Finite Element Simulations of Pulsed Thermography Applied to Porous Carbon Fibre Reinforced Polymers

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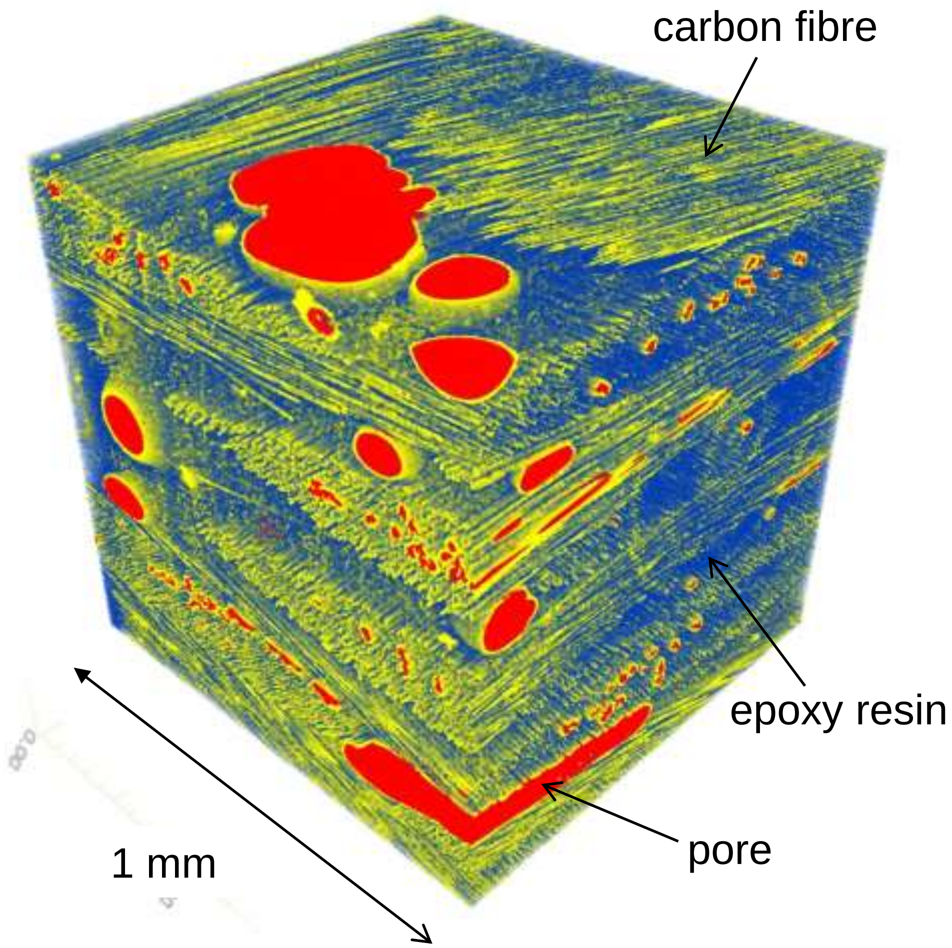
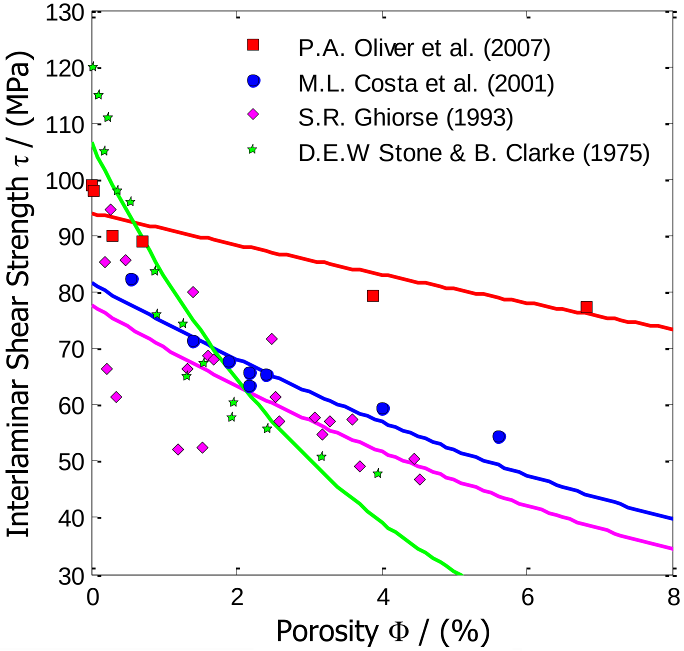
Motivation

Porous Carbon Fibre Reinforced Polymers



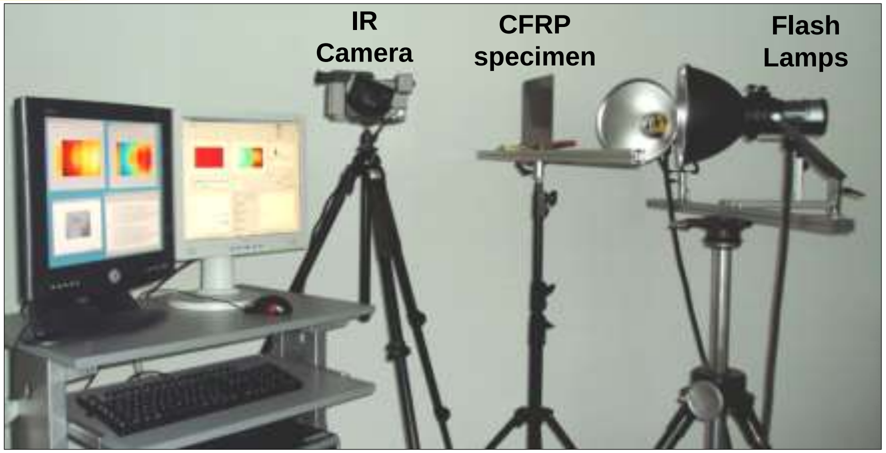
Reasons for Porosity:

