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Institut de Recherche en
Génie Civil et Mécanique

Sensing strain gradients with embedded Bragg gratings across the width of a composite laminate

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Outline

- Optical framework
- An example of strain gradient measurement
- New motivations and experiments
  - Cure monitoring
  - Mechanical testing
- Conclusion and prospect

Which physical phenomena are involved in such sensor ?

Material / Wave interaction:

Comparable to high or low frequency analyses in electrical engineering

Comparable to acoustics: Wave propagation – reflection analysis, defects detection.

Comparable to XRays.

For an optical wave:

Maxwell theory: wave propagation defects due to optical index variations revealed by the optical signal.

Interferences and diffraction: Involve both the geometry and the optical index of a “shape” encountered => analysis of the corresponding variations.

Advantages of an optical fibre:

Low signal reduction => High distance interrogation.

Low size: 125 µm diameter and even 80 µm on custom products.

High sensitivity.

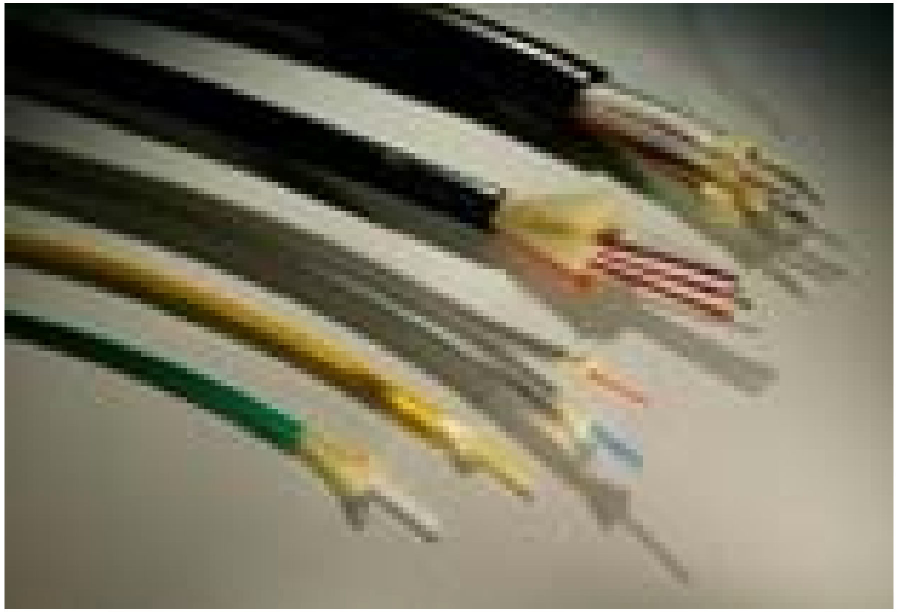
Locate several sensors in a single optical fibre multiplexing.

Low sensitivity to electromagnetic disturbances

Two ways of interrogation:

- Measure the optical index (and its variations) of the constitutive glass of the optical fibre
- Analyze the evolution of the propagation medium which is the optical fibre submitted to environmental constrains.

Which sensors and what kind of interrogation ?



Commercial solutions

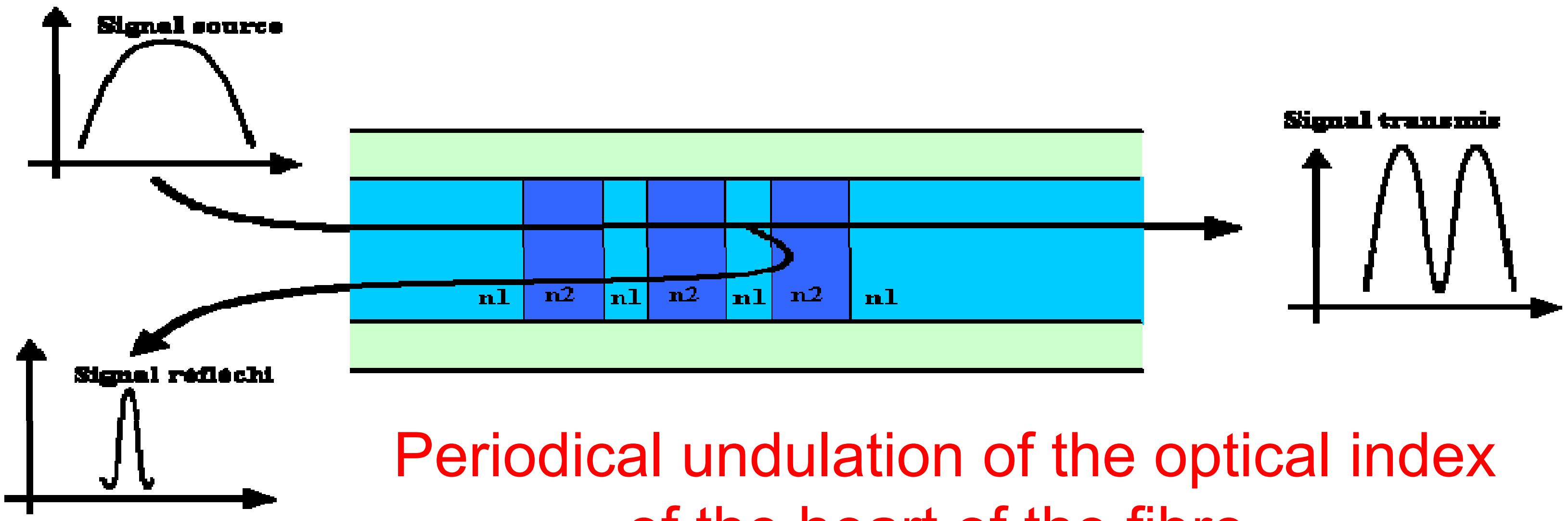
Optical Rayleigh Backscattering :

- Shift of the spectral response <=> Strain (µepsilon)
- Spatial resolution: 2 mm over 100 m
- Sensitivity: +/- 1 µstrain

Optical Stimulated Brillouin Backscattering:

- Shift of the spectral response <=> Strain (µepsilon)
- Spatial resolution: 0.5 m sur 10 km
- Sensitivity: 25 µstrain

Fibre Bragg Grating Sensors - FBGS



λ Bragg wavelength

Periodical undulation of the optical index of the heart of the fibre.

