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ICCS23 - 23rd International Conference on Composite Structures & MECHCOMP6 - 6th International Conference on Mechanics of Composites

Simultaneous temperature-strain measurement in a thin composite panel with embedded tilted Fibre Bragg Grating sensors

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FEUP-Faculty of Engineering, University of Porto, Portugal, 01-04 September 2020

Introduction

Principle of Virtual Displacements for composite plates

$$\int_V \delta \boldsymbol{\epsilon}^T \boldsymbol{\sigma} \, dV + \int_V \rho \, \delta \boldsymbol{u}^T \ddot{\mathbf{u}} \, dV = \int_V \delta \boldsymbol{u}^T \bar{t} \, dV$$

$$\int_\Omega \int_A \delta \boldsymbol{\epsilon}^T \boldsymbol{\sigma} \, d\Omega dz + \int_\Omega \int_A \rho \, \delta \boldsymbol{u}^T \ddot{\mathbf{u}} \, d\Omega dz = \int_\Omega \int_A \delta \boldsymbol{u}^T \bar{t} \, d\Omega dz$$

$$\boldsymbol{\epsilon} = \begin{bmatrix} \epsilon_{xx} \\ \epsilon_{yy} \\ \epsilon_{xy} \\ \epsilon_{xz} \\ \epsilon_{yz} \\ \epsilon_{zz} \end{bmatrix} = \begin{bmatrix} \frac{\partial u}{\partial x} \\ \frac{\partial v}{\partial y} \\ \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \\ \frac{\partial u}{\partial z} + \frac{\partial w}{\partial x} \\ \frac{\partial v}{\partial z} + \frac{\partial w}{\partial y} \\ \frac{\partial w}{\partial z} \end{bmatrix} \qquad \boldsymbol{\sigma} = \begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{xy} \\ \sigma_{xz} \\ \sigma_{yz} \\ \sigma_{zz} \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{16} & 0 & 0 & C_{13} \\ C_{12} & C_{22} & C_{26} & 0 & 0 & C_{23} \\ C_{16} & C_{26} & C_{66} & 0 & 0 & C_{36} \\ 0 & 0 & 0 & C_{55} & C_{45} & 0 \\ 0 & 0 & 0 & C_{45} & C_{44} & 0 \\ C_{13} & C_{23} & C_{36} & 0 & 0 & C_{33} \end{bmatrix} \begin{bmatrix} \epsilon_{xx} \\ \epsilon_{yy} \\ \epsilon_{xy} \\ \epsilon_{xz} \\ \epsilon_{yz} \\ \epsilon_{zz} \end{bmatrix}$$

*J. N. Reddy and D. H. Robbins. "Theories and computational models for composite laminates", Appl. Mech. Rev., 47:147–165, 1994.

PVD for partially coupled thermo-mechanical static problems

$$\int_\Omega \int_A \delta \boldsymbol{\epsilon}^T \left(\boldsymbol{\sigma}_M - \boldsymbol{\sigma}_T \right) \, d\Omega dz = 0$$

$$\int_\Omega \int_A \delta \boldsymbol{\epsilon}^T \boldsymbol{\sigma}_M \, d\Omega dz = \int_\Omega \int_A \delta \boldsymbol{\epsilon}^T \boldsymbol{\sigma}_T \, d\Omega dz$$

$$\delta \boldsymbol{u}: \quad \boldsymbol{K}\boldsymbol{u} = \boldsymbol{P}_T$$

$$P_{T,x} = \lambda_6 \int_A F_r \vartheta_A \, dz \int_\Omega \frac{\partial N_i}{\partial y} \vartheta_\Omega \, d\Omega + \lambda_1 \int_A F_r \vartheta_A \, dz \int_\Omega \frac{\partial N_i}{\partial x} \vartheta_\Omega \, d\Omega$$

$$P_{T,y} = \lambda_2 \int_A F_r \vartheta_A \, dz \int_\Omega \frac{\partial N_i}{\partial y} \vartheta_\Omega \, d\Omega + \lambda_6 \int_A F_r \vartheta_A \, dz \int_\Omega \frac{\partial N_i}{\partial x} \vartheta_\Omega \, d\Omega$$

