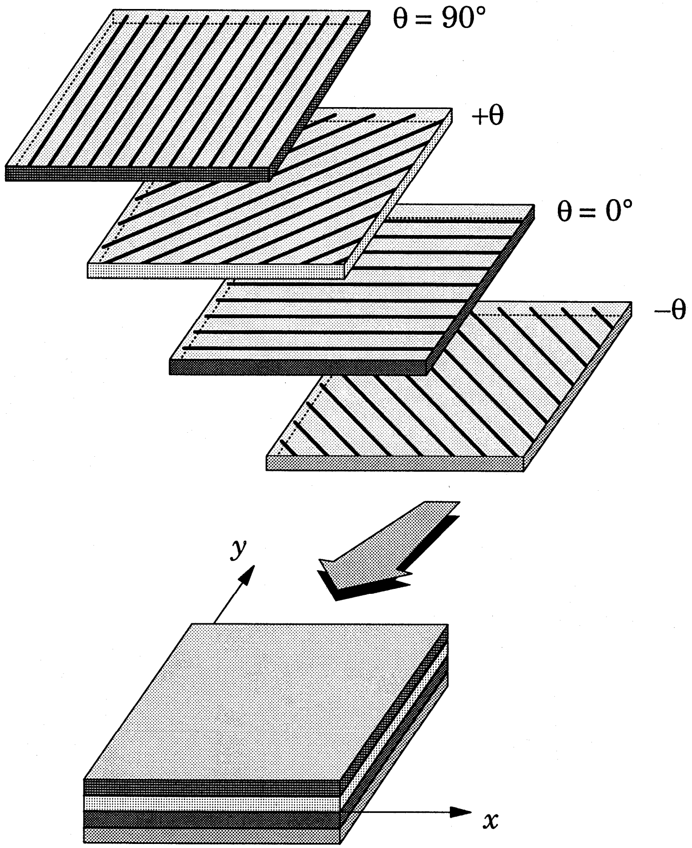
~ $10^{-4}$ m

~ $10^{-3}$ m

~ $10^{-2}$ m

~ $10^{0}$ m





Ref 1

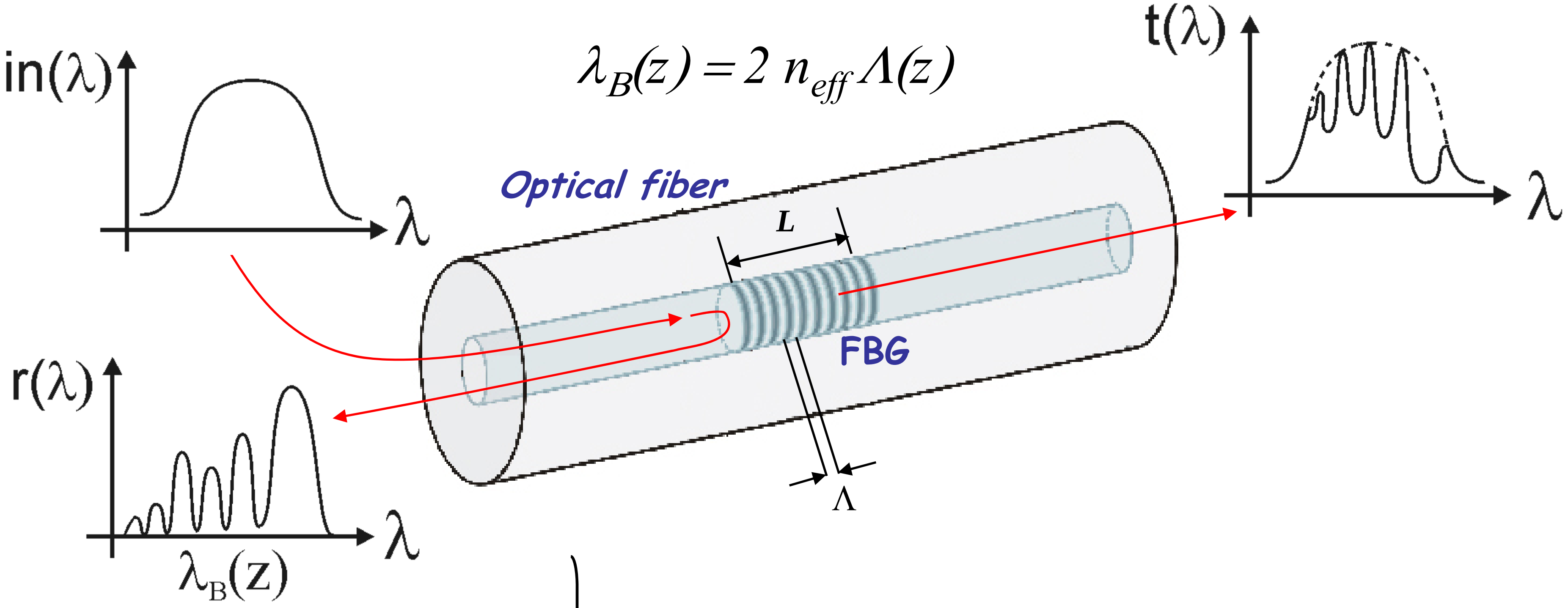
# Motivation - objectives

- Epoxy and epoxy based composites absorb moisture with severe changes on material and mechanical properties

- Investigate the effects of temperature and moisture on matrix and interface in polymer composites using embedded Fiber Bragg Grating sensors

- Develop *semi- experimental methods* to characterize internal strains and micro-mechanisms in composite materials and structures.

# FBG – working principle



$$\lambda_B(z) = 2\, n_{eff}\, \Lambda(z)$$

- $\Delta T = 0$
- No optical loss
- Axisymmetric load

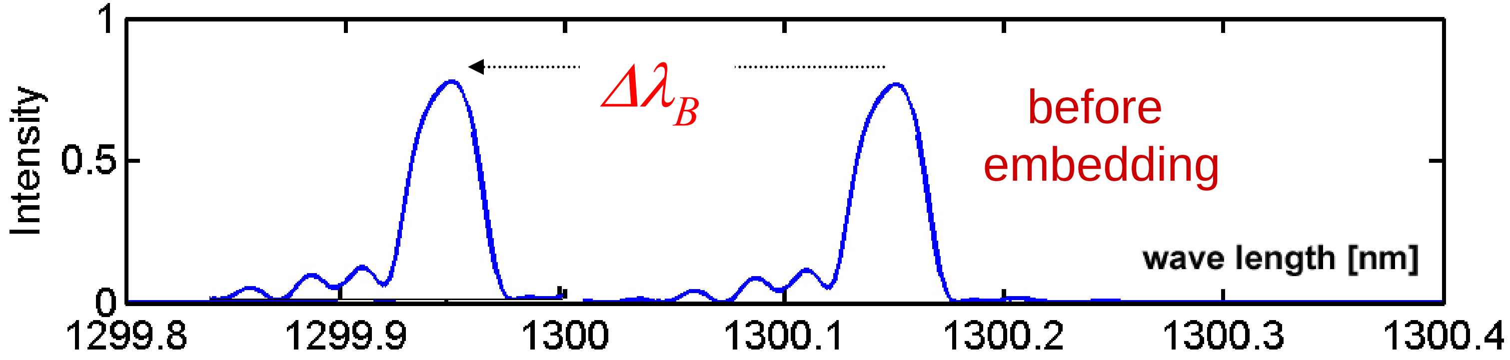
  $(E_f = 20\, E_m)$ $\varepsilon_x = \varepsilon_y = -\nu\varepsilon_z$