The active part is in the heart of the fibre (10/125μm)

→ **Uncoated optical fibres**

FBGS applications

- Sensors
  - Temperature
  - Strain

Shift of the Bragg wavelength → $\lambda_B = 2\eta_{co}\Lambda$ **Averaged effect**

Measurement of the index profile and the phase of the grating → **Local variations**

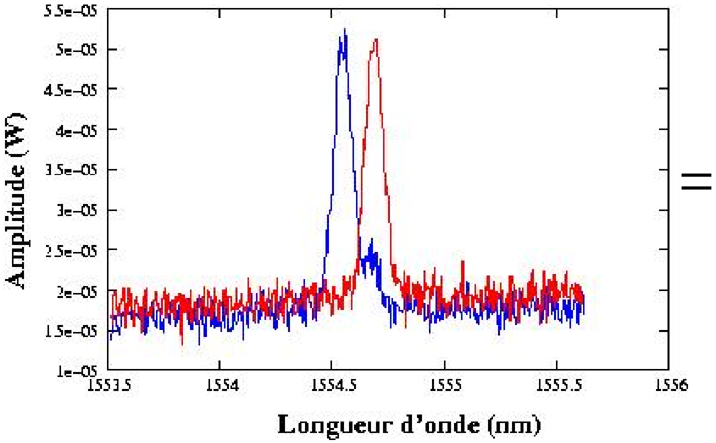
Tracking of the Bragg wavelength
(sensitive to both temperature and strain)

Uniform strain ε along a FBGS:

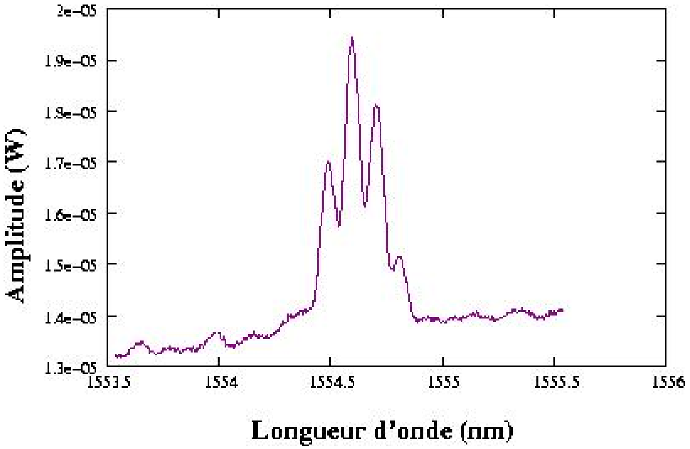
$$\Delta\lambda_{B_0} = \lambda_B \quad 1 - \frac{\eta_{co}^2}{2} \quad P_{12} - \nu\left(P_{11} + P_{12}\right) \quad \varepsilon$$

Temperature variation ΔT :

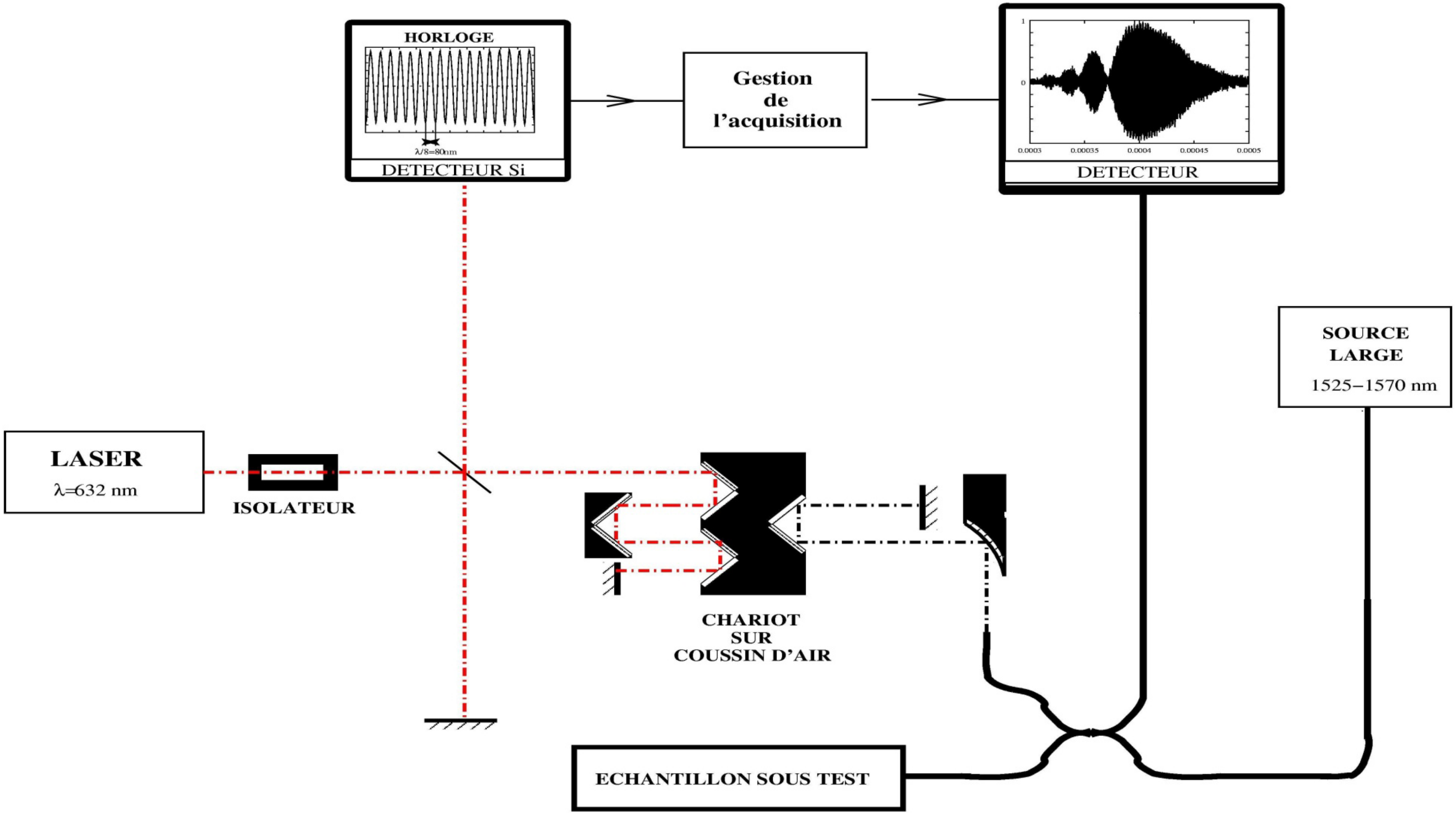
$$\Delta\lambda_{B_T} = \lambda_B(\alpha + \xi)\Delta T$$



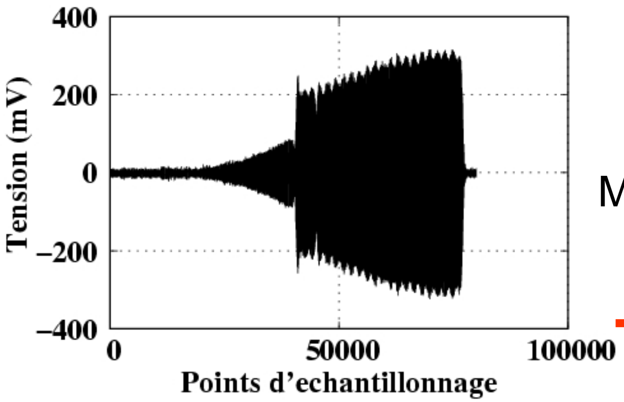
=>*sensitivity 1 pm/$\mu\varepsilon$*



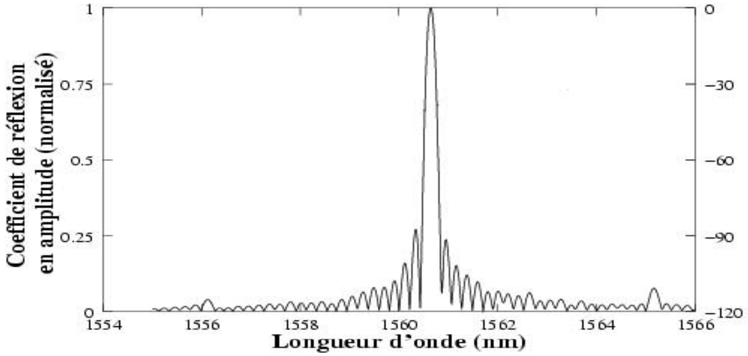
Optical Low Coherence Reflectometry:
Measure of the complex reflection index of a FBGS