- Improper autoclave parameters
- Uneven wetting of the fibres
- Incomplete chemical reactions
- Degassing of contaminates
- Improper debulking



Introduction

Thermal Diffusivity as a Probe for Porosity



Effective Thermal Diffusivity

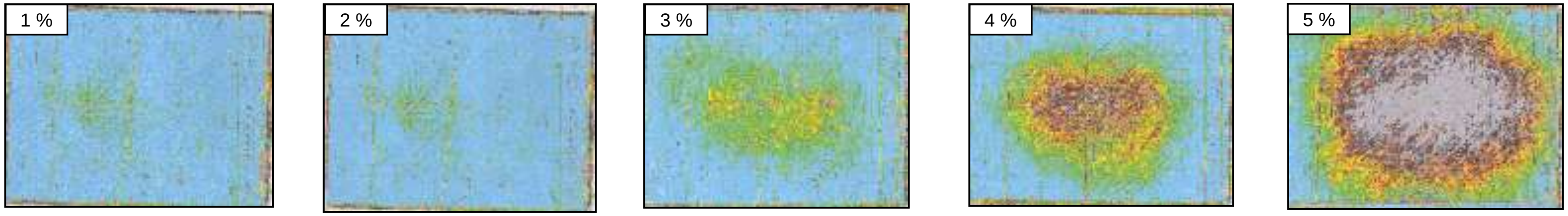
$$\alpha_{\text{eff}} = \frac{k}{\rho \cdot c}$$

k … Thermal Conductivity

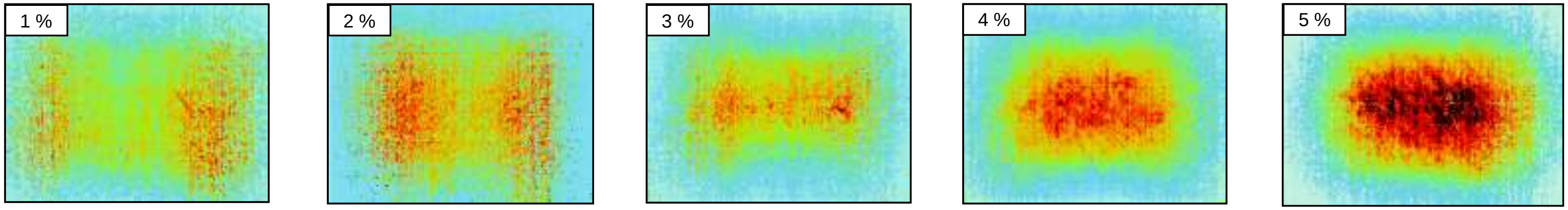
ρ … Density

c … Heat Capacity

Ultrasonic C-scan images [dB / mm]