$$\boxed{\frac{\Delta\lambda_B(z)}{\lambda_{B0}(z)} = (1 - p_e)\epsilon_z(z)}$$

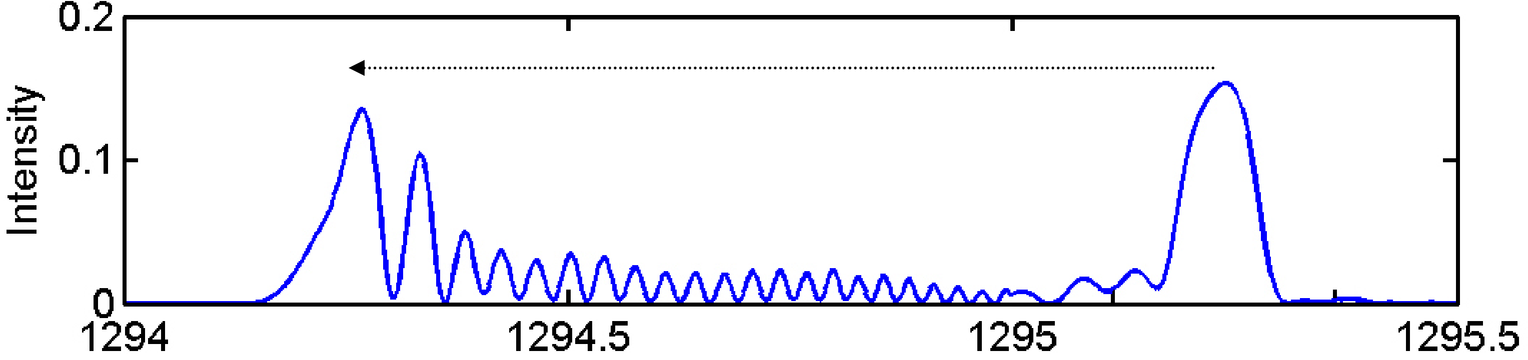
$p_e$ = strain – optic constant

# Spectral response of FBGs

uniform strain field $\varepsilon_z = \Delta\lambda_B / \left((1-p_e)\lambda_B\right)$



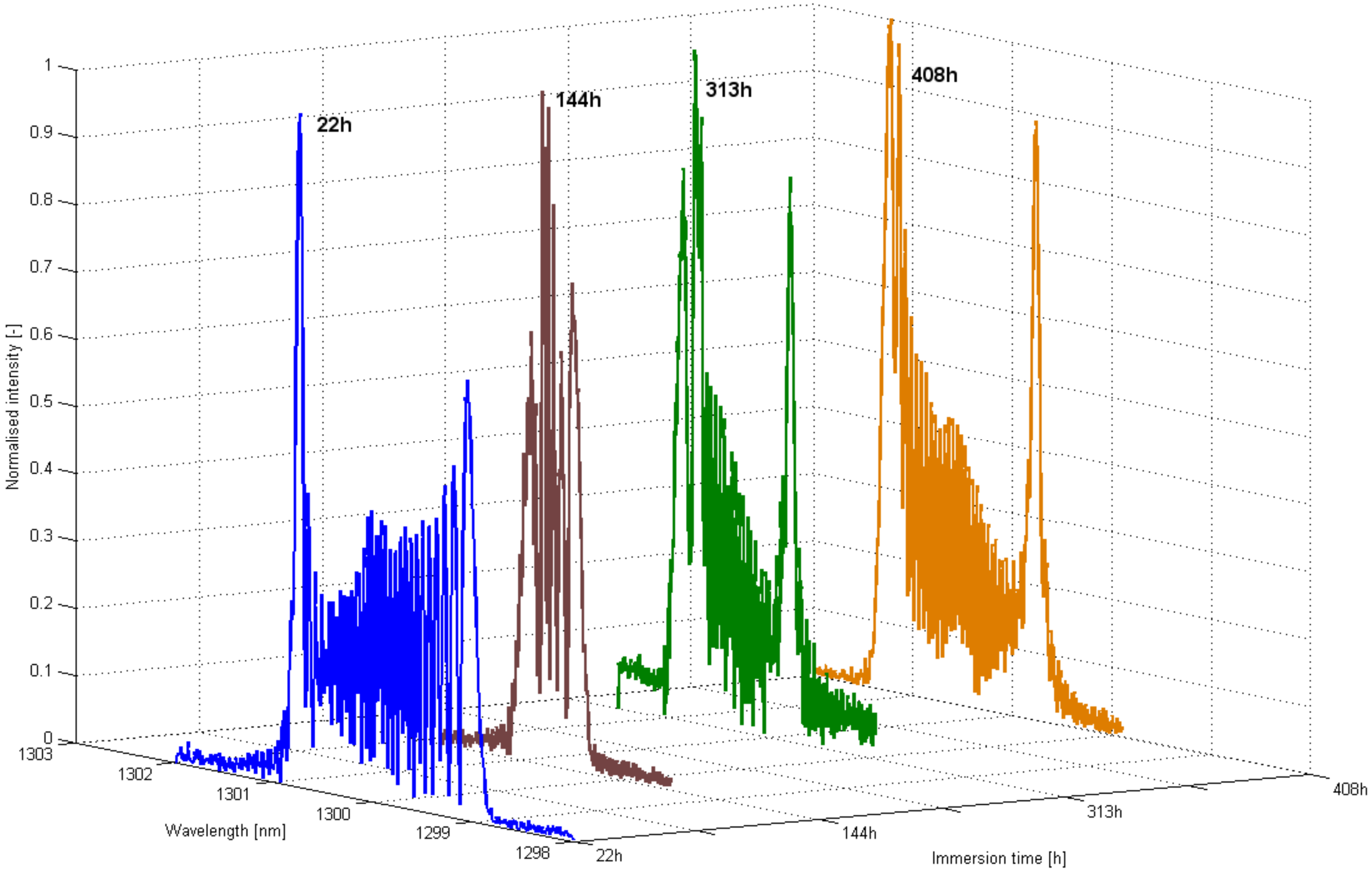
non-uniform strain field $\varepsilon_z(z) = \Delta\lambda_B(z) / \left((1-p_e)\lambda_B(z)\right)$