Phase measurement of a FBGS

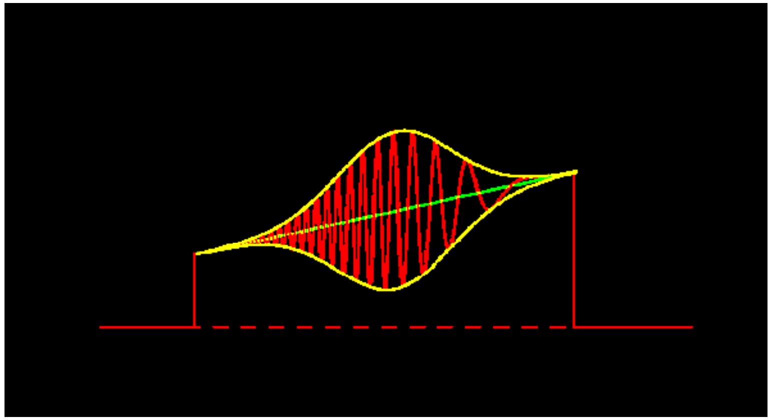


Measure of the complex reflection coefficient



λ BRAGG wavelength

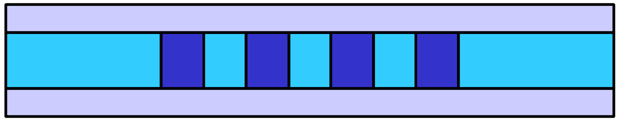
Inverse algorithm: layer-peeling *



$\Delta n(z)$

$\Delta n_{AC}(z)$

$\Delta n_{DC}(z)$



Spatial resolution along z: 20µm

(*) ***On the synthesis of fiber Bragg gratings by layer-peeling***,
J. Skaar, J. of. Quant. Elec., 37(2), 165-173, 2001

Non-uniform strain characterization along a FBGS

$$\varepsilon(z) = K_{\varepsilon} \frac{d\left[\Psi(z) - \Psi_0(z)\right]}{dz}$$

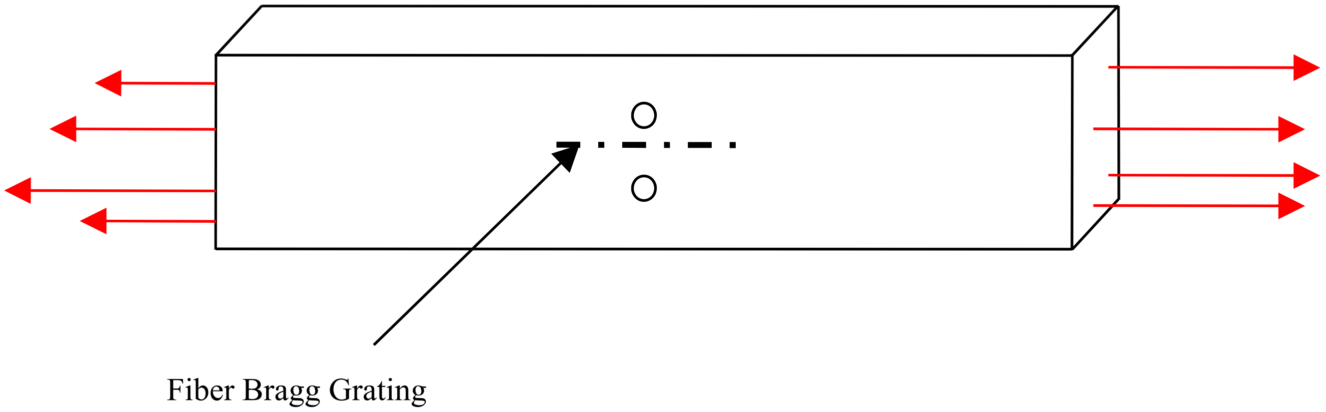
Where:

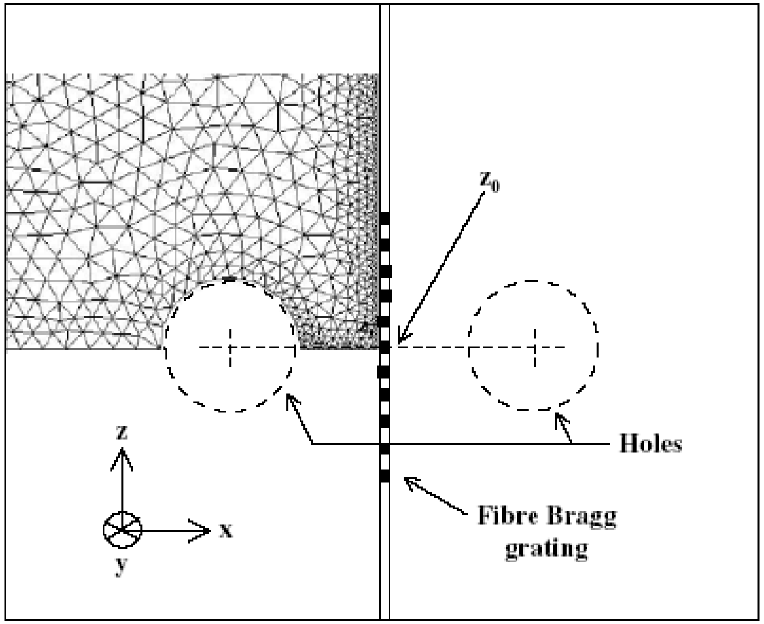
$\Psi_0(z)$ is the phase of the reference state

