Transient thermographic signal analysis for thinning detection in composite plates

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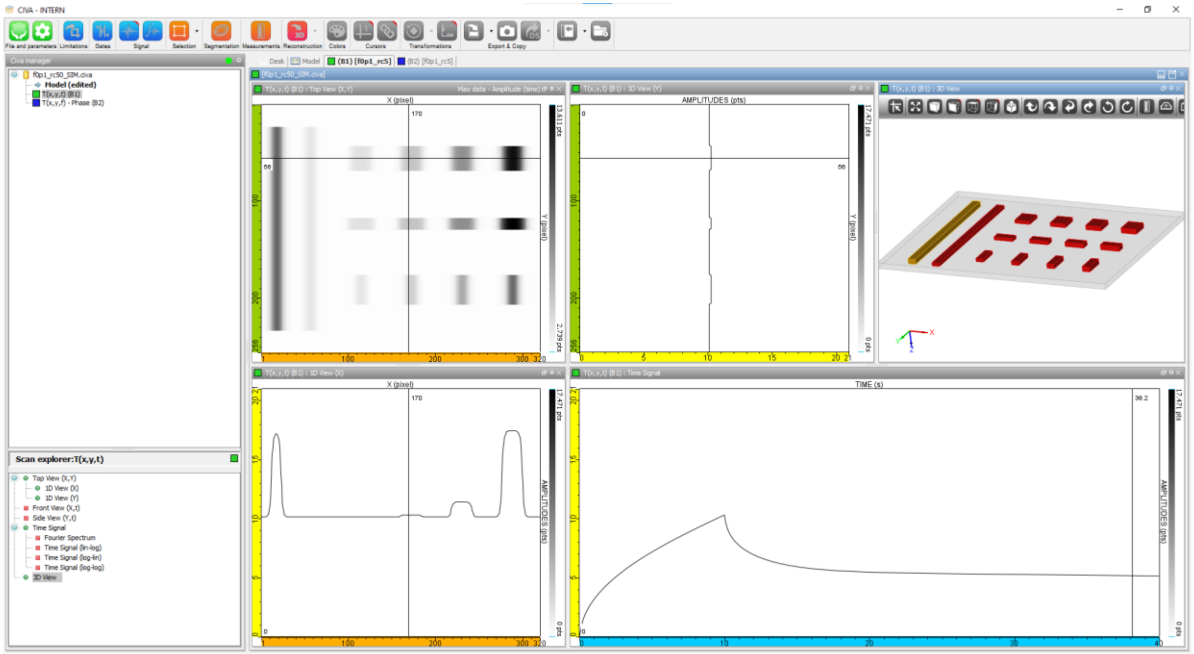
Targeted application and motivation of the work

Inspection of composite panel during manufacturing or in maintenance

- Infrared thermography : non contact imaging technique
- Large inspection area, digital record
- **Active thermography:** excitation using flash lamps or lasers
- Measurement principle: **monitoring in time of the heat diffusion**
- Diffusive regime : **resolution loss w.r.t depth**
- Delamination / porosities :
  Strong contrast of material properties
  (thermal conductivity, specific heat)
- **Modeling tools** can help to design setups, predict performance and characterize flaws and material properties

Targeted application and motivation of the work

- Development of the **CIVA platform**, used in more than 300 companies worldwide
- Thermal testing module: 2 Applications



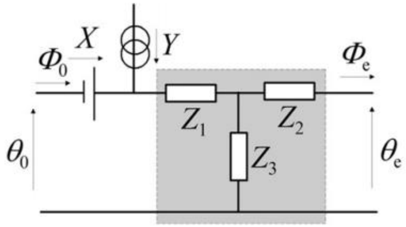
- Objectives:
  - Carry out **experimental comparisons** with experimental data in laboratory conditions
  - **Evaluate assumptions** made by two different models

First modelling approach: thermal quadrupoles*

*D. Maillet et al., Thermal Quadrupoles: Solving the Heat Equation through Integral Transforms. Wiley and Sons, 2000.