*How is the analysis of the deformation done in the non-uniform case?*

Ref 2

# Spectral response of the FBG vs time

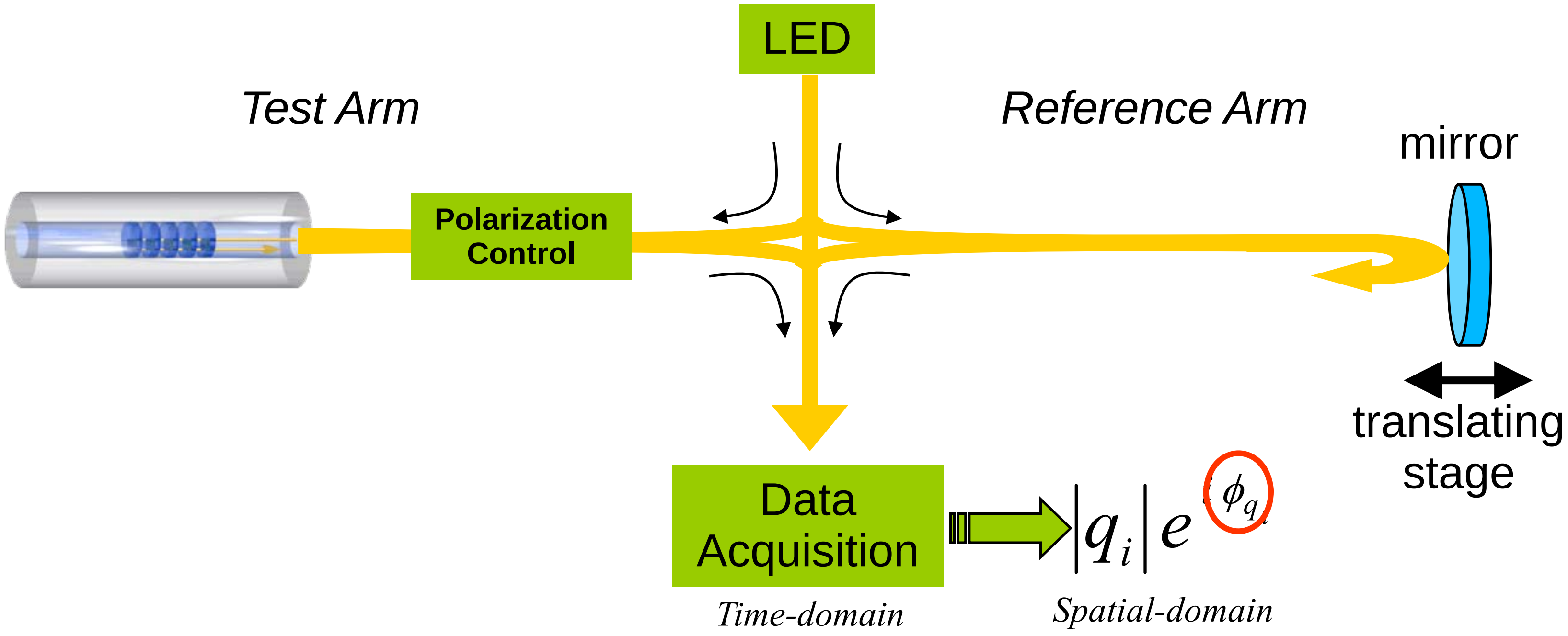


Lack of spatial resolution !

Ref 3,4

# Distributed sensing

- OLCR-based system:



LED

*Test Arm*

*Reference Arm*

mirror

**Polarization Control**

translating stage

Data Acquisition

$|q_i| e^{i\phi_{q_i}}$

*Time-domain*

*Spatial-domain*

- Measure local wavelength via coupling coefficient phase,

$$\lambda_{bi}(z) = \left\{ \frac{1}{\lambda_{bref}} + \frac{1}{4\pi n_0} \cdot \frac{d\phi_{q_i}(z)}{dz} \right\}^{-1} \qquad \boxed{\frac{\Delta\lambda_{bi}(z)}{\lambda_{Bi}} = (1 - p_e)\varepsilon_z(z)}$$

Ref 5

# Opto-mechanical equation

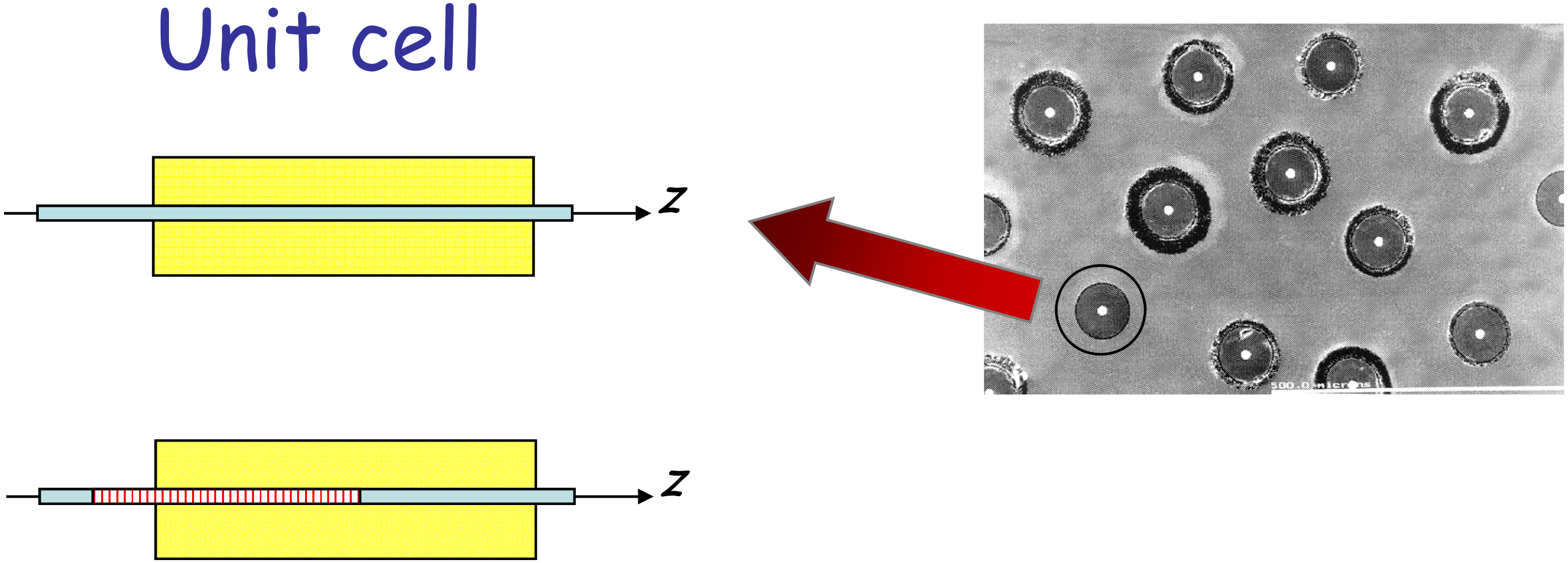
## Contributions to wavelength shift

| | |
|---|---|
| $\dfrac{\Delta\lambda_B(z)}{\lambda_{B0}(z)} = (1-p_e)\,\varepsilon_z^{res}(z)$ | Pre-existing strains |
| $+(\alpha_f+\xi)\Delta T$ | Thermal strains on FBG |
| $+(1-p_e)(\alpha_m-\alpha_f)\Delta T$ | Strains due to thermal mismatch with host material |
| $+(1-p_e)\,\alpha_{chem}\Delta\gamma$ | Strains due to chemical shrinkage of matrix |
| $+(1-p_e)\,\beta\Delta\bar{c}$ | Strains due to Ageing/swelling of matrix |

