Interrelation of Multi-physical Phenomena in Composite Manufacturing Processes

Ismet Baran

Chair of Production Technology

Faculty of Engineering Technology

UNIVERSITY OF TWENTE.

Composites: freedom of design

Composites reliability

Economic

Safety + Economic

Safety

Manufacturing quality is a critical issue for improved reliability.

Composites in our life

2.6 TWh/year

= Electricity for 1.5 million people

CO_2 reduction 1.25 MT/year

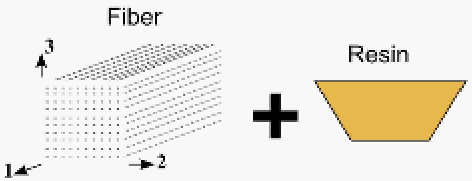
= 270k cars off the road

Paris Climate Accord: limit global temperature rise to 2 °C

We need to ensure that blades endure minimum 20 years of service

Composite life line

Materials



Fiber reinforcement:
- Glass, carbon, aramide, etc.
- Uni-directional (UD) roving, mat, woven, etc.

Thermosetting resin:
- Polyester, epoxy, vinlyester, etc.

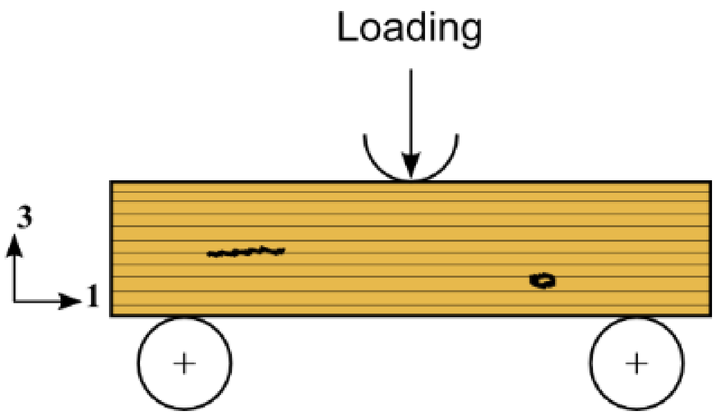
Impregnation
Fluid dynamics

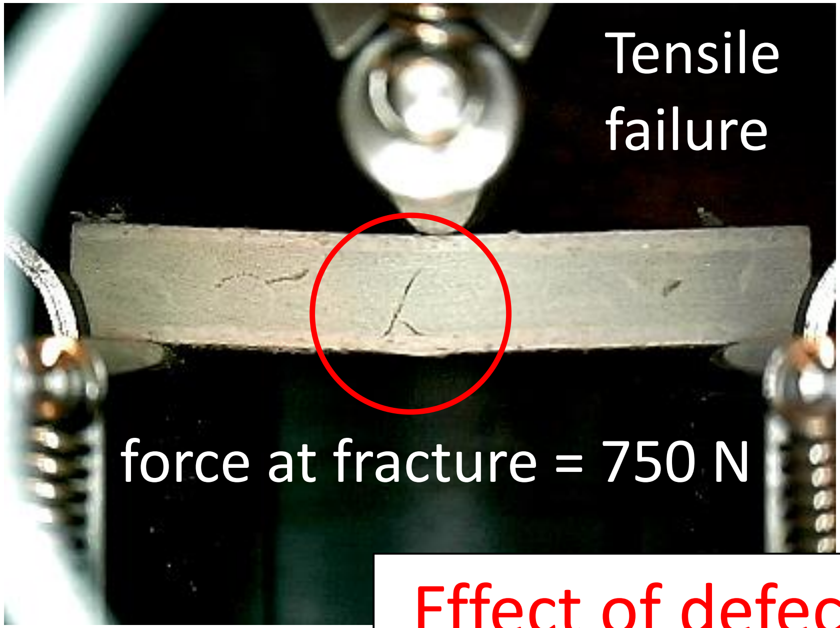
State changes, shrinkage, stresses
Heat transfer + solid mechanics

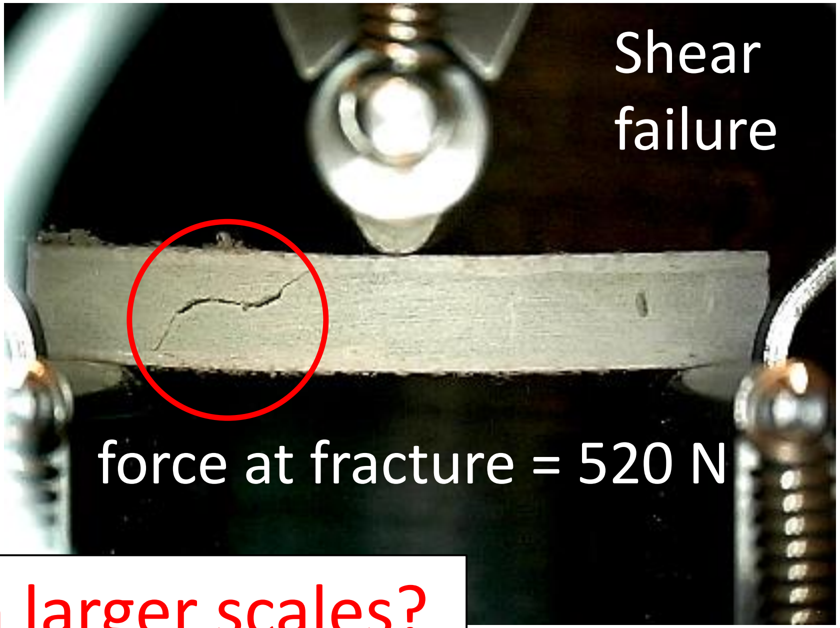
Local Vf distribution
Defects

Effect of defects
Performance

Effect of defects







Effect of defects on larger scales?

Effect of defects

Unknown defects and their unknown effects can cause:

Unexpected catastrophic failure [1]

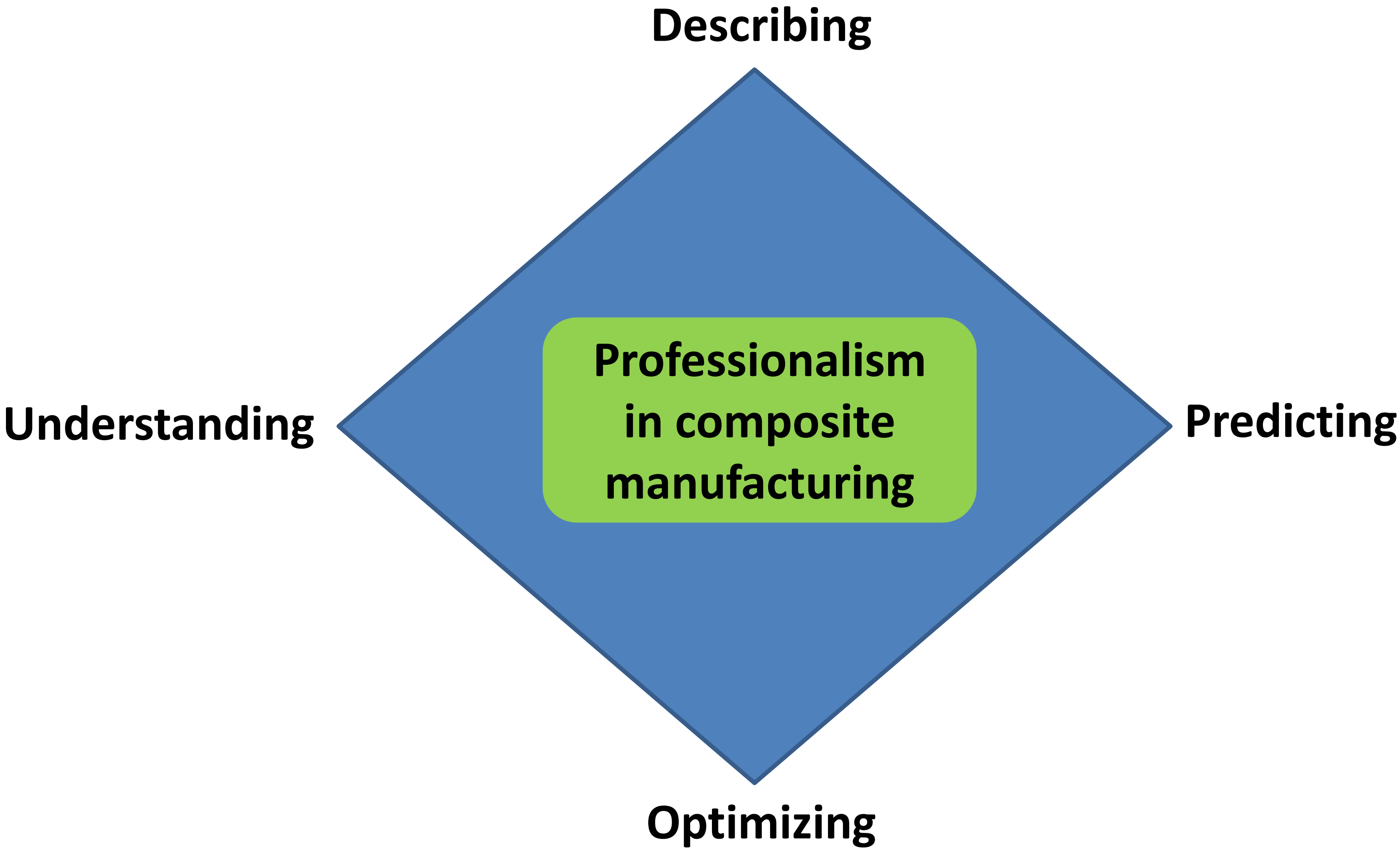
$25 million downtime cost due to a blade cracking Suzlon US in 2010 [1]

Reduced blade life time

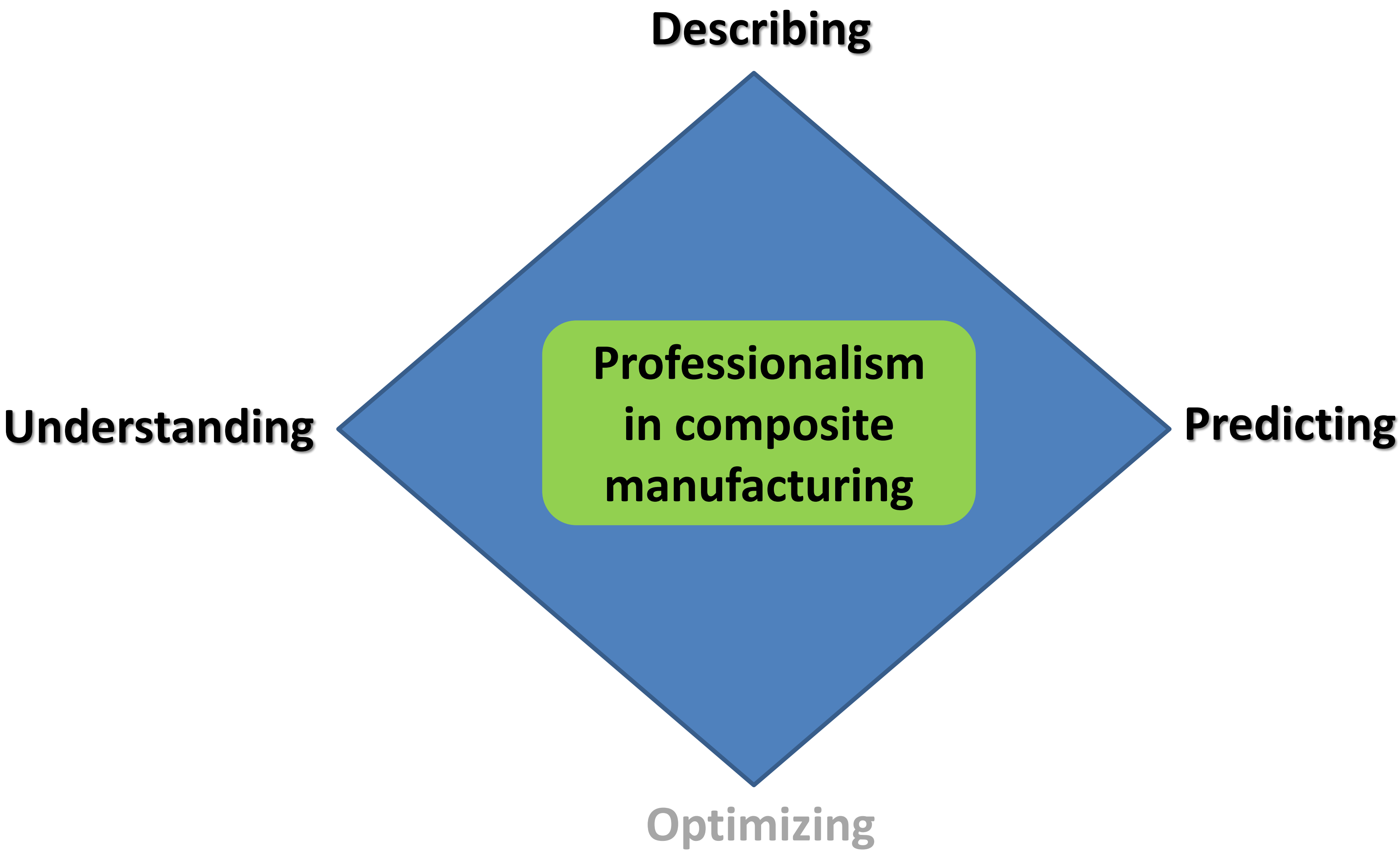
The costs of inaction are higher than the costs of action

[1] Sandia Report, SAND2011-1094, February 2011

Goal

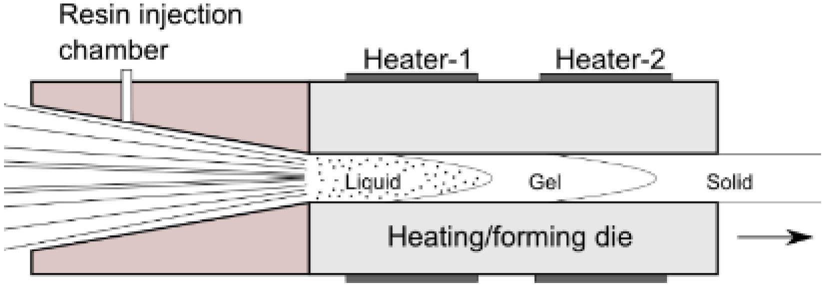

Describing
Understanding
Professionalism in composite manufacturing
Predicting
Optimizing

Goal

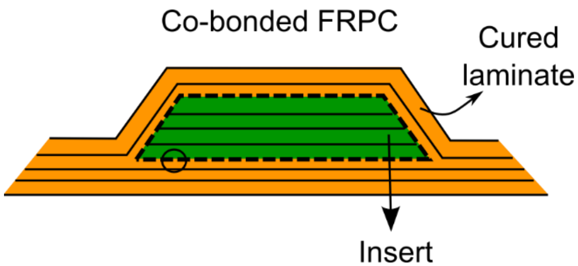

Describing
Understanding
Professionalism in composite manufacturing
Predicting
Optimizing