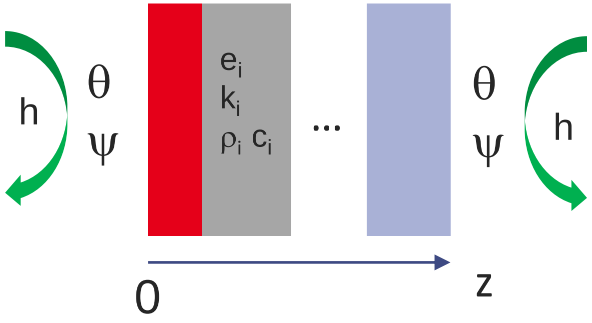
- Solution of the heat equation in the Laplace domain $\theta(x,p) = \int_0^\infty \exp(-pt)\, T(x,t)\, \mathrm{d}t$
- 1D version of the model (z is the piece depth)

$$\left\{ \begin{aligned} \frac{d^2T}{dz^2} &= \frac{\varrho c}{k}\frac{dT}{dt} \\ \phi &= -k\frac{dT}{dz} \end{aligned} \right\} \xrightarrow{\text{Laplace transform}} \left\{ \begin{aligned} \frac{d^2\theta}{dz^2} &= \frac{\varrho c}{k} p\theta \\ \psi &= -k\frac{d\theta}{dz} \end{aligned} \right. \Rightarrow \begin{aligned} \frac{d}{dz}\begin{bmatrix}\theta \\ \psi\end{bmatrix} &= \begin{bmatrix} 0 & -1/k \\ -\varrho c p & 0 \end{bmatrix}\begin{bmatrix}\theta \\ \psi\end{bmatrix} \\ \begin{bmatrix}\theta(z=0) \\ \psi(z=0)\end{bmatrix} &= \begin{bmatrix} A & B \\ C & D \end{bmatrix}\begin{bmatrix}\theta(z=e) \\ \psi(z=e)\end{bmatrix} \end{aligned}$$



e: layer thickness (m)
k: thermal conductivity ($W.m^{-1}.K^{-1}$)
ρ: volumetric mass density ($kg.m^{-3}$)
c: specific heat capacity ($J.kg^{-1}.K^{-1}$)

- Extension to the multilayer case



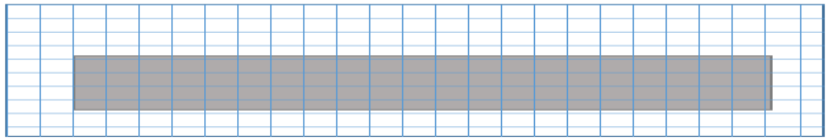
$$\begin{bmatrix}\theta(z=0) \\ \psi(z=0)\end{bmatrix} = \begin{bmatrix} A_1 & B_1 \\ C_1 & D_1 \end{bmatrix} \cdots \begin{bmatrix} A_n & B_n \\ C_n & D_n \end{bmatrix}\begin{bmatrix}\theta(z=\sum_i e_i) \\ \psi(z=\sum_i e_i)\end{bmatrix}$$

Only loss term: convection at the top and bottom surfaces (boundary conditions)

- Inversion of the Laplace transform using numerical technique (e.g Stehfest) $f(t) = \frac{\ln(2)}{t}\sum_{m=1}^{N} V_m F\left(m\frac{\ln(2)}{t}\right)$

Second modelling approach: Finite Integration Technique

- Numerical modelling, 2D implementation
- Iterative solution in time domain (time stepping)



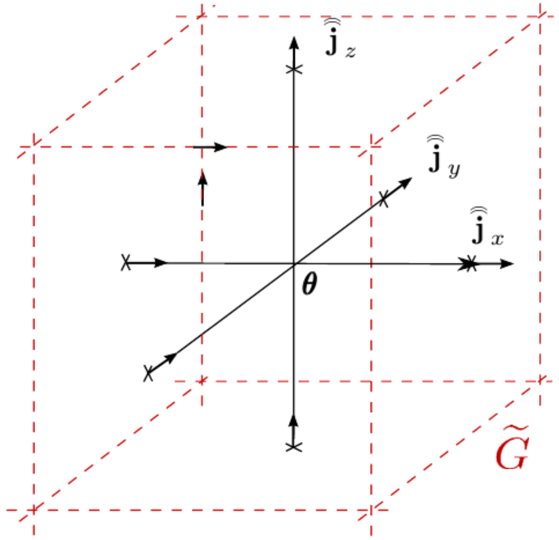
Energy conservation

$$\int_V \rho c_P \frac{\partial T}{\partial t} dV = \int_V \dot{Q}_s dV - \oint_{\partial V} \mathbf{J} \cdot d\mathbf{s}$$