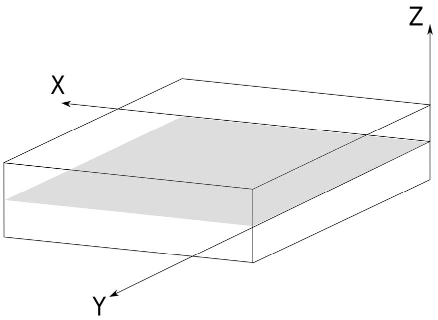
$$P_{T,z} = \lambda_3 \int_A \frac{\partial F_r}{\partial z} \vartheta_A \, dz \int_\Omega N_i \vartheta_\Omega \, d\Omega$$

*M. Cinefra, S. Valvano, and E. Carrera, "Heat conduction and thermal stress analysis of laminated composites by a variable kinematic mitc9 shell element," Curved and Layered Structures, vol. 2, pp. 301–320, 2015.
*M. Cinefra, S. Valvano, and E. Carrera, "Thermal Stress Analysis of laminated structures by a variable kinematic MITC9 shell element," J. Therm. Stresses, vol. 39, no. 2, pp. 121–141, 2016

Galerkin solution for Virtual Dispacements

Approximate solution based on the generalized Galerkin method

2D approximation of **displacements** using the *thickness functions*



$$u(x,y,z) = \sum_{m=0}^{n} u_m(x,y) g_m(z)$$

$$v(x,y,z) = \sum_{m=0}^{n} v_m(x,y) g_m(z)$$

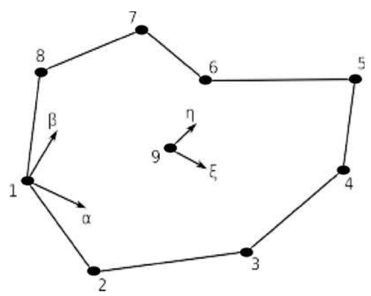
$$w(x,y,z) = \sum_{m=0}^{n} w_m(x,y) g_m(z)$$

*K. Wahsizu, "Variational methods in elasticity and plasticity," Pergamon Press Ltd., Headington Hill Hall, Oxford OX3, UK, 1968.

Finite Element Method

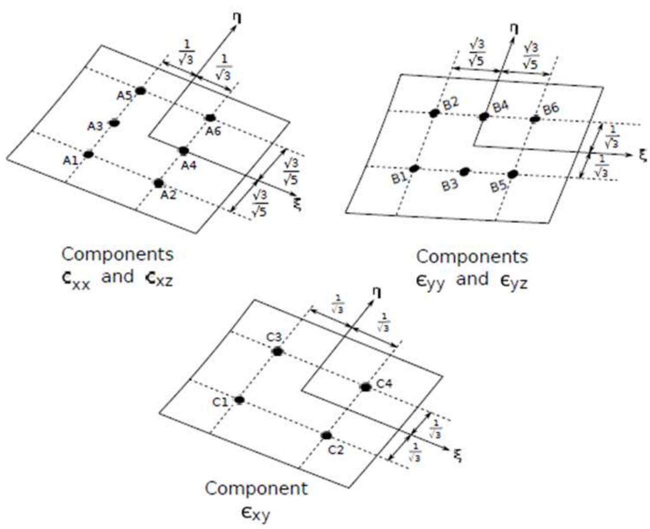
Approximation of **variables** in the mid-reference surface using the *Langrangian* shape functions:

$$\boldsymbol{u}_m(x,y) = \sum_{i=1}^{9} N_i(\xi,\eta)\, \boldsymbol{u}_{mi}$$



MITC

To overcome the problem of the ***membrane and shear locking***, the strain components are calculated using a specific interpolation strategy:



For example:

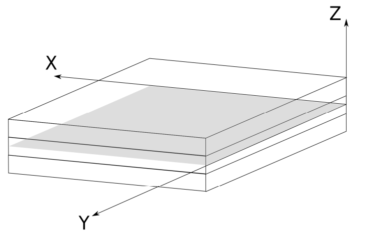
$$\varepsilon_{xx} = N_{A1}\, \varepsilon_{xx_{A1}} + N_{B1}\, \varepsilon_{xx_{B1}} + N_{C1}\, \varepsilon_{xx_{C1}} + N_{D1}\, \varepsilon_{xx_{D1}} + N_{E1}\, \varepsilon_{xx_{E1}} + N_{F1}\, \varepsilon_{xx_{F1}}$$