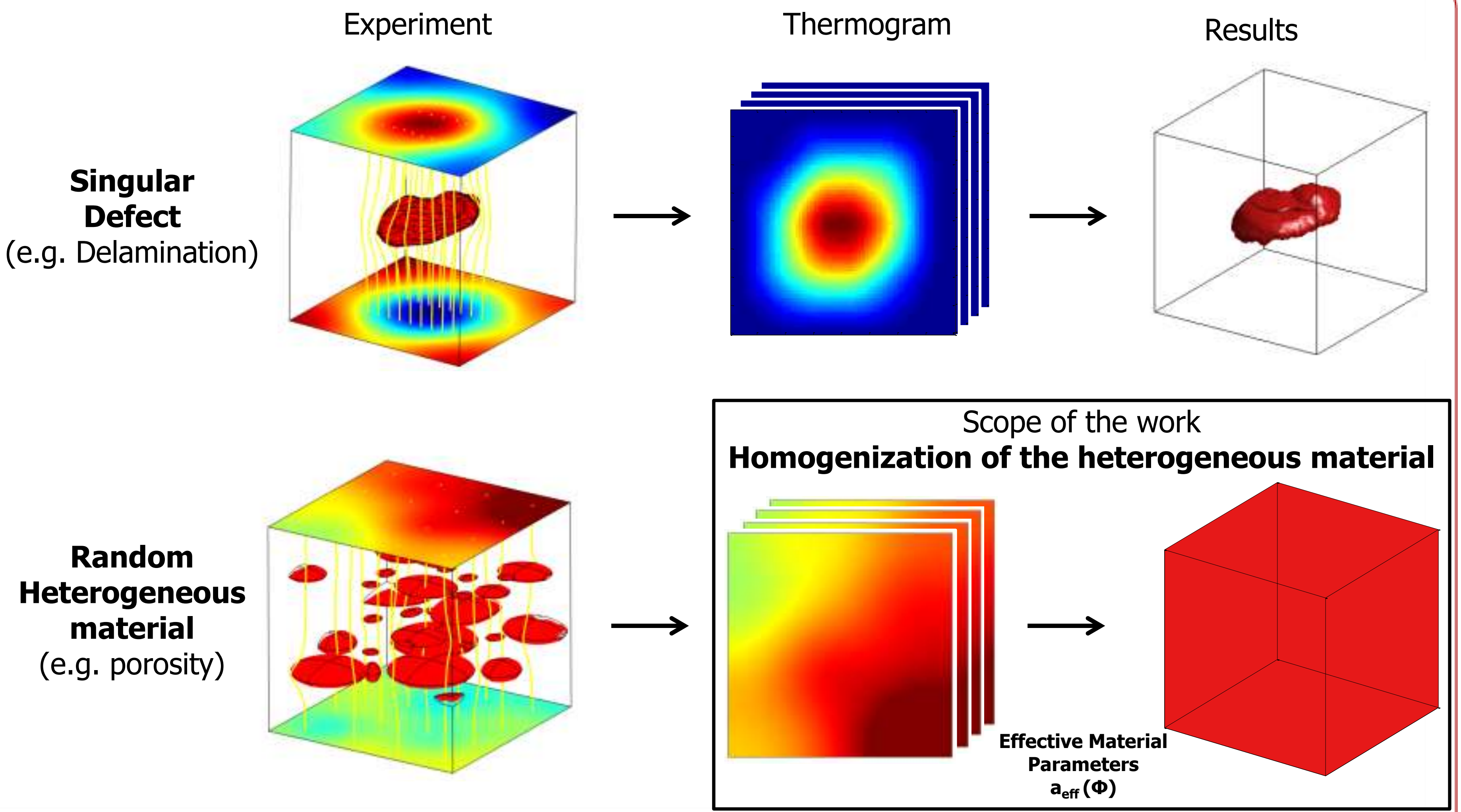


Active Thermography – Diffusivity images [m^2 / s]



Introduction

Effective Medium Theory for Porosity Evaluation



Experiment

Thermogram

Results

Singular Defect
(e.g. Delamination)

Random Heterogeneous material
(e.g. porosity)

Scope of the work

Homogenization of the heterogeneous material

Effective Material Parameters
$a_{eff}(\Phi)$

Effective Medium Theory (EMT)

Maxwell-Garnett Approximation (MG)

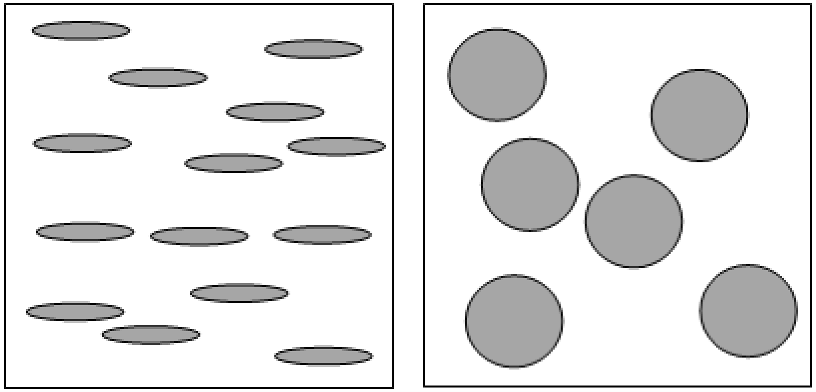
Effective thermal diffusivity: $\alpha_{\mathrm{eff}} = \dfrac{k_{\mathrm{eff}}}{(\rho \cdot c)_{\mathrm{eff}}}$

Effective volumetric heat capacity: $(\rho \cdot c)_{\mathrm{eff}} = (\rho \cdot c)_{\mathrm{p}} \cdot \Phi + (\rho \cdot c)_{\mathrm{m}} \cdot (1 - \Phi)$

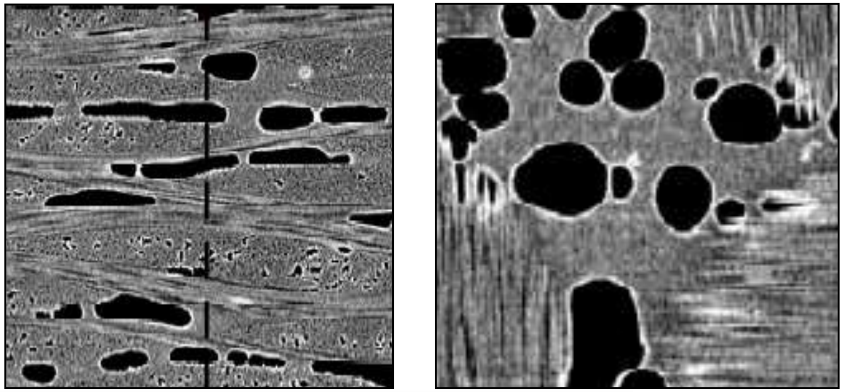
Effective thermal conductivity (MG – Approximation):

$$k_{\mathrm{eff}} = k_{\mathrm{m}} + \Phi \cdot (k_{\mathrm{p}} - k_{\mathrm{m}}) \cdot \frac{k_{\mathrm{m}}}{k_{\mathrm{m}} + \eta \cdot (k_{\mathrm{p}} - k_{\mathrm{m}}) + \Phi \cdot \eta \cdot (k_{\mathrm{m}} - k_{\mathrm{p}})}$$

