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# Composite manufacturing, characterization and monitoring for a better control of final quality

Arthur Lévy

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Submitted on 21 Sep 2022

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# Composite manufacturing characterization and monitoring for a better control of final quality.

Arthur Levy  
[arthur.levy@univ-nantes.fr](mailto:arthur.levy@univ-nantes.fr)

# Arthur Levy

Grew up in Paris

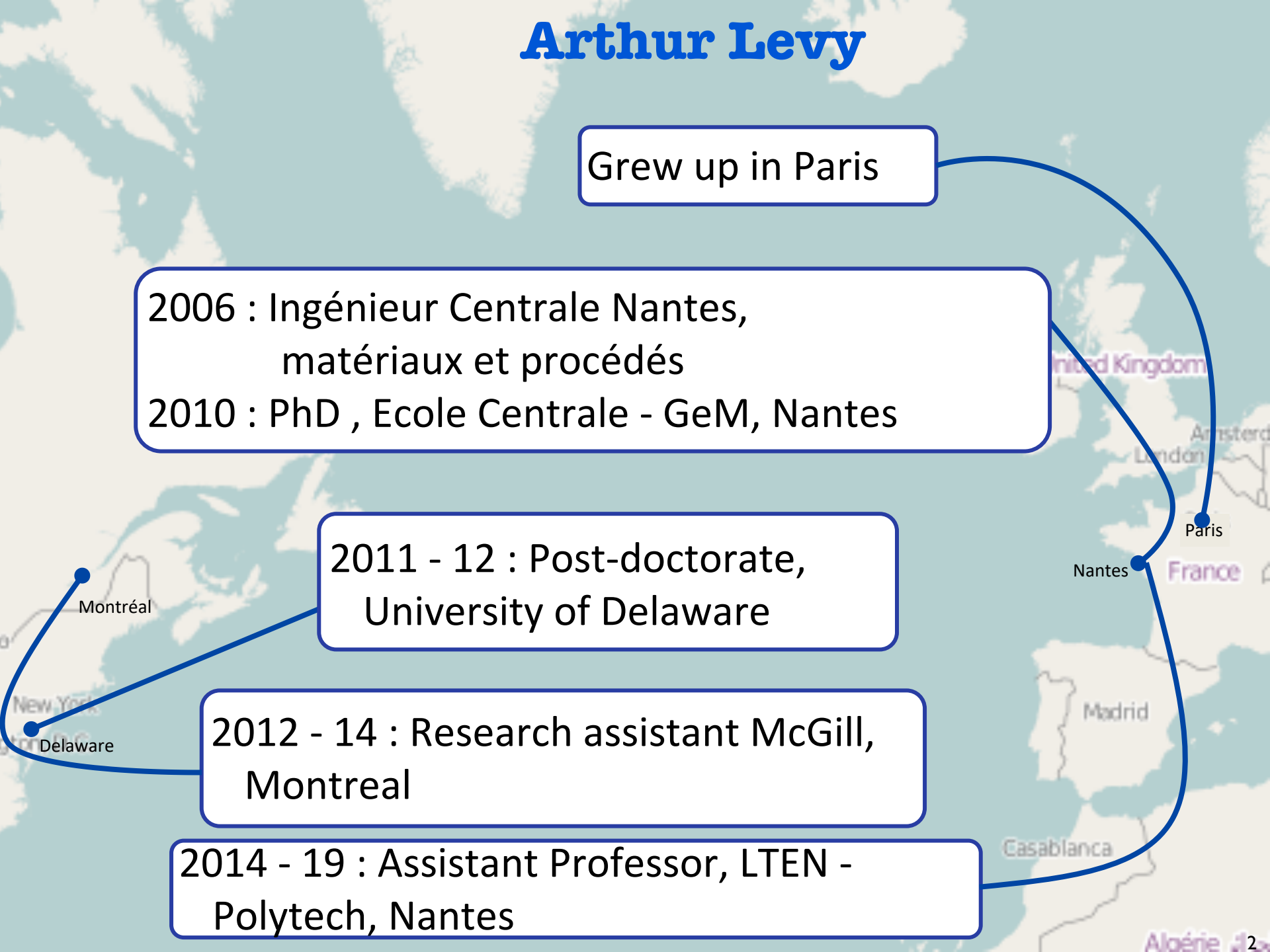
2006 : Ingénieur Centrale Nantes,  
matériaux et procédés

2010 : PhD , Ecole Centrale - GeM, Nantes

2011 - 12 : Post-doctorate,  
University of Delaware

2012 - 14 : Research assistant McGill,  
Montreal

2014 - 19 : Assistant Professor, LTEN -  
Polytech, Nantes



# Agenda

- Nantes, France,
  - University / Polytech
  - Laboratoire de Thermique et Energie de Nantes
  - Polymer and composite manufacturing team
- Composite manufacturing processes
  - Flow front monitoring in infusion processing
  - Adhesion kinetics in TP composites



# Nantes

# Nantes (600 000 inhab.)

Région PAYS DE LA LOIRE

main campus



Chantrerie



# A Composite hub in France

## Industries

**AIRBUS**  
GROUP

**ARKEMA**  
INNOVATIVE CHEMISTRY

**DAHER**

**OP**  
PLASTIC OMNIUM

**SOLVAY**

**CORIOLIS**  
composites

PSA PEUGEOT CITROËN

## Academics

**Nantes**  
Université

**cnrs**  
Département des Matériaux

**IMT Atlantique**  
Bretagne-Pays de la Loire  
Ecole Mines-Télécom

**CENTRALE**  
NANTES

**icam**

## Institutes

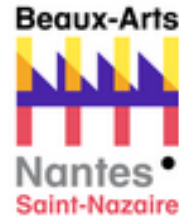
**IRT**  
JULES  
VERNE

**EMC2**

**Technocampus**  
Composites  
Innovative manufacturing for composite structures

# Nantes Université

Created in 2022.



Second biggest university in France by number of students.

The largest University and second most important centre for research in the West of France.



# Nantes Université

- 43,000 students, including 5,000 international students (License - Master – Doctorate)
- 7,800 members of staff including:
  - 4,600 support staff and technicians
  - 3,257 lecturers, lecturer-researchers
- 20 faculties, schools or institutes
- 1,500 (approximately) PhD students
- 42 research structures

# Polytech Network



- 🕒 Écoles membres du réseau
- Écoles associées Polytech
  - ENSIM de l'Université du Mans
  - ESGT du Cnam au Mans
  - ESIREM de l'Université de Bourgogne
  - ISEL de l'Université Le Havre Normandie

## THE NETWORK OF FRENCH GRADUATE SCHOOLS OF ENGINEERING

- **15** public graduate engineering faculties
- an alliance with **4** partners schools
- **12** different scientific fields
- **17 500** students
- **90 000** alumni
- **100** partner universities around the world
- **2 000** Masters and Ph.D students



POLYTECH®

[www.polytech-reseau.org](http://www.polytech-reseau.org)

# Polytech' Nantes



## 7 engineering specialities

ETN	Electronic and Digital Technologies
GC	Civil Engineering
GE	Electrical Engineering
GPB	Process and Bioprocess Engineering
INFO	Computer Science
MAT	Materials Sciences
TE	Thermal and Energy Sciences

400  
Graduates every year

1500  
Engineering  
students

250  
Master's and  
PhD students

7100  
Alumni

120  
Professors and  
assistants professors

# Laboratoire de Thermique et Energie de Nantes (LTEN)



~70 people

 Nantes  
Université



Transferts Thermiques dans les Matériaux et aux Interfaces

Transferts aux interfaces et dans les micro-systèmes

Transferts thermiques dans la mise en forme des polymères et composites

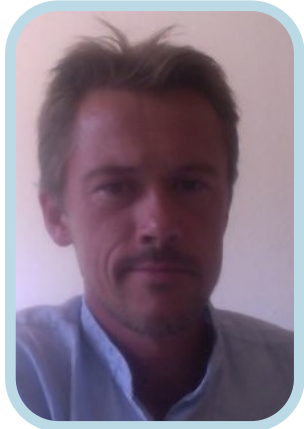
Caractérisation et fonctionnalisation des propriétés radiatives des matériaux

Transfert dans les Fluides et Systèmes Energétiques

Transferts dans les fluides et écoulements complexes

Transferts dans les Systèmes Energétiques

# Composite team



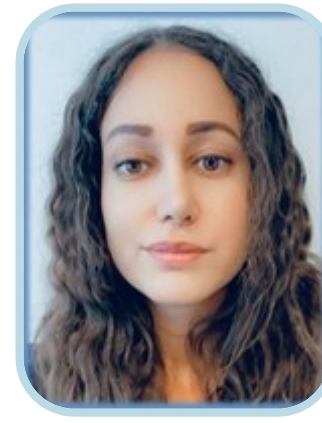
Steven Le Corre



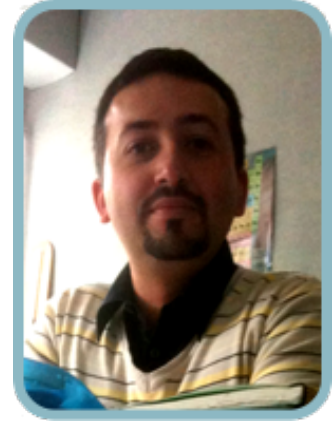
Jean-Luc Bailleul




Vincent Sobotka



Elissa El Rassy

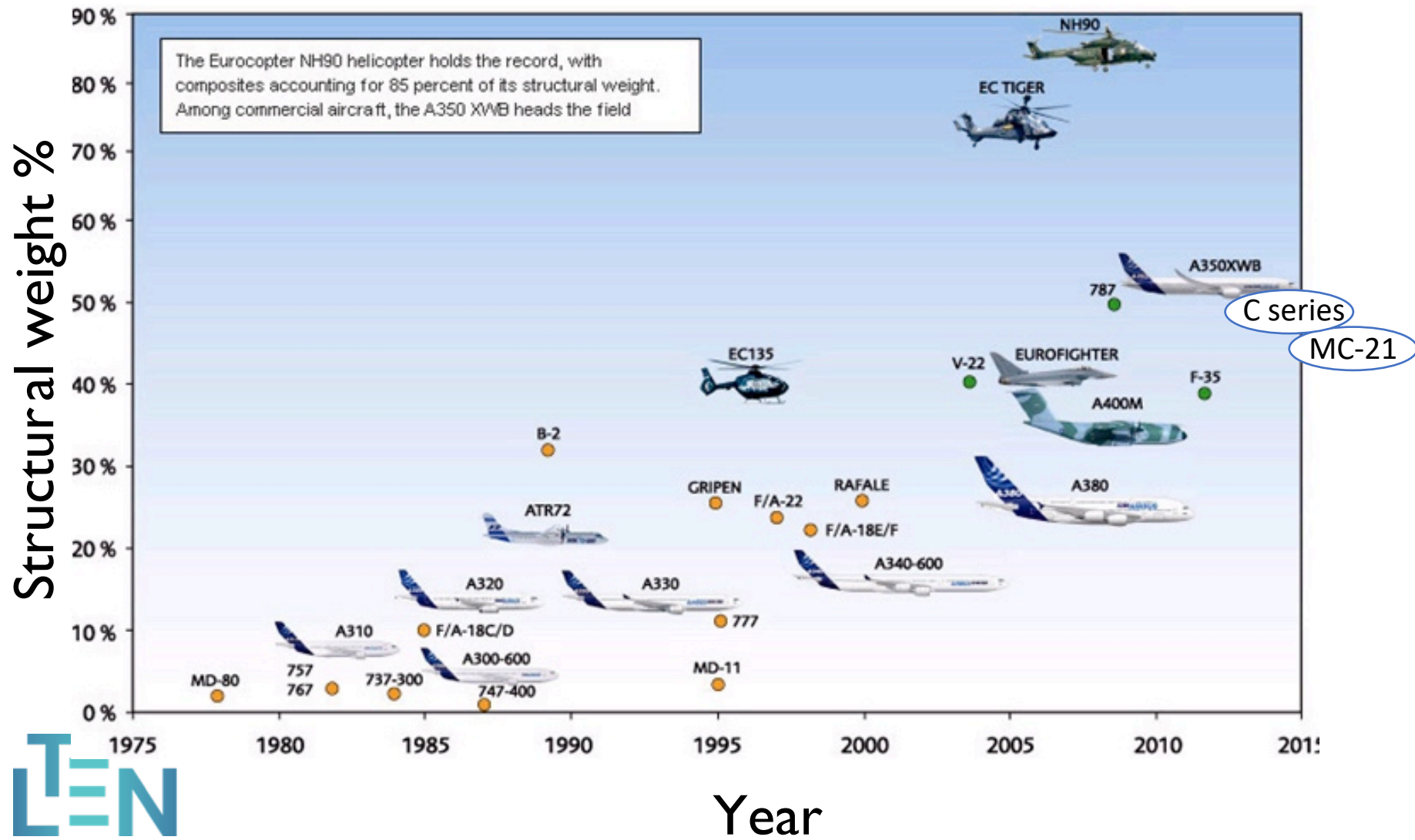


Nicolas Boyard



# Composite manufacturing processes

# Composite use in aeronautical industry





# Today's challenges

## Increase part complexity



Pylone MATCH project



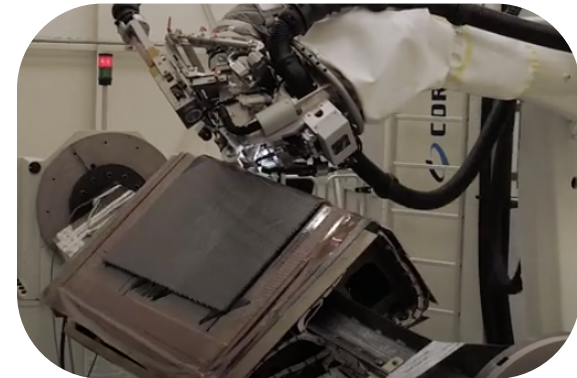
Boeing assembly line

- Intricate / thick parts
- Large parts
- Assembly

## Cheap / sustainable



[www.sabca.be](http://www.sabca.be)



- Fast and efficient cycles
- Out-of-autoclave
- Defect free



New and robust forming processes

# Motivation

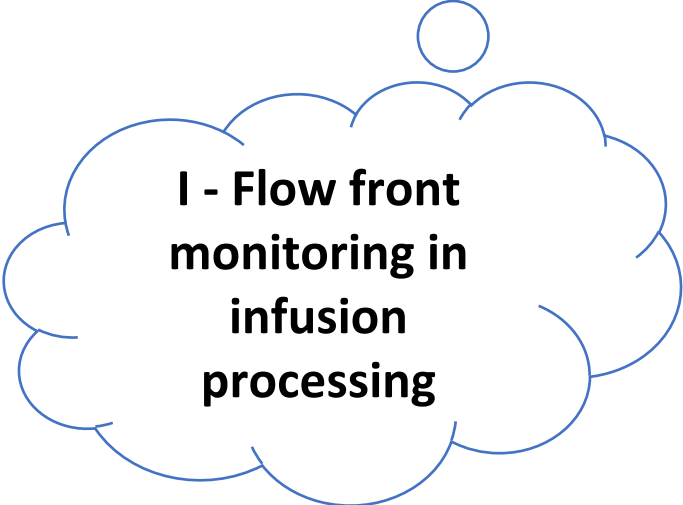
**Industrial goal:** control and optimize forming/assembling processes.

**Method:** ~~trial and error~~  
monitoring, predictive tools (simulation).

# Outline

Industrial goal: control and optimize forming/assembling processes.

Method: ~~trial and error~~  
monitoring, predictive tools (simulation).