# Materials & methods

## Long fiber composites

Unit cell



reinforcing fiber &
distributed sensor

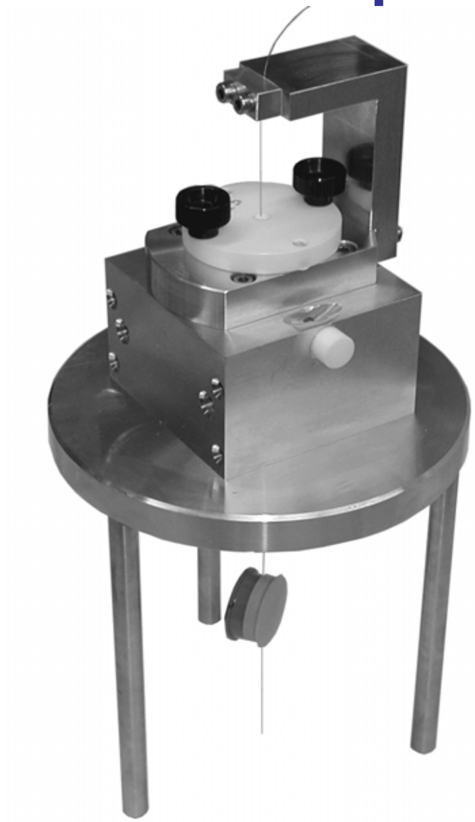
# Materials & methods

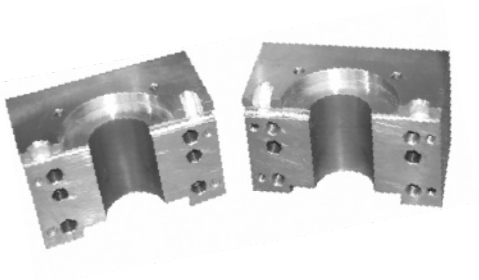
## Materials

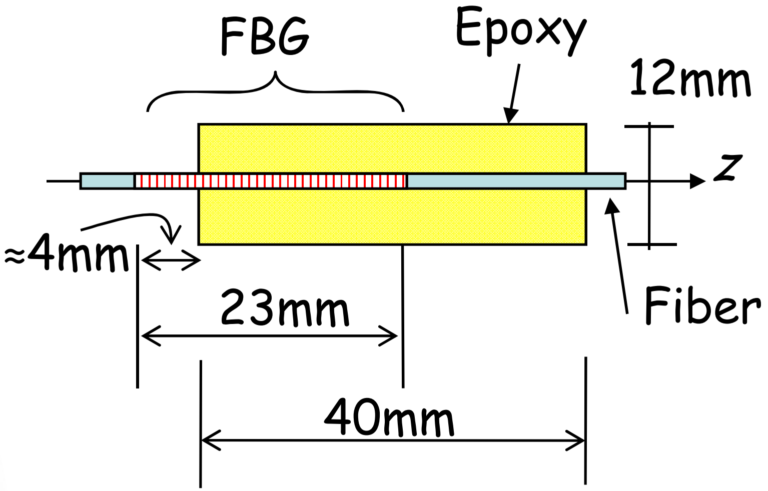
**EPOXY**: DER330© & DER732 © ; DEH26 © hardener (70:30:10 )

Low temperature curing; Low shrinkage

**FIBER: Optic glass fiber:** 125 mm in diameter ; 24 mm FBG



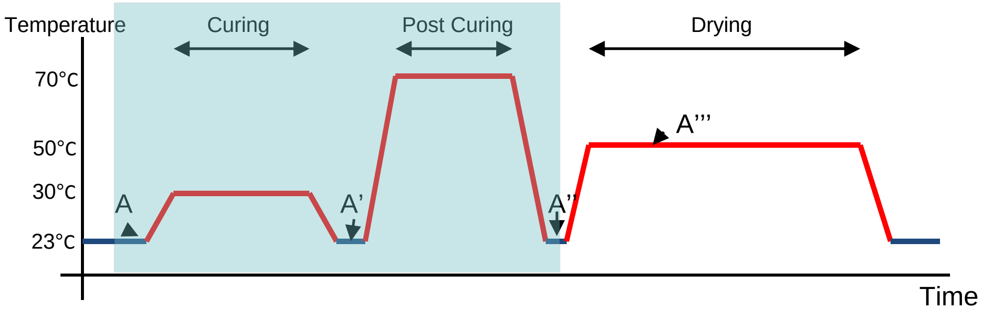




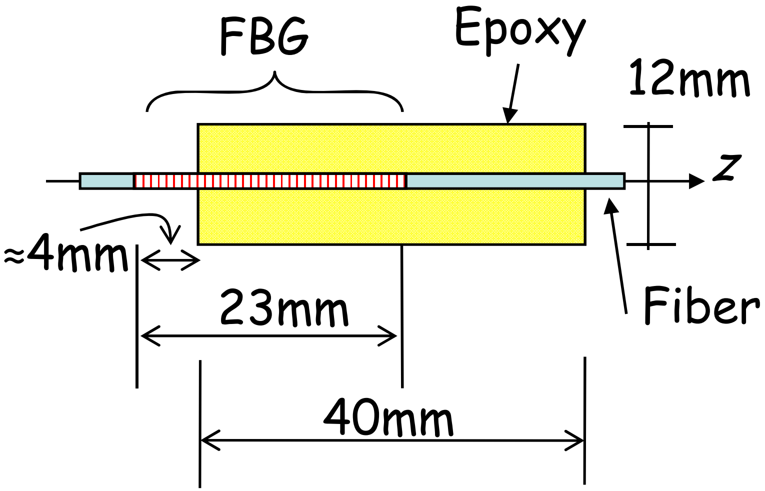
# Materials & methods

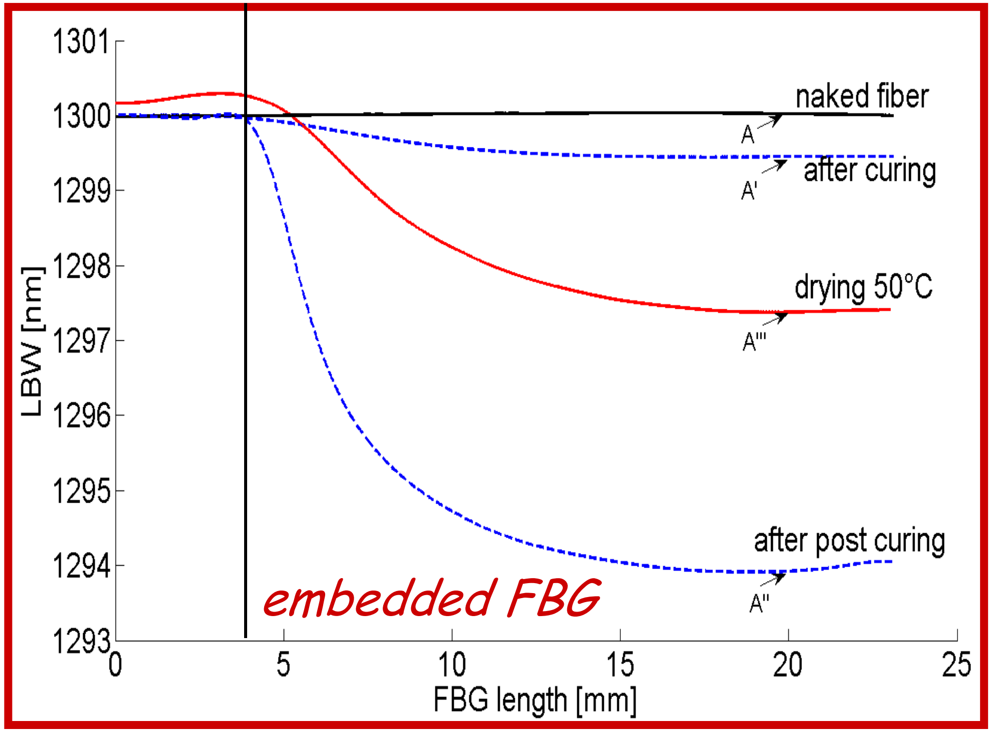
- Characterization of residual strains
- Modeling: fracture mechanics; Thermoelasticity; FE
- Degree of curing
- Thermal expansion coefficient
- Coefficient of moisture expansion
- Modeling: diffusion & heat transfer; fracture mechanics; FE

# Typical FBG strain response



*water bath*





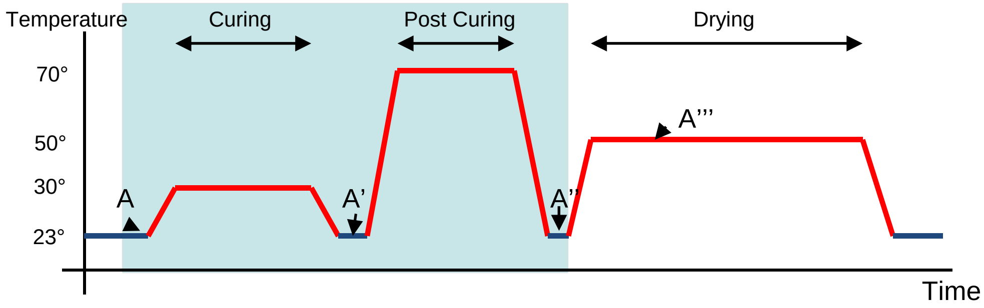
# Degree of conversion

- Consider points A and A' : residual strains are attributed to chemical shrinkage only

$$\frac{\Delta\lambda_B(z)}{\lambda_{B0}(z)} = (1-p_e)\alpha_{chem}\Delta\gamma$$