Model: Aligned ellipsoids



Porous CFRP: real microstructure



3D Xray Computed Tomography

Equipment

Voxel sizes: (2.75 µm)^3 and (10 µm)^3
Volume: (5 x 5 x 5) mm^3 and (20 x 20 x 20) mm^3

Heat Conduction Model

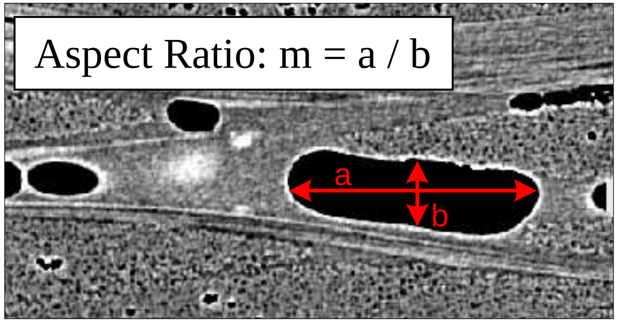
Depolarization Factor

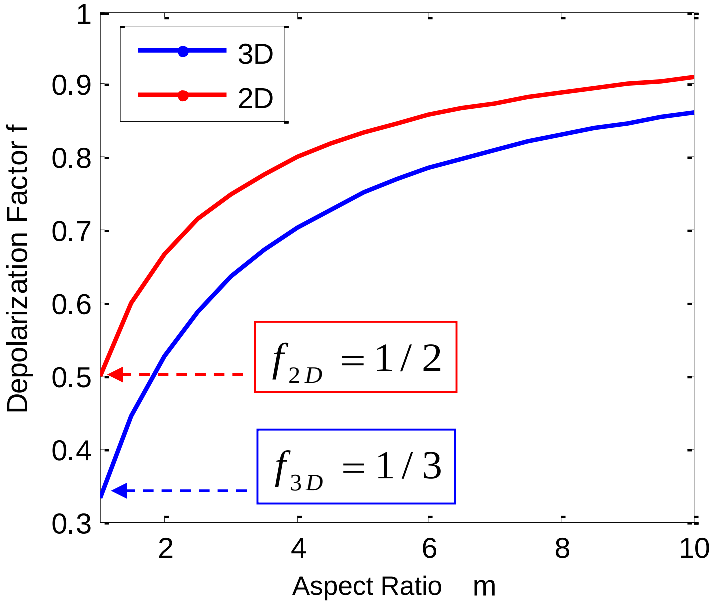
2D – Depolarization Factor:

$$\eta_{2D} = \frac{m}{m+1}$$

3D – Depolarization Factor [3]**:**

$$\eta_{3D} = \frac{m^2}{m^2-1} - \left(\frac{m^2}{\left(m^2-1\right)^{3/2}}\right) \operatorname{asin}\left(\frac{\left(m^2-1\right)^{1/2}}{m}\right)$$


Aspect Ratio: m = a / b



$f_{2D} = 1/2$

$f_{3D} = 1/3$

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[3] H.I. Ringermacher et al., In: QNDE 21, pp. 528-535 (2002).

Finite Element Simulation

Subdomain and Boundary Settings

Steady – State Model:

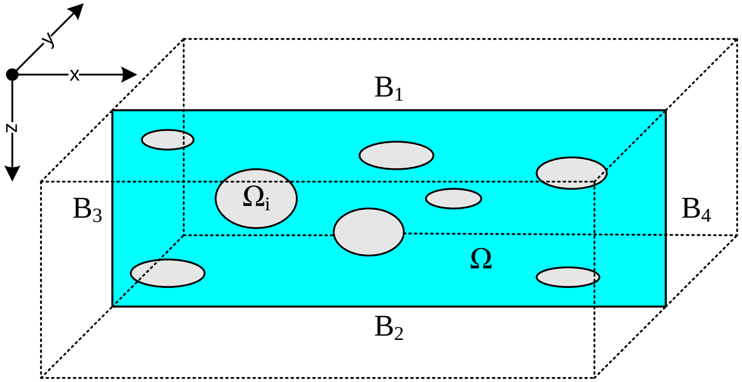
$$0 = \nabla\left(k(x,z)\nabla T(t,x,z)\right)$$

Boundary settings:

$$T\big|_{B1} = T_1 = 303\ K$$

$$T\big|_{B2} = T_2 = 293\ K$$

$$-k\nabla T\big|_{B3,B4} = 0$$



Transient Model:

$$\rho(x,z)c(x,z)\frac{\partial T(t,x,z)}{\partial t} = \nabla\left(k(x,z)\nabla T(t,x,z)\right)$$

Boundary settings:

$$-k\nabla T\big|_{B1} = \begin{cases} \dot{q} \rightarrow t \in [t_0, t_p] \\ 0 \rightarrow t \in]t_p, t_{end}] \end{cases}$$

$$-k\nabla T\big|_{B2,B3,B4} = 0$$

Boundary conditions:

$$\dot{q} = 2\cdot 10^6 W/m^2, t_p = 0.05\,s$$

Initial conditions:

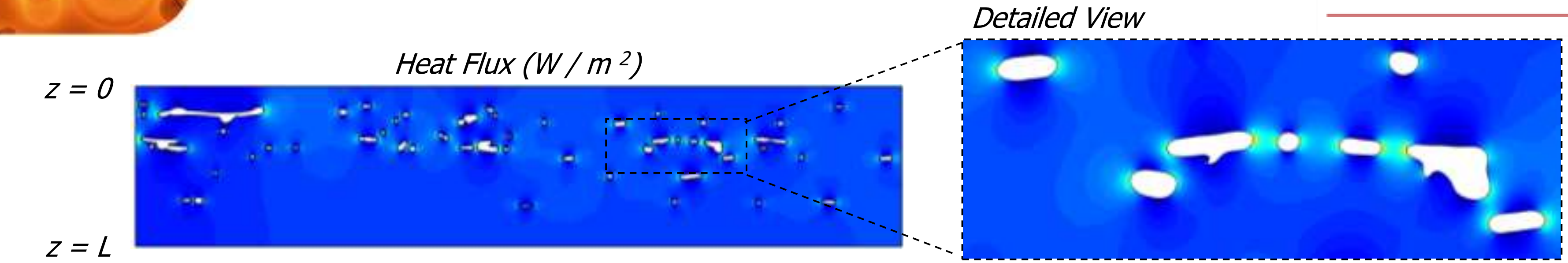
$$T = T_0 = T_\infty = 293\ K$$

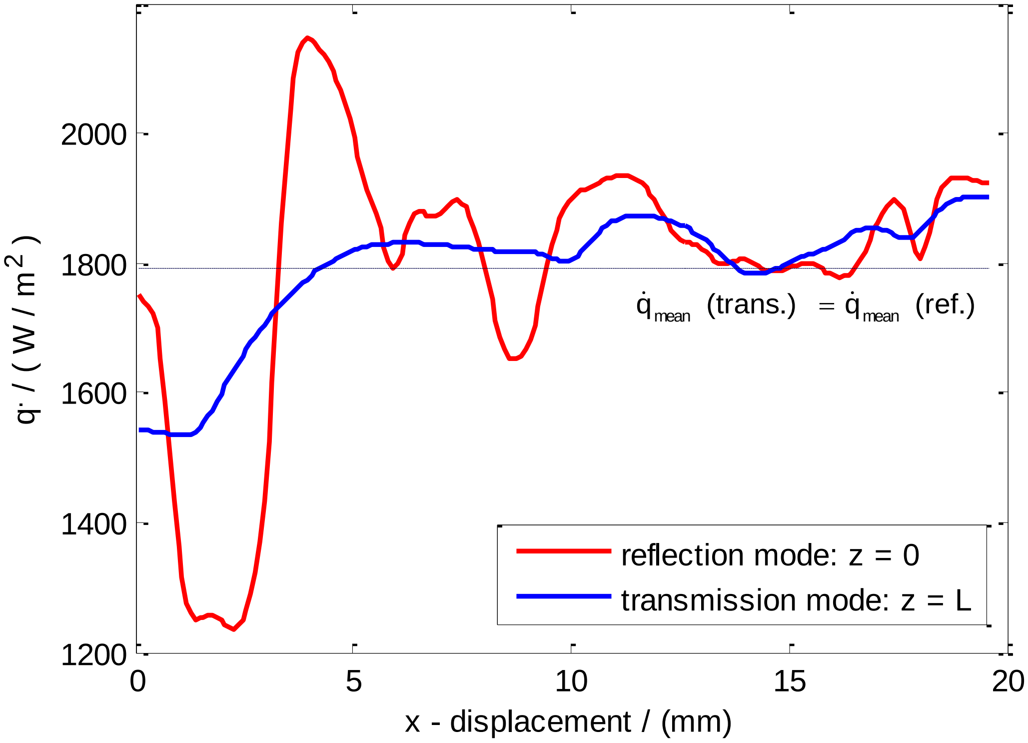
Material parameters:

$$k_M = 0.8\frac{W}{m\cdot K}, \rho = 1600\frac{kg}{m^3}, c = 1200\frac{J}{kg\cdot K}$$

Finite Element Simulation

Post Processing – Steady State Model





Effective Thermal Conductivity:

$$k_{eff} = \frac{\dot{q}_{mean} \cdot L}{(T_1 - T_2)}$$

Volumetric Heat Capacity :