Recent activities

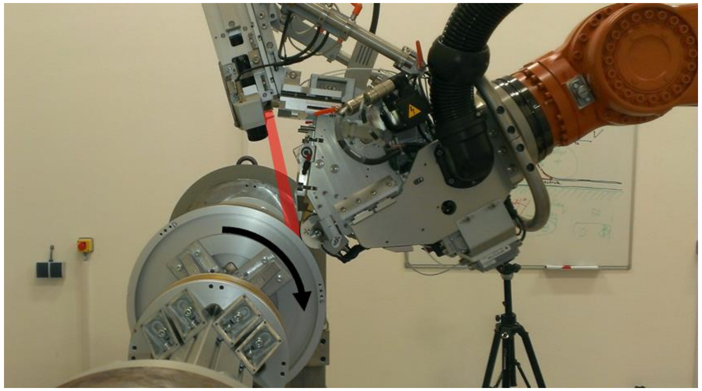
Pultrusion:
Heat transfer, curing, solid mechanics



Co-bonding/over infusion:
Interface bonding

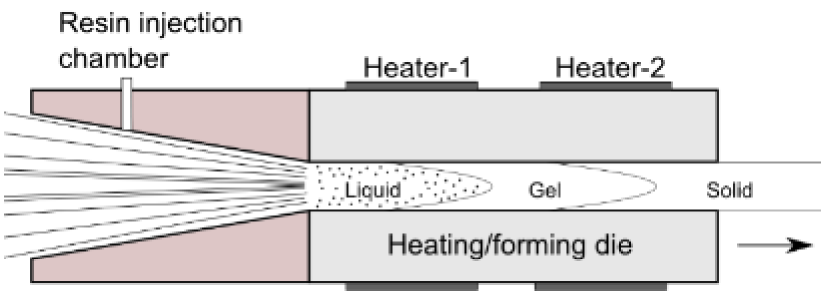


Laser Assisted Tape Winding (placement):
Laser optics, irradiation heat transfer



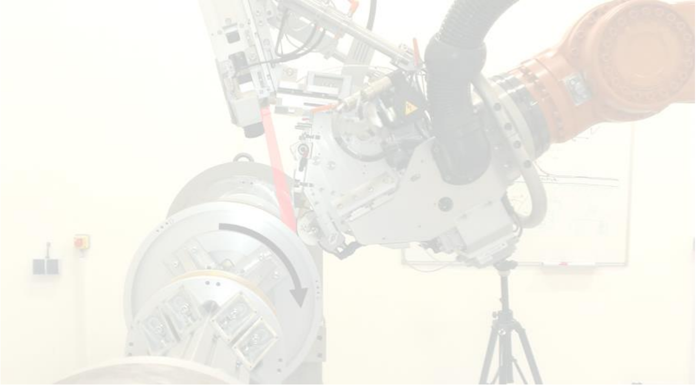
Recent activities

Pultrusion:
Heat transfer, curing, solid mechanics



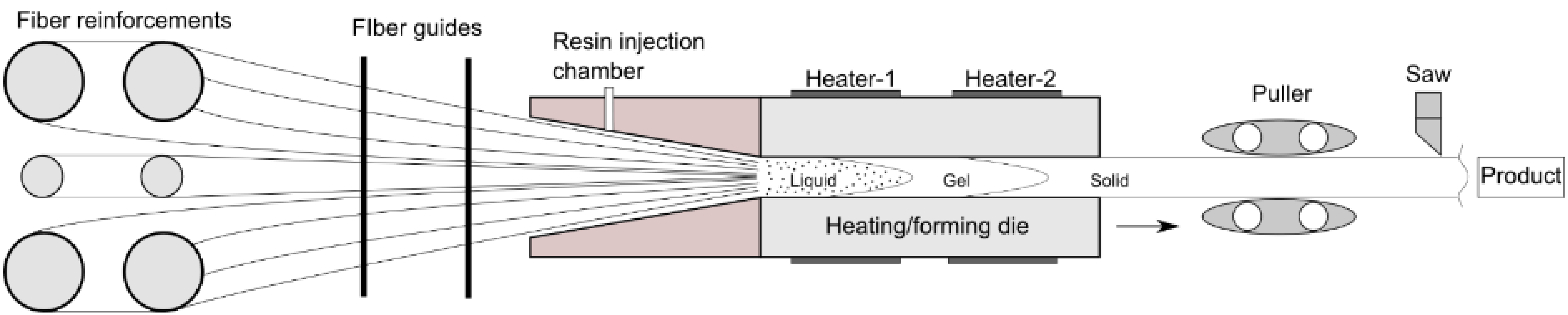
Co-bonding/over infusion:
Interface bonding

Laser Assisted Tape Winding (Placement):
Laser optics, irradiation heat transfer

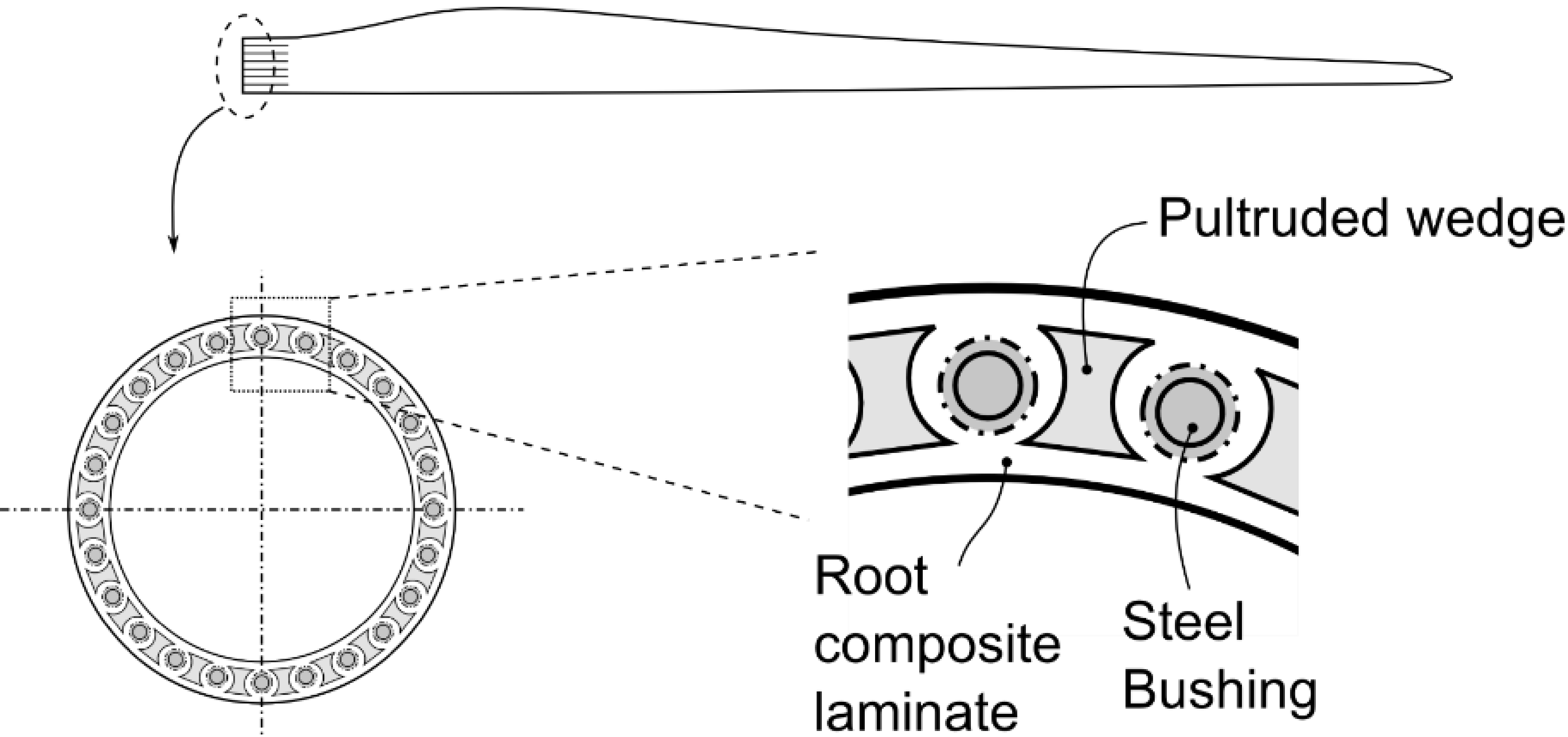


Pultrusion process

In principle it is a simple process…



Pultruded profiles

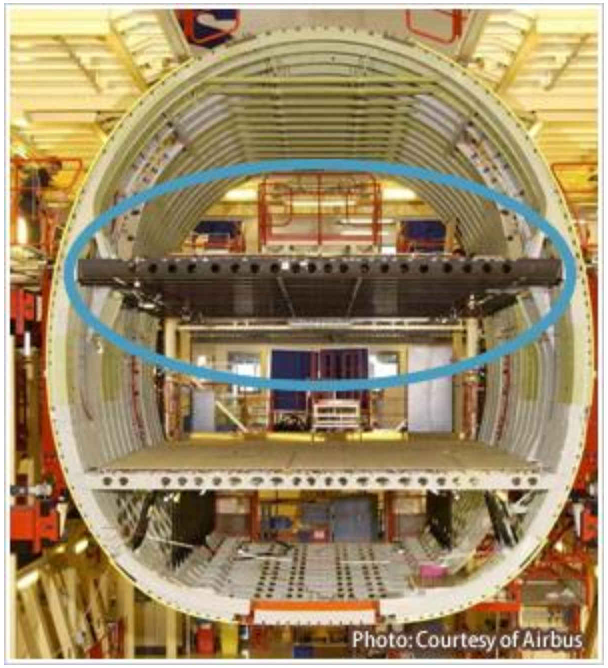


Baran. *Pultrusion: State-of-the-art process models*. Smithers Rapra. (2015)

Pultruded profiles

Carbon/epoxy

CFRP upper deck floor beams s

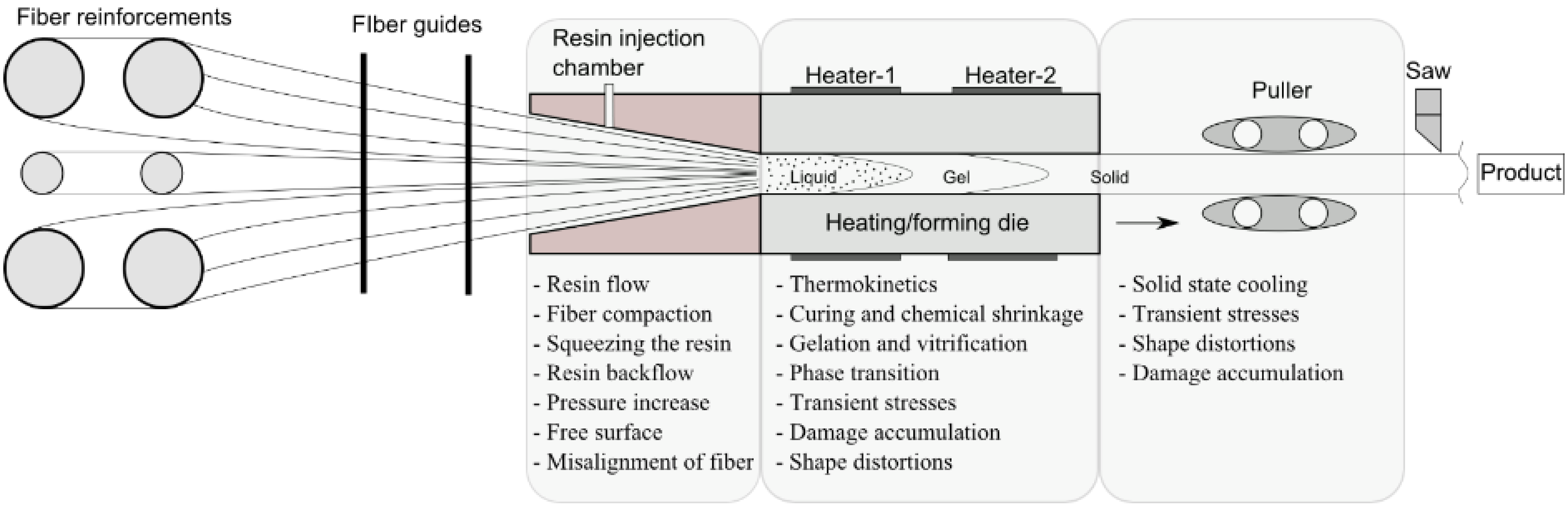


CFRP structural parts for vertical stabilizers

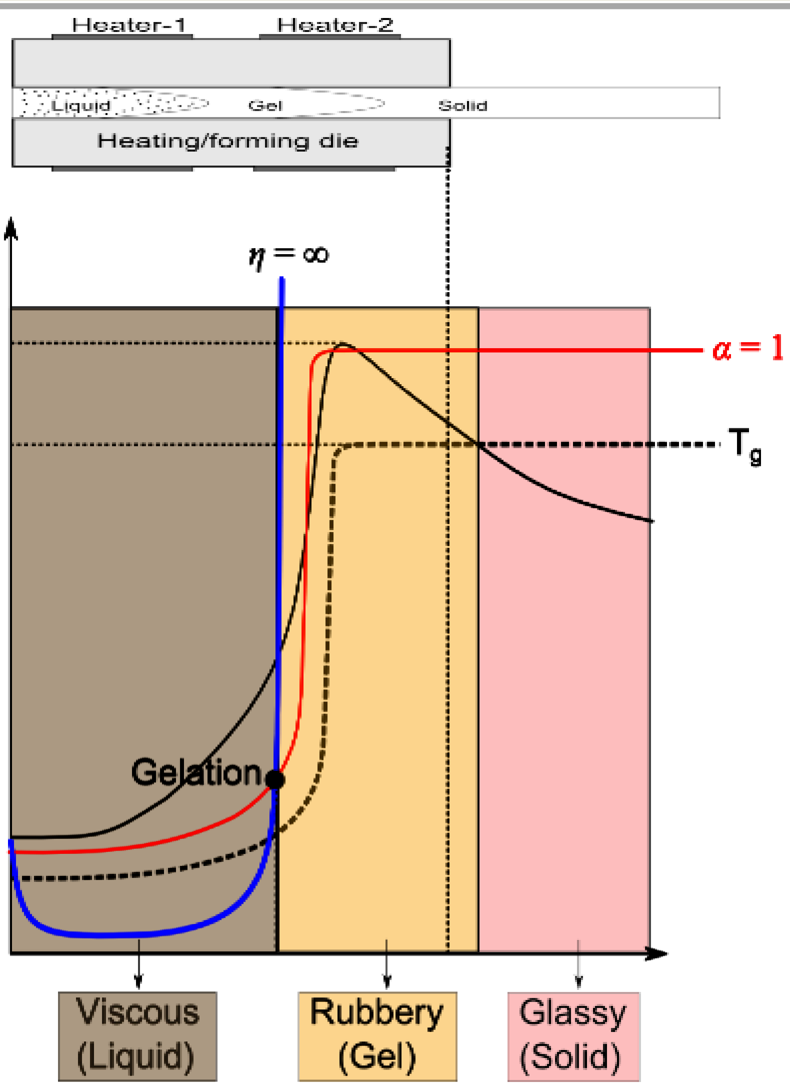
Example: Pultrusion process

In principle it is a simple process…

In reality:

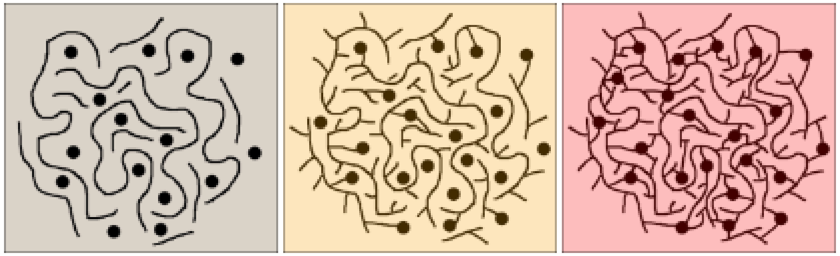


Processing



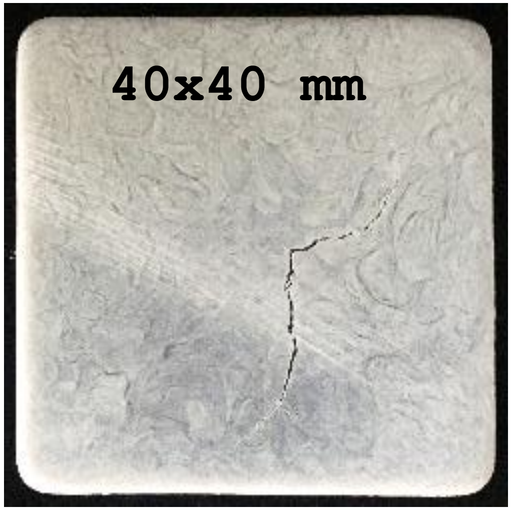
— Temperature
— Degree of cure (α)
— Viscosity (η)
------- Glass transition temperature (T_g)

+ Internal stresses

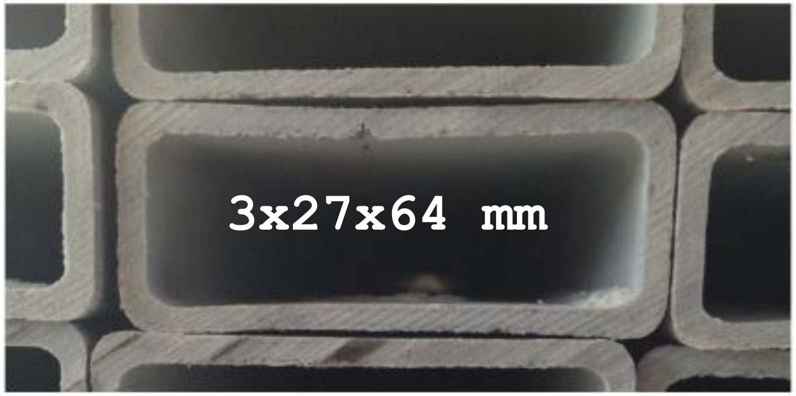


Challenges

Residual stresses, shape distortions and variation in properties

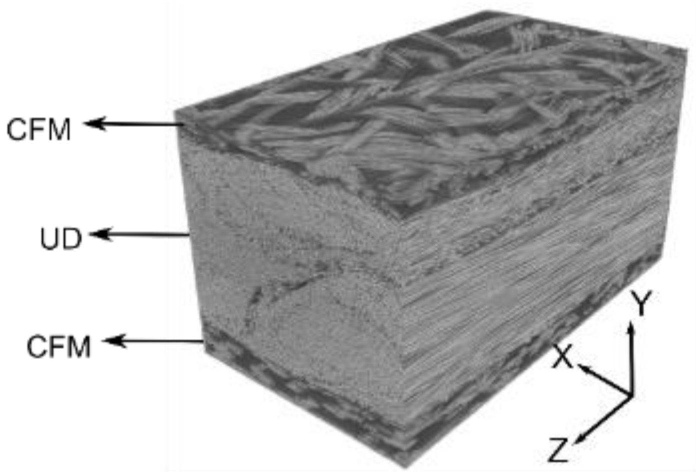


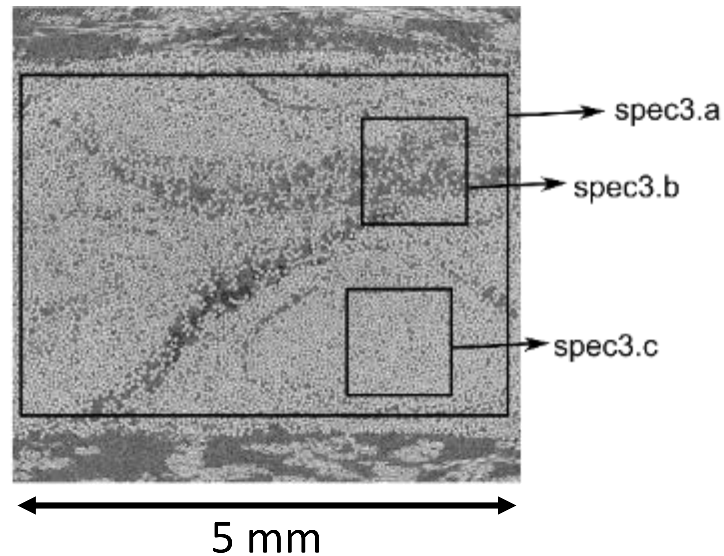
- Anisotropy
- Non-uniform shrinkage
- Through-thickness gradients
- Tool/part interaction