**I - Flow front  
monitoring in  
infusion  
processing**



**II – Thermomechanical  
characterization - The  
PVT series**

# I - Flow front monitoring in infusion processing

Arthur Levy, James Kratz

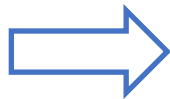


# Reclaimed Carbon Fibre mats



Carbon

Ply cutter waste materials

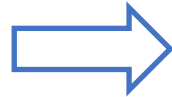


How to process it

[Kratz et al. 17]

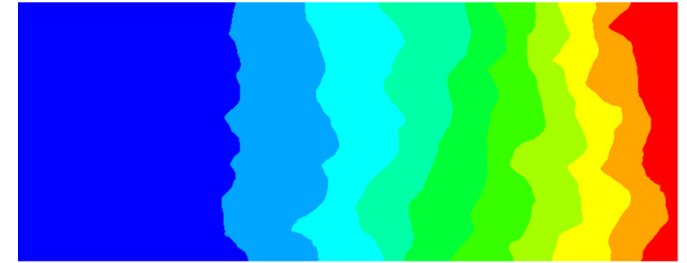
# Manufacturing

RTM

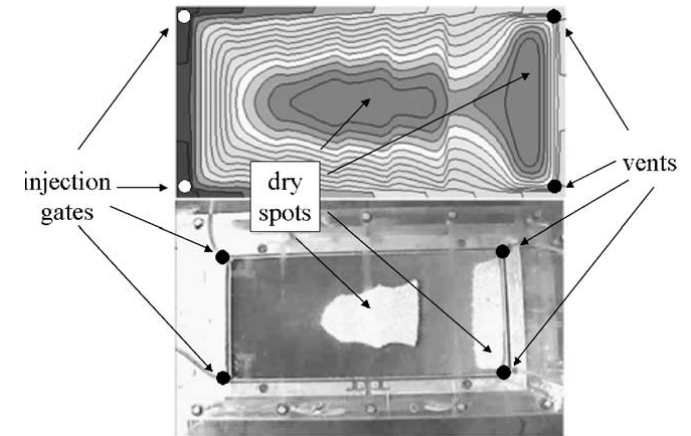


- Material looks variable
- Poorly oriented

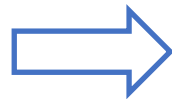
## Defects



[Endruweit et al. 08]



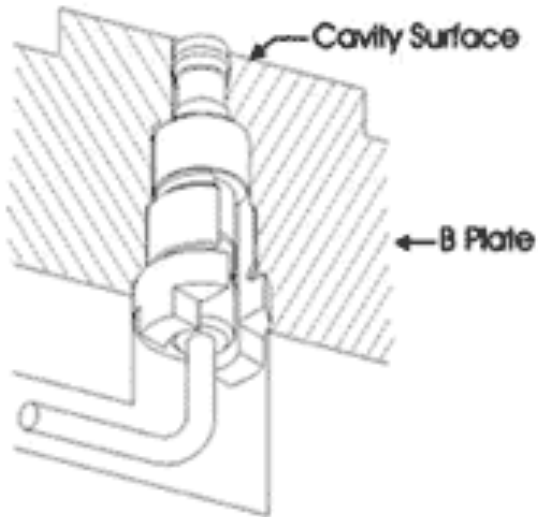
[Lawrence et al 02]



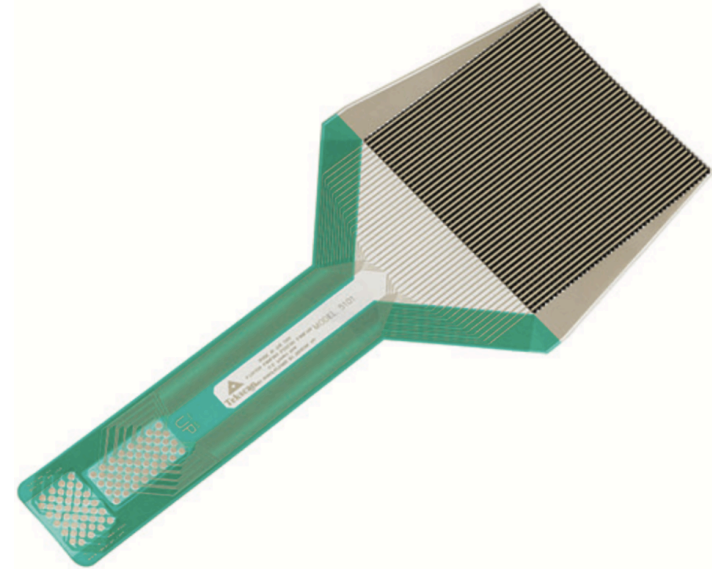
Requires process monitoring

# In-situ monitoring

## Pressure sensor



## Tekscan mapping



Non intrusive  
~2000 cells  
Quantitative data

[Konstantopoulos et al. 14,  
Di Fratta et al 13]

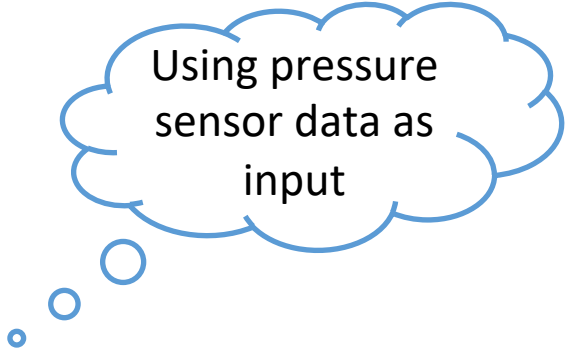
# Motivation

Can the pressure sensor give useful information ?



# Outline

- Experimental RTM setup
- Material characterization
- Flow front monitoring
- Direct numerical modeling

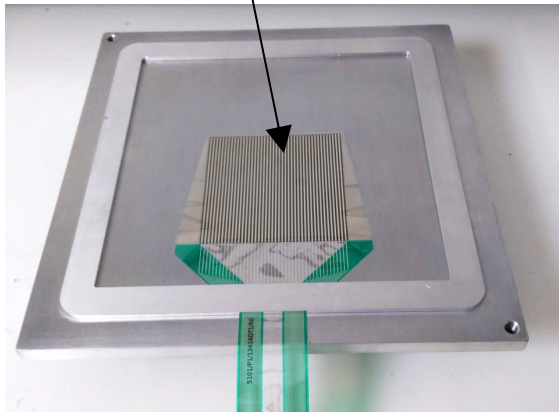


Using pressure sensor data as input

# Experimental RTM setup

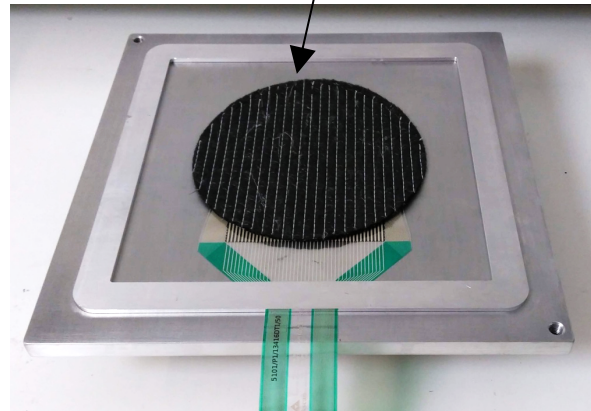
# Experimental Setup

Surface mapping sensor



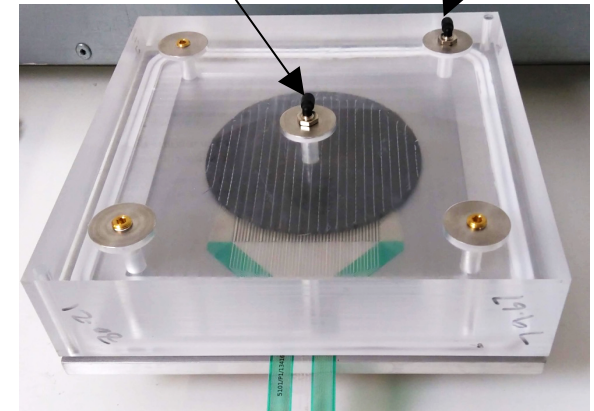
TekScan 5101  
112 mm square grid  
Measurement every 2.5 mm

Reclaimed fibre preform  
(4 mm)



Recatex Type 62 complex  
Non-woven 200 g/m<sup>2</sup>

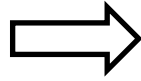
Central injection  
(160 kPa) Perimeter vent  
(atmosphere)



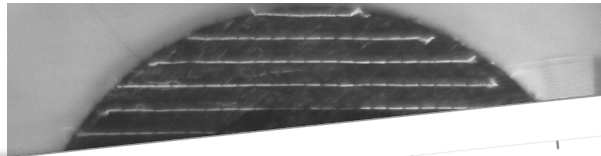
80 mm acrylic upper mould  
Camera to record flow  
position

# Visual flow front tracking

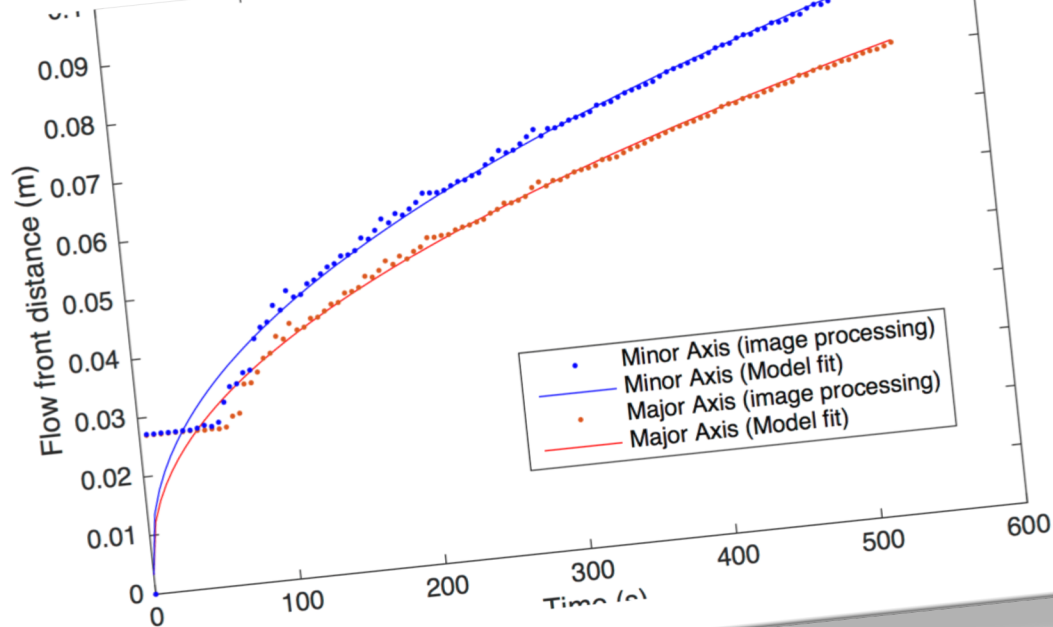
Video



Threshold and  
Ellipse fit



0.08



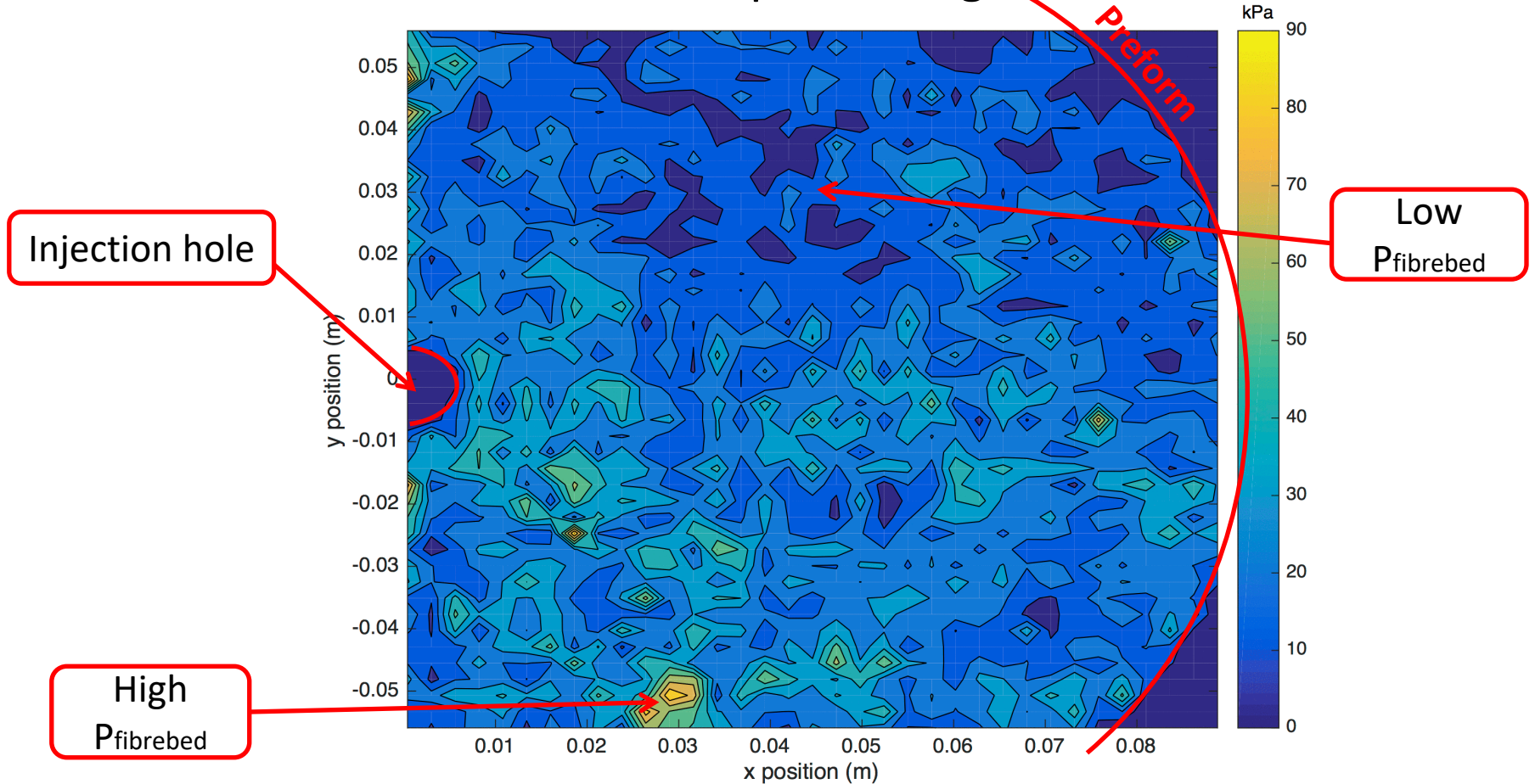
0.02 0.04 0.06 0.08

Golden syrup  
diluted 15%



# Pressure mapping sensor

Before processing

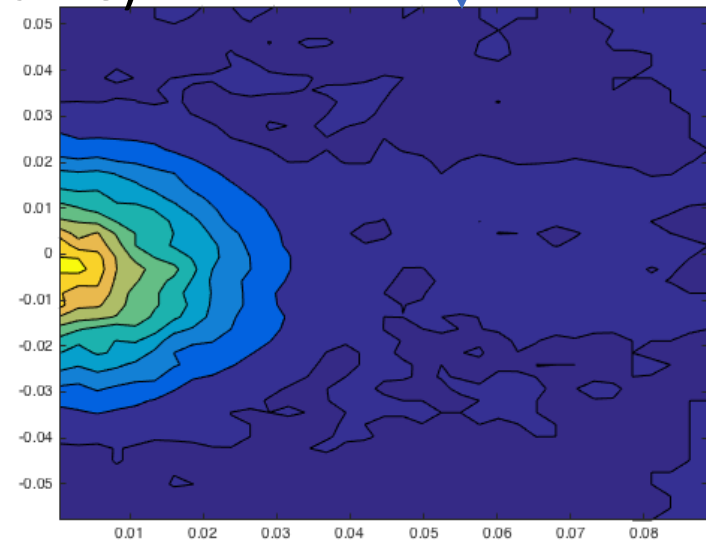
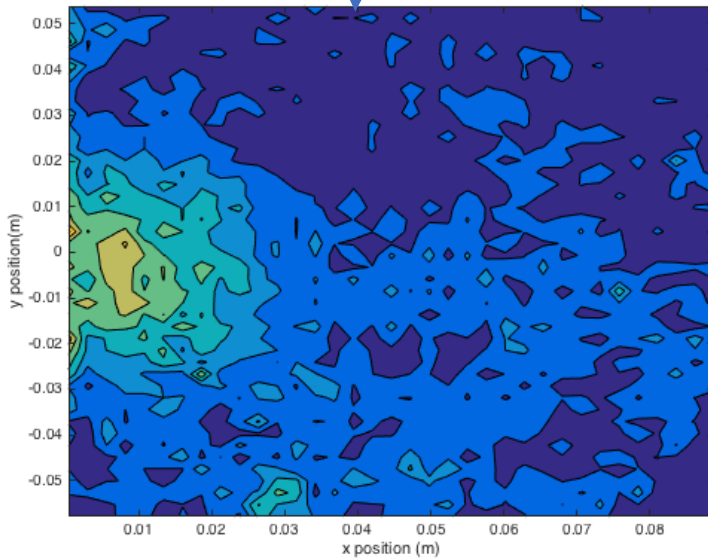


# Processing in-situ pressure map

Assuming  $P_{Applied} = \sigma_{Fibrebed} + P_{Resin}$

Constant throughout  
process

Subtract dry  
mat pressure  
(initial frame)