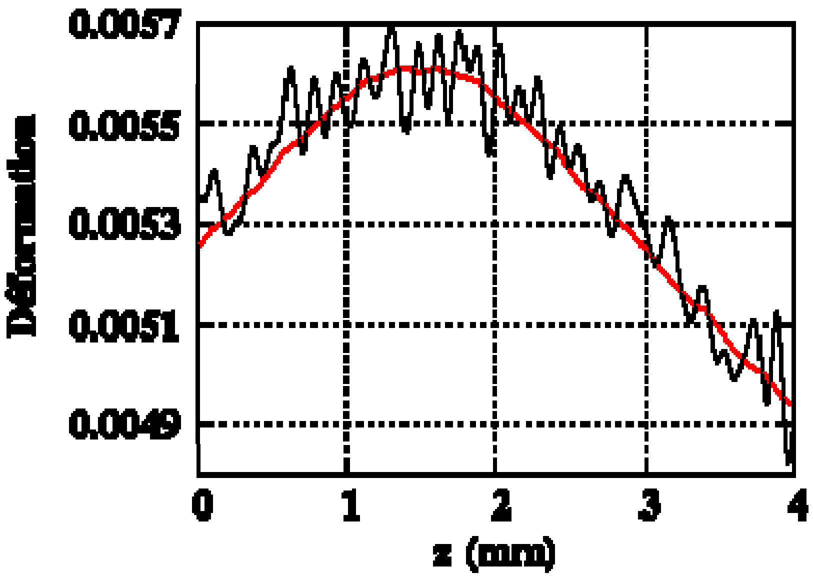
$\Psi(z)$ is the phase of the deformed state (*)

***(*)Determination of strain distribution and temperature gradient profiles from phase measurements of embedded fibre Bragg gratings (**X Chapeleau et al.)

- # An example of strain gradient measurement





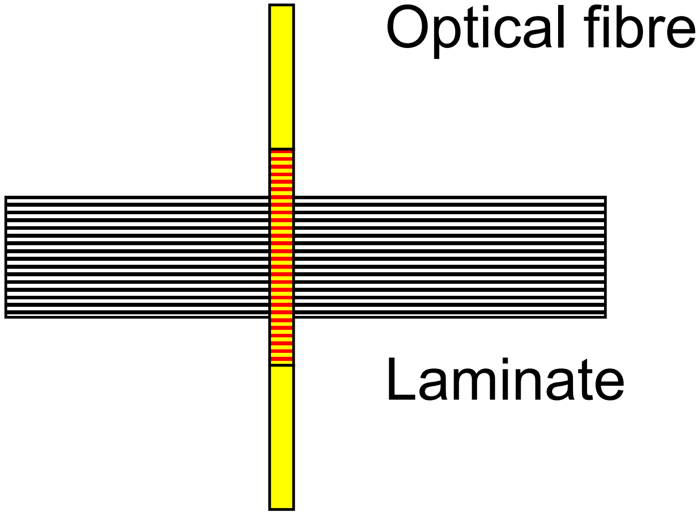


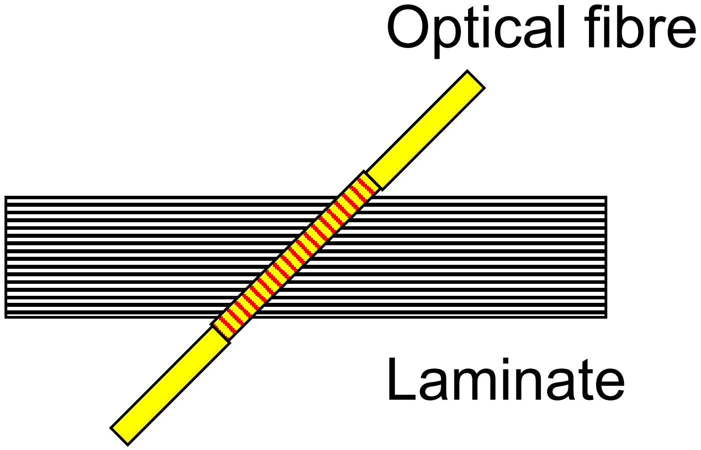
— Numerical deformation calculated (CASTEM)

Determination of strain distribution and temperature gradient profiles from phase measurements of embedded fibre Bragg gratings (X Chapeleau et al.)

Where ?

Across the width of a laminate





Opportunity for 3D strain measurement

Why ?

Assumptions validation with in-situ measurement

The Importance of Signs of Shear Stress and Shear Strain in Composites

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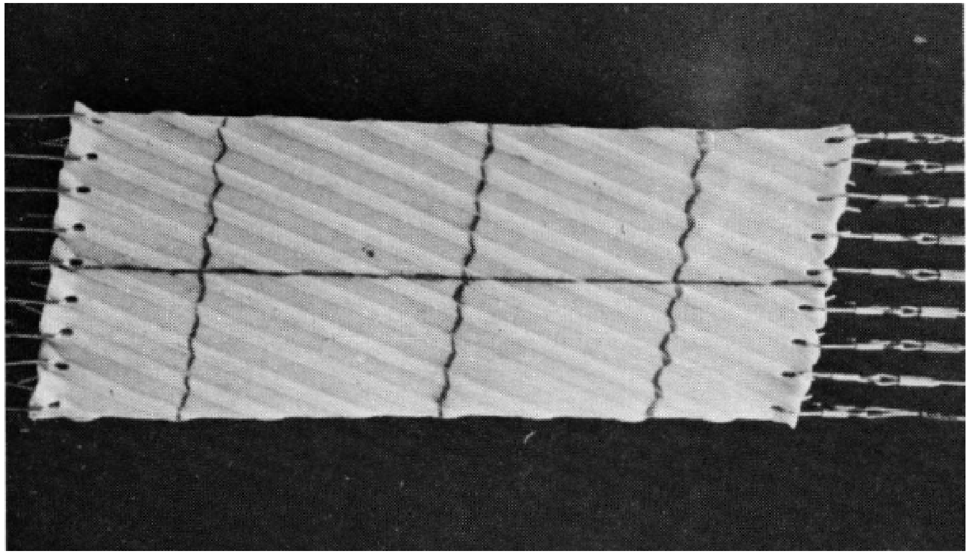
(Received October 15, 1968)



Why ?

Sensor evaluation

Composite materials investigation

Physics

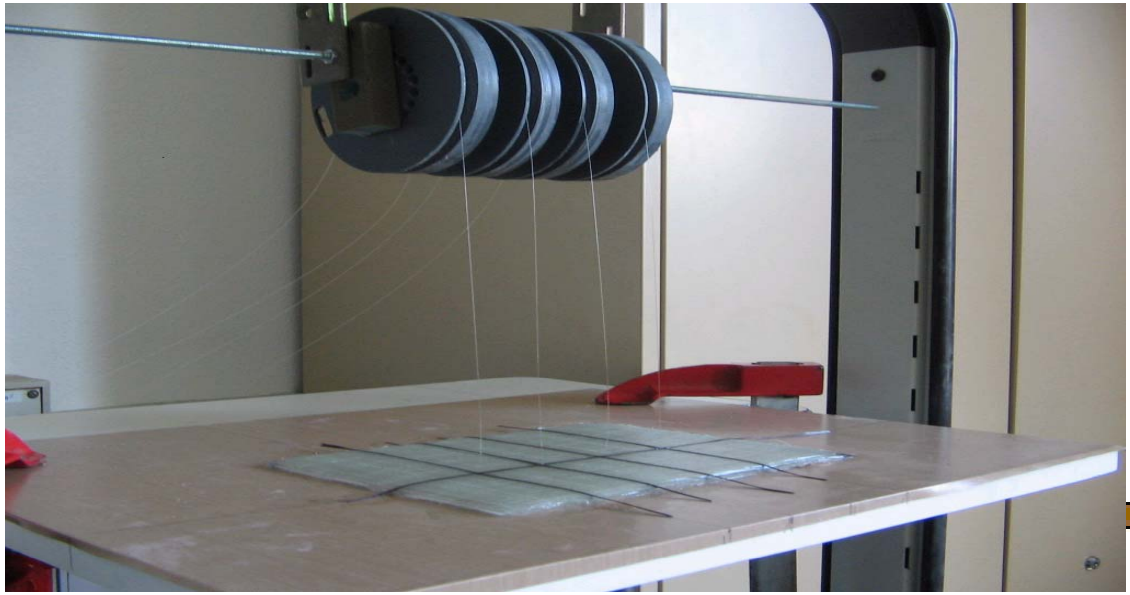
- Cure shrinkage
- Residual stresses
- Complex strain state
- Durability
- Damage, delamination