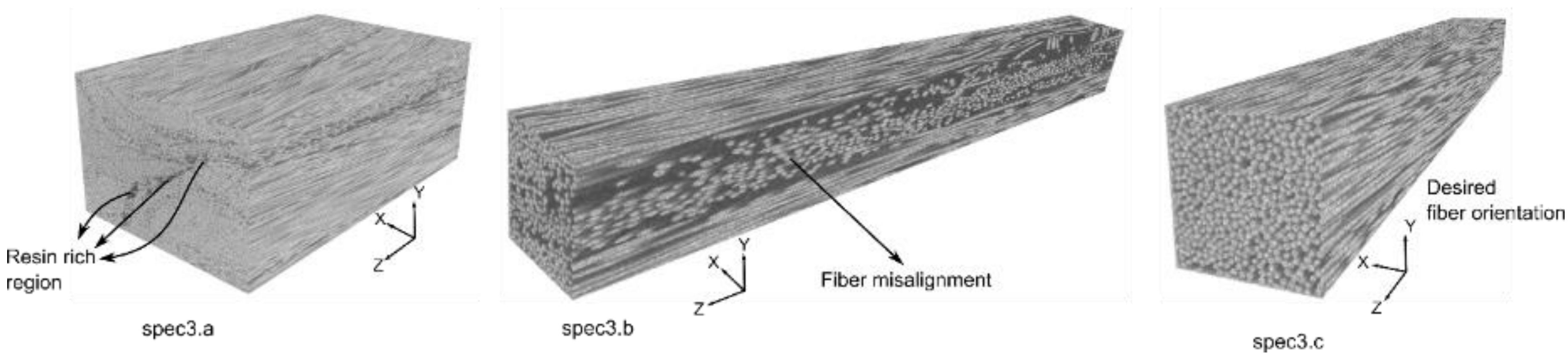


12x100 mm

Micro-CT – internal structure

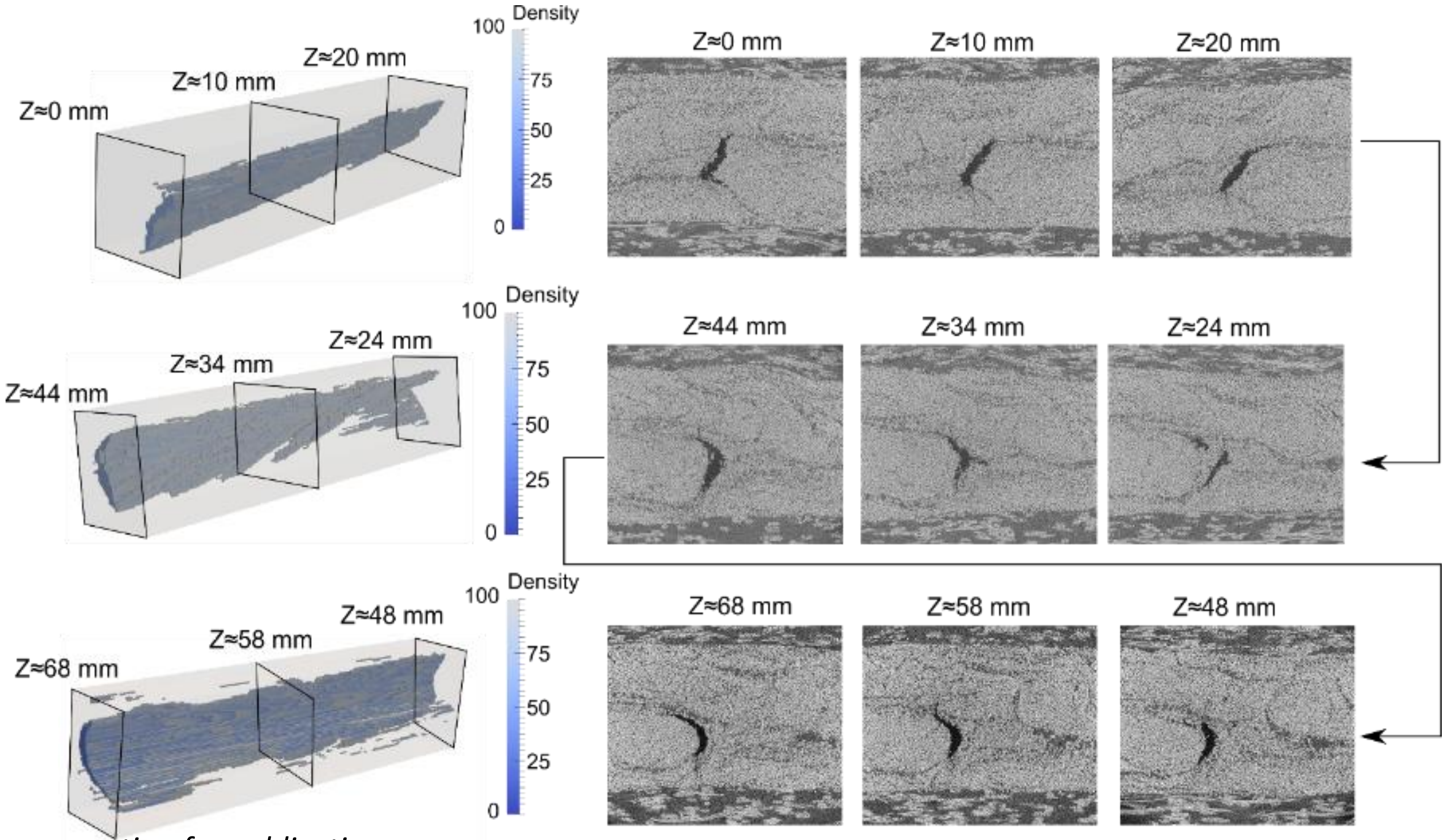






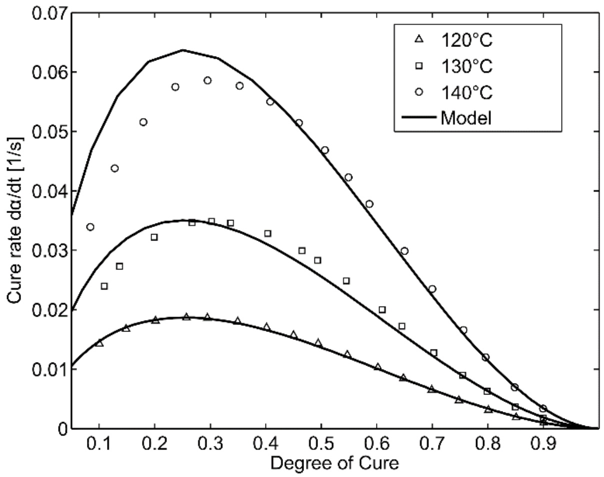
In preparation for publication

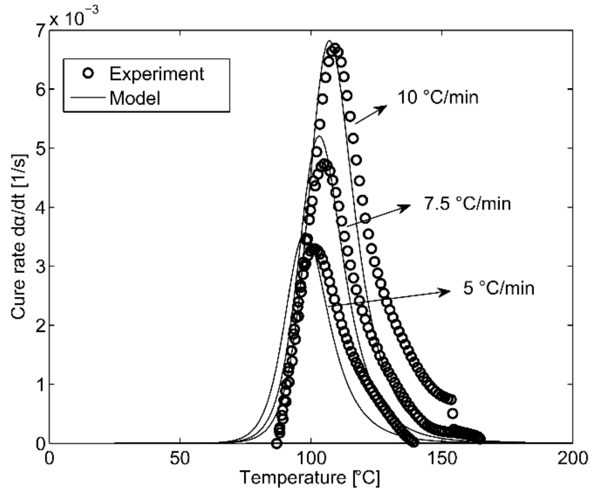
Micro-CT – 3D porosity/crack

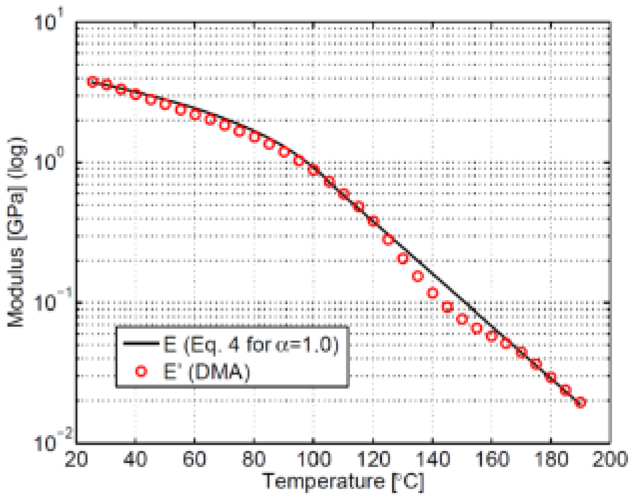


In preparation for publication

Material characterization



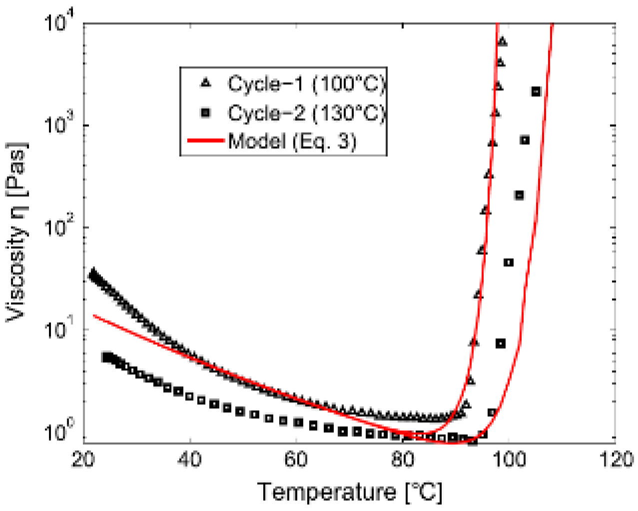




Chemo-rheology

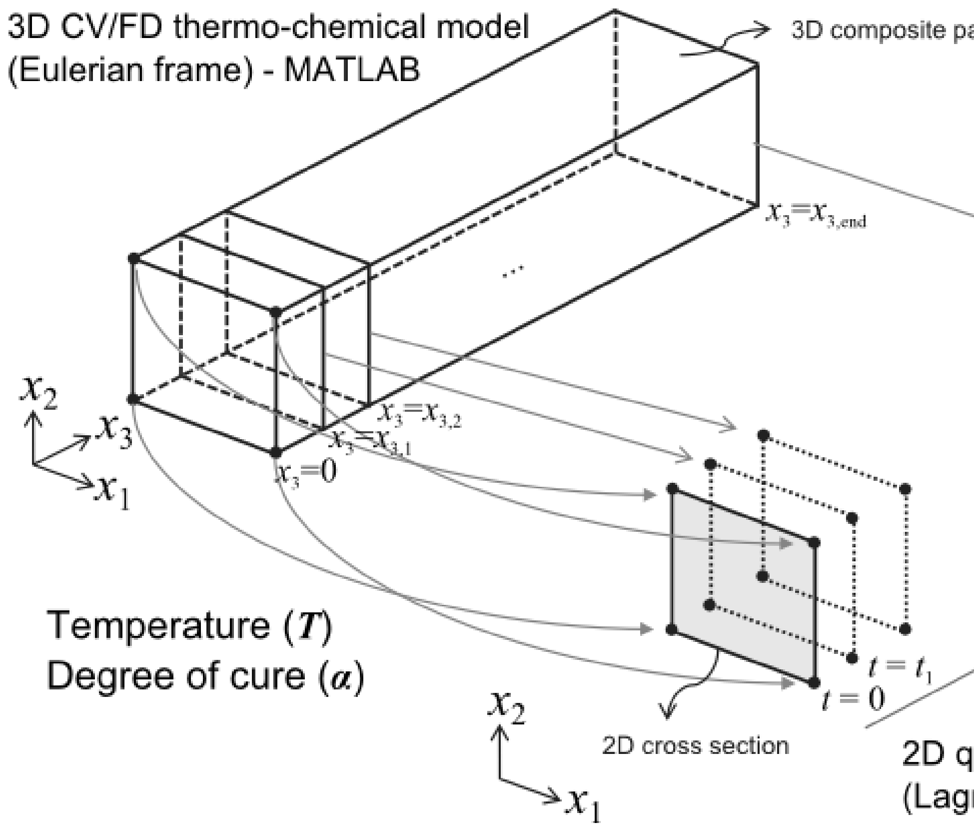
Thermo-kinetics

Thermomechanical properties

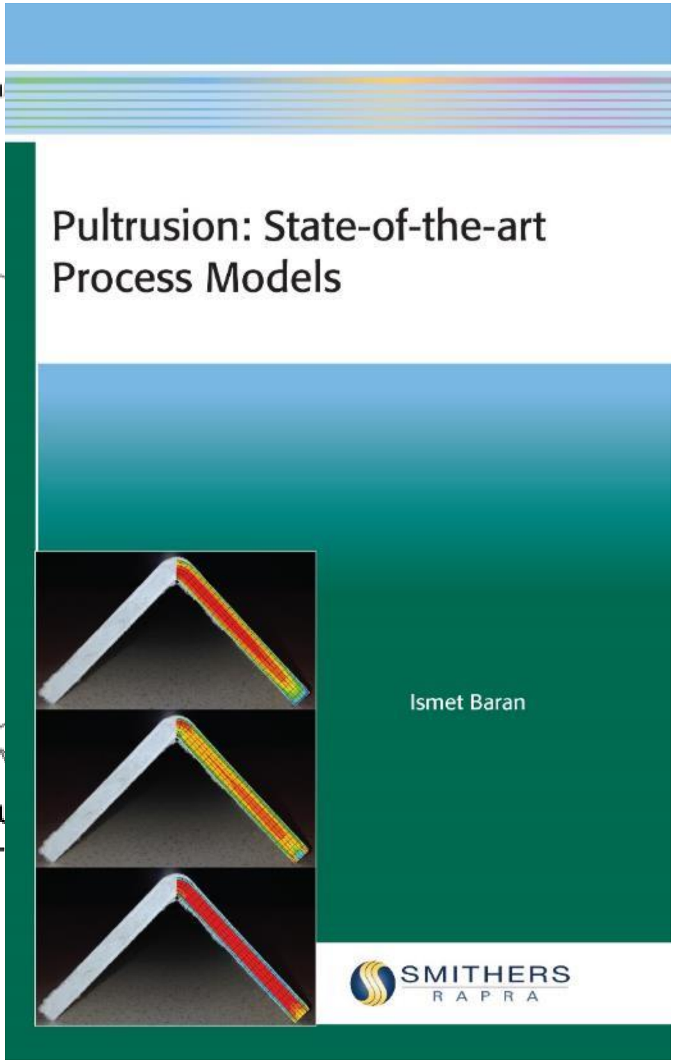


Baran et al. *Composites Part B* (2014)

Numerical process modelling

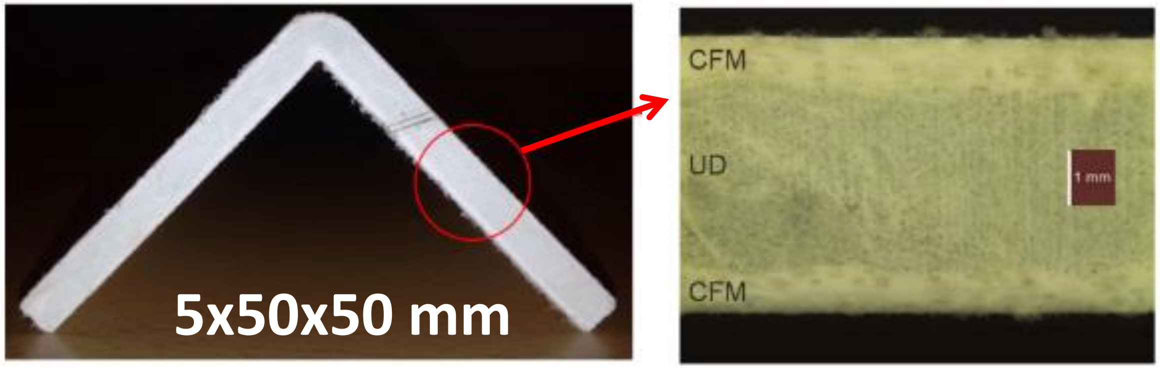


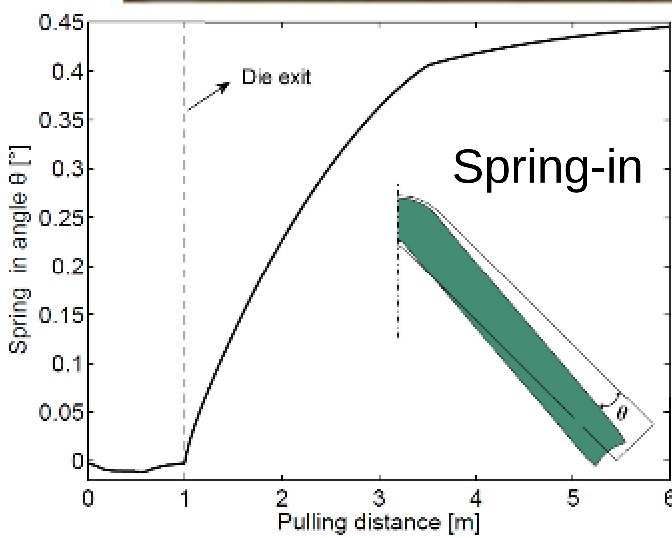
Baran et al. *Composites Part B* (2013)

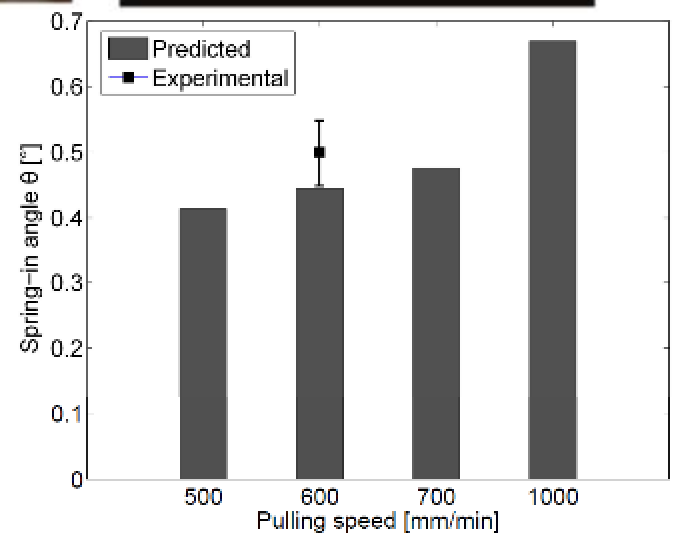


Shape deformations

Simulation of the pultrusion process: L-shaped profile

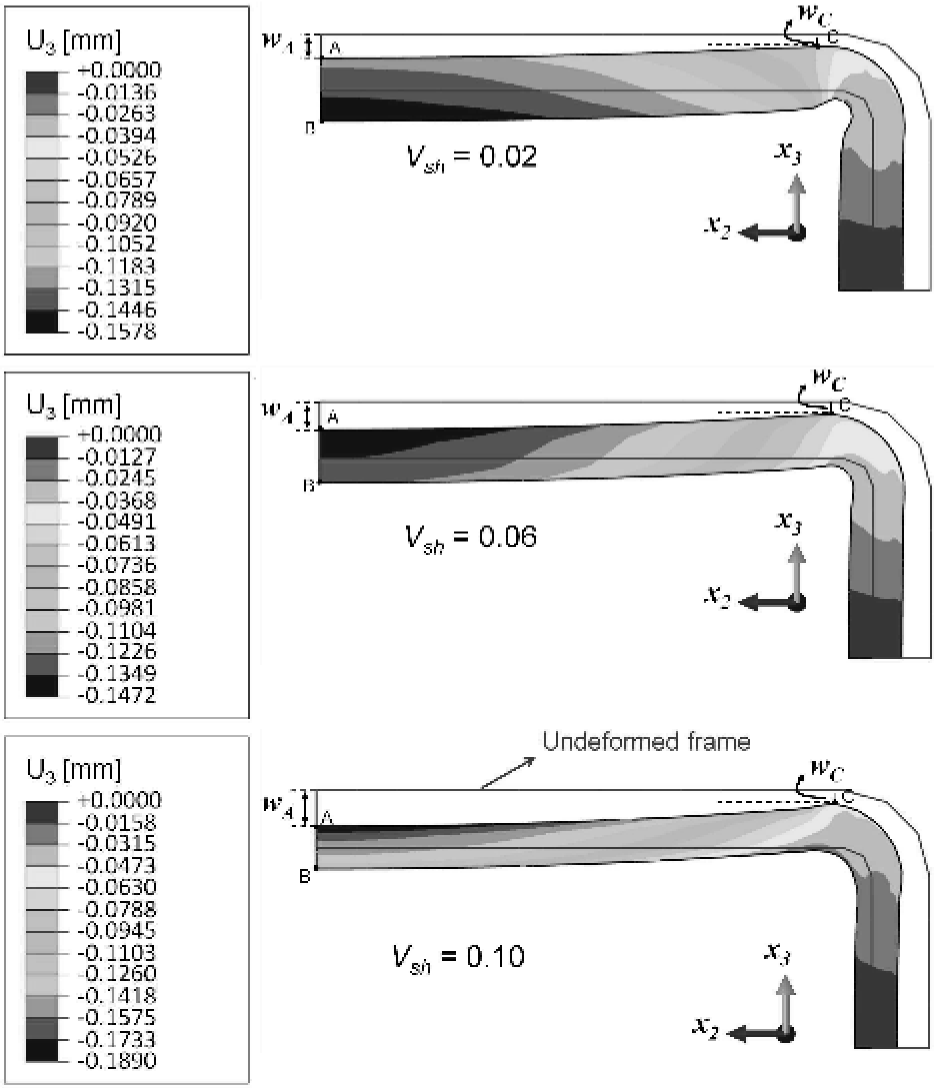


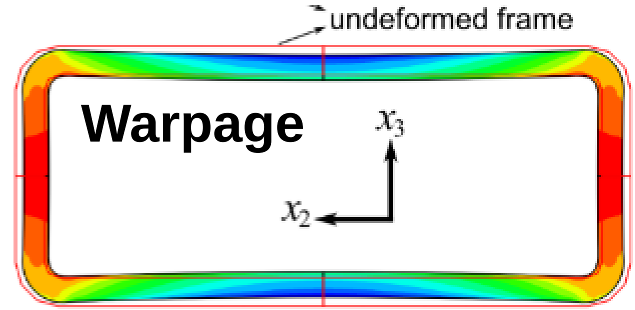




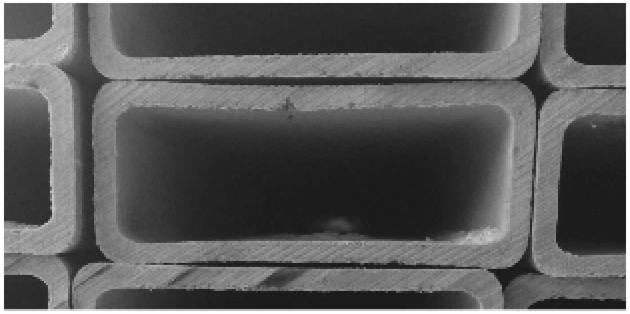
Baran et al. *Composites Structures* (2014)