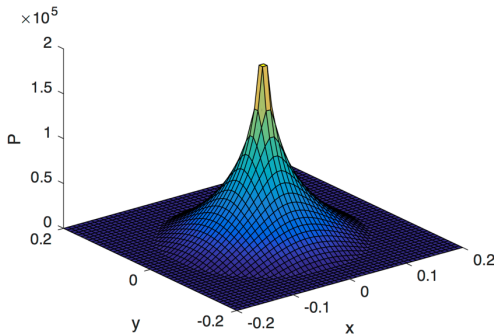


# Permeability characterization

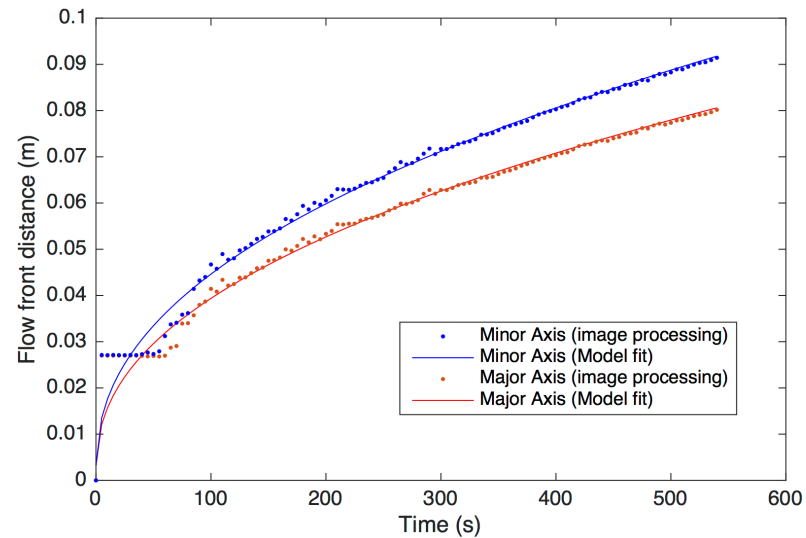
# Permeability from Camera

## Direct Model

- Darcy flow
- 2D radial
- Central injection point
- Anisotropic
- Analytical



## Inverse Method

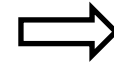
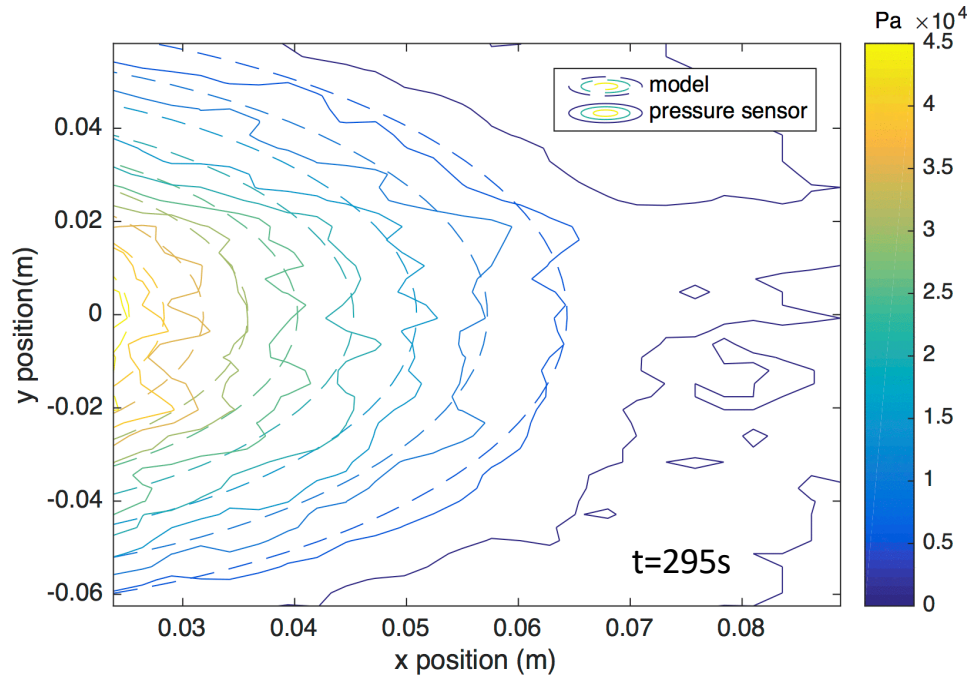


$$\frac{K_x}{\mu} = 1.62 \times 10^{-10} m^2 \cdot Pa^{-1} \cdot s^{-1} \quad \frac{K_y}{\mu} = 1.20 \times 10^{-10} m^2 \cdot Pa^{-1} \cdot s^{-1}$$



# Permeability from Pressure Field

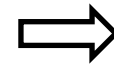
## Inverse Method with a Direct Analytical Model



$$\left\{ \begin{array}{l} \frac{K_x}{\mu} = 1.57 \times 10^{-10} m^2 \cdot Pa^{-1} \cdot s^{-1} \\ \frac{K_y}{\mu} = 1.27 \times 10^{-10} m^2 \cdot Pa^{-1} \cdot s^{-1} \end{array} \right.$$

-3% from camera

+6% from camera



**Difference between contours due to material  $V_f$  variability**

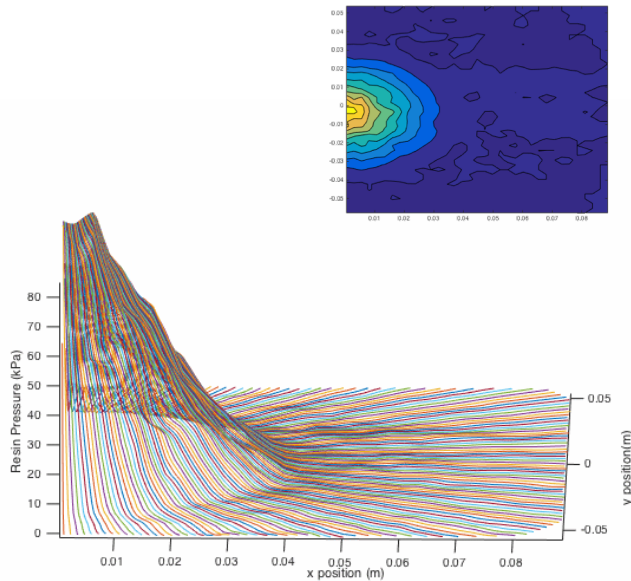
# Flow front monitoring

[Kratz et al, FPCM 18 – Lulea]

# Flow front identification

Calculate flow front distance for each angle using all the pressure data

## Polar Description



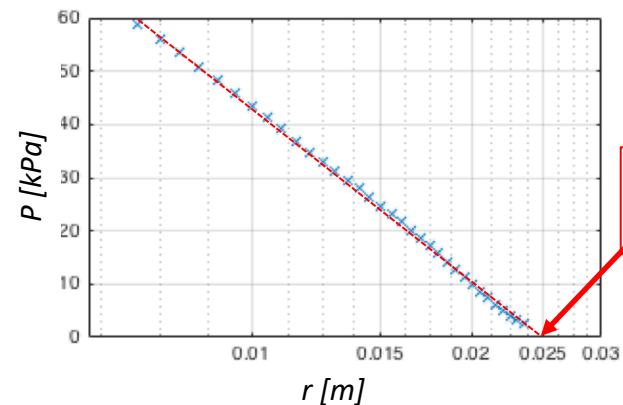
Adapted to central injection

## For each angle

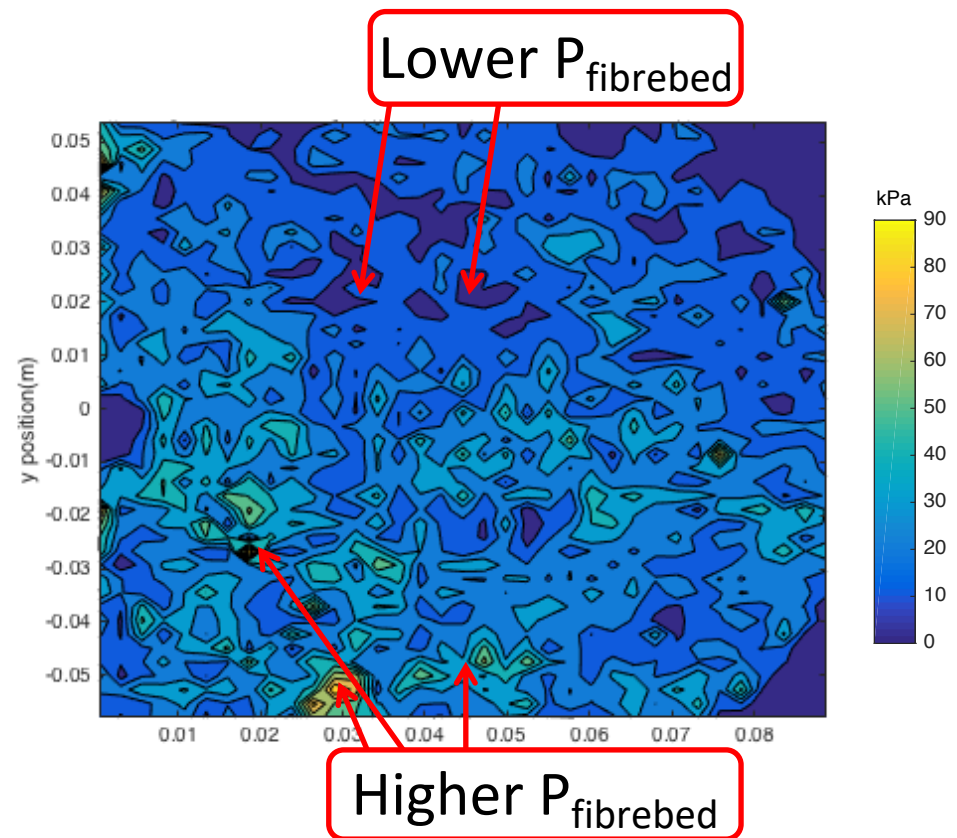
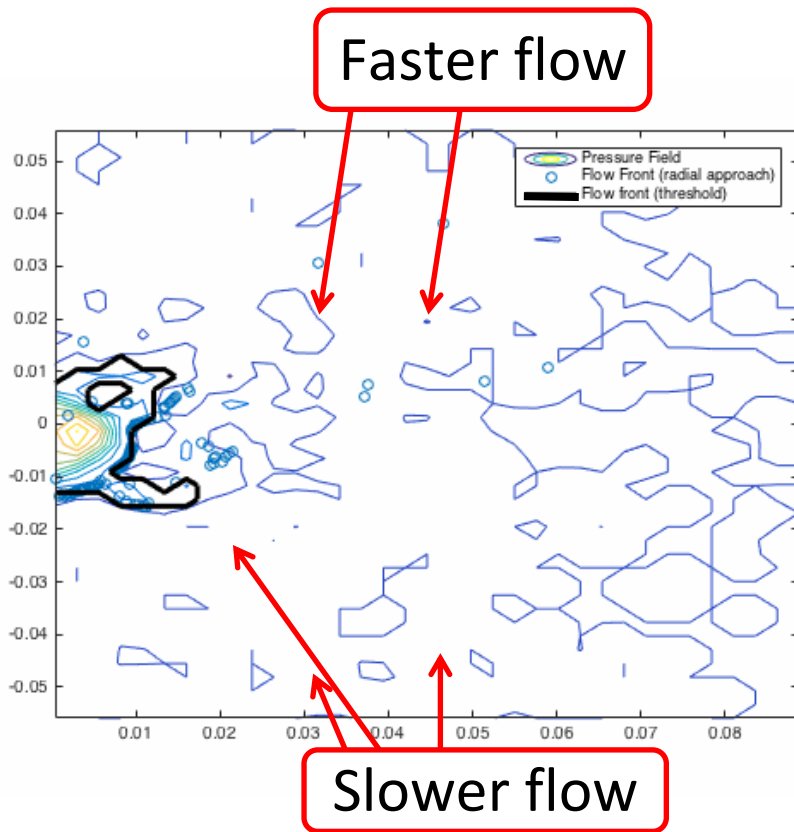
Direct model says :

$$P(r) = P_{inj} \times \frac{\ln(r) - \ln(l)}{\ln(r_0) - \ln(l)}$$

Flow front distance



# Defect identification



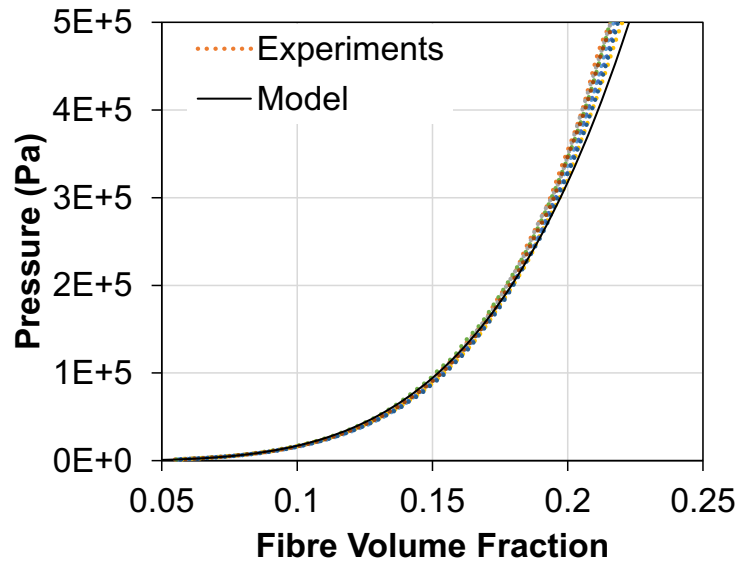
⇒ Pressure sensor **accurate** for monitoring flow defects

# Direct numerical modeling

[Levy et al, ICMAC 18, Nottingham]

# From dry pressure to Vf

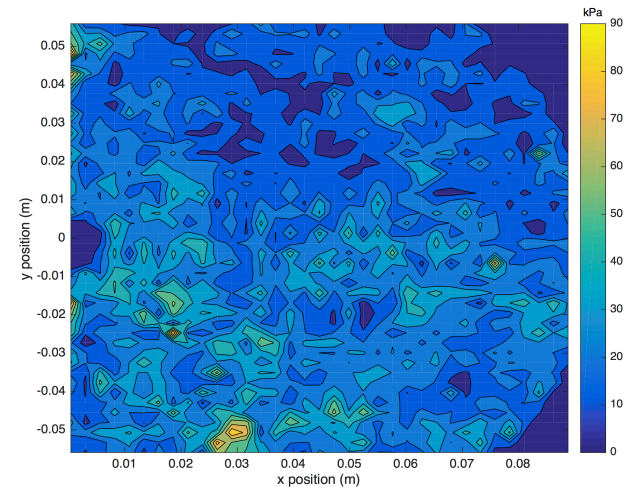
## Compaction curve



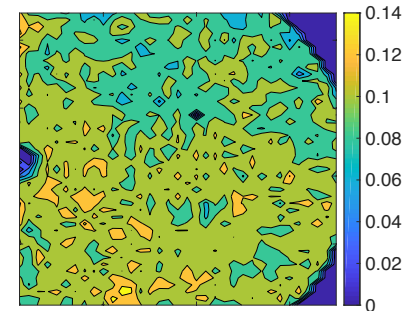
$$P = E f^4 V_f^A$$

[Toll & Manson 94]