Assume

$$\alpha_{chem} = \left(\Delta V / V_0 + 1\right)^{1/3} - 1$$



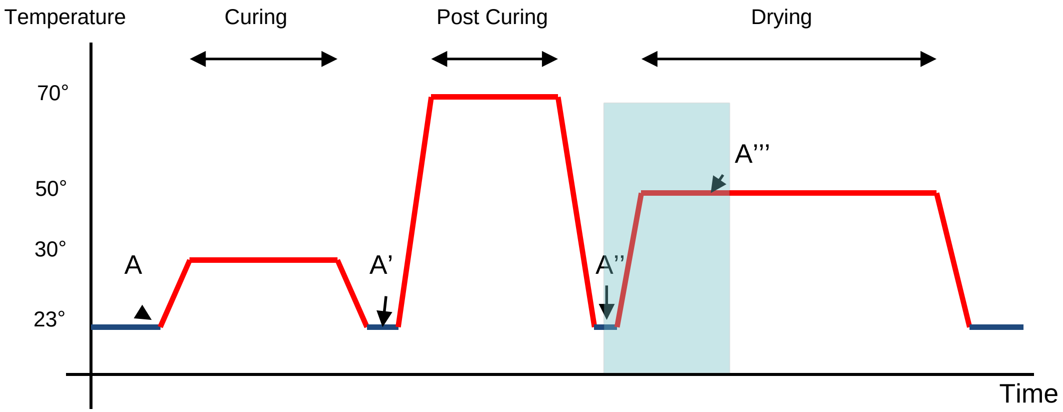
- Consider points A and A'' : additional residual strains are attributed to chemical shrinkage only

$$\frac{\Delta\lambda_B(z)}{\lambda_{B0}(z)} = (1-p_e)\varepsilon_z^{res} + (1-p_e)\alpha_{chem}\Delta\gamma$$

$$\Delta\gamma$$

| | | Specimen 1 | Specimen 2 |
|---|---|---|---|
| **Point** | **Position** | **(total)** | **(total)** |
| **A->A'** | After Curing | 7.20% | 3.90% |
| **A->A''** | After Post-Curing | 74.30% | 70.87% |

# Coefficient of thermal expansion



$$\frac{\Delta\lambda_B(z)}{\lambda_{B0}(z)} = (1-p_e)(\alpha_m-\alpha_f)\Delta T + (\alpha_f+\xi)\Delta T$$

Consider point A'' & A''':

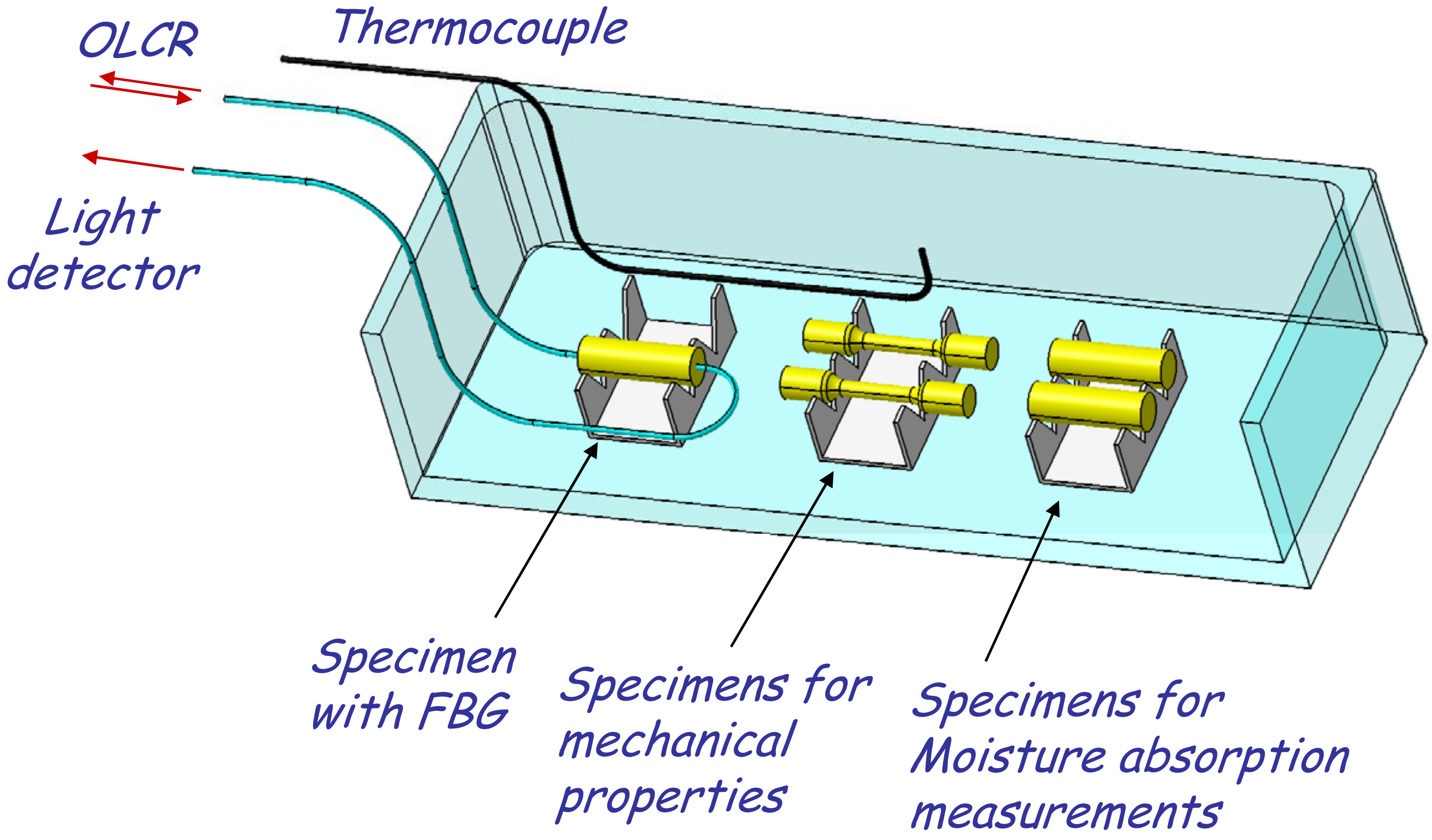
$$\alpha_m = \frac{\Delta\lambda_B(z)}{\lambda_{B0}(z)(1-p_e)\Delta T} - \frac{(\alpha_f+\xi)}{(1-p_e)} - \alpha_f$$