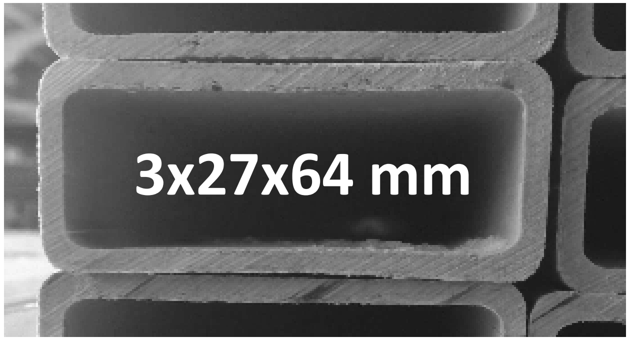
Shape deformations



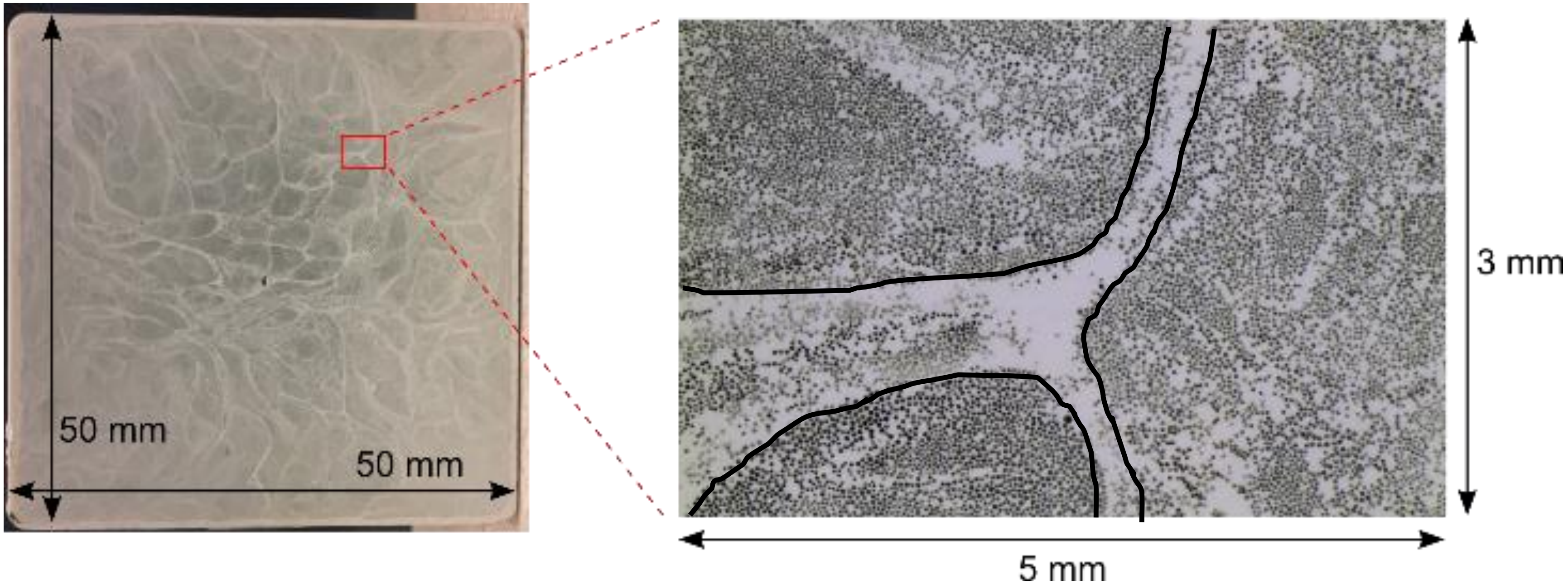


Baran et al. *Composites Part B* (2015)





Local V_f distribution

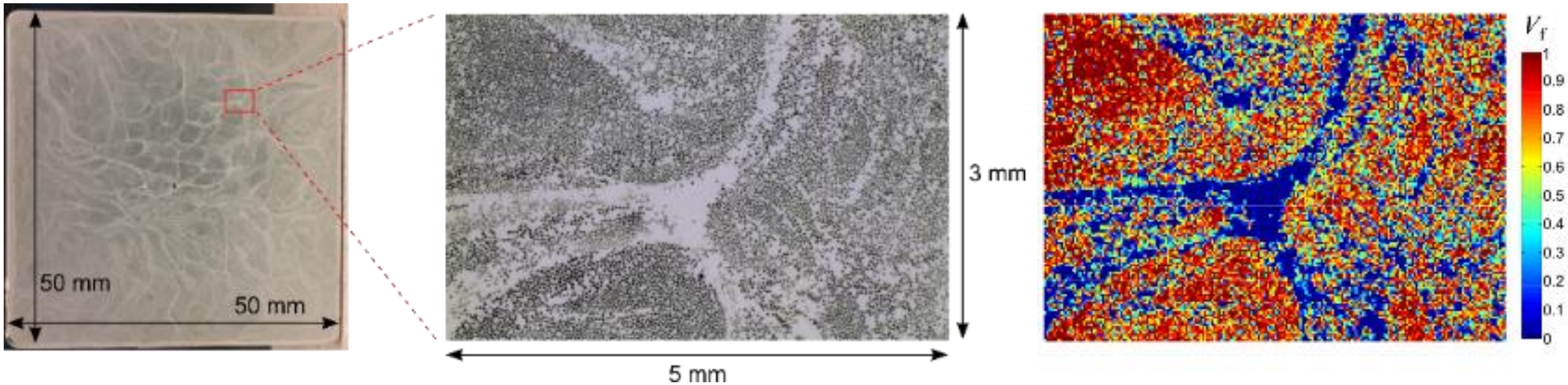


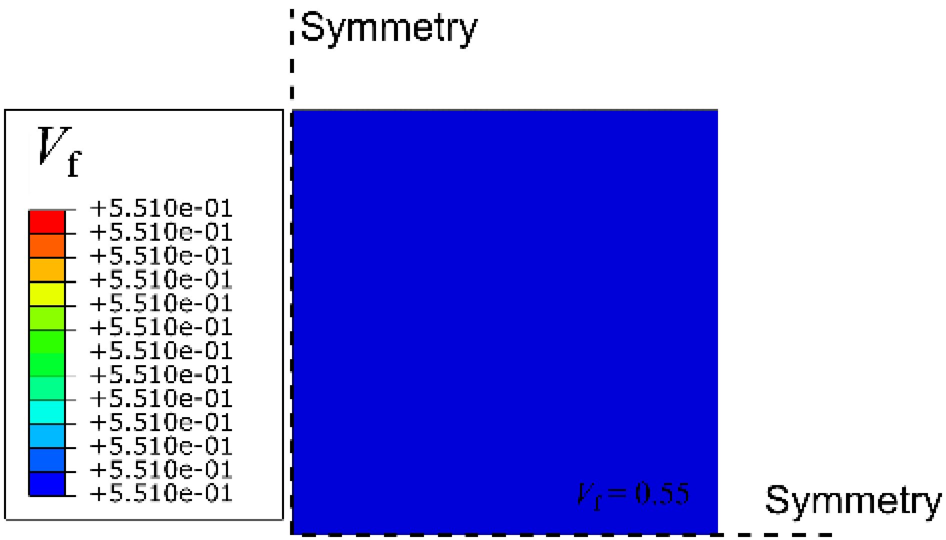
Glass/polyester (UD Vf = 55 %)

Baran. ESAFORM (2017)

Local V_f distribution

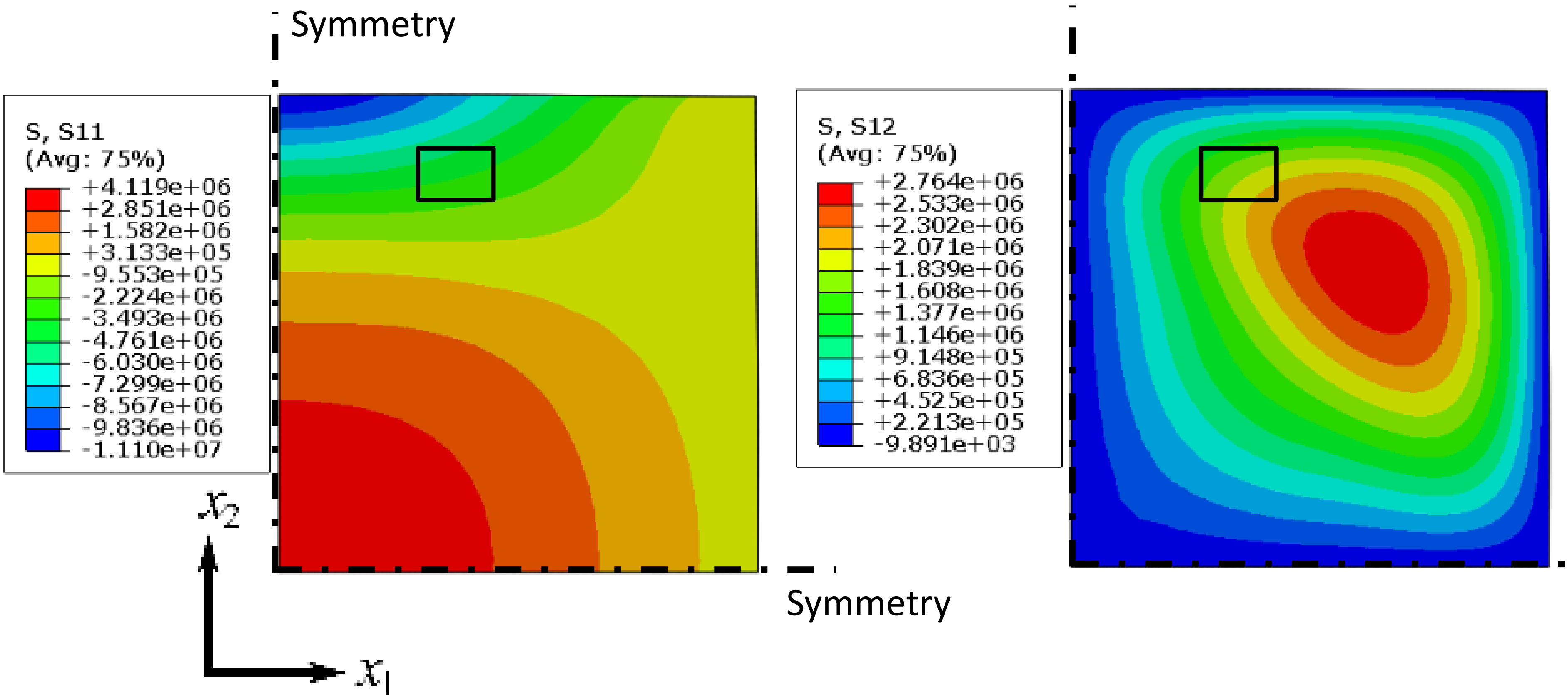
Baran. ESAFORM (2017)





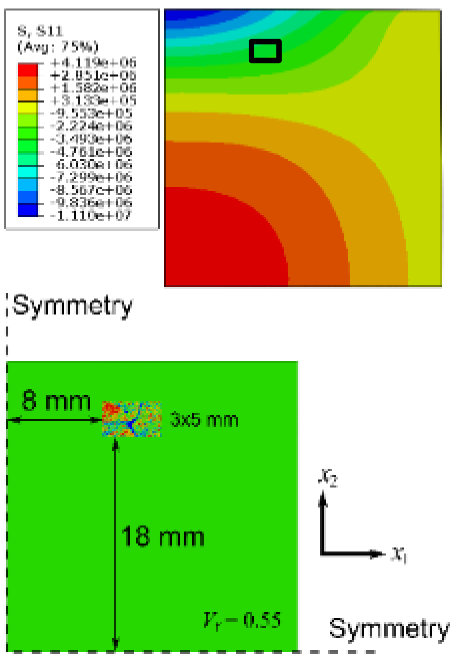
Local V_f distribution

Uniform fiber volume distribution:

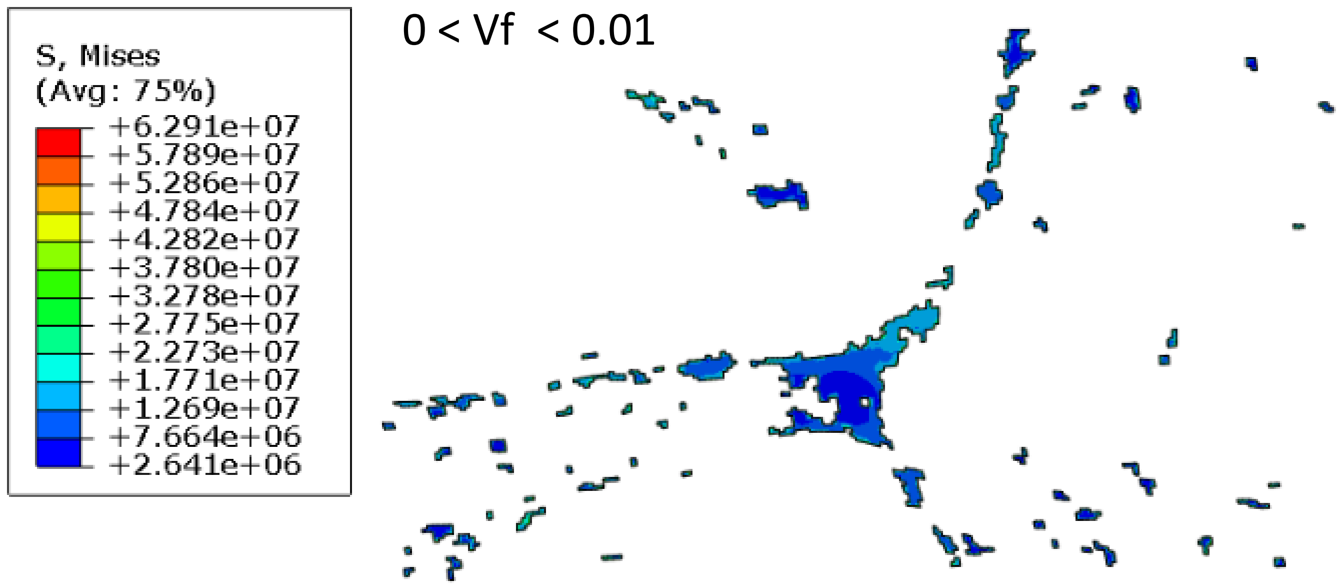


Baran et al. *Applied Composite Materials* (2014)