## Dry pressure map

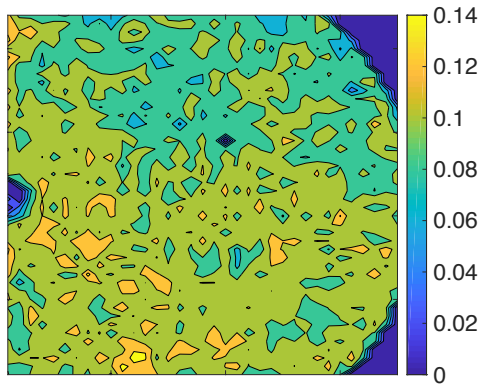


## Fibre volume fraction map



# From $V_f$ to permeability

Fibre volume fraction map

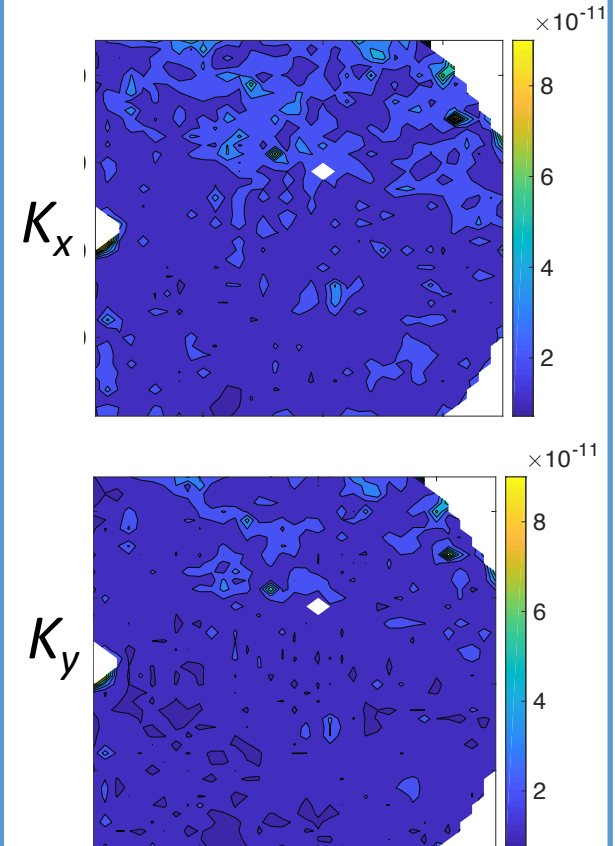


Kozeny  
Carman

$$K = C \frac{(1 - v_f)^3}{v_f^2}$$

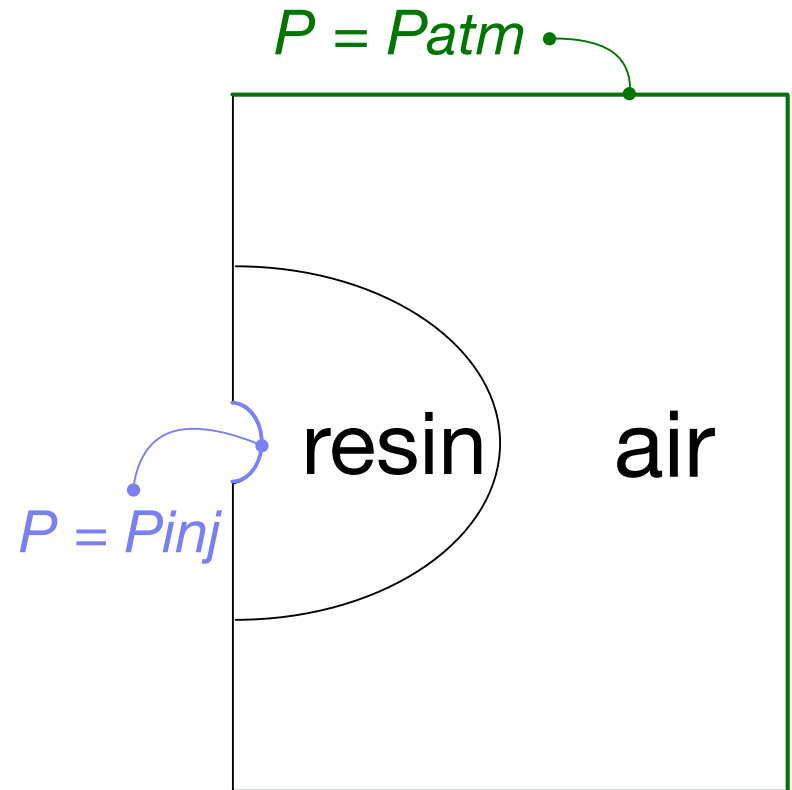
Identified from  
previous work

Nonuniform  
permeability map



# Modeling infusion

- Darcy flow
- Incompressible resin
- Two fluids
- Pressure BC
- K map from sensor

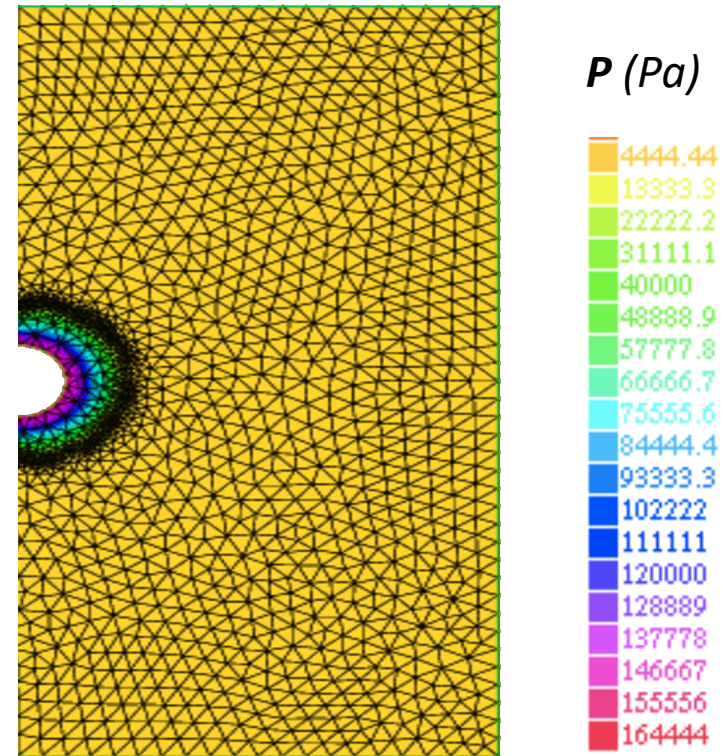


[Endruweit et al. 08]

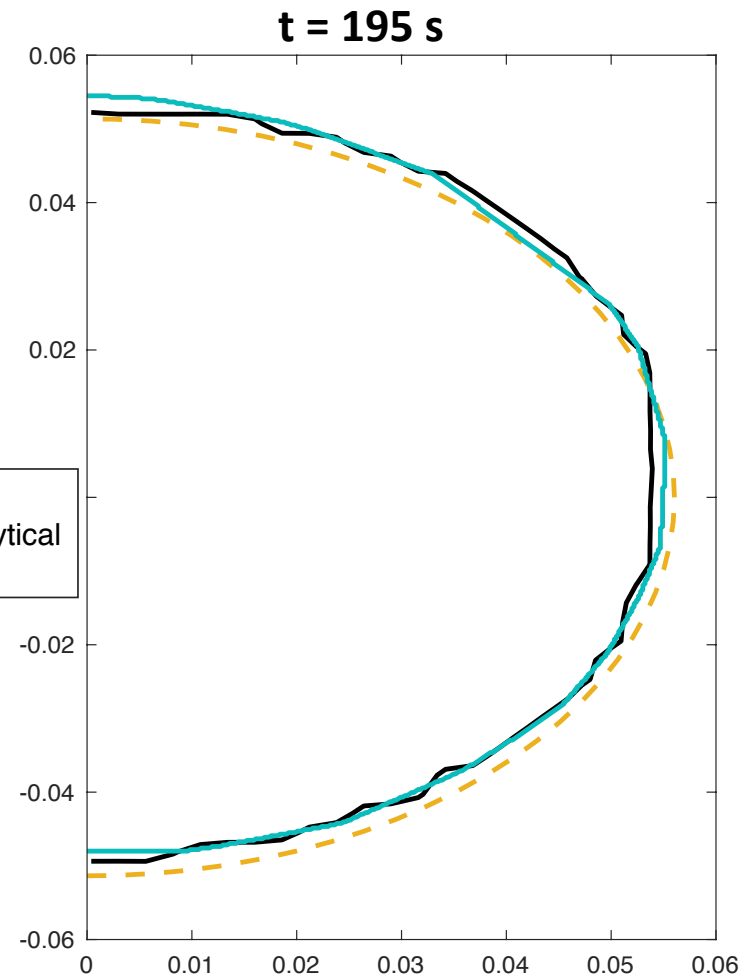
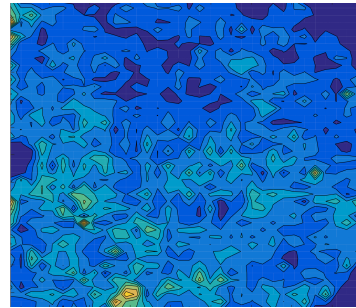
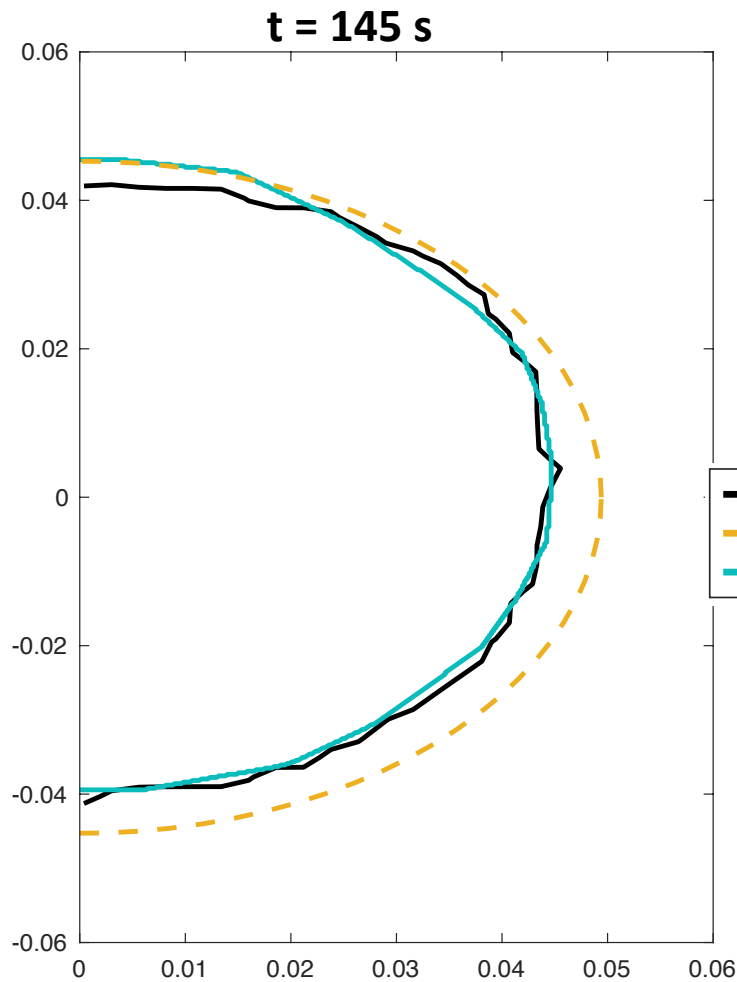


# Direct numerical simulation

- 2D Finite elements
- FreeFem library
- Levelset for flow front
  - Mesh adapt
  - Reinitialization

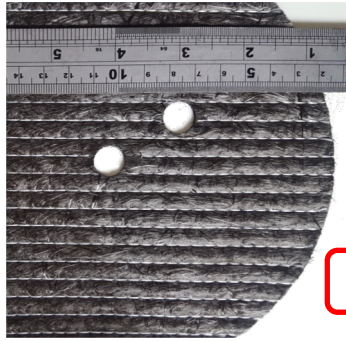


# Results for as-received material

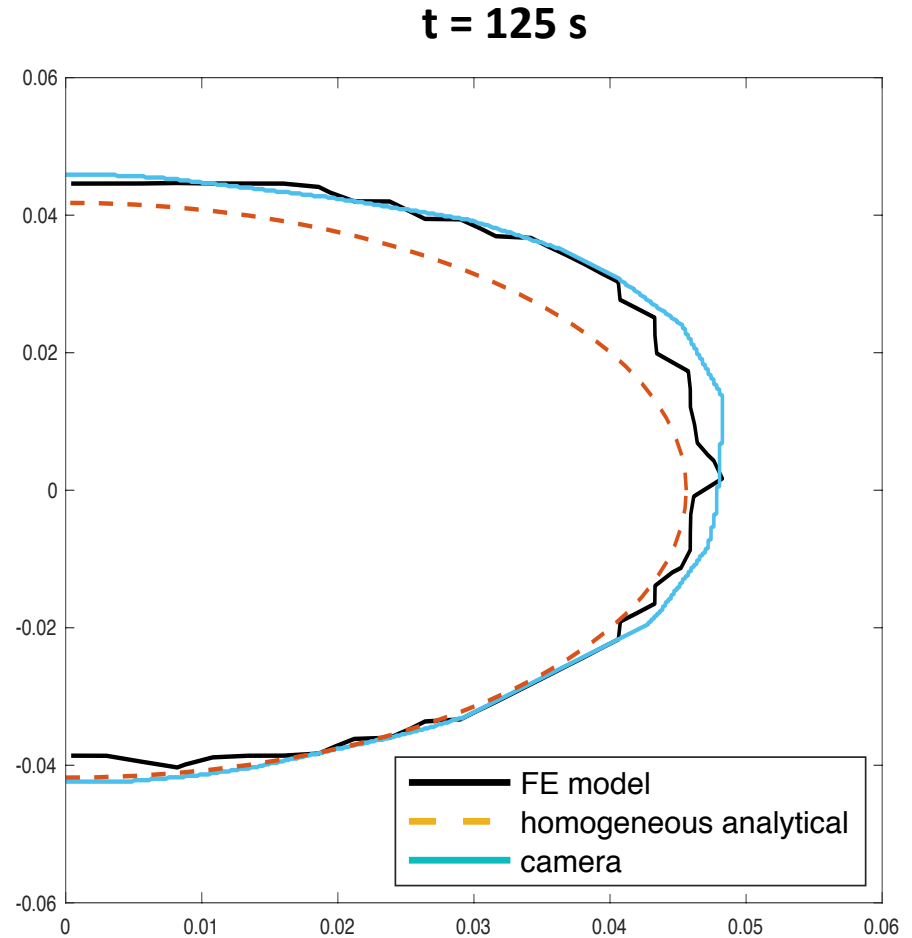
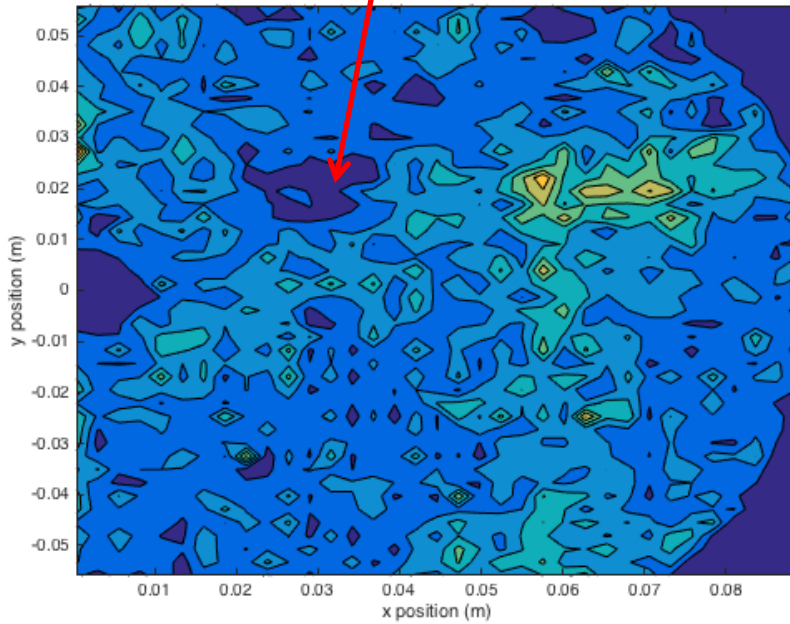


⇒ Flow front defects can be inferred from P dry

# Material material with defects



Hole



⇒ As bad as as-received material

# Conclusion

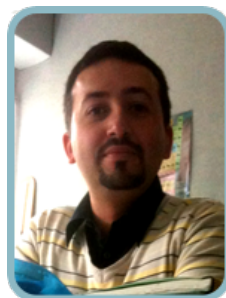
The pressure mapping sensor was used to:

- Characterize permeability
- Track flow front
- Feed a Direct Numerical Simulation

# II – The PVT series



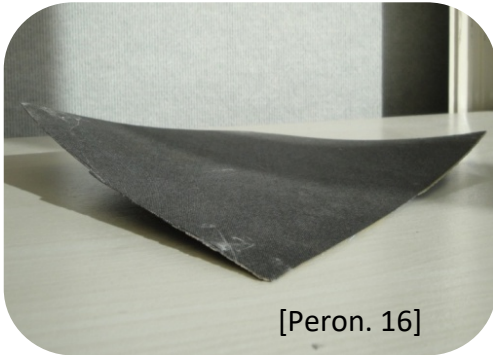
Sourour Traouli, Rima Sfar Zbed, Mael Peron, Xavier Tardif,  
Vincent Sobotka, Nicolas Boyard, Steven Le Corre, Didier Delaunay



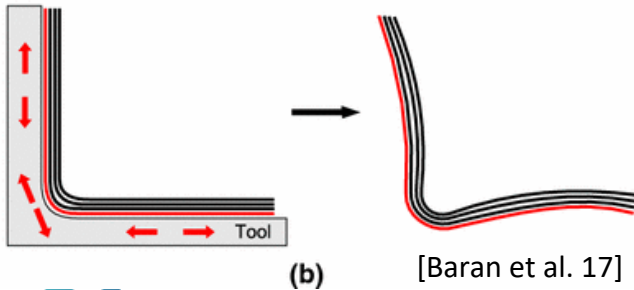
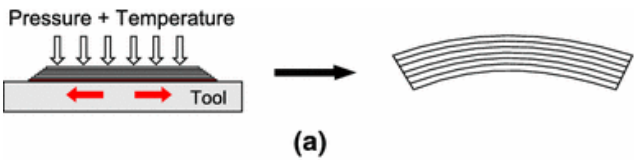
# Classical defects in manufacturing