Coefficient of thermal expansion

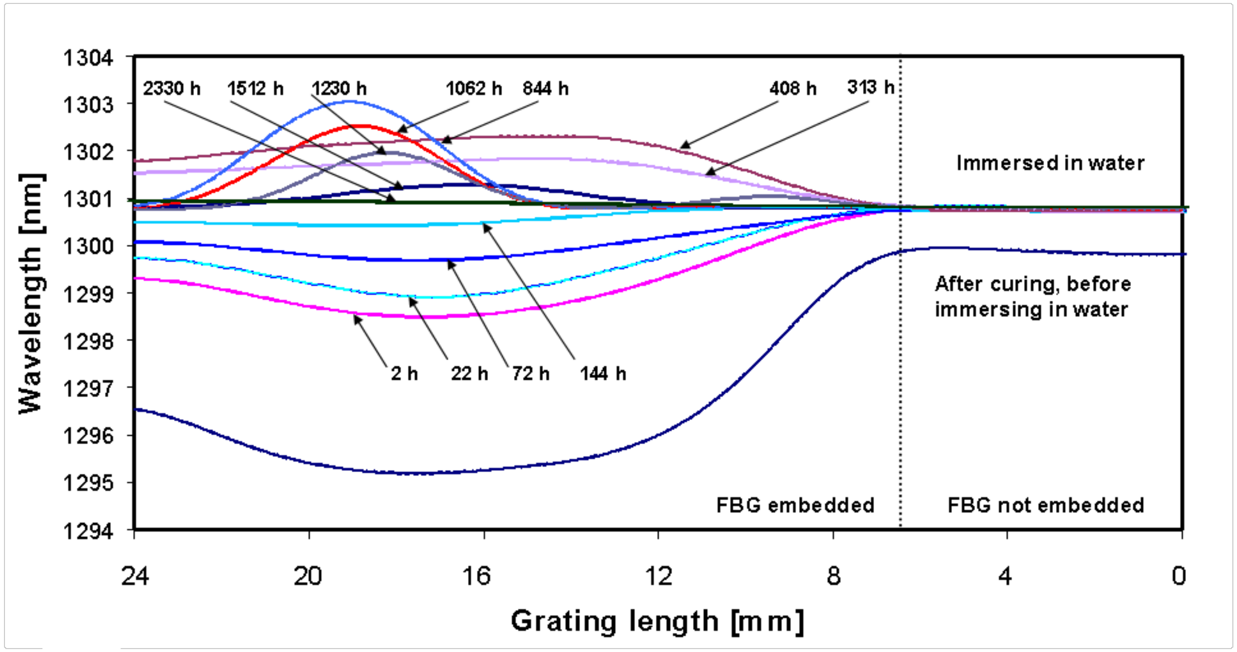
| | [illegible] | [illegible] | Diff. |
|---|---|---|---|
| **23->50°C (**Point A->A''') | 10.61 x $10^{-5}$ | 11.00 x $10^{-5}$ | 3.7% |