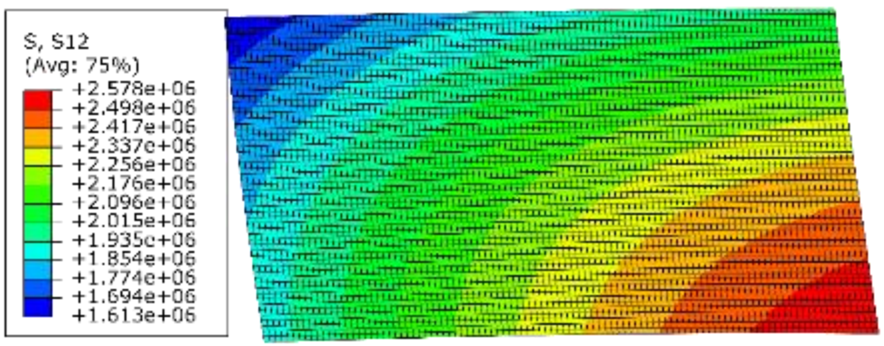
Local V_f distribution

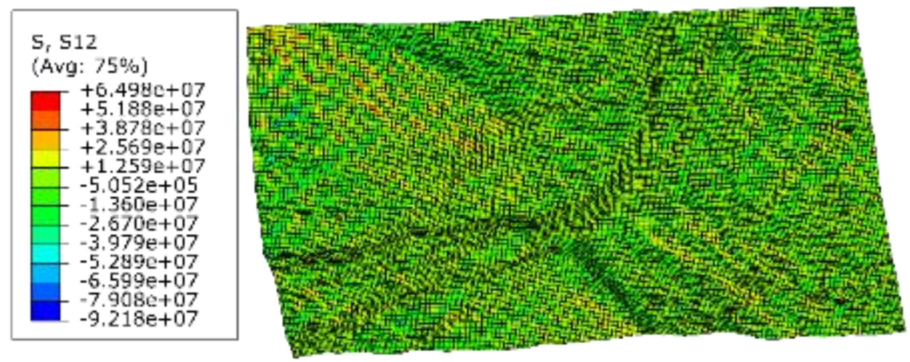


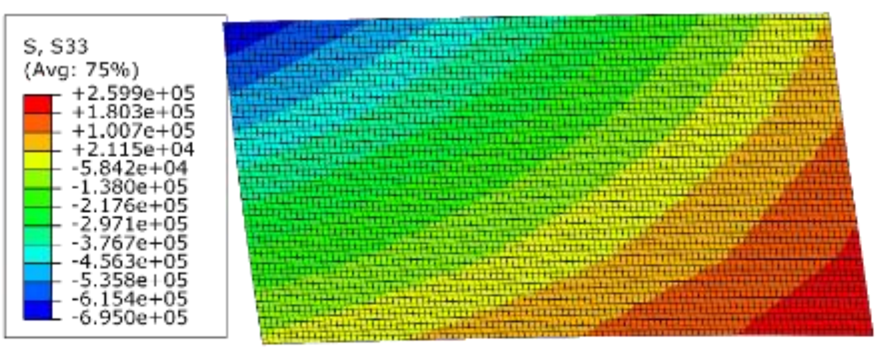
0 < Vf < 0.01

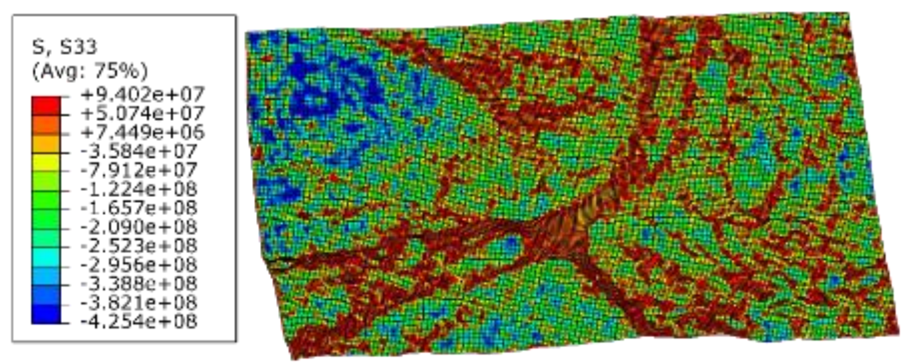


Local V_f distribution





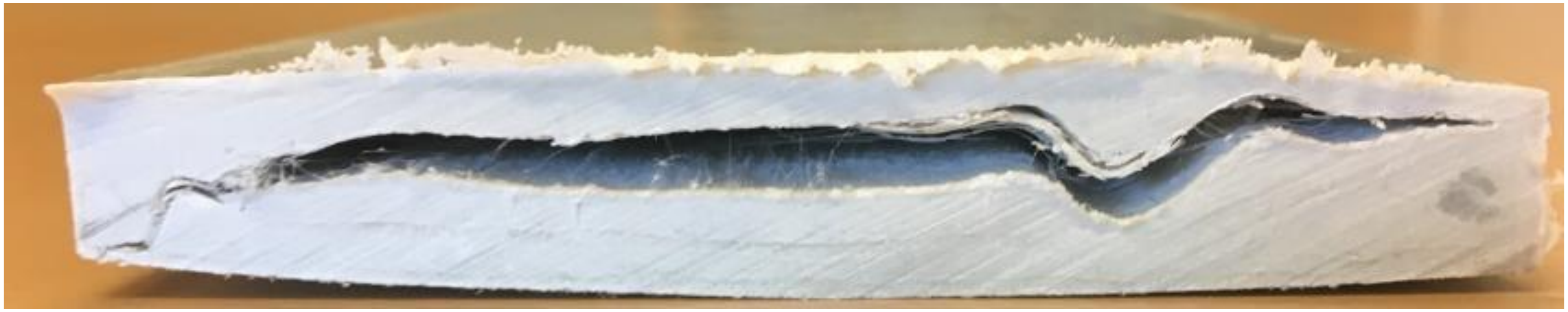




Non-uniform curing

Partial curing due to higher pulling speed

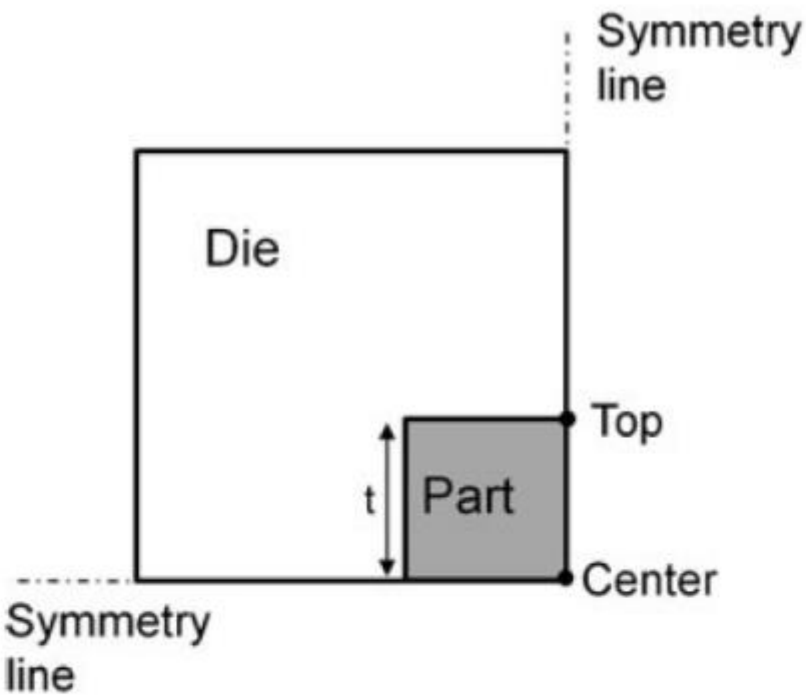
Delamination during the process

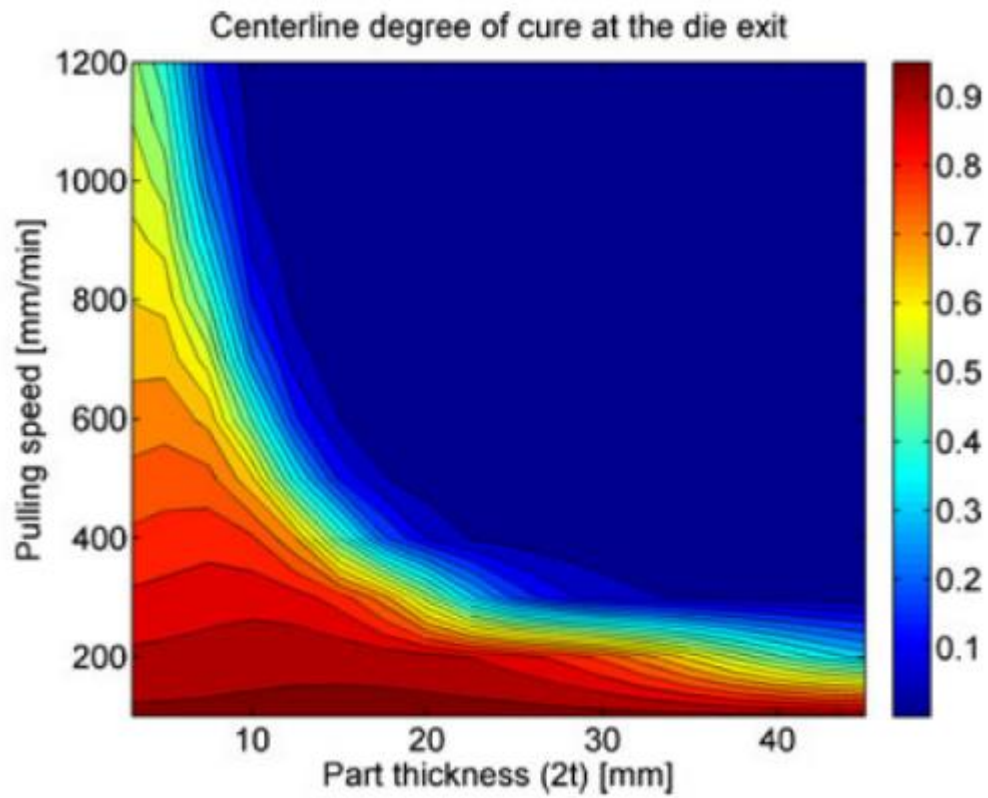


Thickness 12 mm, width = 100 mm

In preparation for publication

Non-uniform curing

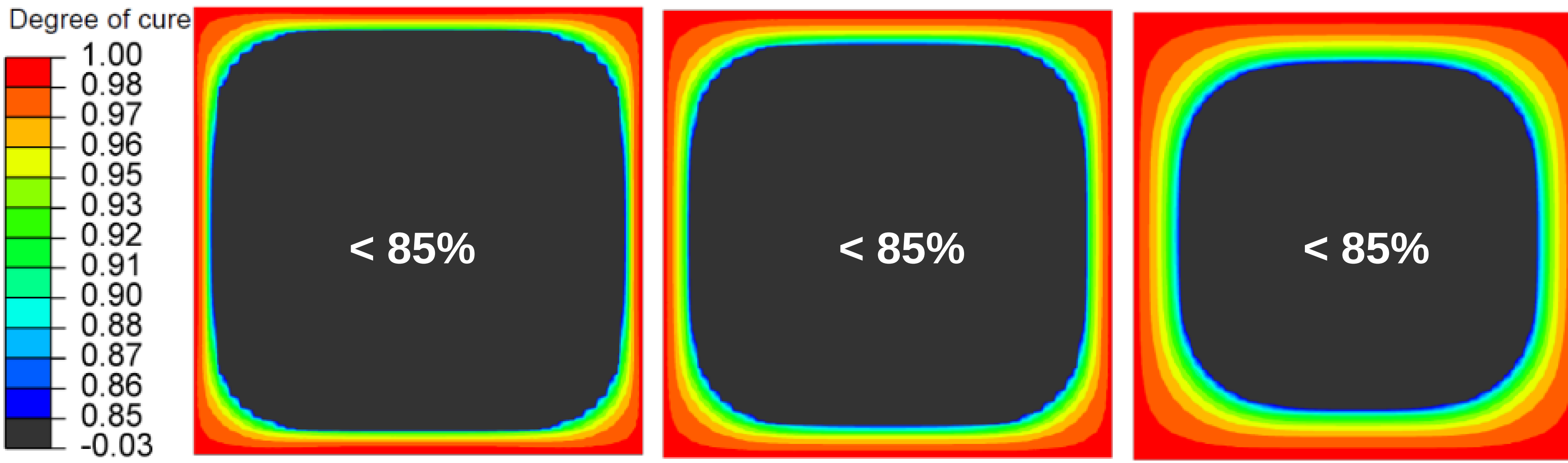




Baran et al. *Applied Composite Materials* (2013)

Non-uniform curing

Degree of cure at die exit



a) T_{inlet} = 20 °C b) T_{inlet} = 40 °C c) T_{inlet} = 60 °C

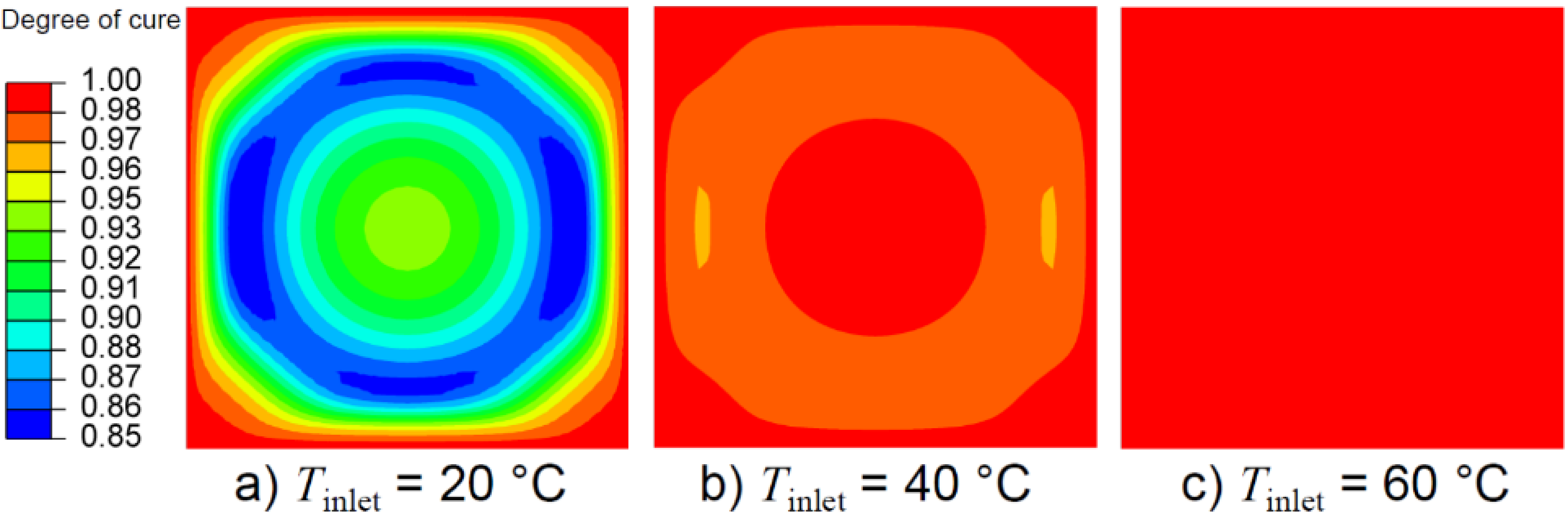
100 x 100 mm (glass polyester)

Baran. *AMPCS* (2016)

Pulling speed 100 mm/min

Non-uniform curing

Degree of cure at room temperature (part is cooled down)



100 x 100 mm (glass polyester)

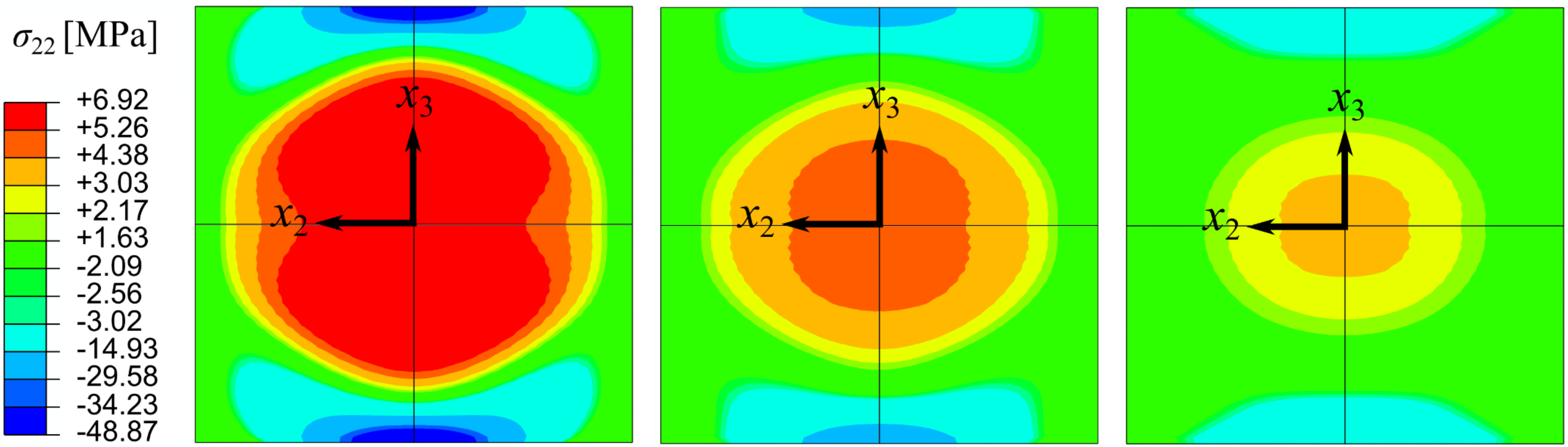
Baran. *AMPCS* (2016)