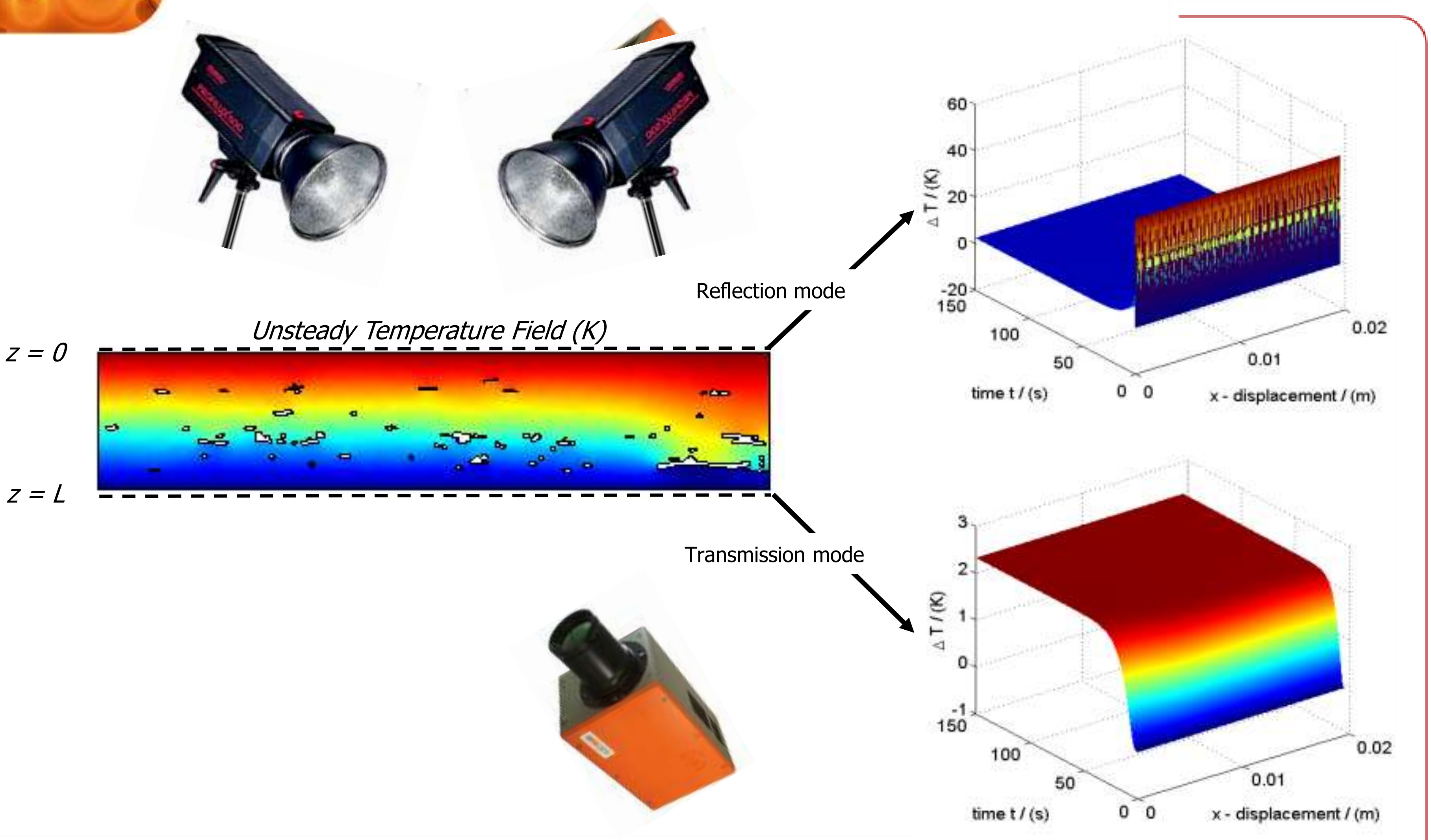
$$(\rho c)_{eff} = \Phi \cdot (\rho c)_P + (1 - \Phi) \cdot (\rho c)_M$$

Effective Thermal Diffusivity:

$$\alpha_{eff} = \frac{k_{eff}}{(\rho c)_{eff}}$$

Finite Element Simulation

Post Processing – Transient Model



Reflection mode

Unsteady Temperature Field (K)