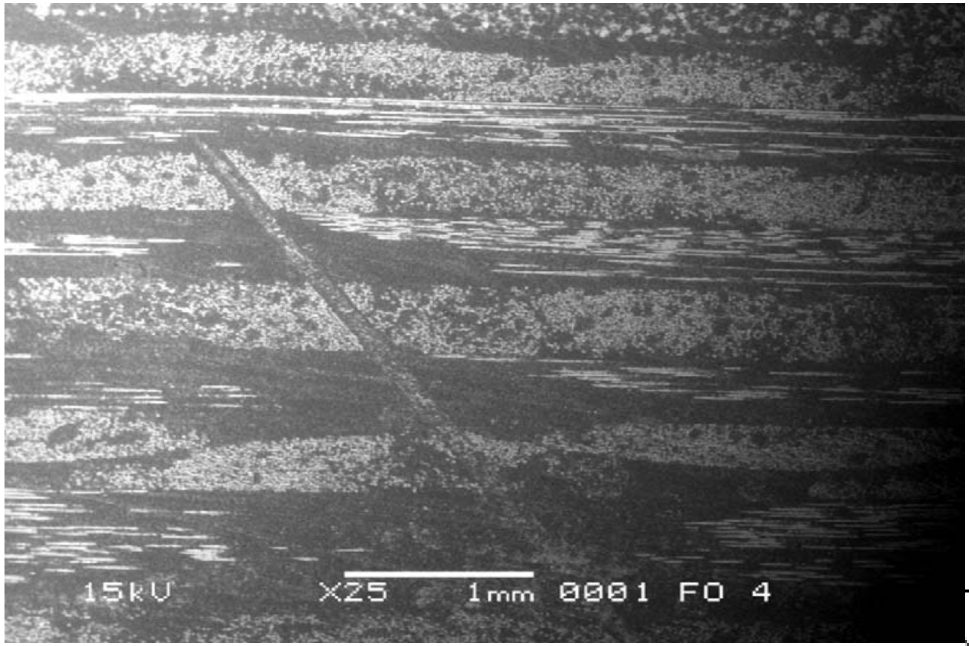
⇔

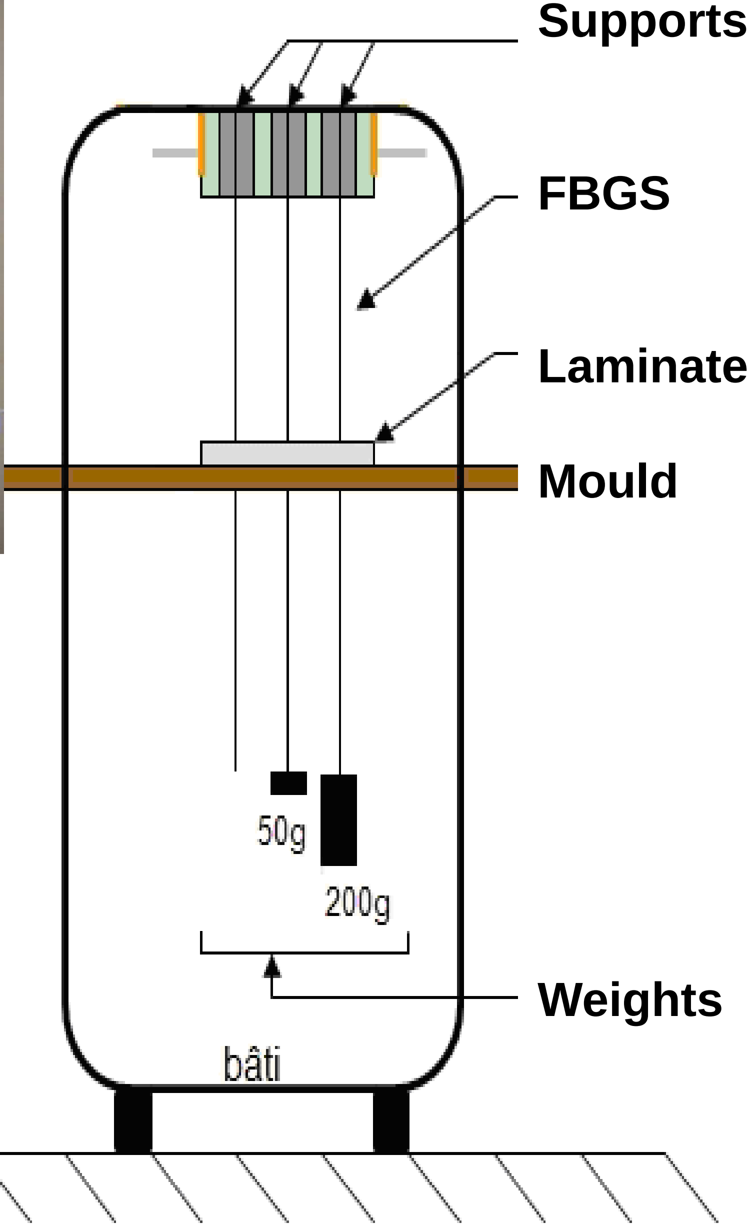
Useful for

- Composites manufacturing
- Characterization
- Structural Health Monitoring

How ?