Pulling speed 100 mm/min

Non-uniform curing

Normal stress distribution

50 % reduction in tensile stresses at center



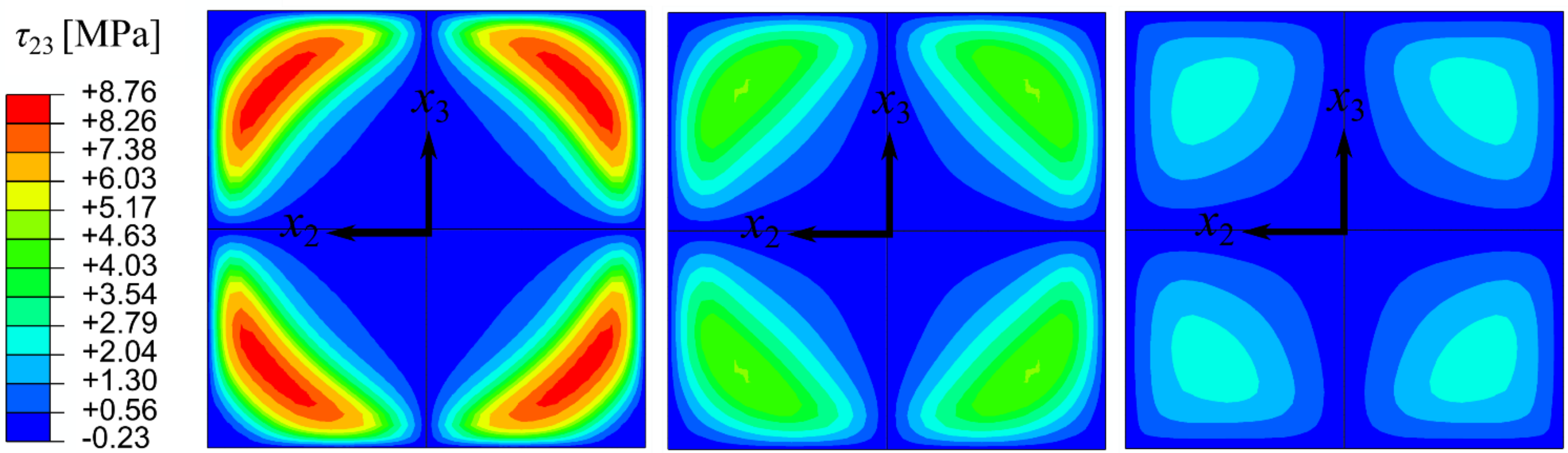
a) $T_{\text{preheat}} = 20$ °C b) $T_{\text{preheat}} = 40$ °C c) $T_{\text{preheat}} = 60$ °C

Baran. *AMPCS* (2016)

Non-uniform curing

Transverse shear stress distribution

70 % reduction in maximum transverse shear stress



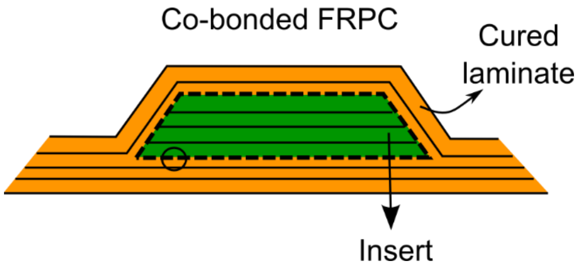
a) $T_{\text{preheat}} = 20\ °\text{C}$ b) $T_{\text{preheat}} = 40\ °\text{C}$ c) $T_{\text{preheat}} = 60\ °\text{C}$

Baran. *AMPCS* (2016)

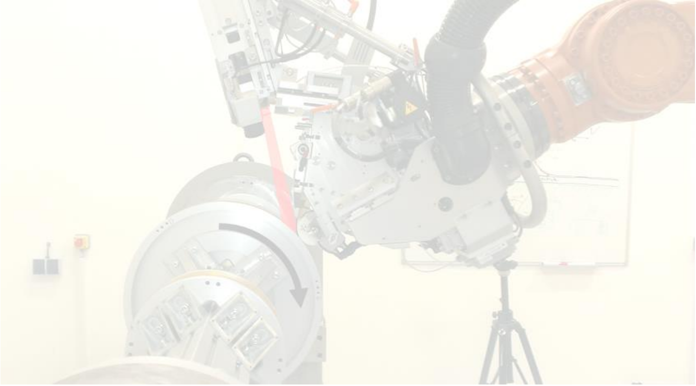
Recent activities

Pultrusion:
Heat transfer, curing, solid mechanics

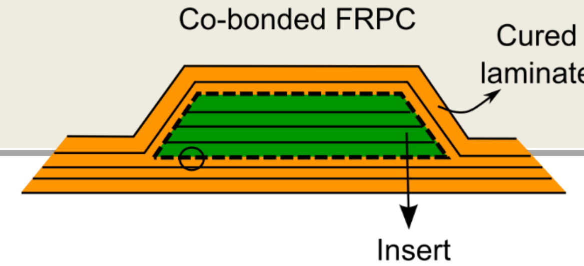
Co-bonding/over infusion:
Interface bonding



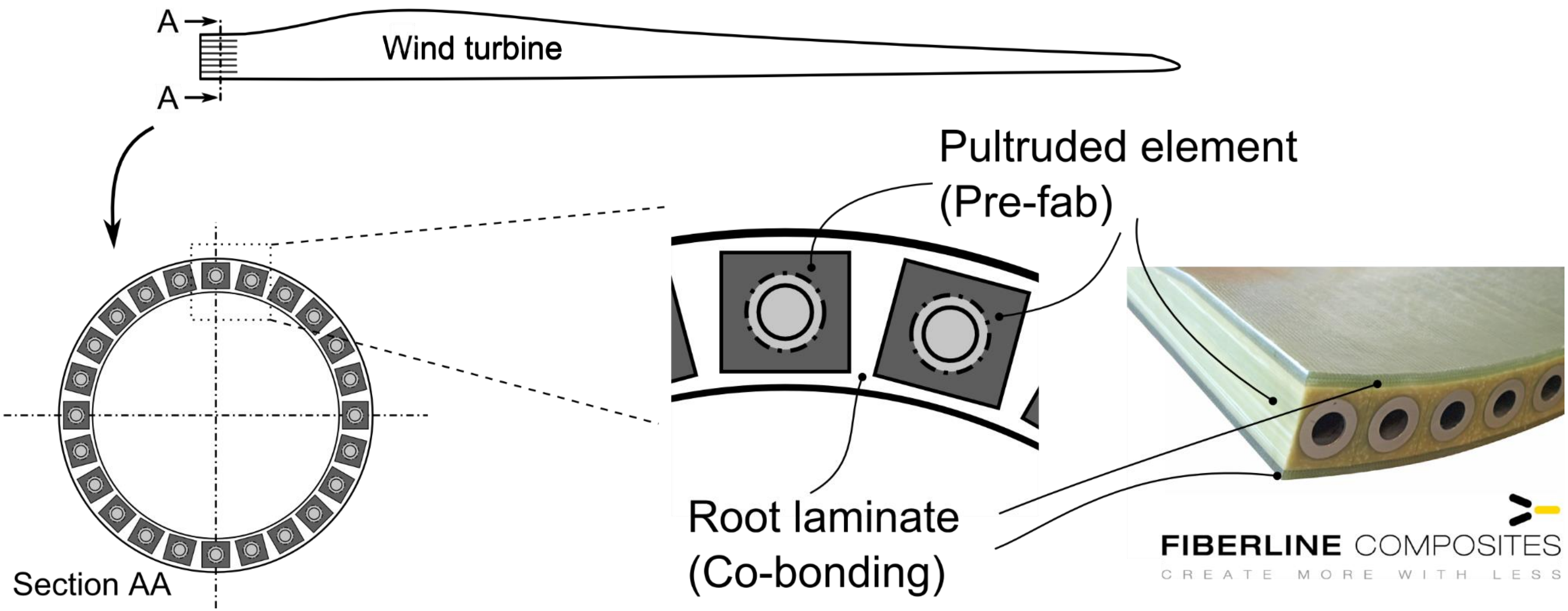
Laser Assisted Tape Winding (Placement):
Laser optics, irradiation heat transfer



Co-bonding

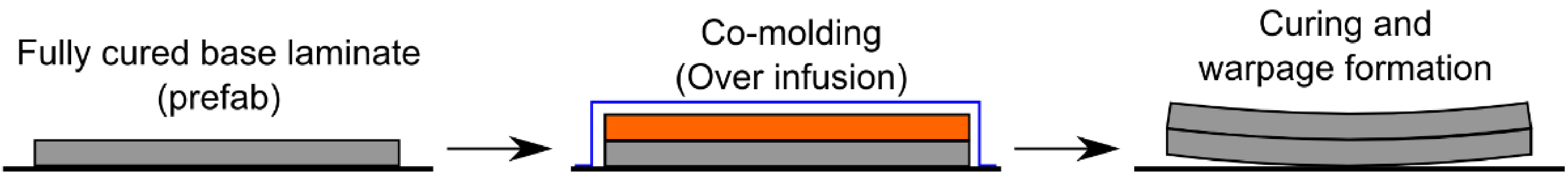


Co-bonded FRPC
Cured laminate
Insert



A
A
Wind turbine
Section AA
Pultruded element (Pre-fab)
Root laminate (Co-bonding)
FIBERLINE COMPOSITES
CREATE MORE WITH LESS

Co-bonding challenges

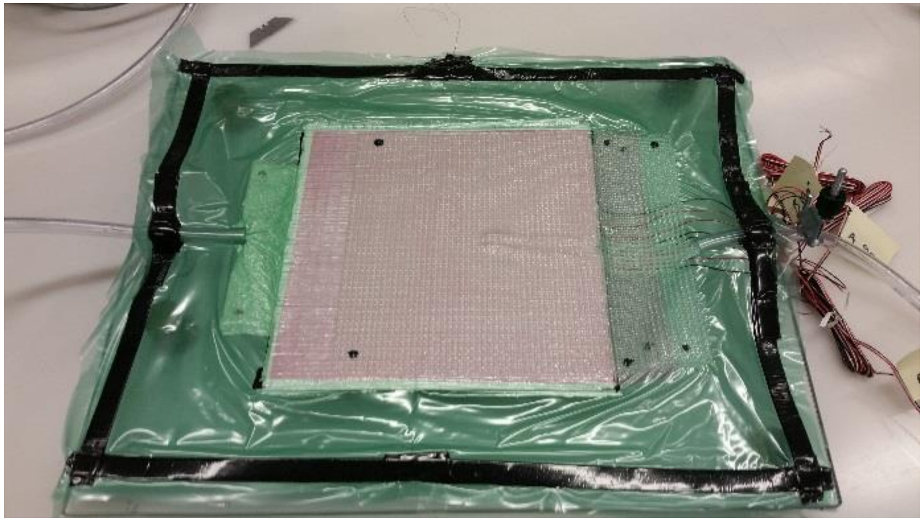


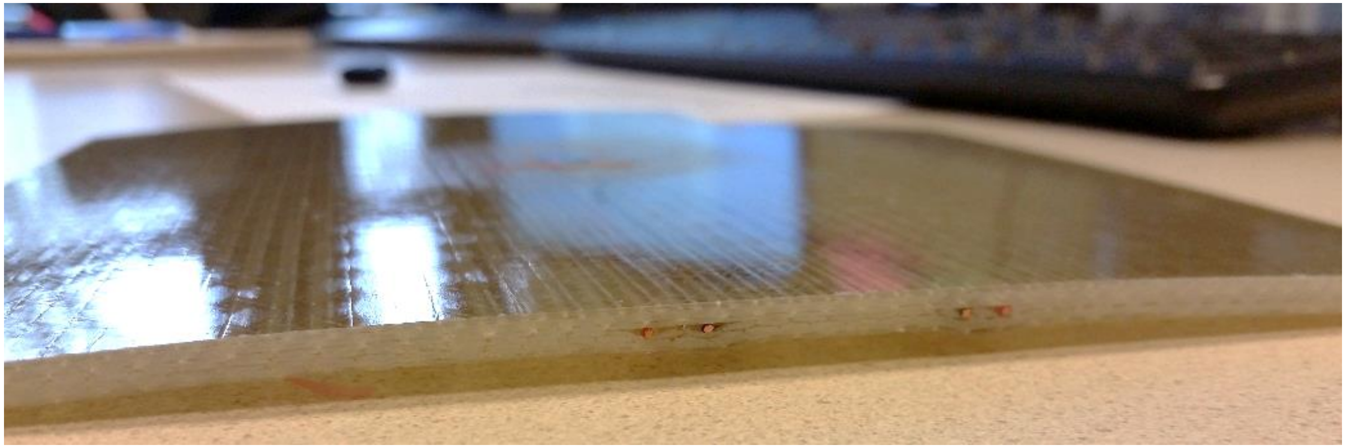
- Multiphysics
- Mechanics and constitutive behaviour of interface
- Load transfer at interface

- **Bond quality & strength**

Co-bonding warpage

- Glass/polyester
- $[0]_{4s}$ prefab + $[0]_{4s}$ over infused laminate
- 4.5 mm total thickness
- Curing at RT 30 hrs.