## Macroscopic

Warpage

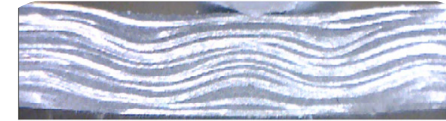


Spring in



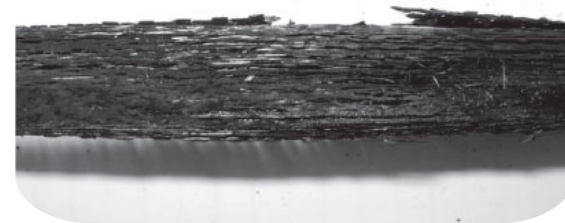
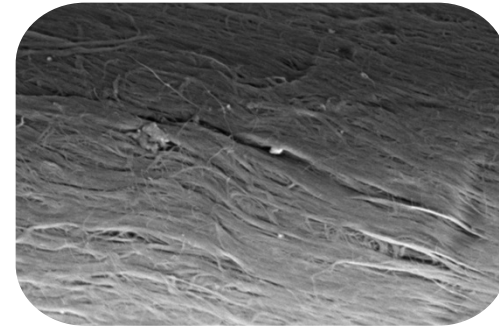
## Microscopic

Fibre waviness



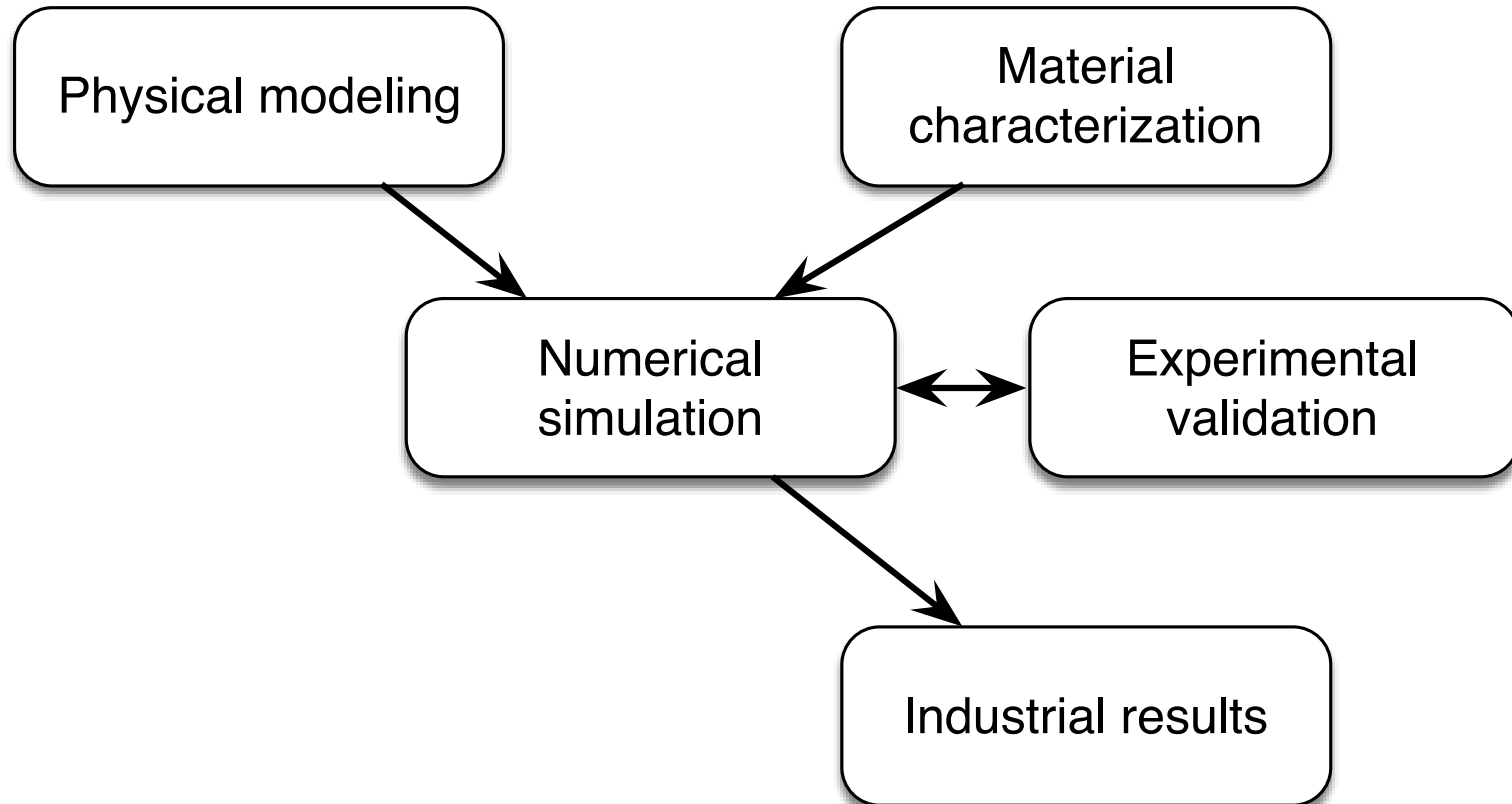
[Elhajjar et al. 16]

Buckling / kinking

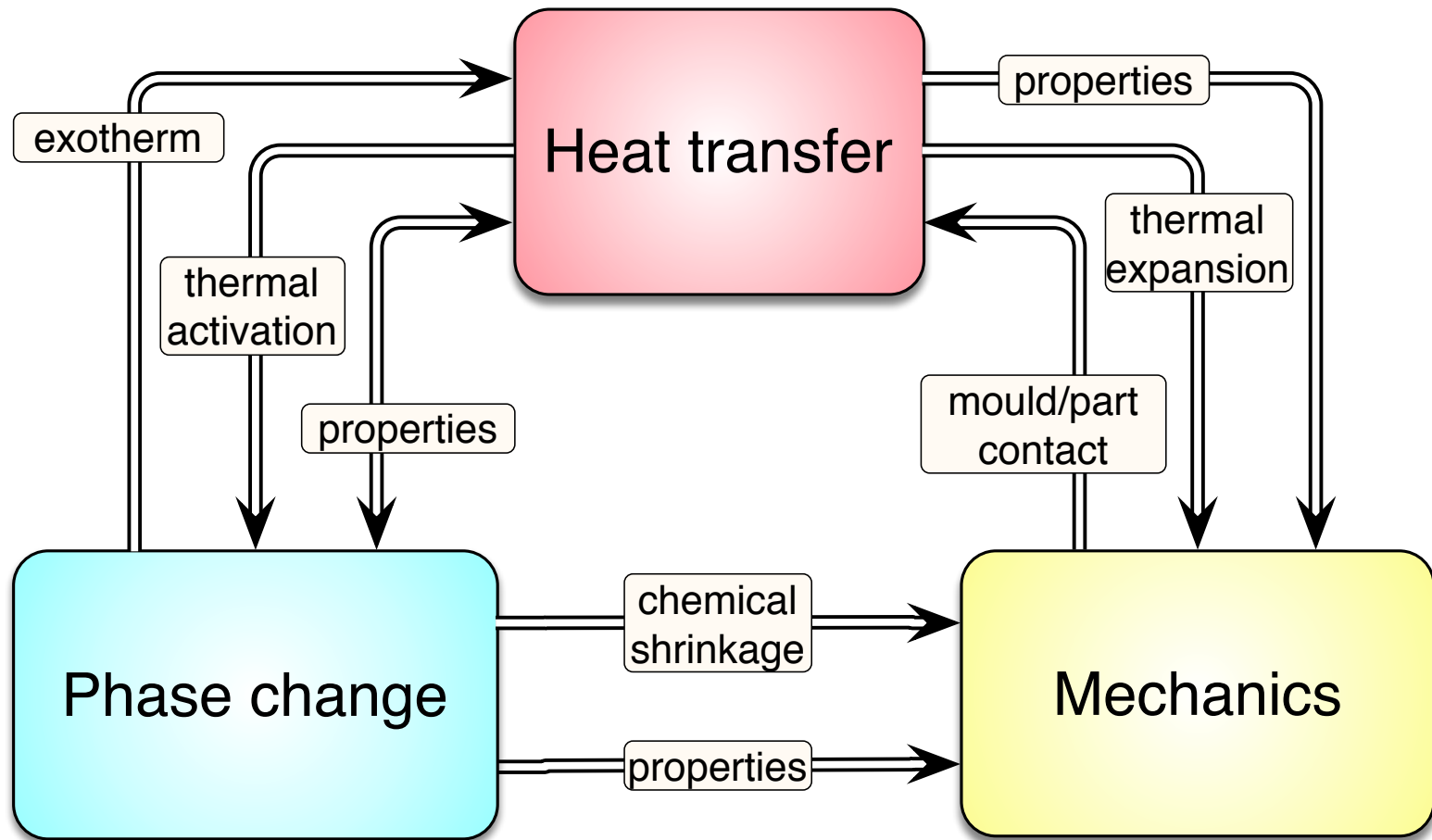


[Peron. 16]

# Scientific approach



# Multi-physical modeling

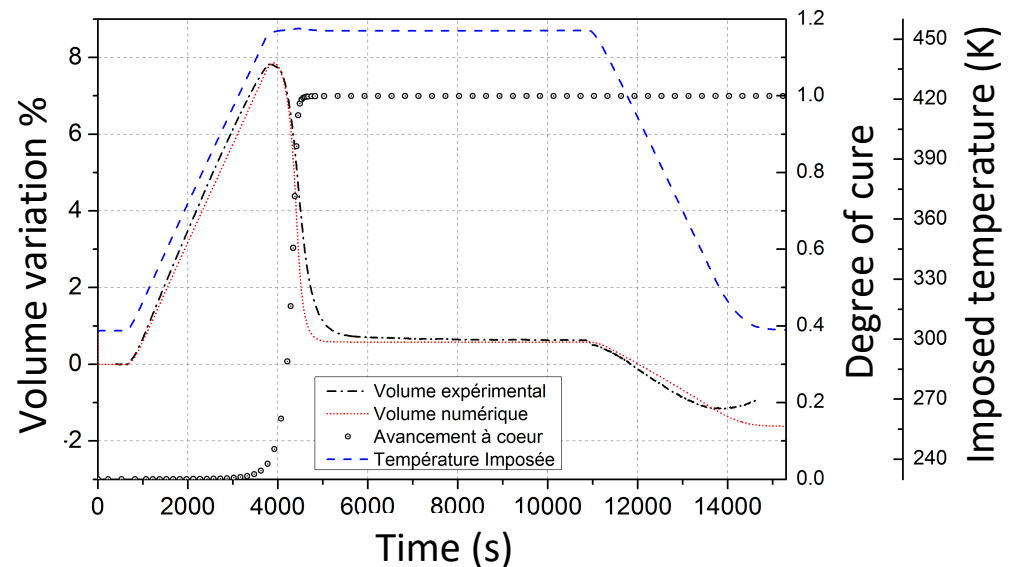
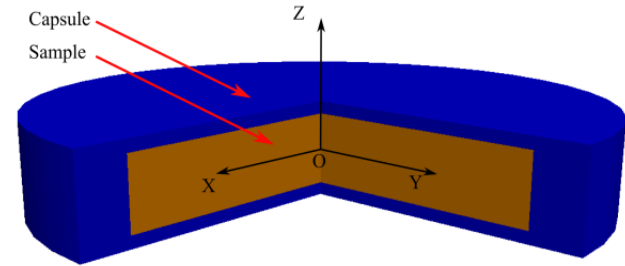
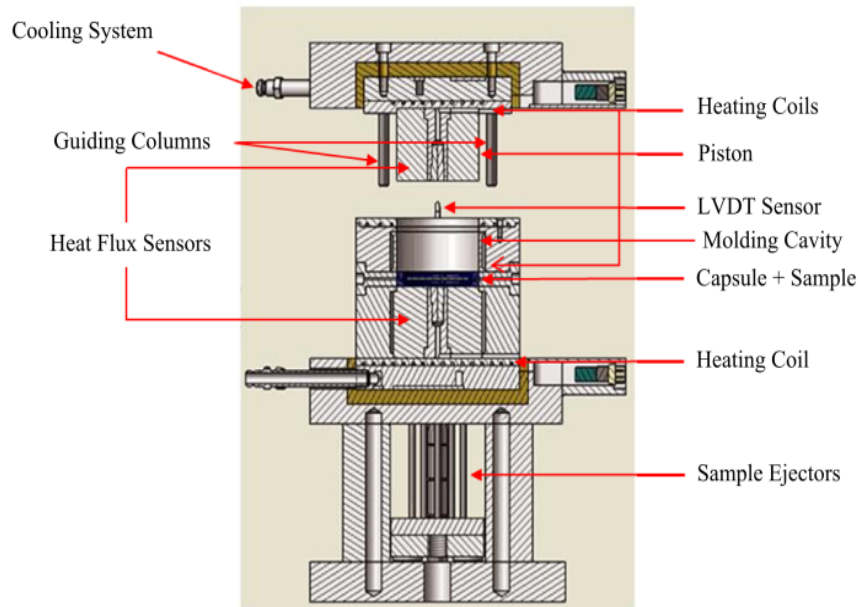




PVT- $\alpha$

# First of a kind : PVT $\alpha$

## Multiphysical characterization of neat resin

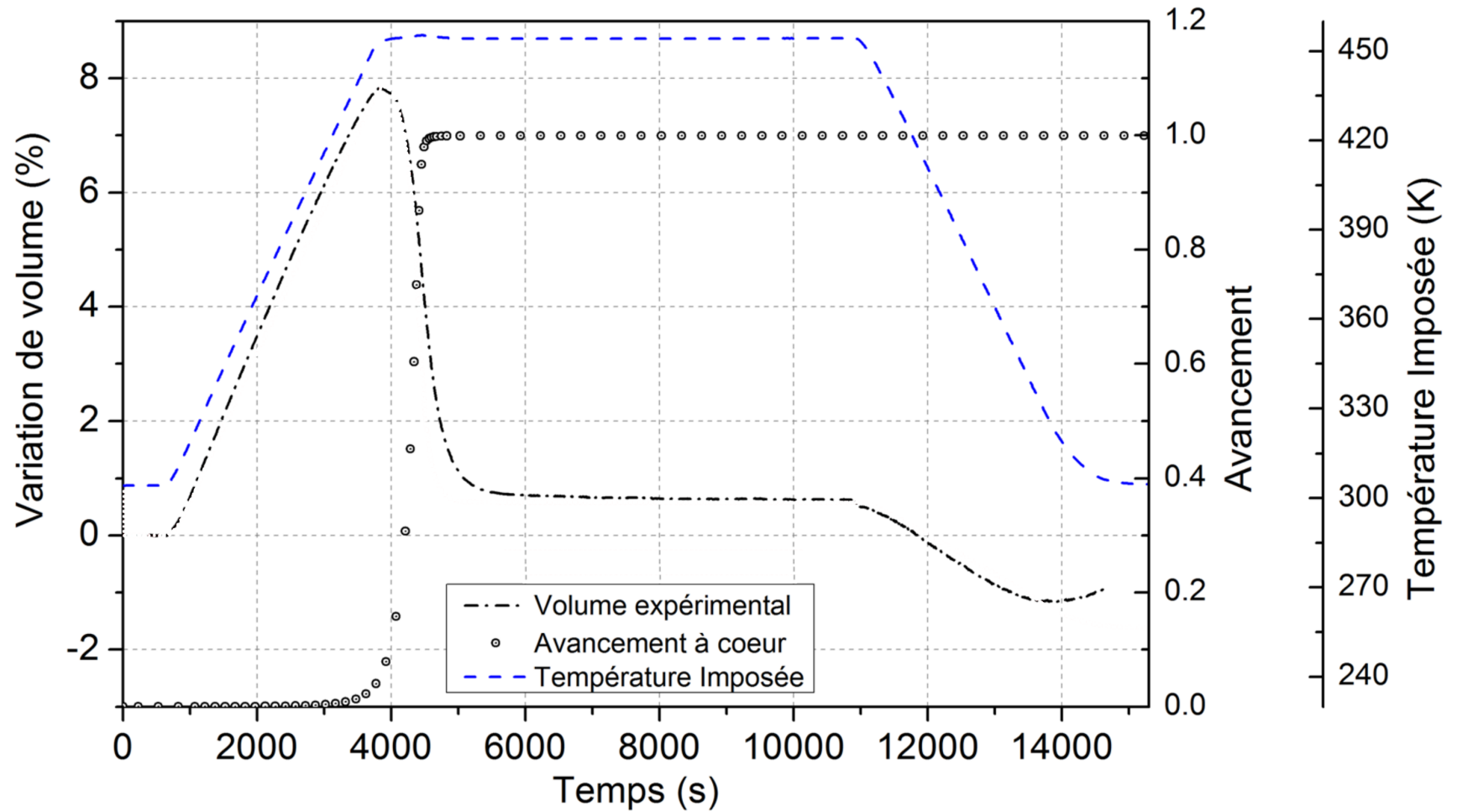


[Millischer & Delaunay 00, Yassir et al 13, Peron et al 16]