Fourier law

$$\mathbf{J} = -\kappa \nabla T$$

$$\boxed{\begin{aligned} \mathrm{M}_C \dot{\boldsymbol{\theta}} &= \dot{\mathrm{q}} - \widetilde{\mathrm{S}} \widehat{\widehat{\mathrm{j}}} \\ \mathrm{M}_\kappa^{-1} \widehat{\widehat{\mathrm{j}}} &= -\mathbf{G}\boldsymbol{\theta} \end{aligned}}$$



Description of material properties

$$[M_C]_i := \int_{\tilde{V}_i} \rho c_p dV$$

$$\left[M_\kappa^{-1}\right]_i := \frac{1}{\tilde{A}_i} \int_{\tilde{A}_i} \int_{L_i} \kappa^{-1} ds dl$$

FIT Formulation of the heat equation

$$\boxed{\widetilde{\mathrm{S}} \mathrm{M}_\kappa \mathbf{G} \boldsymbol{\theta} - \mathrm{M}_C \dot{\boldsymbol{\theta}} = -\dot{\mathrm{q}}}$$

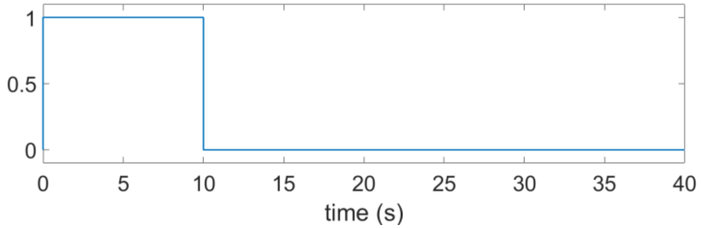
Possibility to model both conduction and convection losses

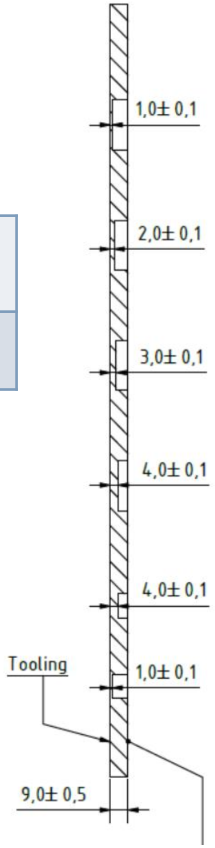
Experimental setup: inspection of a composite plate in reflection

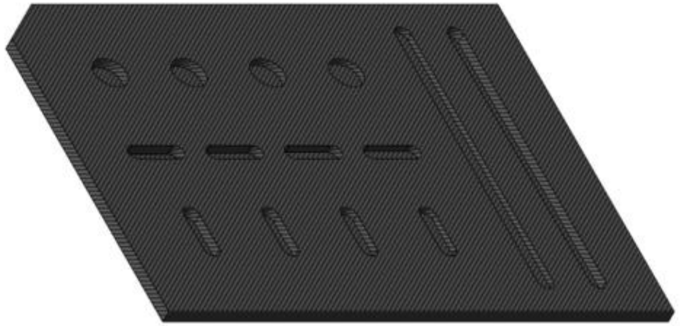
- Reference bock made of CFRP material
- 34 layers with perpendicular orientation (0°/45°/90°/135°)
- Total thickness 9,01 mm
- Large flaws (Ø25 mm for the holes)
- Reference values for thermal properties:

Thermal conductivity k	Specific Heat ρ.c	Diffusivity a
0.63 $W.m^{-1}.K^{-1}$	1.58 10^6 $J.m^{-3}.K^{-1}$	4.0 10^{-7} $m^2.s^{-1}$