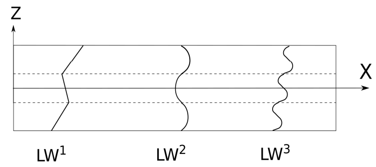
Higher-Order Layer-Wise Approach (LW)

Legendre Polynomial

$$\boldsymbol{g}_d^k(z) = \boldsymbol{g}_0^k(z) + \boldsymbol{g}_1^k(z) + \boldsymbol{g}_2^k(z) + \boldsymbol{g}_3^k(z) + \boldsymbol{g}_4^k(z)$$

$$\boldsymbol{g}_0^k(z) = \left(\frac{1+\zeta}{2}\right) \text{ (top)}$$
$$\boldsymbol{g}_1^k(z) = \left(\frac{1-\zeta}{2}\right) \text{ (bottom)}$$
$$\boldsymbol{g}_2^k(z) = \frac{3\left(\zeta^2-1\right)}{2}$$
$$\boldsymbol{g}_3^k(z) = \frac{5\zeta\left(\zeta^2-1\right)}{2}$$
$$\boldsymbol{g}_4^k(z) = \frac{\left(35\zeta^4-42\zeta^2-1\right)}{8}$$

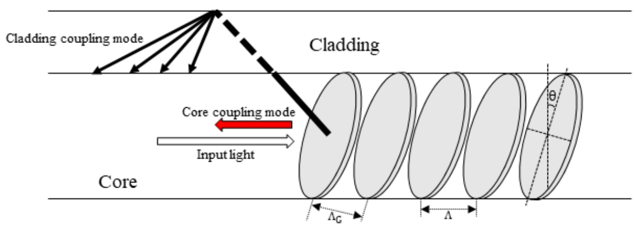


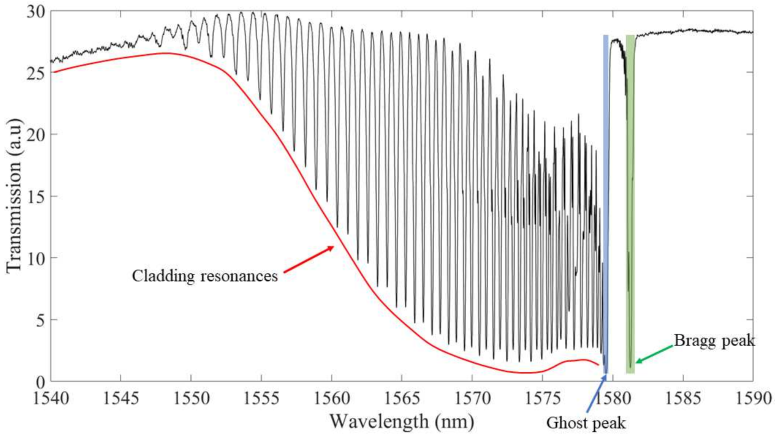


*J. N. Reddy. An evaluation of equivalent-single-layer and layerwise theories of composite laminates. Compos. Struct., 25:21–35, 1993.

Tilted Fibre Bragg Grating (TFBG) sensor

Weakly tilted FBG (TFBG)