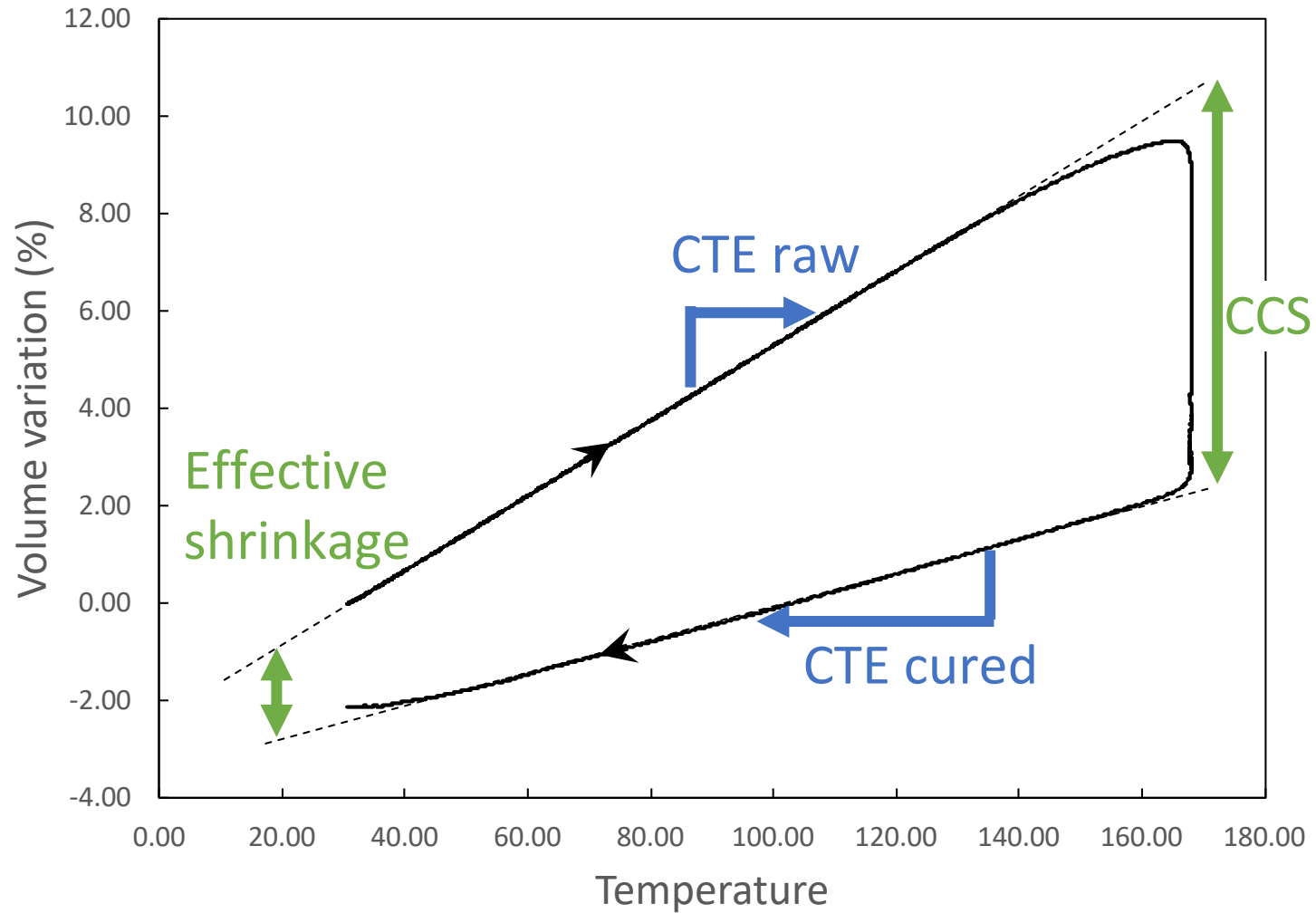
Analytical data extraction: assumptions  
Incompressible, contact, hydrostatic

→  $\alpha, \beta, k$

# Raw measurements



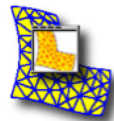
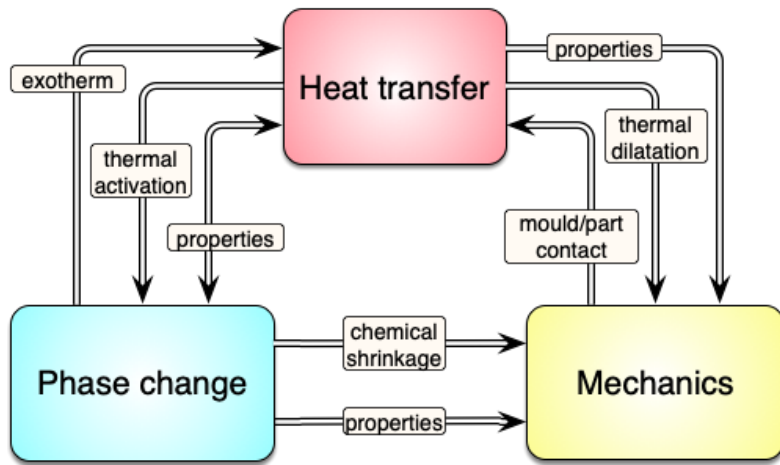
# Graphical analysis



[Epoxy system]

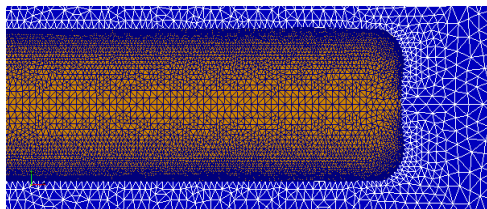
# Improved analysis

## Multiphysical numerical resolution



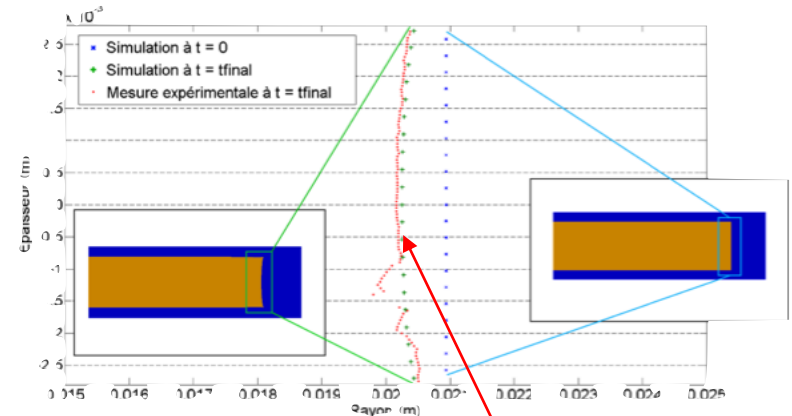
FreeFem++

## Contact handling



## Results

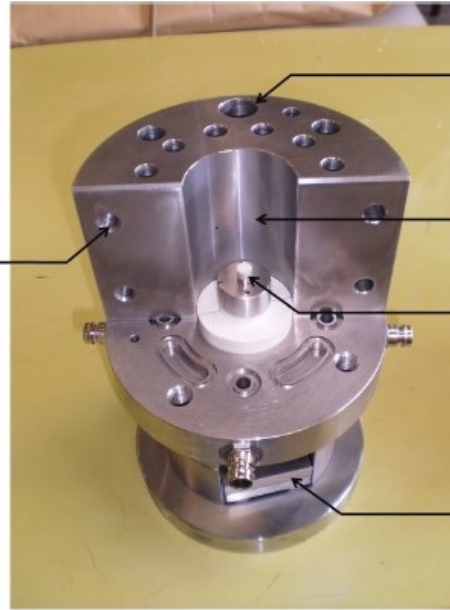
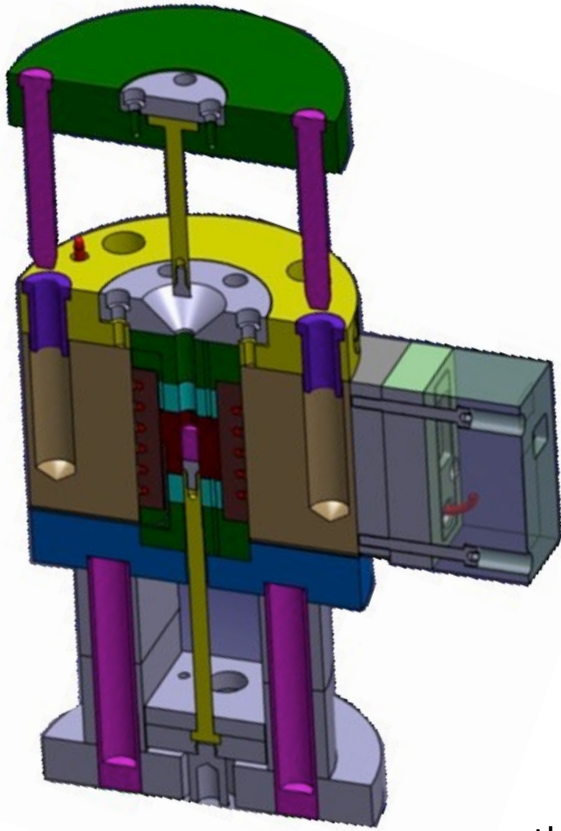
- Compressible material
- Possible loss of contact
- Good correlation



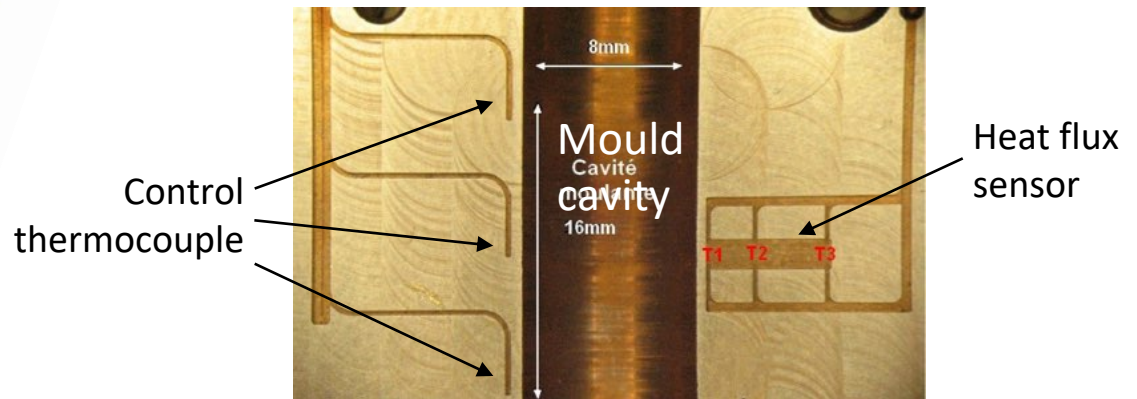
[Peron et al 16]

PVT-XT

# PVT - XT

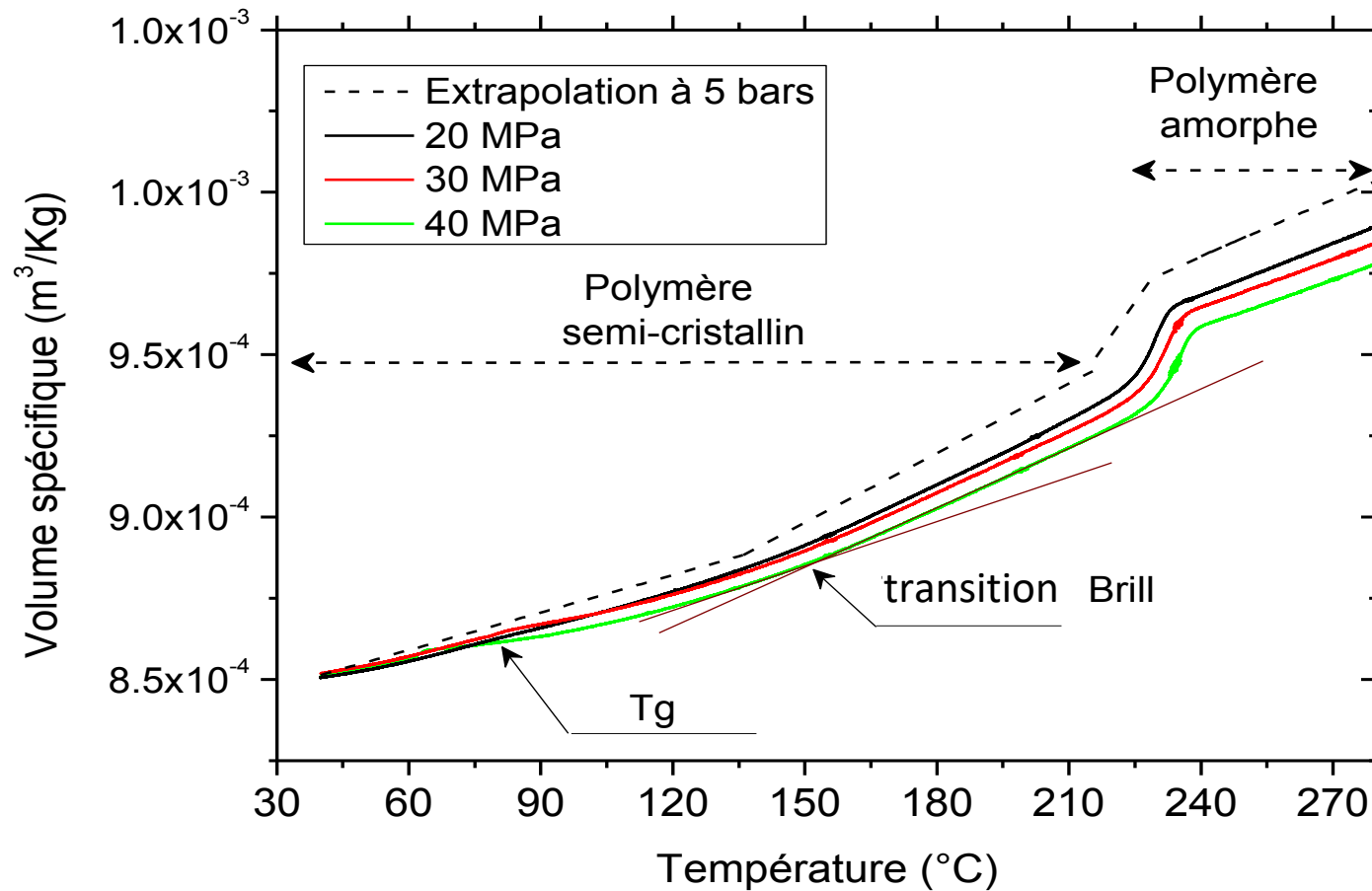


Sample



[Tardif et al 12]

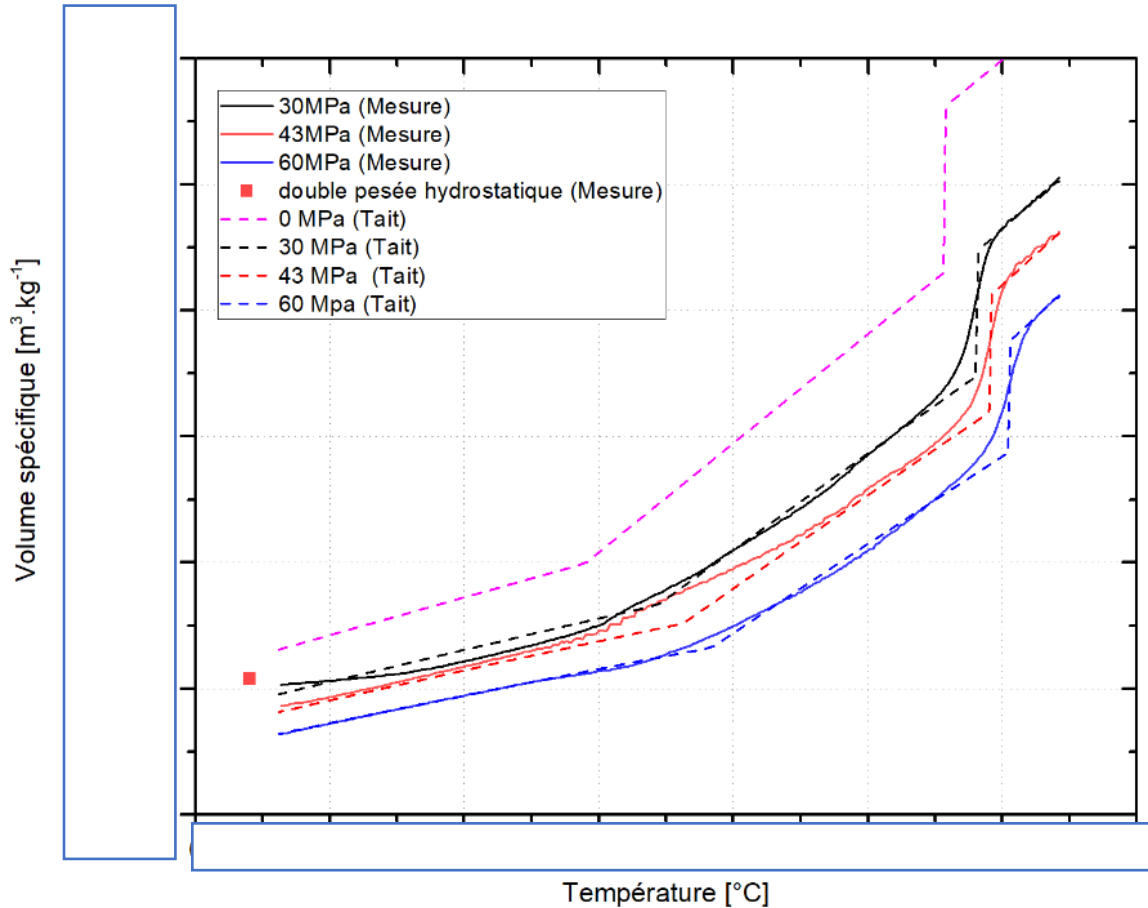
# Typical results



PA66 [Faraj 2016]