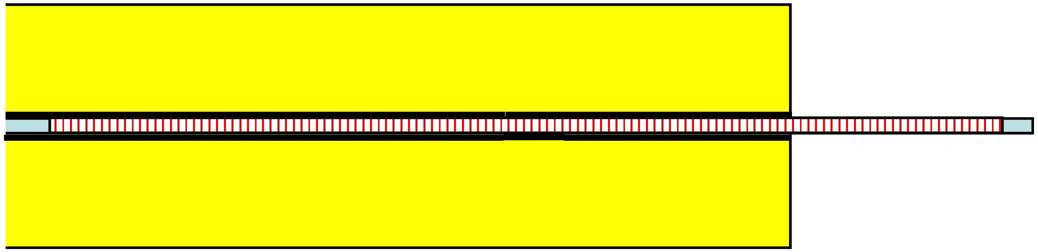
# Hygrothermal studies

## Water bath with specimens @ 50°C



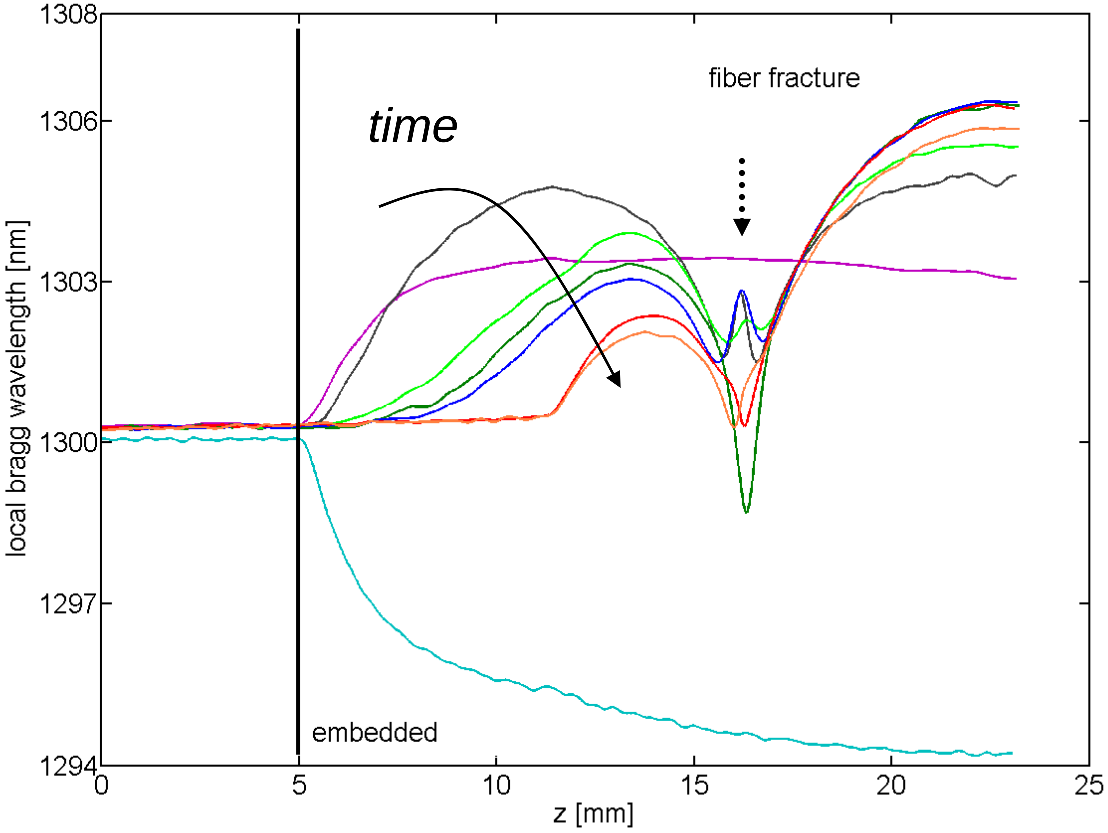
# strain along the fiber - time

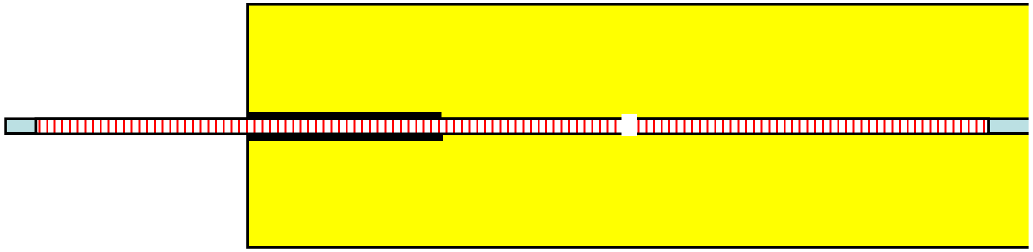




Ref 4

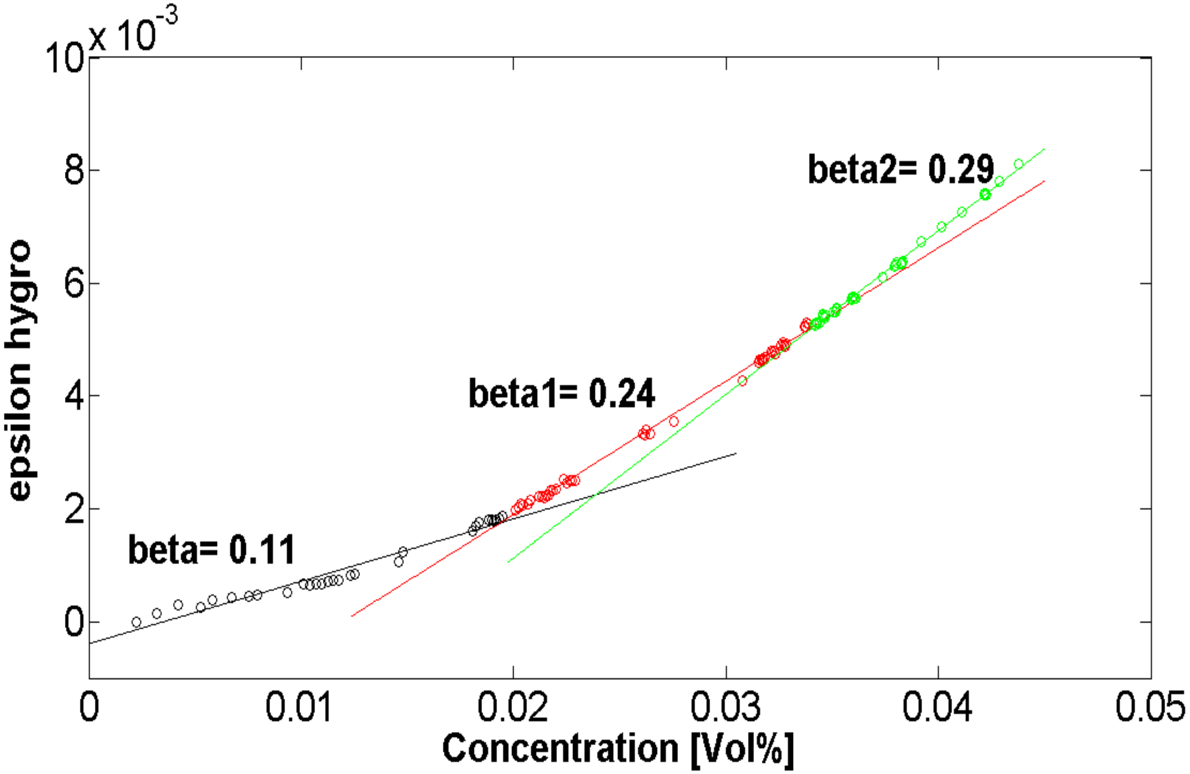
# strain along the fiber - time





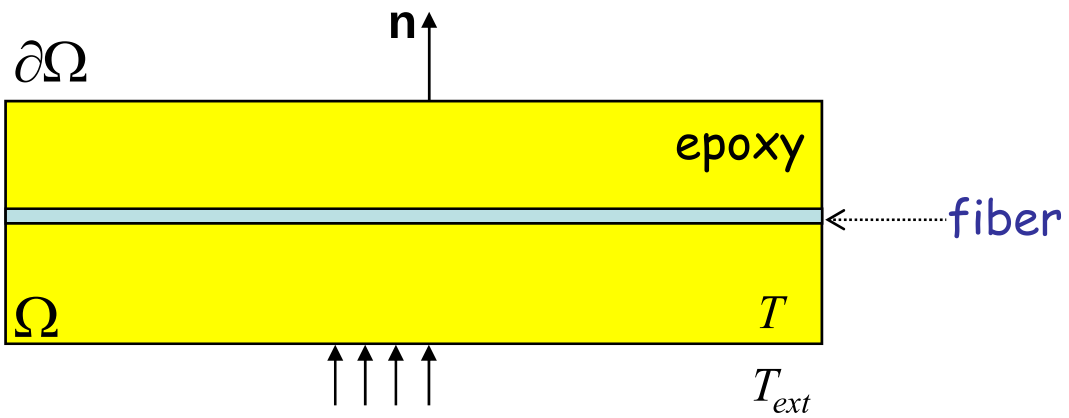
# Coefficient of moisture expansion

*Periodic weight measurements of control specimens* $\rightarrow \Delta\bar{c}$



$$\frac{\Delta\lambda_B(z)}{\lambda_{B0}(z)} = (1-p_e)\,\beta(\bar{c})\Delta\bar{c} \quad \Rightarrow \quad \beta(\bar{c}) = \frac{1}{(1-p_e)}\frac{1}{\Delta\bar{c}}\frac{\Delta\lambda_B(z)}{\lambda_{B0}(z)}$$

# Analysis of heat transfer



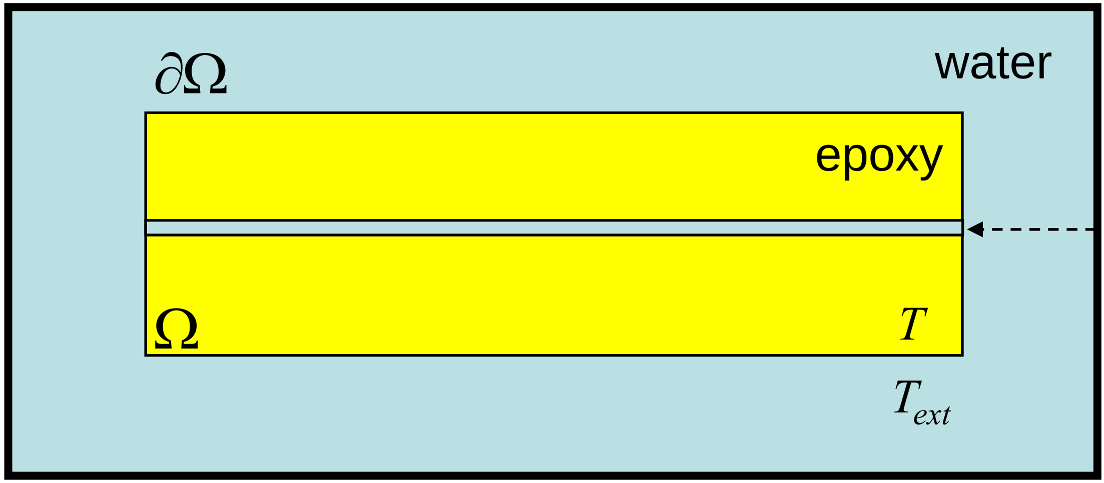
$$\rho c_p \frac{\partial T}{\partial t} = k\nabla^2 T \quad with \quad T = T_0 \quad at \quad t = 0 \; in \; \Omega$$

$$and \; q = -(k\nabla^2 T)\cdot \mathrm{n} = h_{ext}(T - T_{ext}) \quad on \quad \partial\Omega$$

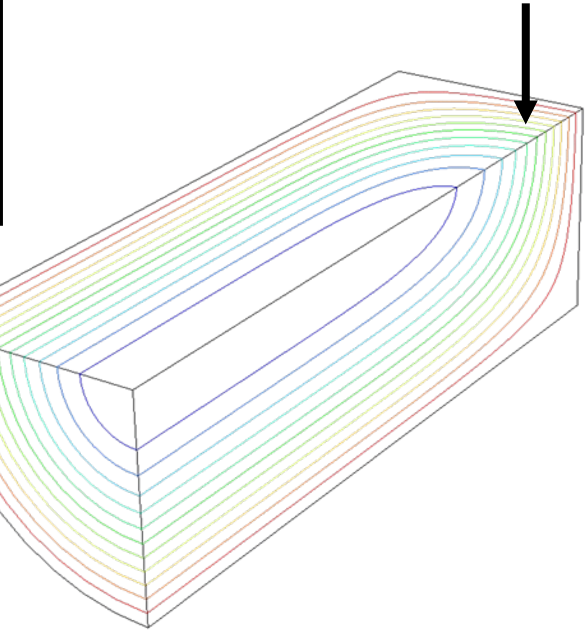
➡ Thermal equilibrium is achieved in 15 min