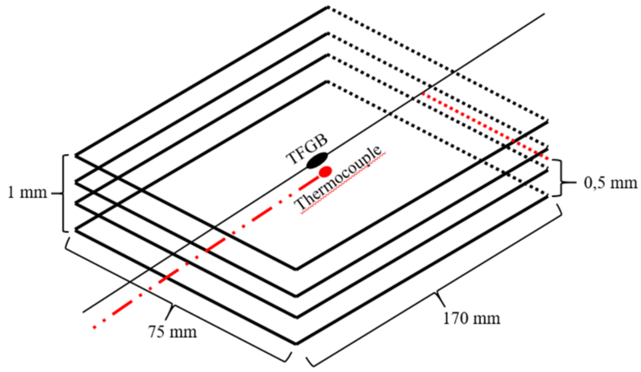
Thermomechanical sensitivity matrix

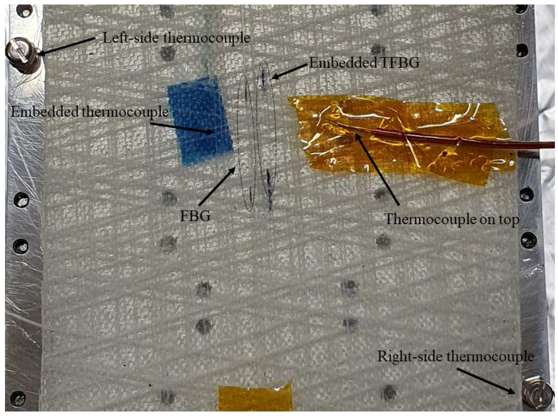
$$\begin{bmatrix} \Delta\lambda_{Bragg} \\ \Delta\lambda_{clad} \end{bmatrix} = \begin{bmatrix} k_{Bragg,\varepsilon} & k_{Bragg,T} \\ k_{clad,\varepsilon} & k_{clad,T} \end{bmatrix} \begin{bmatrix} \Delta\varepsilon \\ \Delta T \end{bmatrix}$$

Methodology

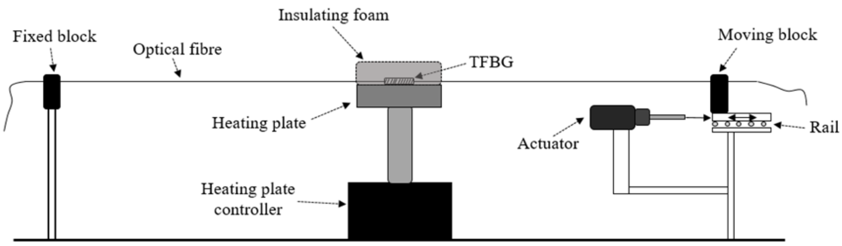
Design and setup

Glass Fibre/Epoxy resin plate with embedded TFBG sensor and thermocouple.