# Modeling



Adaptation of Tait model [1988]:

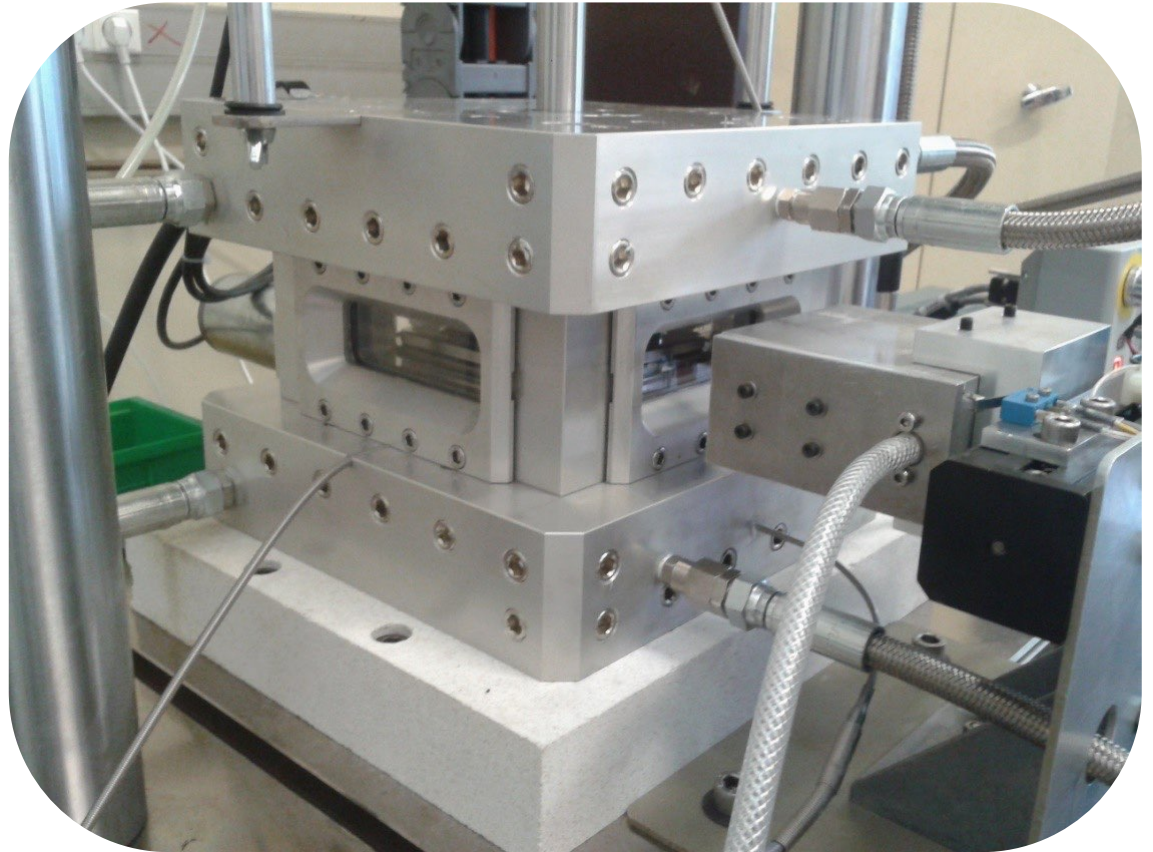
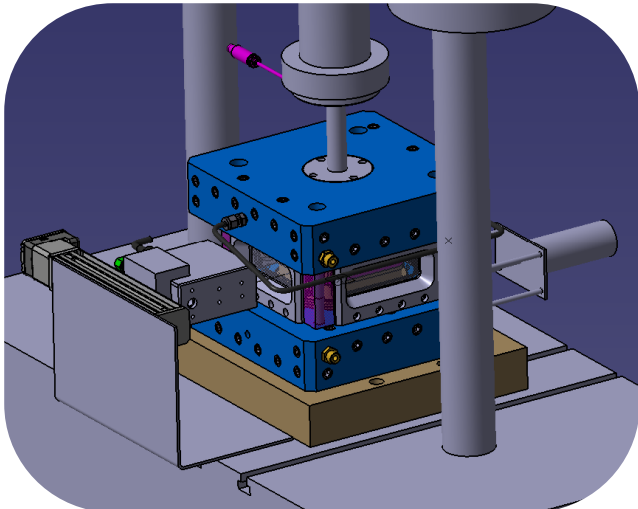
$$\rho(P, T, \alpha)$$

PAEK

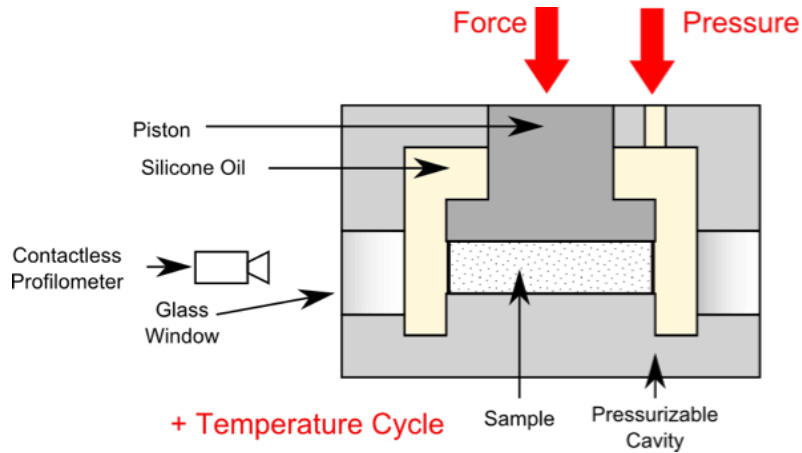
# PVT-HADDOC

# PVT-HADDOC

Homogeneous Anisotropic Deformation and Degree of Cure



# Procedure



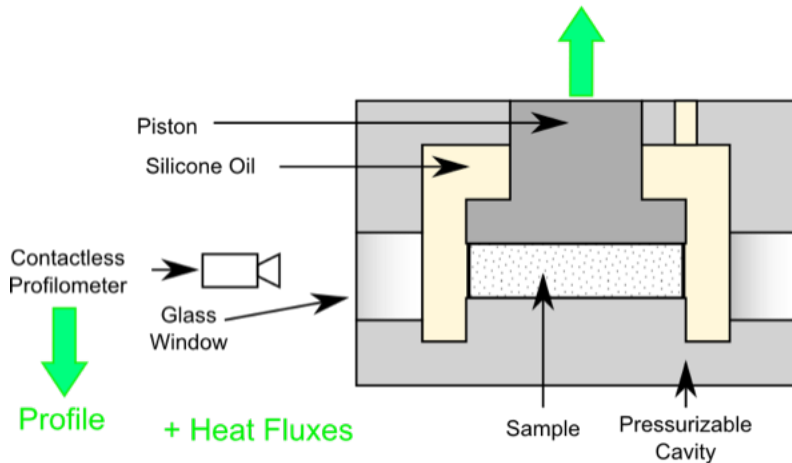
## Loading range

$$T \in [20^\circ - 200^\circ], \quad \dot{T} < 5\text{K}\cdot\text{min}^{-1}$$

$$p < 10\text{bars}(\pm 0.1\text{bar})$$

$$F \leq 10(\text{kN}), f \leq 100\text{Hz} \quad : \text{Instron Electropulse Press}$$

Displacement



## Measured data

**2D dimensional variation** (thickness & in-plane)

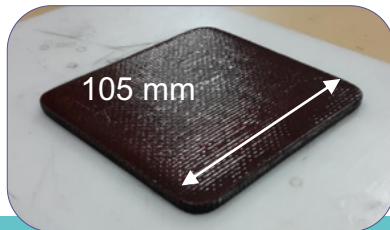
Extraction over the **whole curing cycle**

Heat flux sensor : évolution of **curing state**

## Dimensions

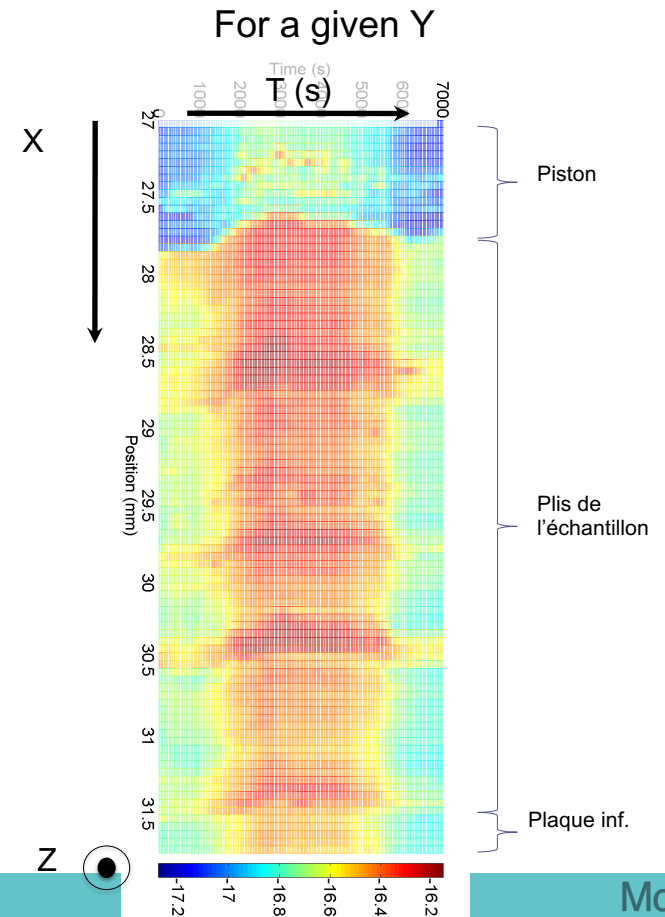
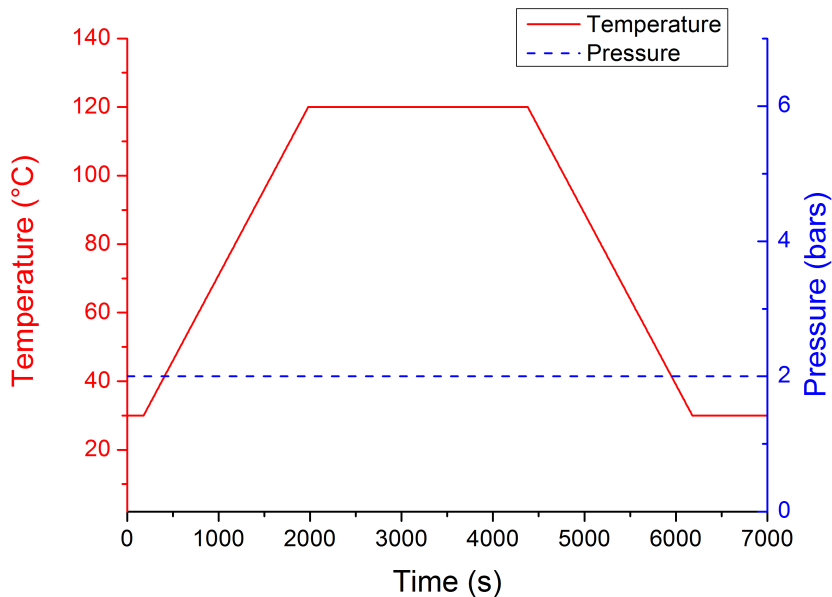
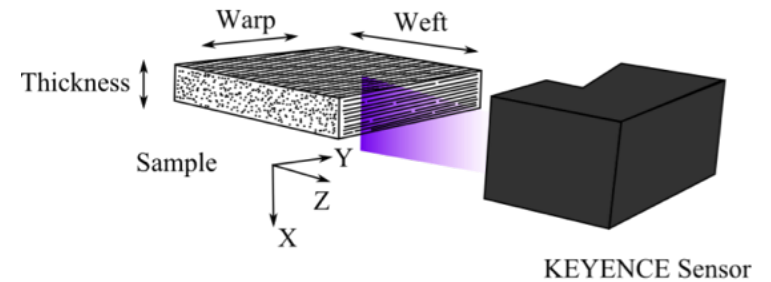
**105 mm x 105 mm**

thickness : up to 20mm

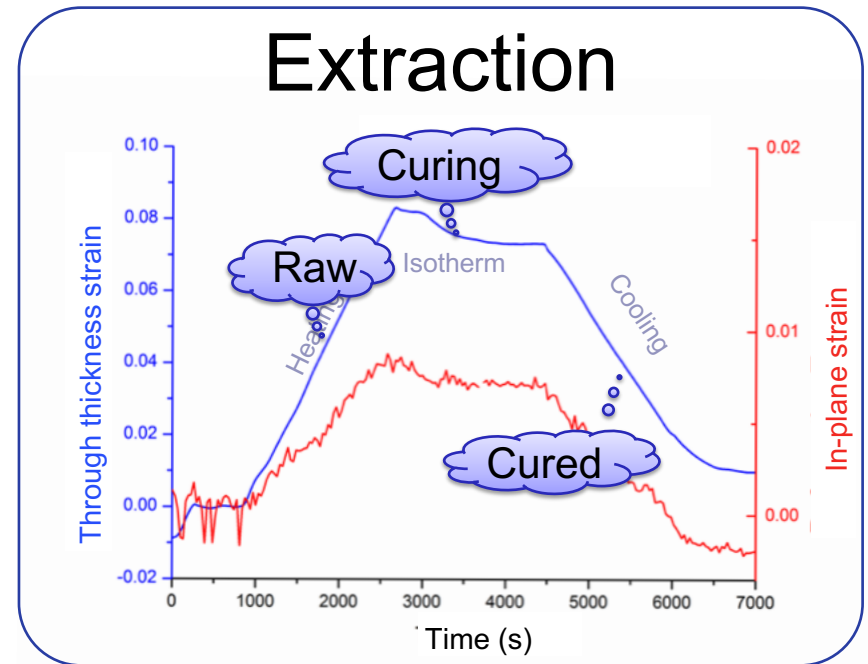
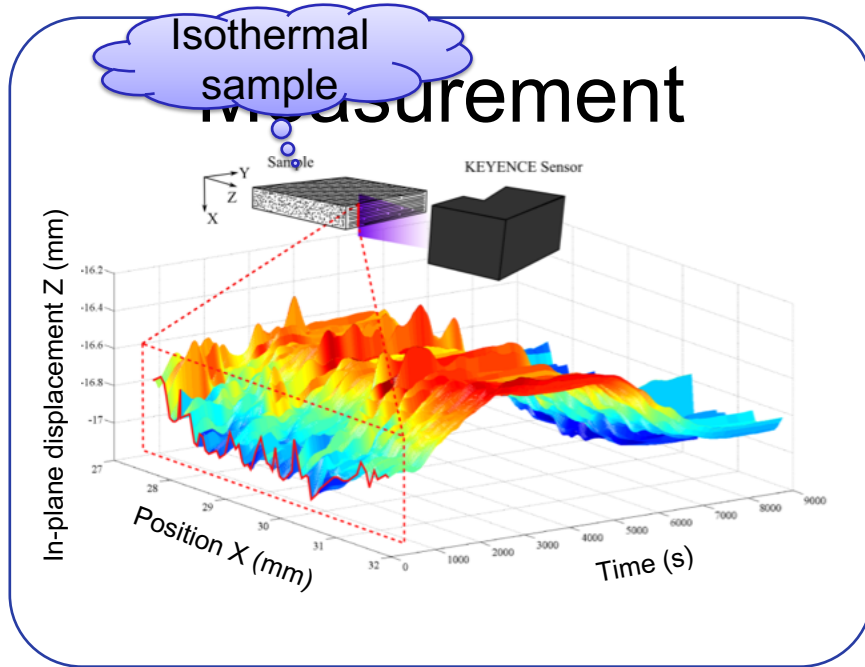