# Diffusion analysis

## contours of equal moisture for 400 hrs

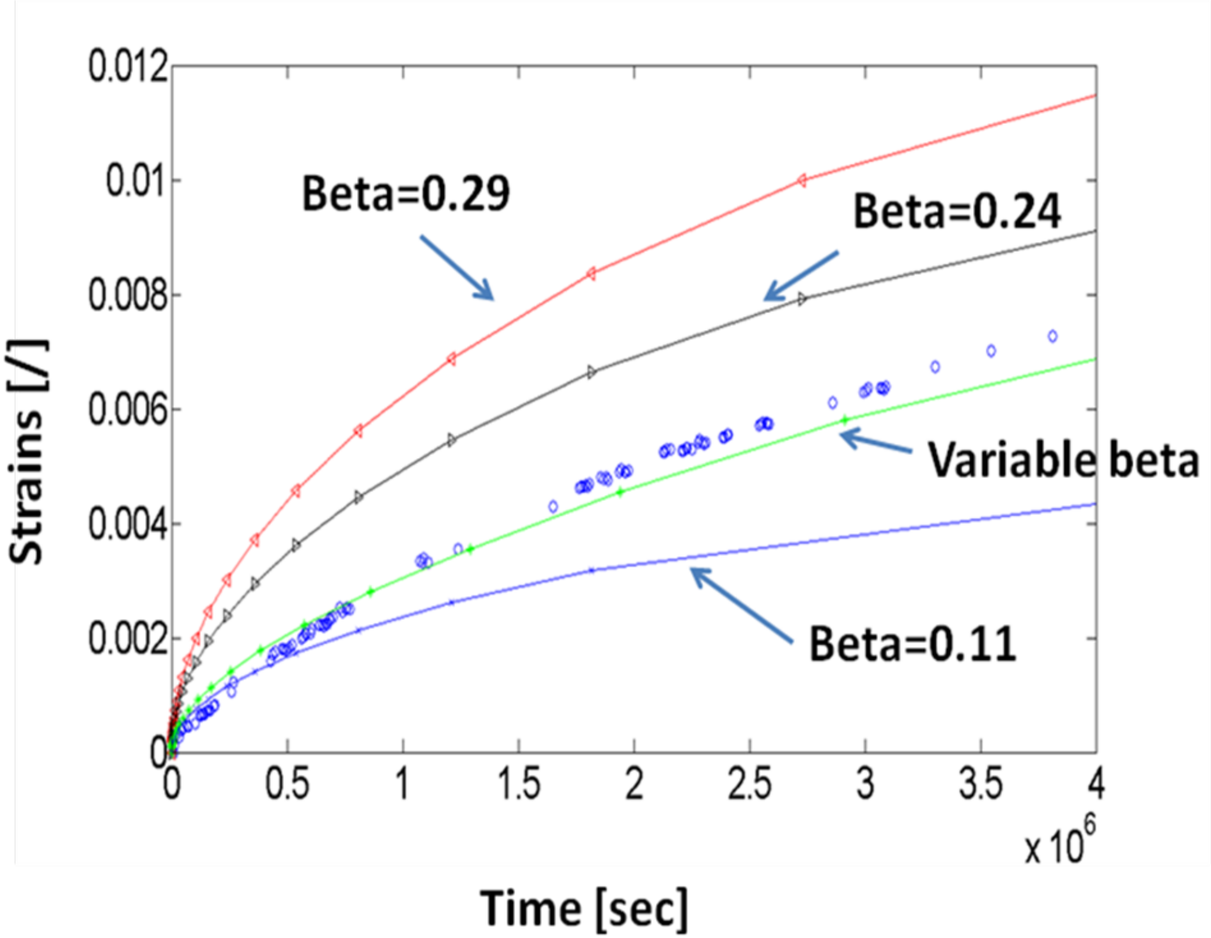


High gradients

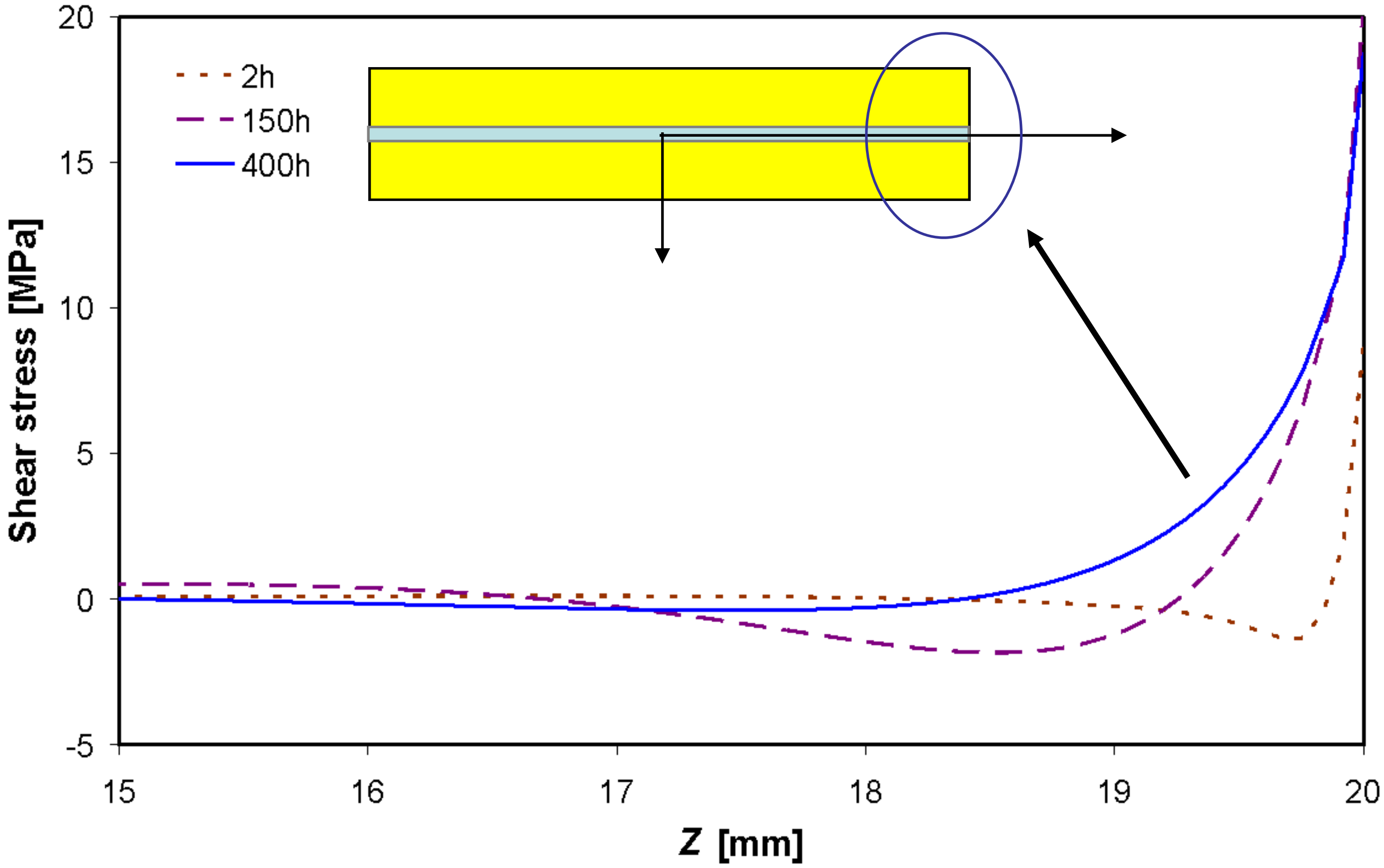


$$\left\{\begin{array}{l} \dfrac{\partial c^*}{\partial t} = D\nabla^2 c^* \quad \mathit{with}\ \ c^* = 0 \quad \mathit{at} \quad t = 0 \quad \mathit{in} \quad \Omega \\ \mathit{and} \quad \mathit{boundary} \quad \mathit{condition}:\ c^* = 1 \quad \mathit{on} \quad \partial\Omega \\ \nabla\cdot\boldsymbol{\sigma} = 0 \quad \mathit{in} \quad \Omega \quad \mathit{with} \quad \boldsymbol{\sigma} = \mathbf{C}\left(\boldsymbol{\varepsilon} + \beta_m s c^* \mathbf{I}\right) \end{array}\right\}$$

# Analysis of axial strain - time



# Shear stress at interface



Ref 4

# Conclusions

- A constant coefficient of moisture expansion is not sufficient to describe the hygrothermal effects on an epoxy material for relatively long exposure times

- Combined with realistic stress analysis FBGs are proven to be effective tools in developing methods to investigate internal strains due to processing & hygrothermal loads

# references

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