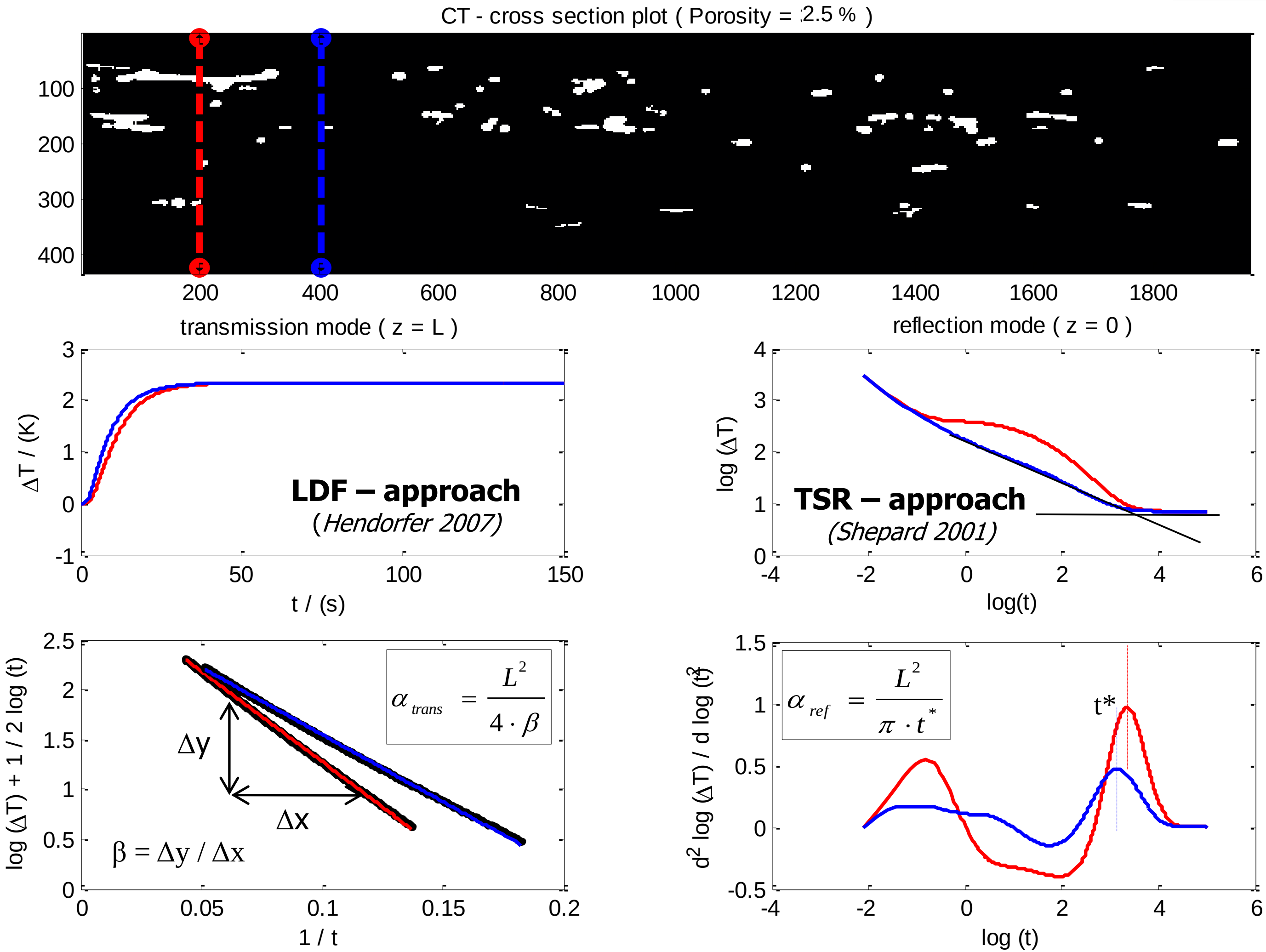
z = 0

z = L

Transmission mode

Finite Element Simulation

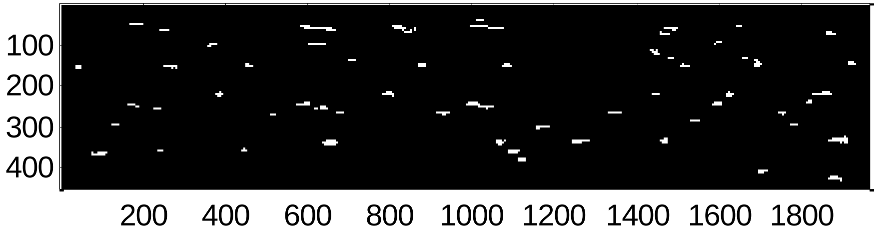
Post Processing – Transient Model



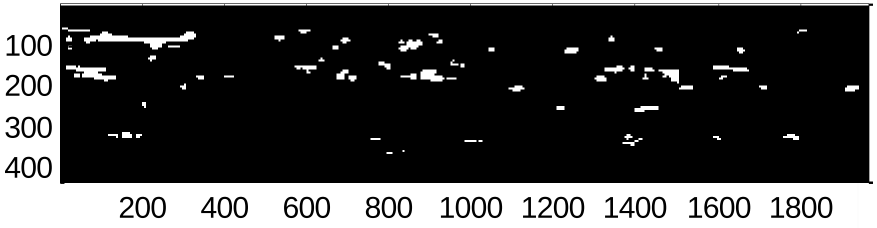
Finite Element Simulation

Post Processing – Transient Model

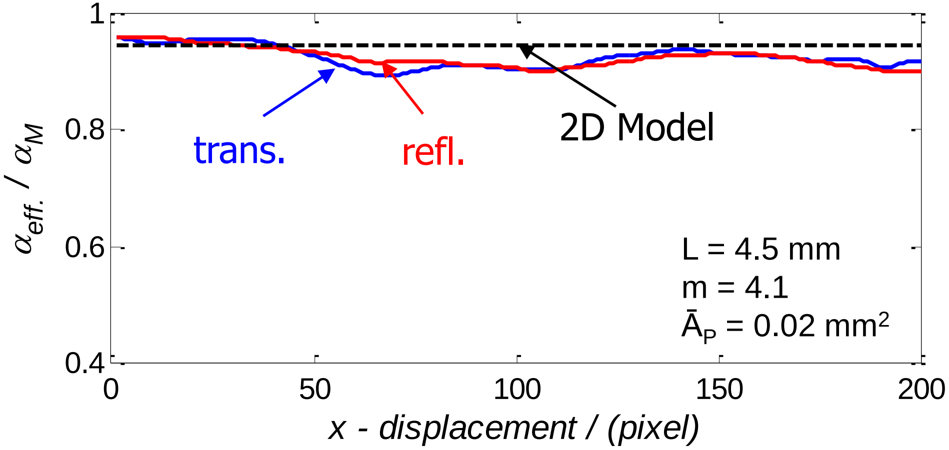
Porosity Specimen: Φ = 1.3 %



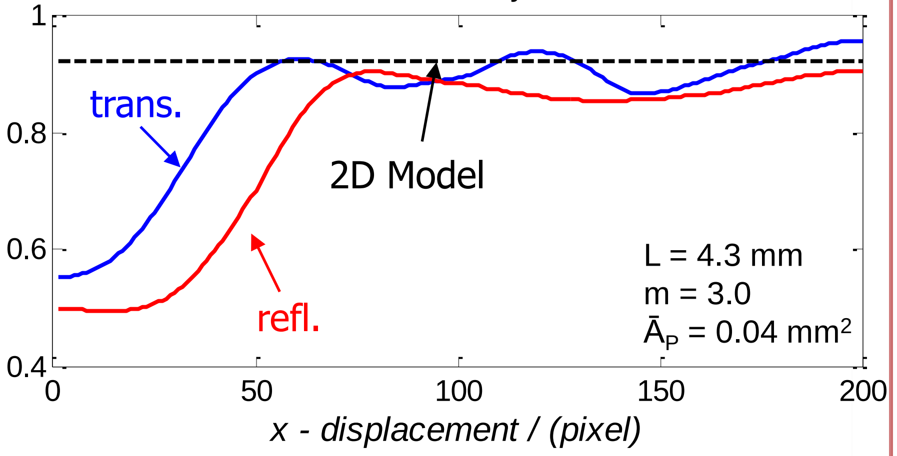
Porosity Specimen: Φ = 2.5 %



Thermal Diffusivity Profiles

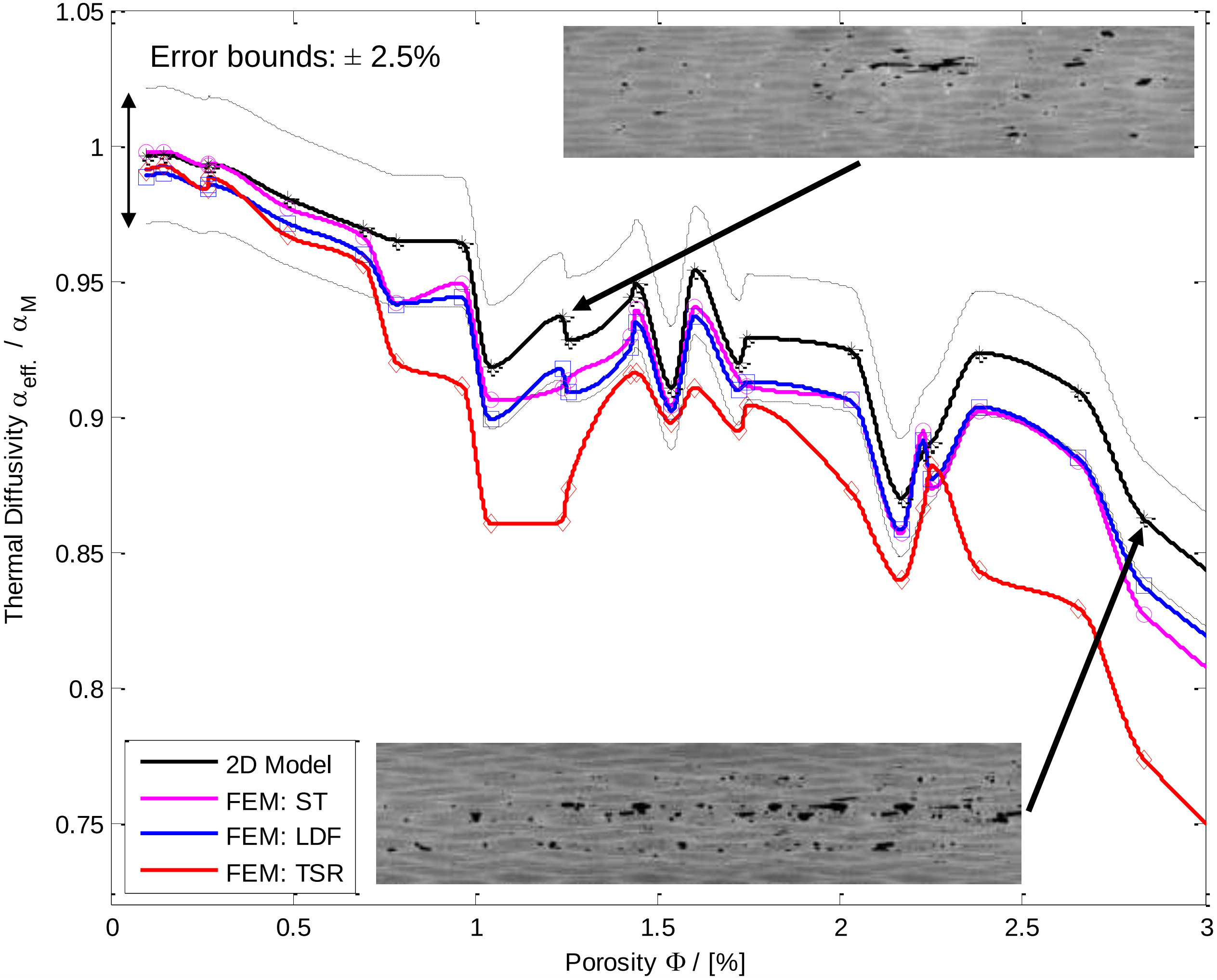


Thermal Diffusivity Profiles



Results

Verification of the Heat Conduction Model



Conclusion

- Numerical results of the **steady state** and the **transient simulations in transmission configuration follow** the analytical **heat conduction model** as the aspect ratio is taken into account.

- **Transient simulations in reflection configuration diverge** in their predictions for the effective thermal diffusivity due to the strong dependence on the pore morphology.

- "**Dethermalization Theory**" can be verified as a **quantitative model** for the prediction of the **effective thermal diffusivity** of **porous CFRP**.

Acknowledgement

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