- Source: 2 halogen lamps (2 kW each)
- Excitation: rectangular pulse

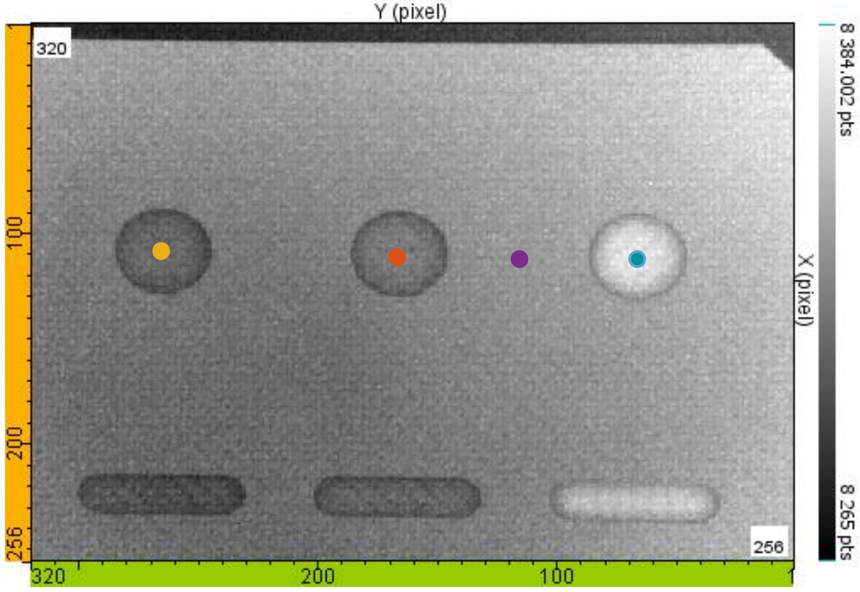


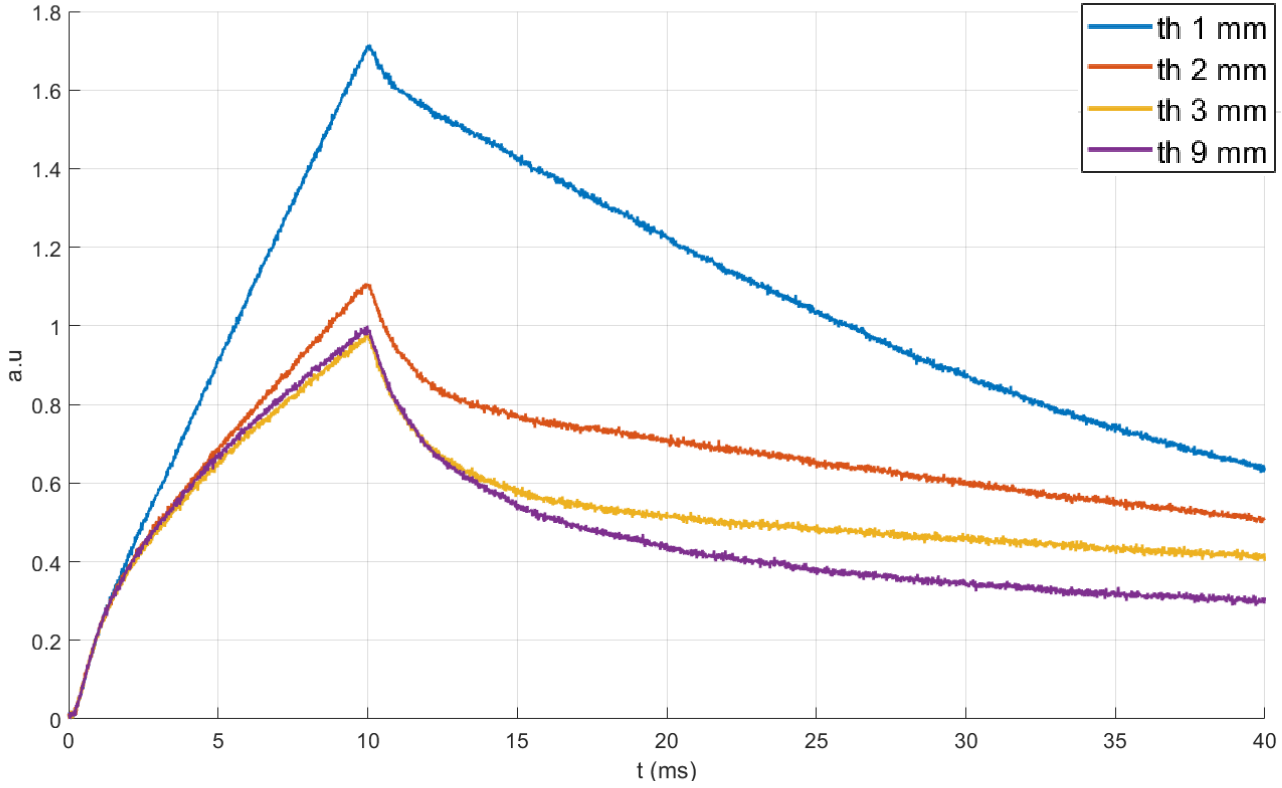




Experimental signals used for comparison

- Thermal camera: FLIR SC 7000 not yet calibrated ➡ comparisons carried out on normalized data for three holes and a sound area