Supports

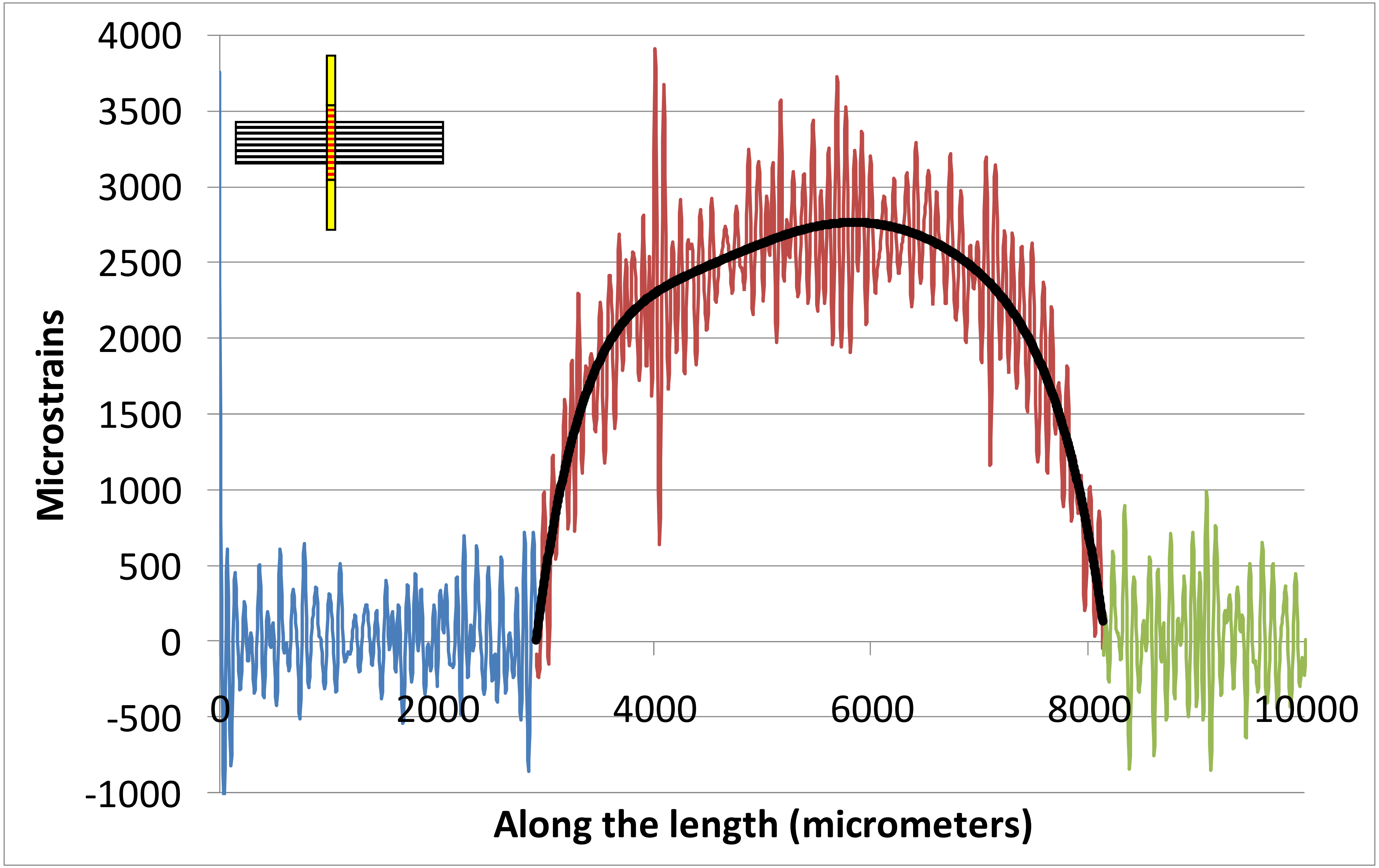
FBGS

Laminate

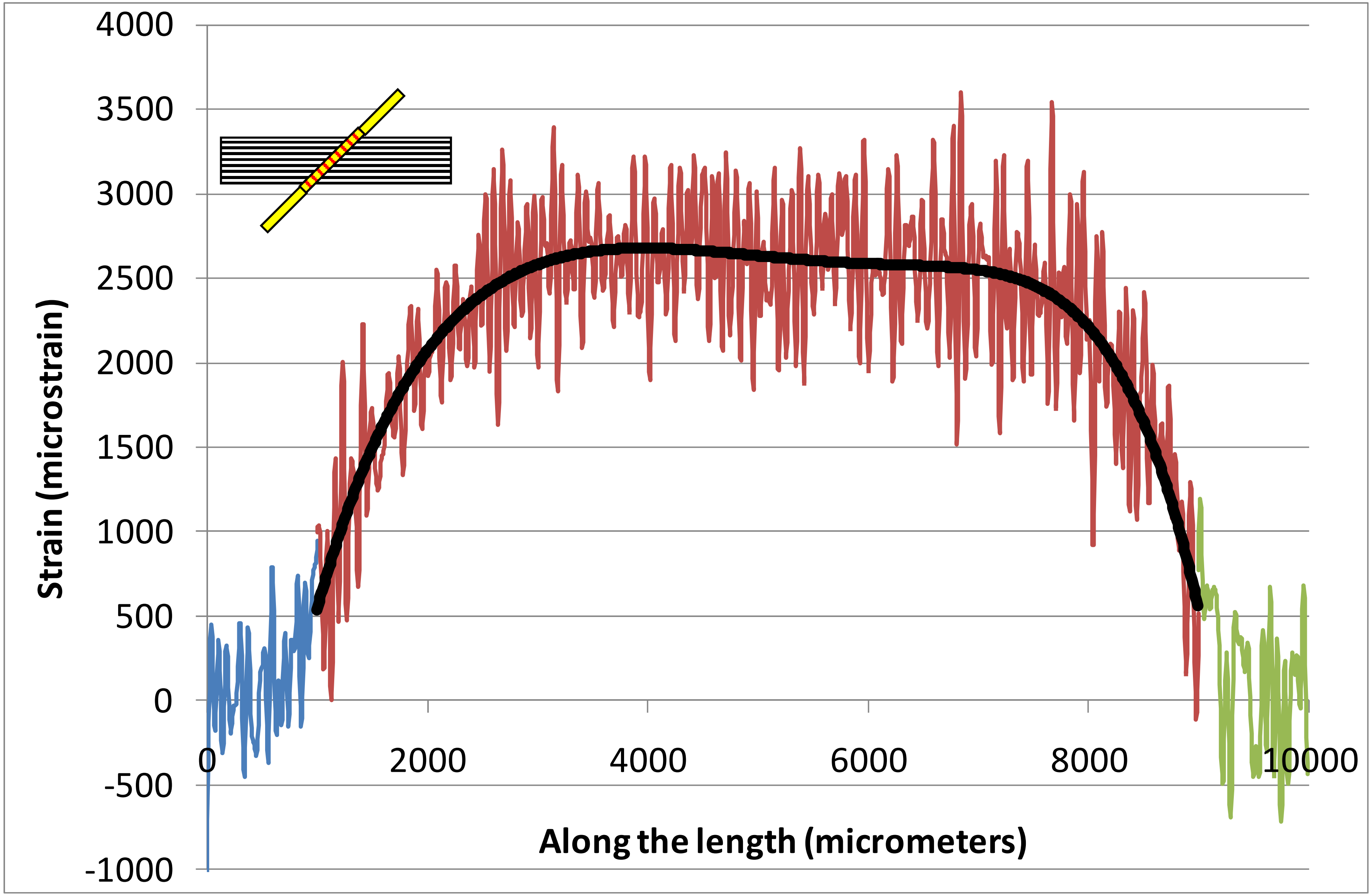
Mould

Weights

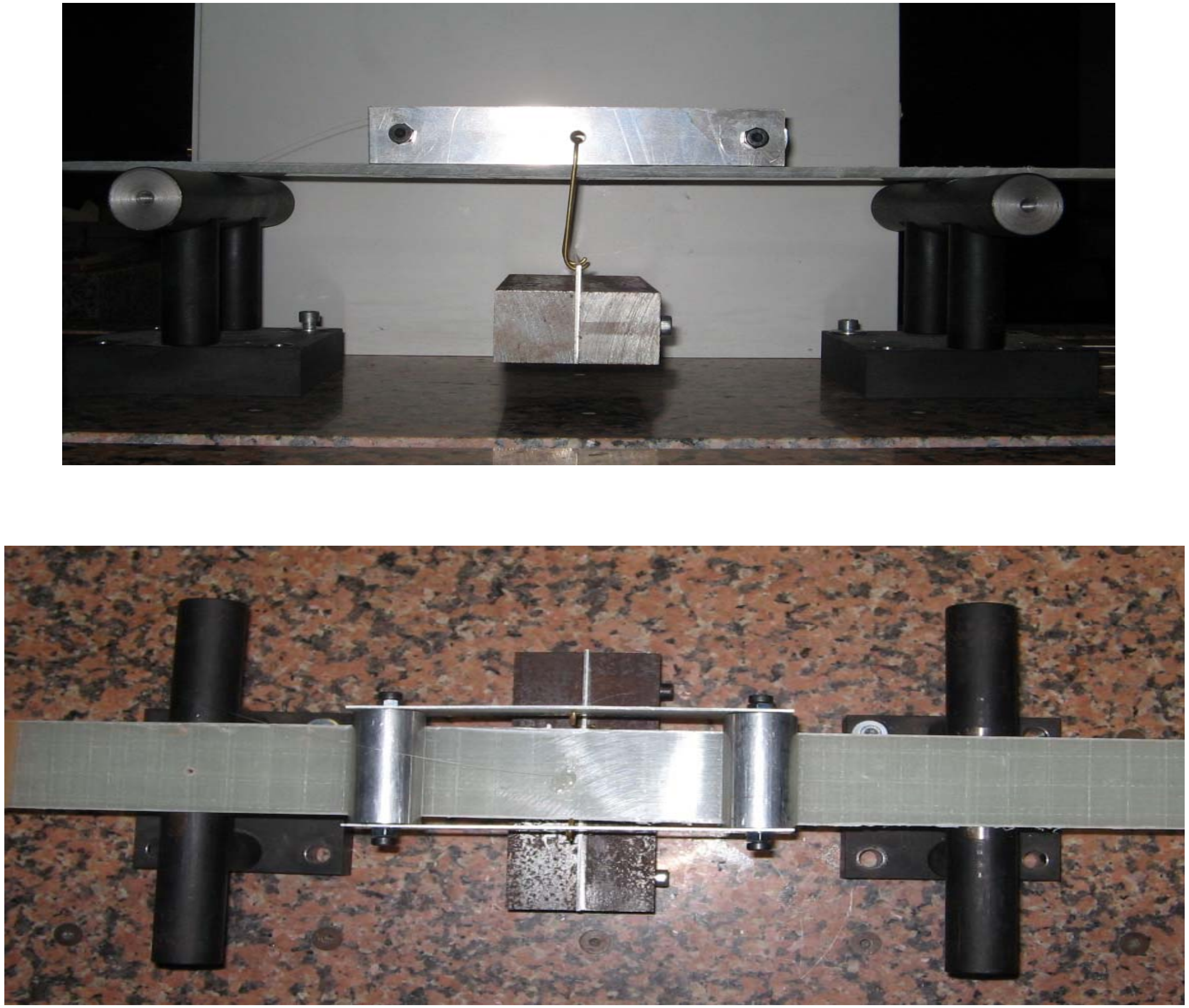
Cure shrinkage at 90° from the laminate surface



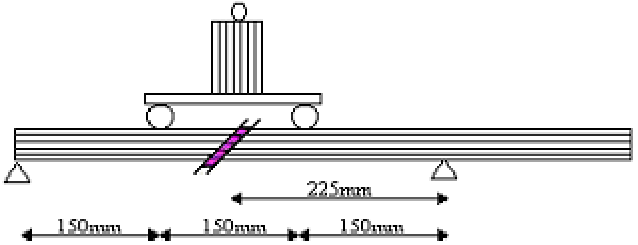