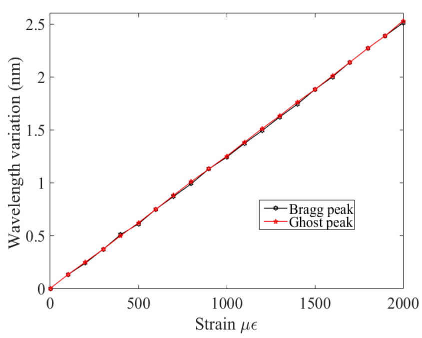


TFBG calibration



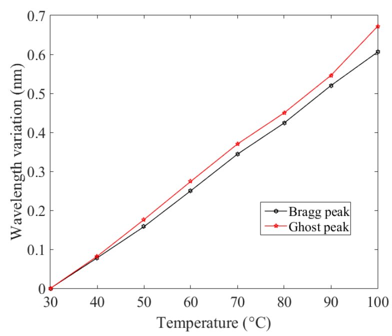
Thermal resolution

$swR = 4$ pm $\Longrightarrow$ $TR = 8.2305$ °C



$k_{\text{Bragg},\varepsilon} = 1.255 \pm 0.004$ pm/με

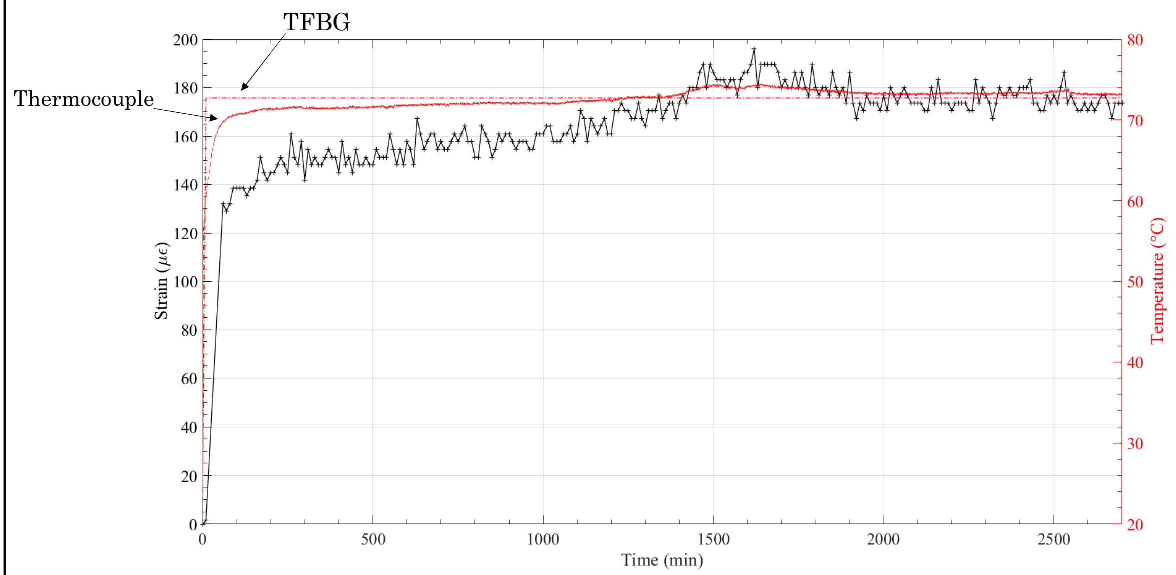
$k_{\text{clad},i,\varepsilon} = 1.255 \pm 0.006$ pm/με



$k_{\text{Bragg,T}} = 9.114 \pm 0.007$ pm/°C

$k_{\text{clad},i,\text{T}} = 9.6 \pm 0.01$ pm/°C

Experimental measurement with single TFBG sensor during exposure to infrared lamps



Modelling and numerical simulation

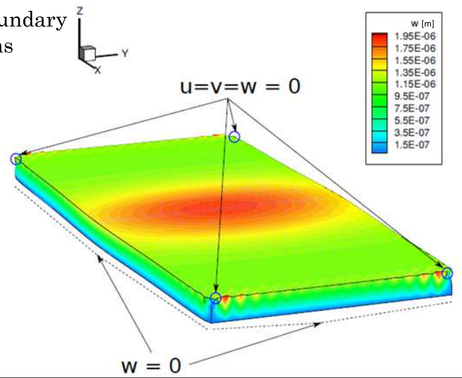
Partial model

Composite material properties		
ρ	1954	$[kgm^{-3}]$
E_1	54.56	$[GPa]$
$E_2 = E_3$	13.32	$[GPa]$
$G_{12} = G_{13}$	2.356	$[GPa]$
G_{23}	3.13	$[GPa]$
$\nu_{12} = \nu_{13}$	0.272	$[-]$
ν_{23}	0.2584	$[-]$
α_1	4.131×10^{-6}	$[K^{-1}]$
$\alpha_2 = \alpha_3$	3.504×10^{-5}	$[K^{-1}]$
κ_1	0.85	$[WK^{-1}m^{-1}]$
$\kappa_2 = \kappa_3$	0.6679	$[WK^{-1}m^{-1}]$
c_v	842.5	$[JK^{-1}kg^{-1}]$

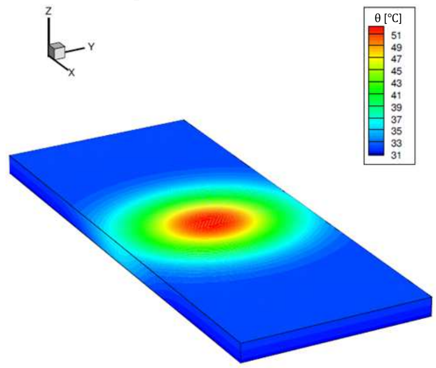
Gaussian temperature profile

$$\vartheta(x,y,z,t) = \vartheta_A(z,t)\vartheta_\Omega(x,y) = \left[\overline{T}(z_{bottom},t) + z\cdot\left(\overline{T}(z_{top},t) - \overline{T}(z_{bottom},t)\right)/h\right]\cdot$$
$$\cdot\left[\left(\frac{32}{52.5}\right) + \left(\frac{20.5}{52.5}\right)\cdot\exp^{-\left[1300(x-a/2)^2+2(x-a/2)(y-b/2)+1800(y-b/2)^2\right]}\right]$$