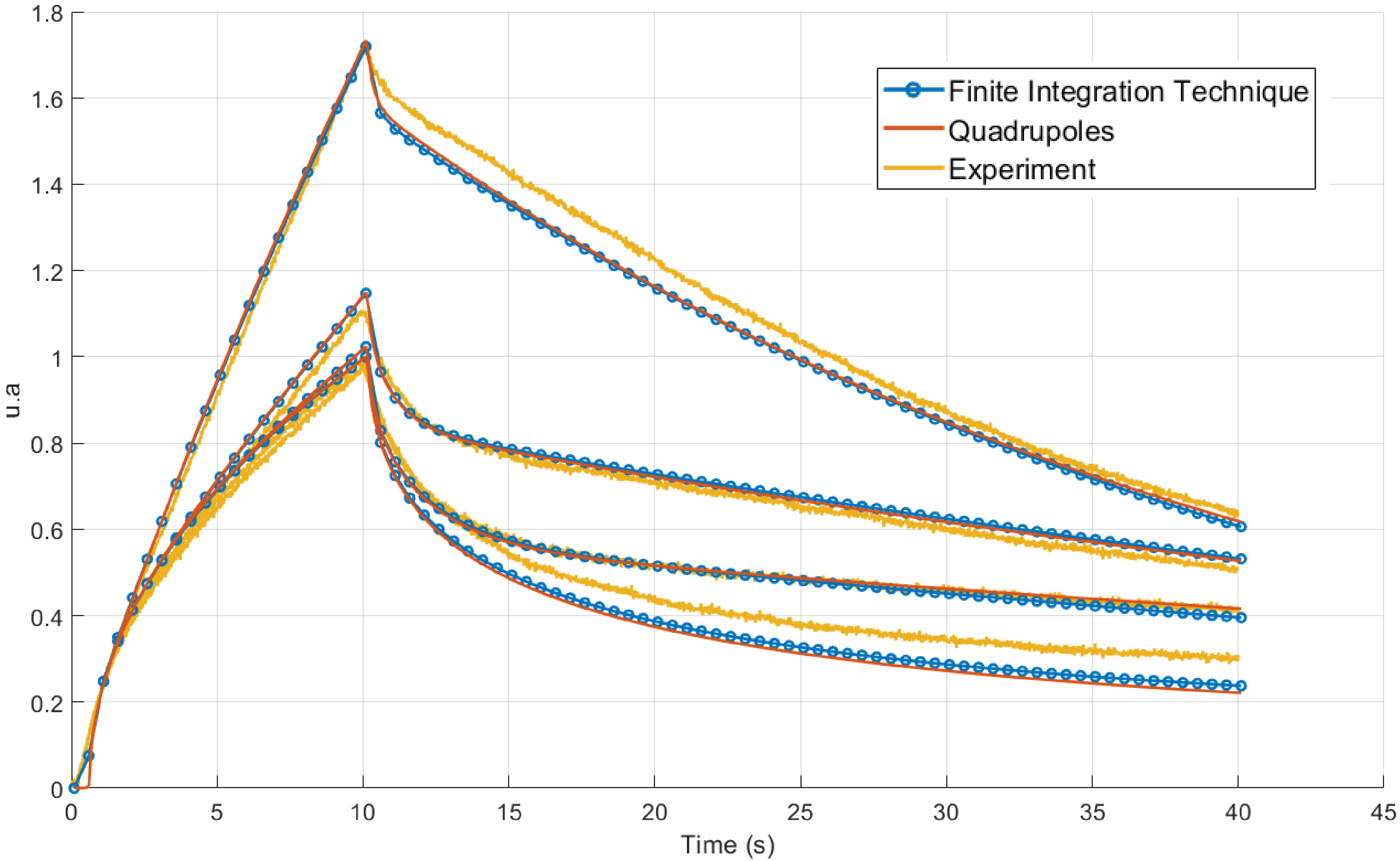




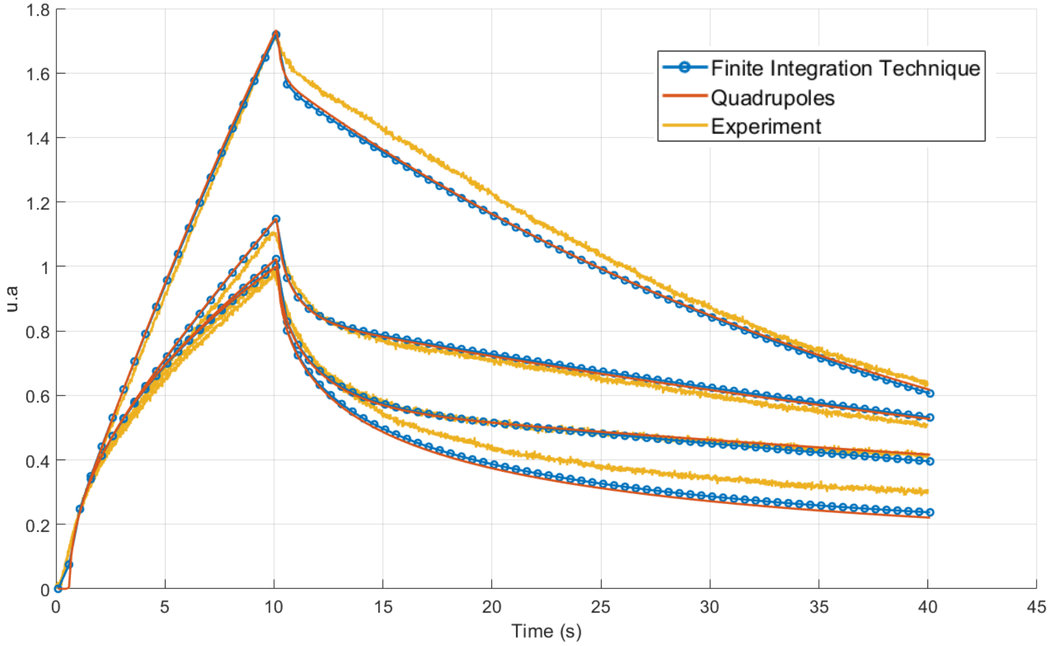
- 4 characteristic areas of the curves:
  Heating / short time decay / long time decay / relative amplitudes

- Thicknesses between 3 mm and 9 mm may be hard to separate (signals close to each other, except at longer times)

Comparisons between experimental data and simulation results