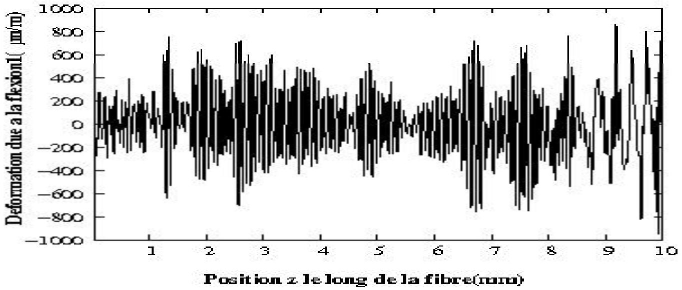
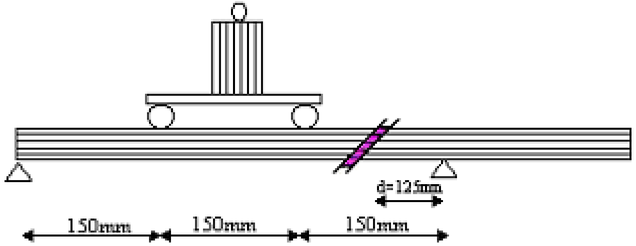
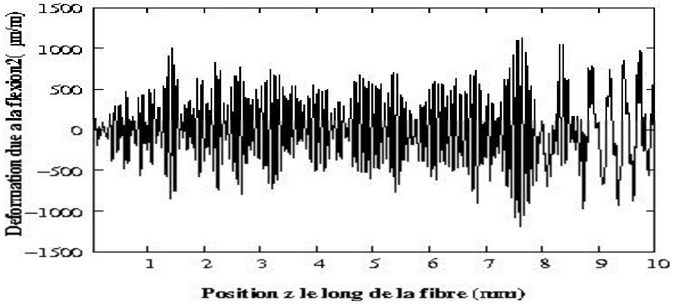
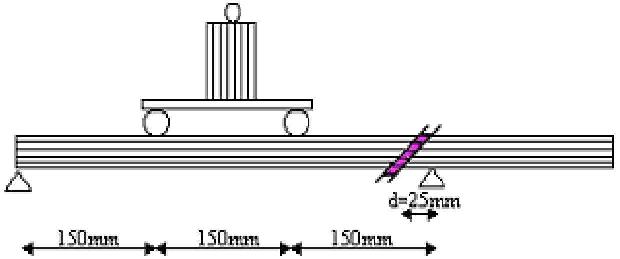
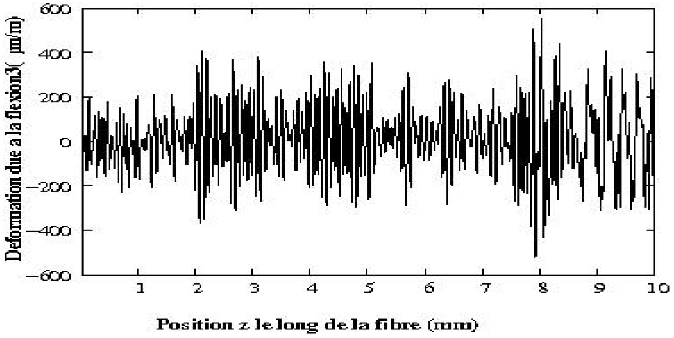
Cure shrinkage at 45° from the laminate surface