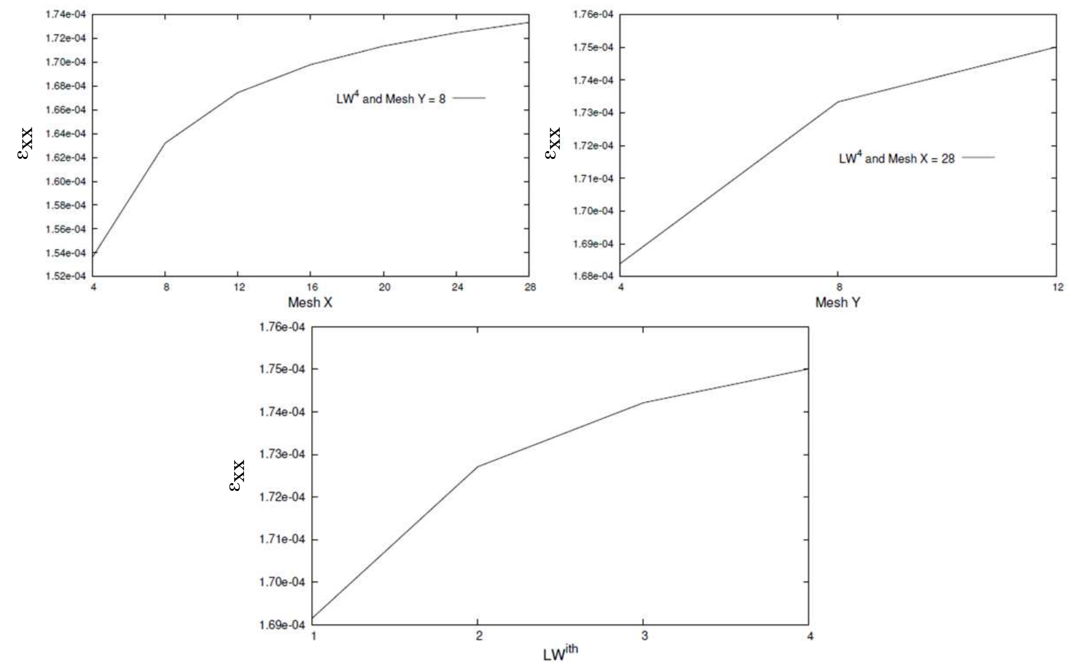
Mechanical boundary conditions



Temperature distribution

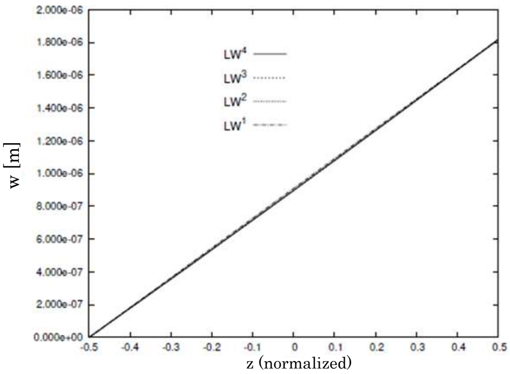


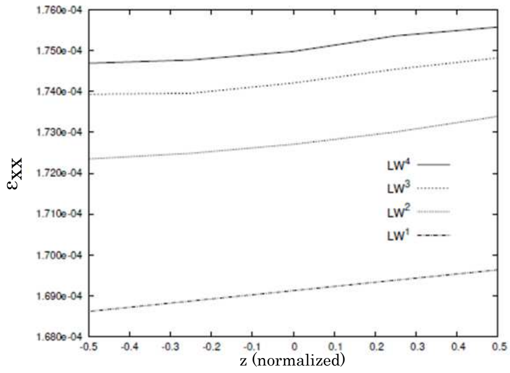
Mesh and Layer-Wise convergence study



Error, transverse displacement (w) and in-plane strain

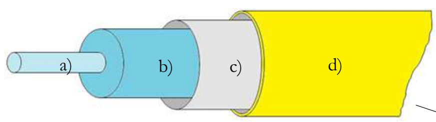
Method	$\epsilon_{xx} \cdot 10^{-4}$	*Error %*
Experimental	1.754	
Without Correction	1.702	2.95
Selective	1.702	2.95
MITC	1.750	0.22