Comparisons between experimental data and simulation results



- Very good agreement between both models

- Same values of thermal conductivity ***k*** and specific heat ***ρ.c*** were used but different values of convection coefficient ***h***

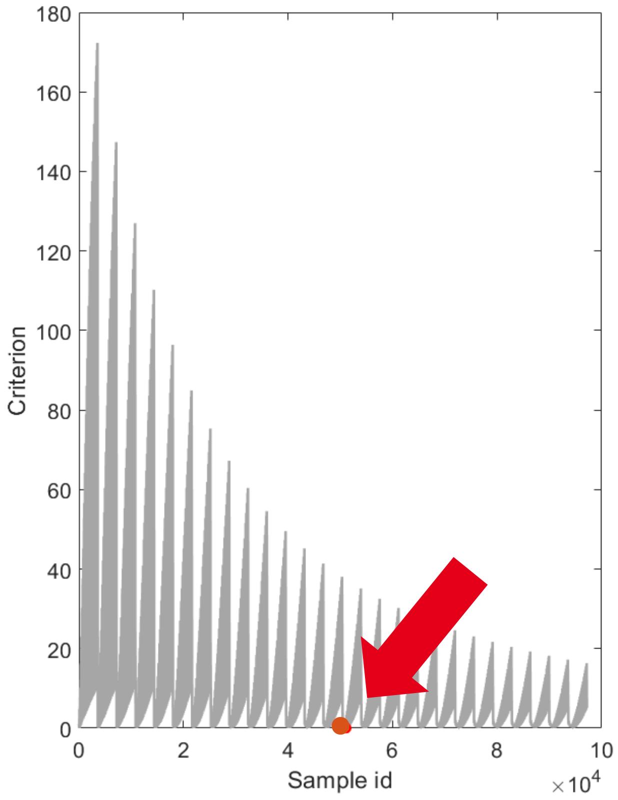
  The Quadrupole model only loss term is ***h*** (probably overestimated)
  The FIT model takes both conduction and convection losses into account