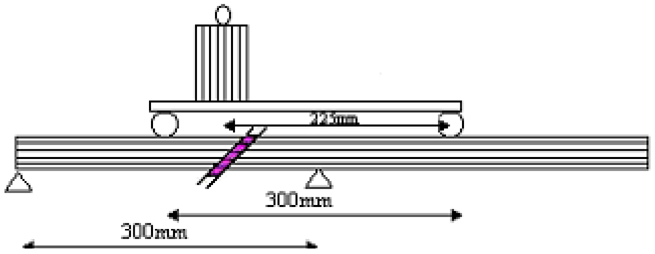
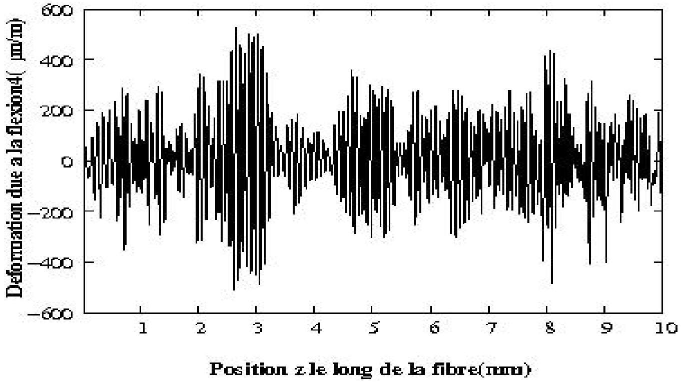
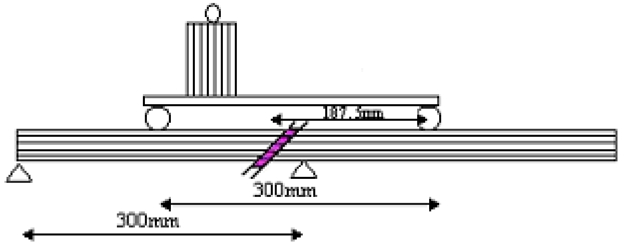
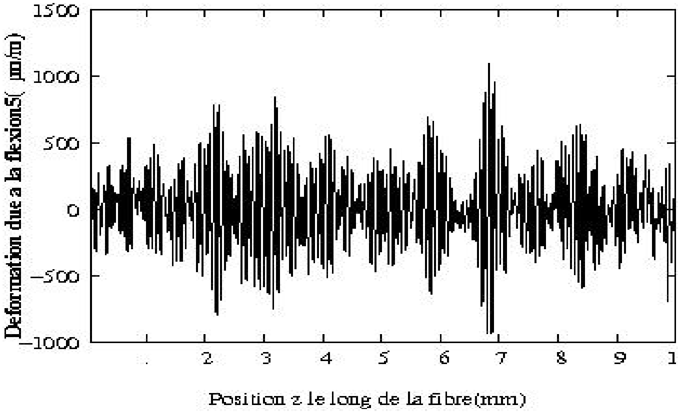
4 points bending test



Response of the FBGS under 4 points bending test

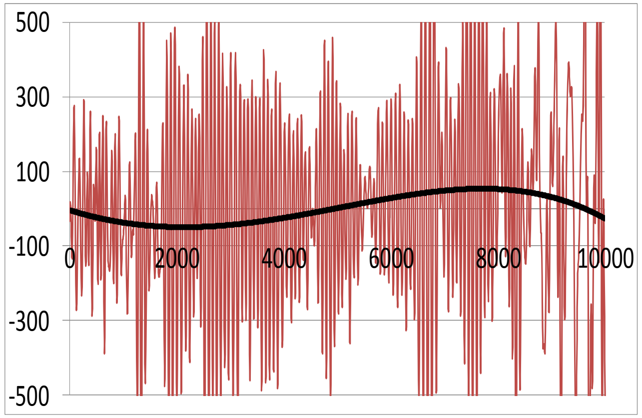
Test setup	$M_{(N.mm)}$	$T_{(N)}$	Strain profile (µm/m)
	1975	0	
	1646	13.17	
	329	13.17	

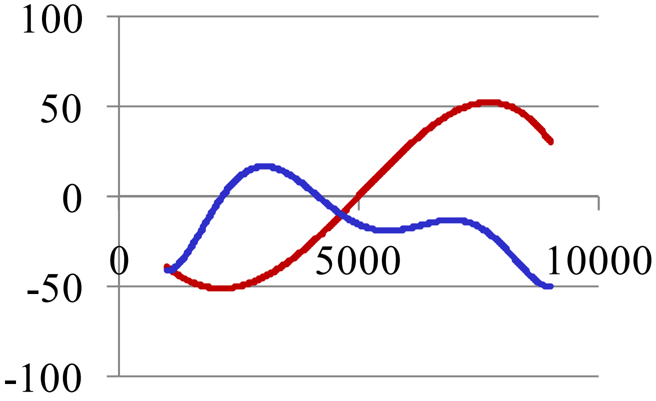
Response of the FBGS under 4 points bending test

Séries de mesures	M(N.mm)	T(N)	Déformation (µm/m)
	0	13.17	
	494	13.17	

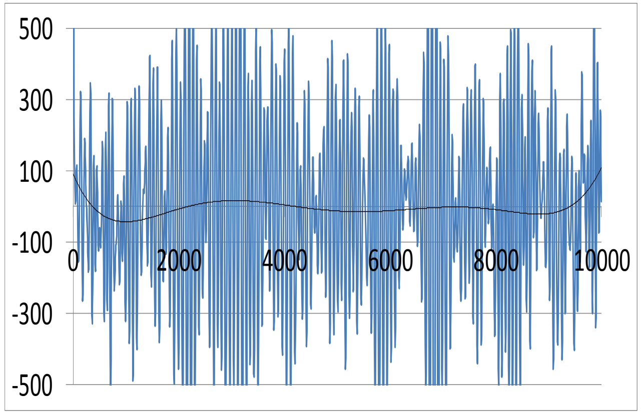
Response of the FBGS under 4 points bending test

Under pure bending





Under pure shear



?

Require a better analysis

Signal filtering

Spectral response

Conclusions and prospects

This in-situ strain gradient measurement technique is promising

But it requires a specific know-how to insert the optical fibres

Still to improve

- **Need of a better signal processing to**
- **Understand the “noise” significance and**
- **Find the plies across the width**

Candidate for 3D reinforcement stress analysis ?