# First tests

- quasi UD glass-epoxy
- 16 plis prepreg
- Manual layup + precompaction
- hydrostatic 2 bars load



# First results

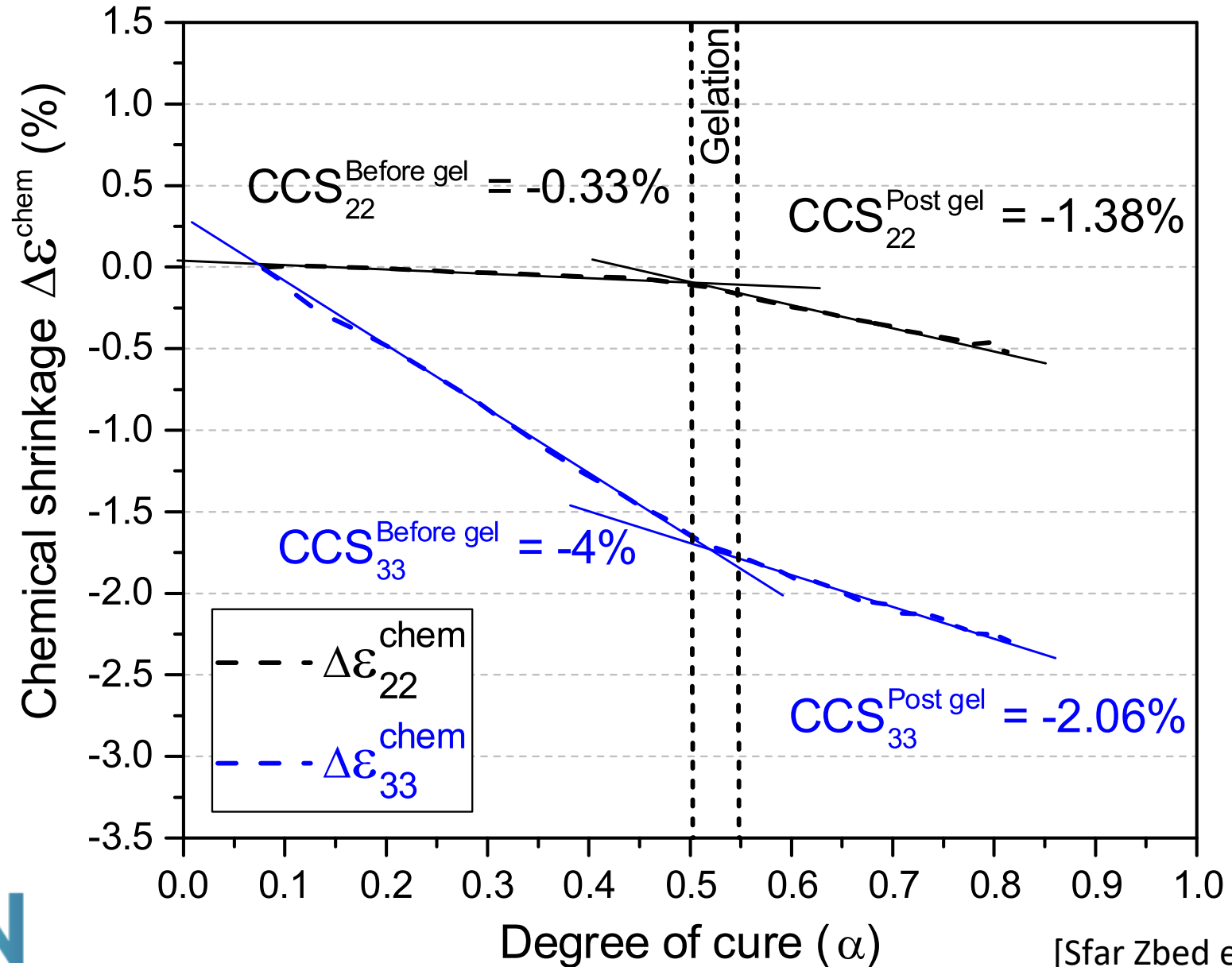


## Results

		Through thickness	In-plane
CTE raw	[K <sup>-1</sup> ]	317.0 10 <sup>-6</sup> (±2.0 10 <sup>-6</sup> )	117.0 10 <sup>-6</sup> (±7.0 10 <sup>-6</sup> )
CTE cured	[K <sup>-1</sup> ]	47.4 10 <sup>-6</sup> (±3.0 10 <sup>-6</sup> )	90.4 10 <sup>-6</sup> (±6.0 10 <sup>-6</sup> )
CCS	[%]	0.77 (±0.02 10 <sup>-4</sup> )	0.12 (±0.02 10 <sup>-4</sup> )

[Peron et al 18]

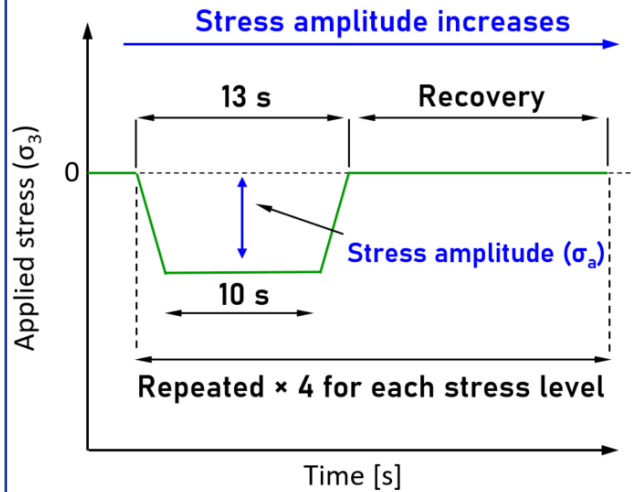
# Fine CCS identification



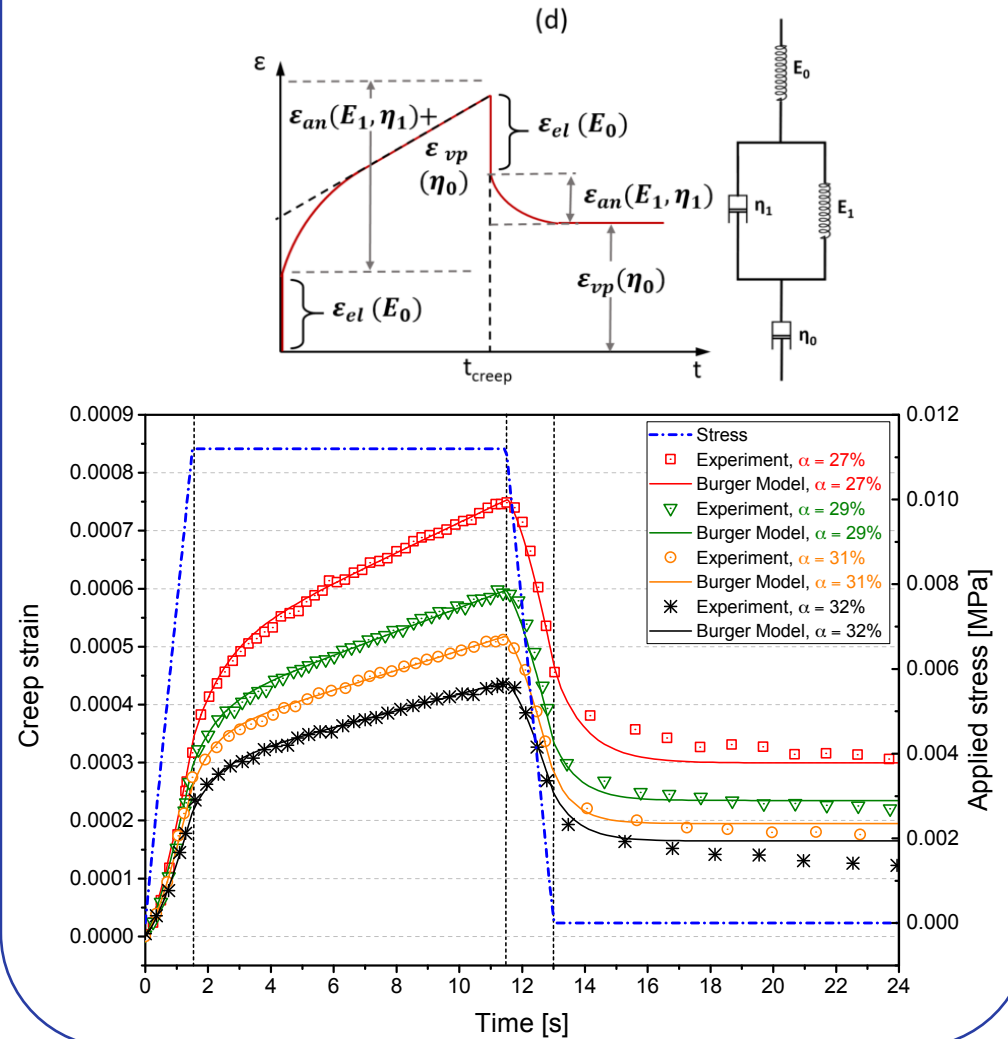
[Sfar Zbed et al. 22]

# Ongoing work : Mechanical analysis

## Loading



## Characterization

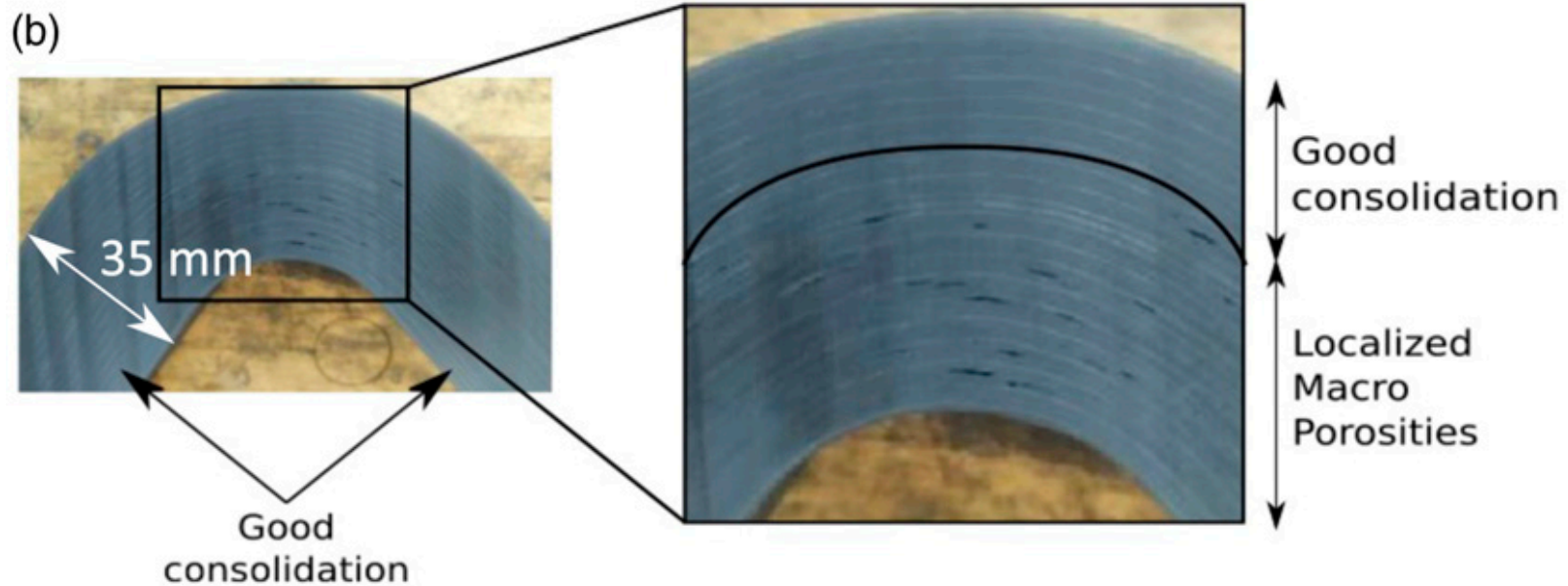




# Application

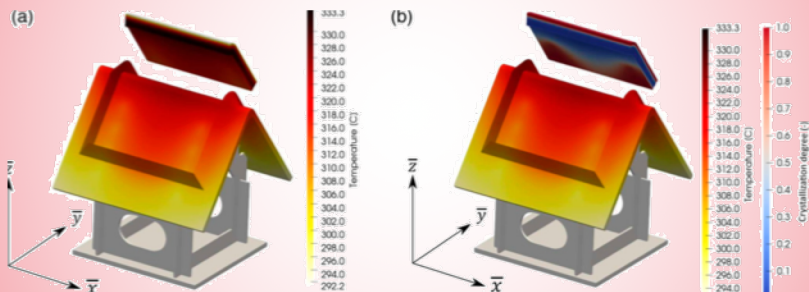
# TP composite consolidation

Carbon / PAEK system. Thick part (96 plies)

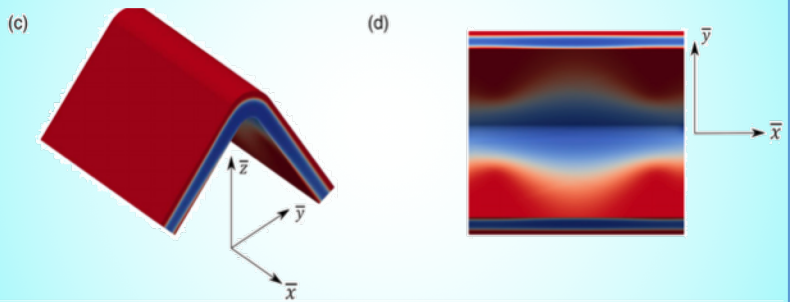


# Simulation

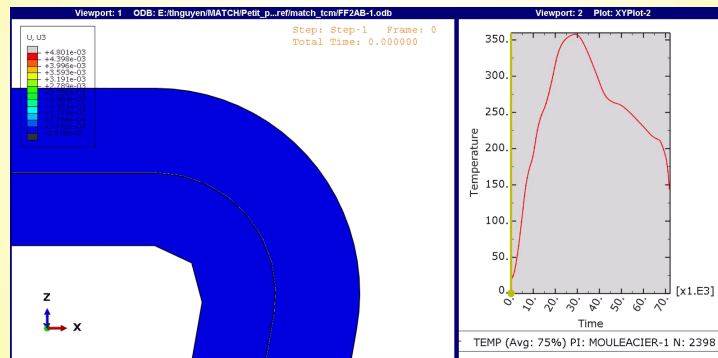
## Heat transfer



## Crystallization



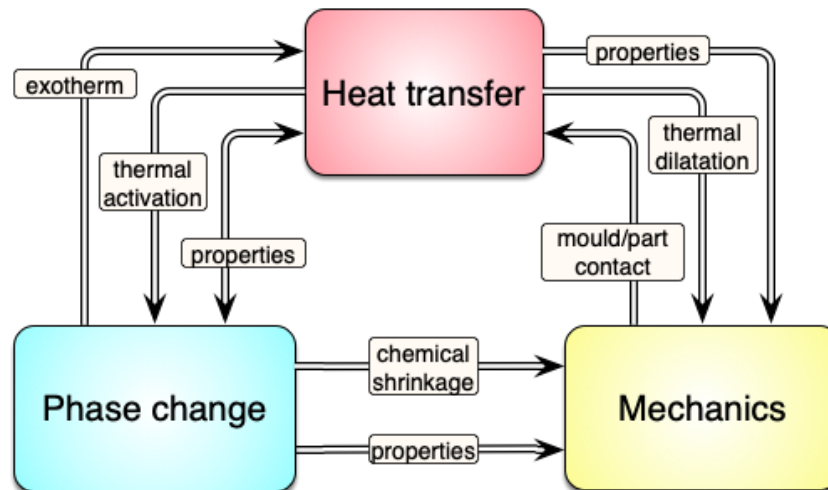
## Mechanics



Industrial results (fin effect, bagging thermal resistance...)

# Conclusion

- PVT-X for TS / TP / TS-composites
- Processing conditions (pressure, temperature)
- Give strains and exotherm (and ...)





# Perspectives

# Sustainability

## **Material**

End of life

Recyclability

Low tech / footprint

## **Manufacturing**

Energy efficiency

Scraps

Consummable

# Acknowledgments

Polytech Nantes, Martine Dubé and Pascal Hubert  
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Nicolas Lefevre, Arnaud Arrivé, Julien Aubril

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