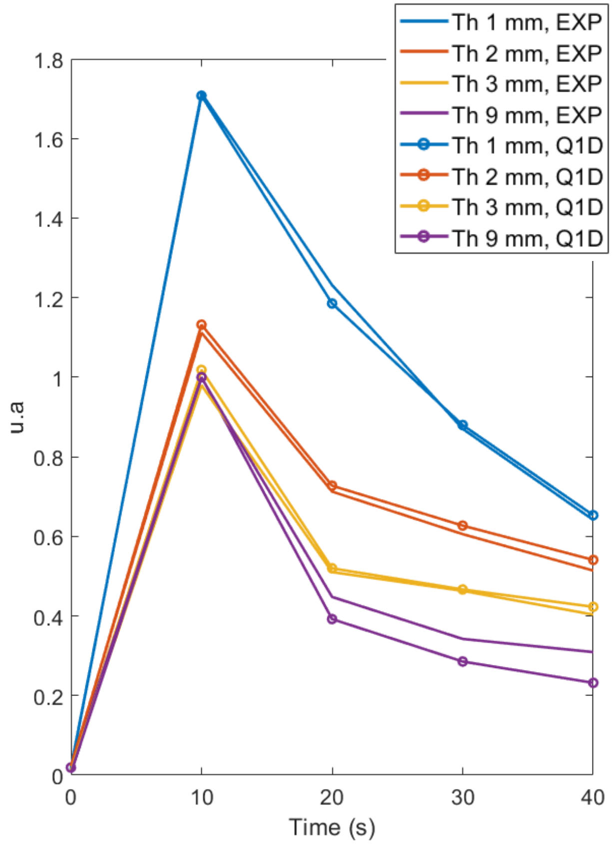
- Good agreement with experimental data in the 4 characteristic areas of the curves: Heating / short time decay / long time decay / relative amplitudes

- In this simple configuration, the 1D model seems to be sufficient to predict signals accurately

Estimation of material properties using model based inversion

- The 4 thicknesses values are supposed to be known precisely
- Objective: estimation of the material properties ***k*** and ***ρ.c***
- Criterion: mean square error between experimental data and simulation for the 4 thicknesses
- To accelerate the model evaluation and get a proper balance between shape and amplitude in the criterion, 5 times are used for the comparison: t = [0 10 20 30 40] s
- $h \in [0\ 30]$; $k \in [0\ 3]$; $\rho.c \in [0.4\ 3]\ .10^6$
- « Brute force » computation of the criterion because the model evaluation has almost no cost