Full model

	Optical fiber core	Acrylate coating	
ρ	2300	1100	$[kgm^{-3}]$
$E_1 = E_2 = E_3$	73.1	3.1	$[GPa]$
$G_{12} = G_{13} = G_{23}$	31.5	1.7	$[GPa]$
$\nu_{12} = \nu_{13} = \nu_{23}$	0.16	0.36	$[-]$
$\alpha_1 = \alpha_2 = \alpha_3$	$5.5{\times}10^{-7}$	$7.8{\times}10^{-5}$	$[K^{-1}]$
$\kappa_1 = \kappa_2 = \kappa_3$	1.4	0.189	$[WK^{-1}m^{-1}]$
c_v	703	1360	$[JK^{-1}kg^{-1}]$

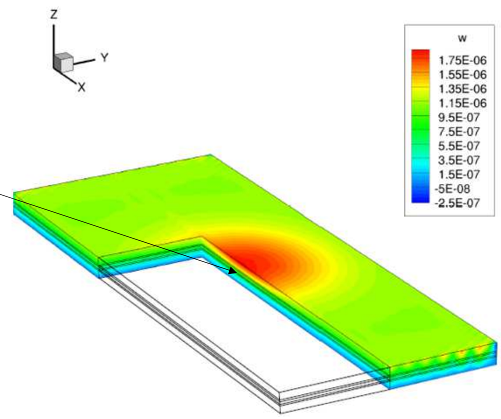


a) Core (≈10 μm)

b) Cladding (≈125 μm)

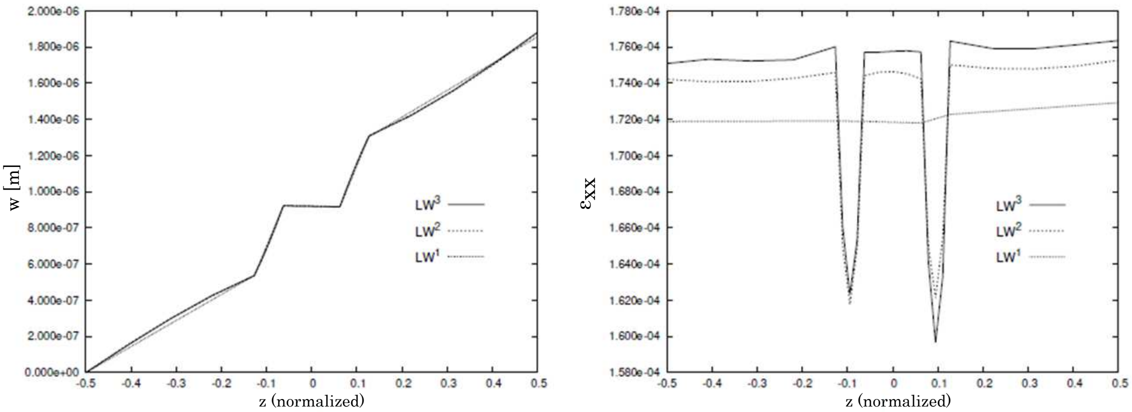
c) Coating (≈245 μm)

d) Jacket (Removed)



Transverse displacement (w) and in-plane strain

	FEM Simplified Model	FEM Full Model	Experimental TFBG	Experimental compensated
$3D$			1.754	1.711
LW^3	1.742	1.754		
LW^2	1.727	1.743		
LW^1	1.691	1.721		



Conclusions

- The results regarding the strain in the Full model report a good matching with the measurements performed through the TFBG sensor.

- The proposed advanced plate element, with Layer-Wise kinematic, demonstrated important capabilities to implement real boundary conditions in order to reproduce experimental tests.

- The present numerical models reach accurate solutions with higher-order thickness polynomial expansions.

- The proposed method can be used as an effective and efficient numerical tool for the thermomechanical analysis of composite structures embedding optical fibre sensors.

Thank you.