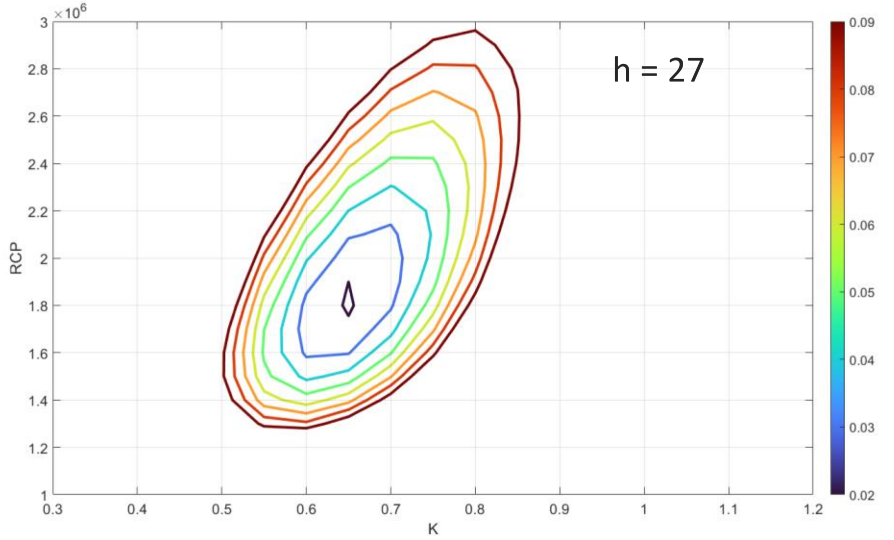


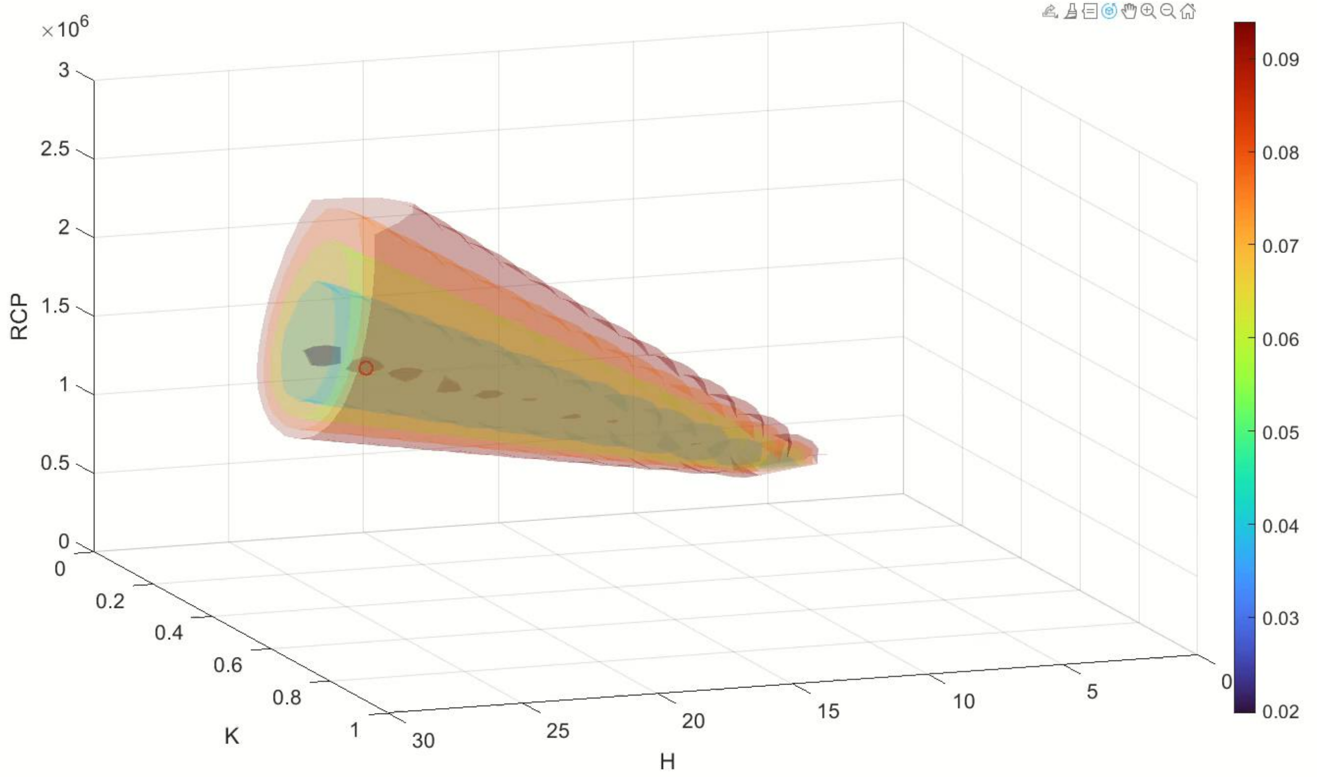


Estimation of material properties using model based inversion

- Results of the model based inversion

	Thermal conductivity k ($W.m^{-1}.K^{-1}$)	Specific Heat $\rho.c$ ($J.m^{-3}.K^{-1}$)	Diffusivity a ($m^2.s^{-1}$)
Reference values	0.63	$1.58\ 10^{6}$	$4.0\ 10^{-7}$
Estimated values	0.65	$1.8\ 10^{6}$	$3.61\ 10^{7}$





- The estimation of the three parameters (*h*,*k*,ρ.*c*) is not well posed as illustrate the isosurfaces of the criterion
- **However**, *h* can be determined separately from the slope at longer times, then the problem becomes well posed

Conclusions and perspectives

- Two different modelling approaches (1D in Laplace domain vs. 2D in time domain) have been compared and validated with respect to experimental data in a simple configuration
- When applicable, the 1D quadrupole model is a very fast tool that can be used to estimate unknown parameters (even if it tends to overestimate the convection contribution)
- For the estimation of material properties to be well posed, one should first to estimate the convection term separately, this can be done by matching the slope of the signal at longer times
- For more complex cases, the FIT model can be used to describe more complex geometries, material properties and 3D sources

Conclusions and perspectives

Current assumptions in CIVA TT:

- Uniform source defined in time only, applied on the piece surface
- 3D results (x,y,z) obtained by superposition of 2D simulations in (x,z) plane

Perspectives of development:

- Introduction of more complex sources (induction, laser, non uniform lamp heating)
- 2,5D and 3D solver for the heat equation
- Solution via Laplace domain or time stepping