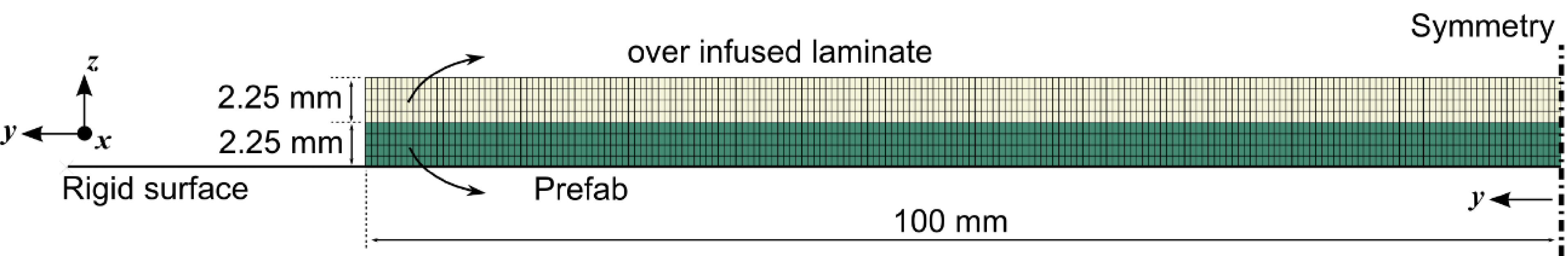




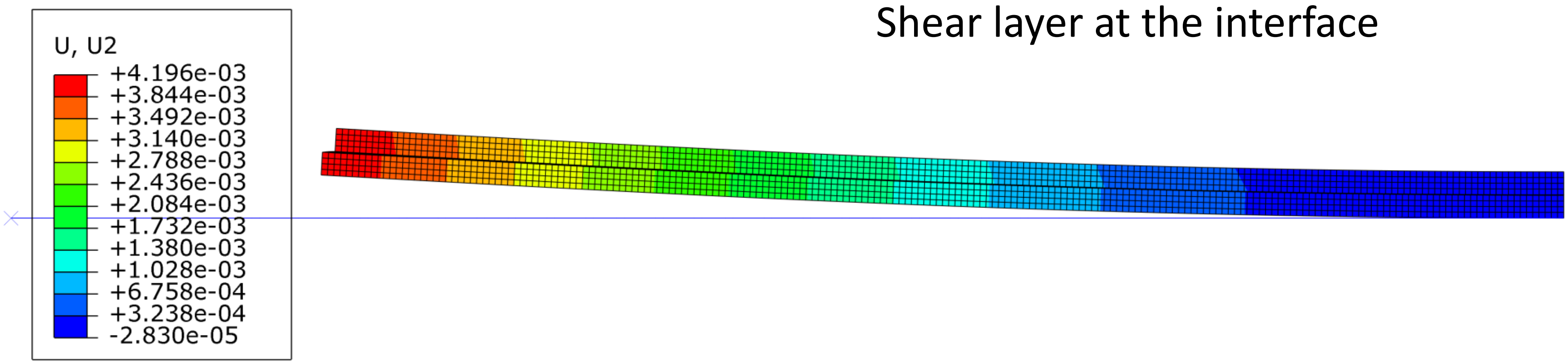
Baran, ECCM21 (2017)

Co-bonding warpage

Thermo-chemical-mechanical process simulation



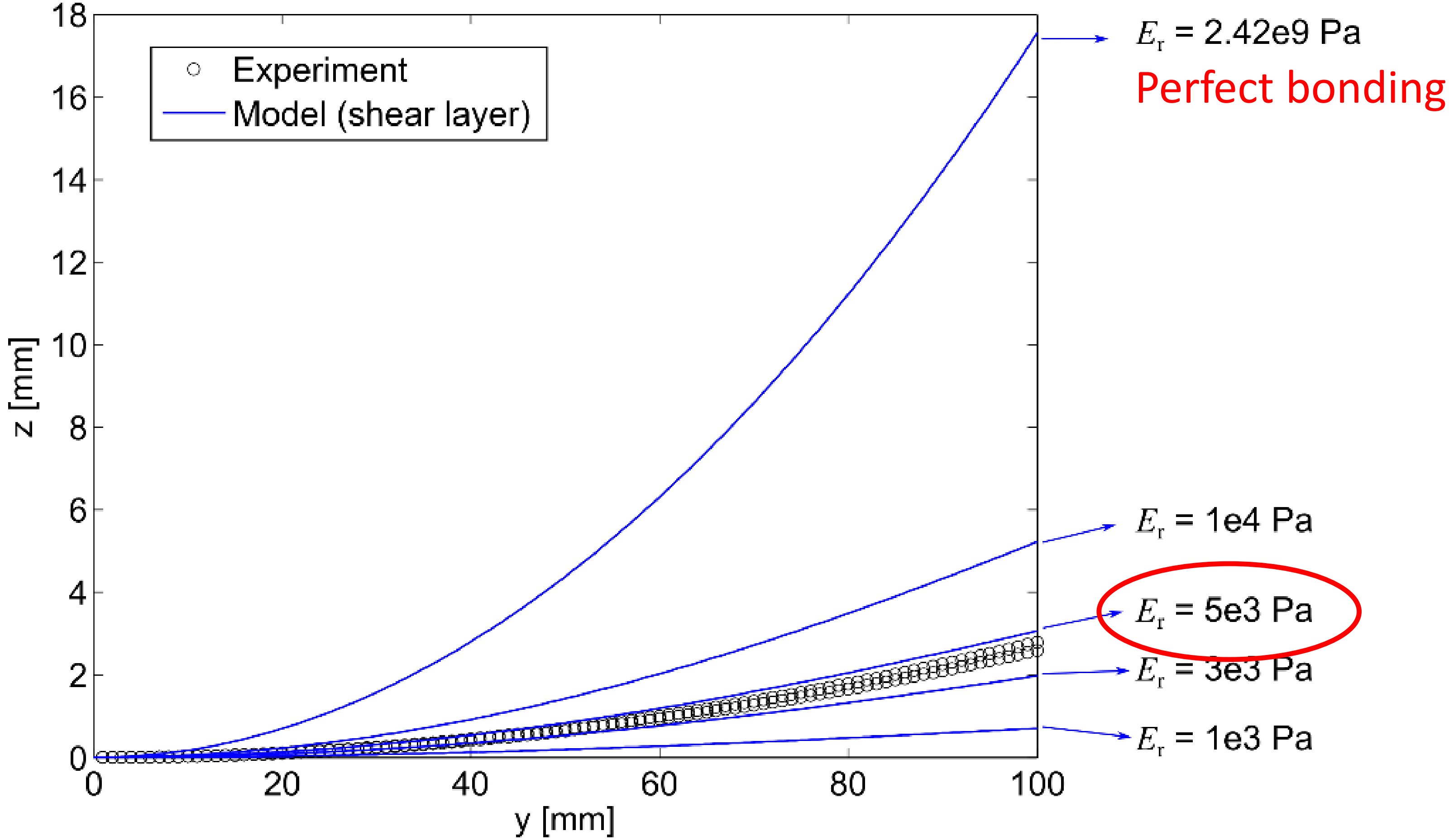
Shear layer at the interface



Baran, ECCM21 (2017)

Co-bonding warpage

Warped geometry

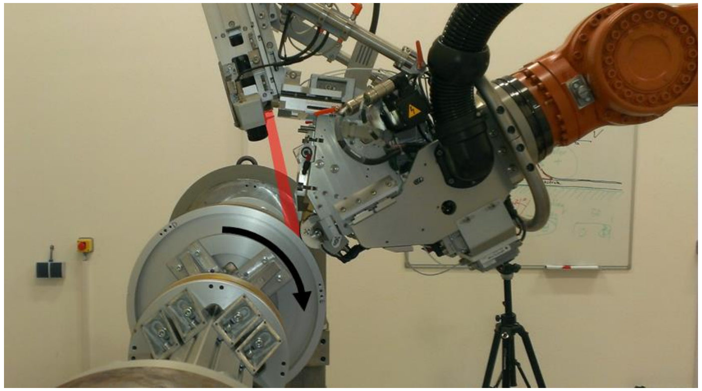


Recent activities

Pultrusion:
Heat transfer, curing, solid mechanics

Co-bonding/over infusion:
Interface bonding

Laser Assisted Tape Winding (Placement):
Laser optics, irradiation heat transfer



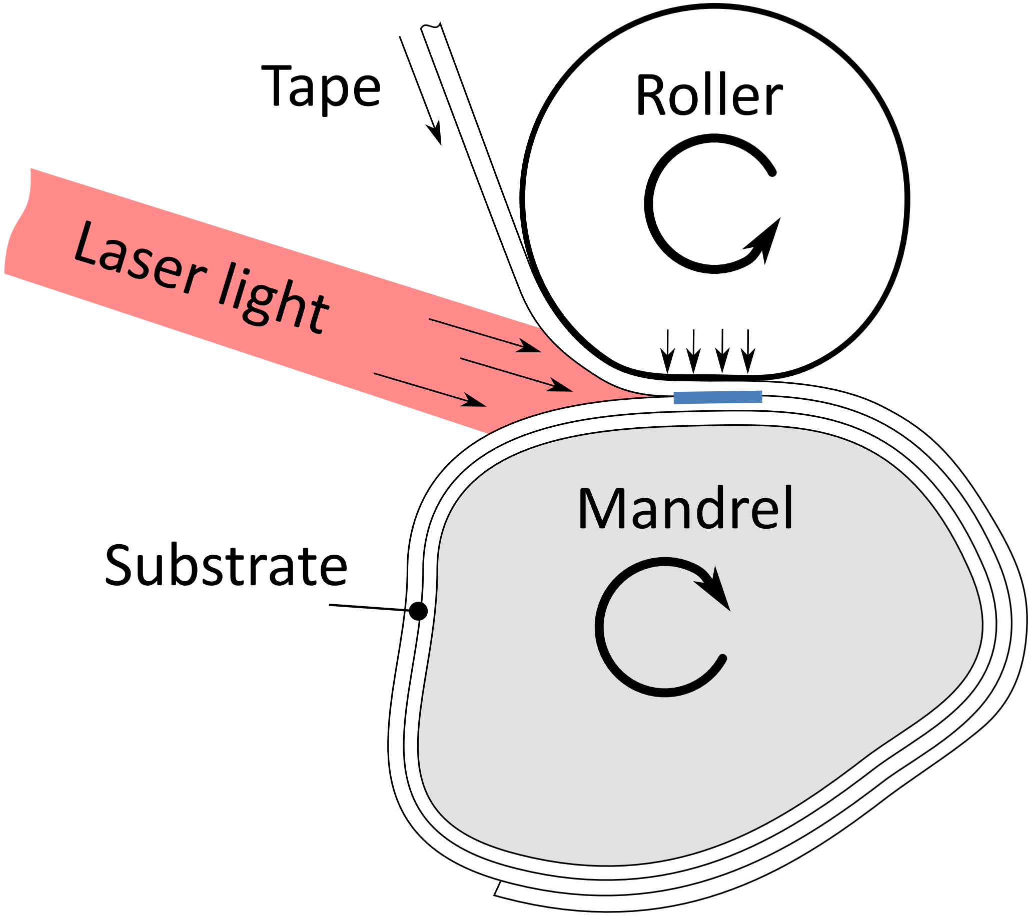
Laser Assisted Tape Winding (LATW)

Main advantages:

- Tailorable lay-up
- No post-curing (autoclave) needed
- Automation possible

Consolidation requires:

- Heat (laser)
- Pressure (roller)
- Time



LATW applications

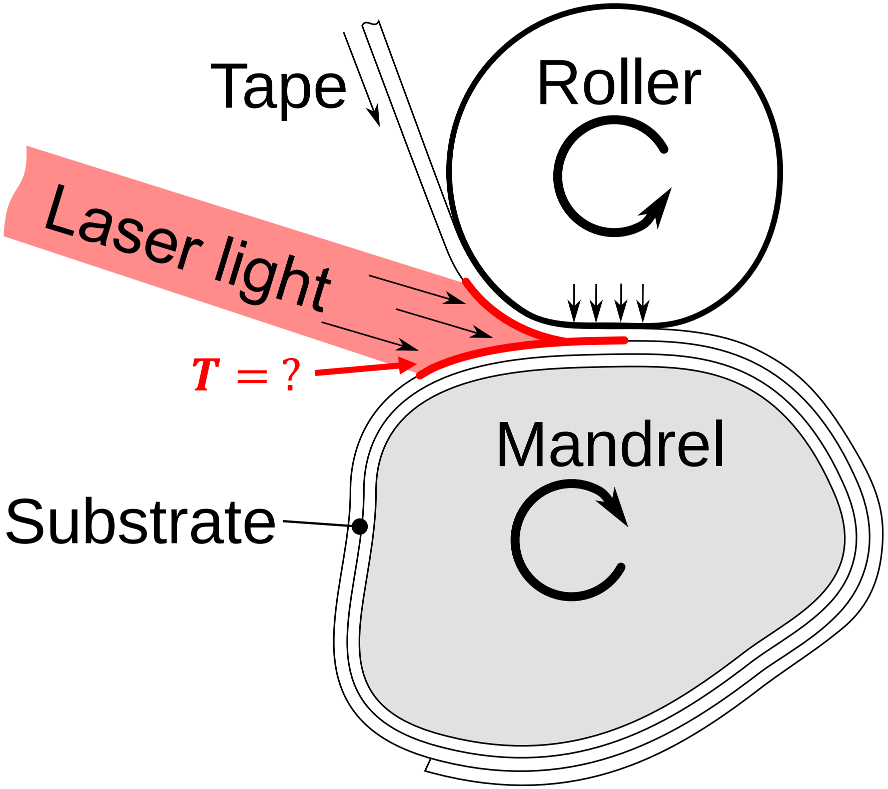
Risers for deep-sea oil/gas drilling

Automobile H_2 storage tank

LATW processing challenges

Temperature?

- Too low:
  - ➢ Insufficient consolidation or intimate contact
- Too high:
  - ➢ Material degradation
  - ➢ Excessive deformation



LATW process optimization/control

<u>Laser assisted tape winding process</u>

Physics based process model

⇩

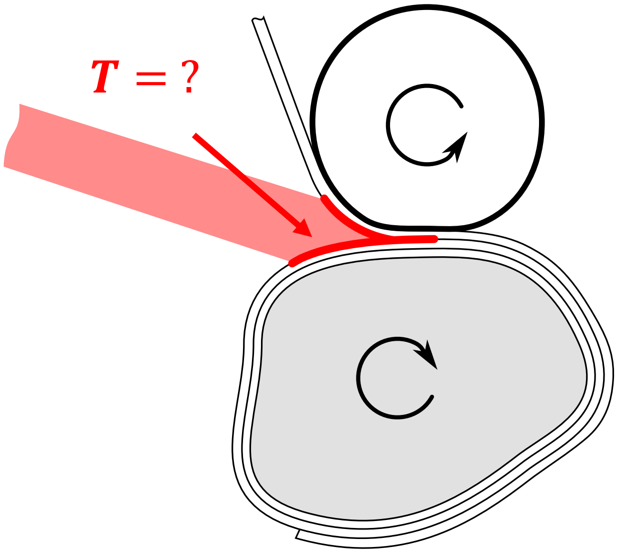
Fast calculation of nip-point temperature

⇩

Machine control

⇩

Improved bonding quality



Model based inline process control

Hosseini, Baran and Akkerman. *ICCM21* (2017)
Zaami, Baran and Akkerman. *ICCM21* (2017)
Zaami, Baran and Akkerman. *FTF2017* (2017)
Zaami, Baran and Akkerman. *ESAFORM* (2017)
Reichardt, Baran and Akkerman. *ECCM17* (2016)

LATW process model

Input parameters
Machine, geometry, material data, …

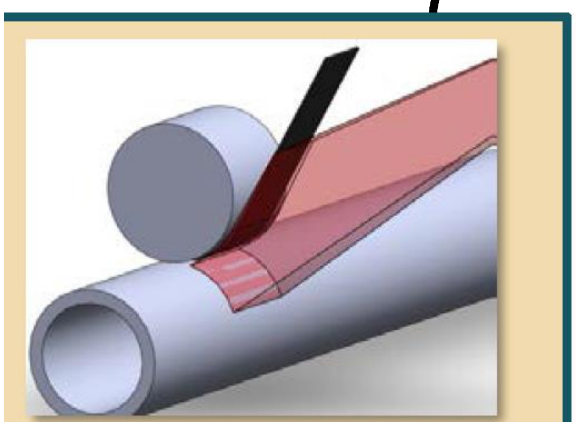
Kinematic model
Machine movements?

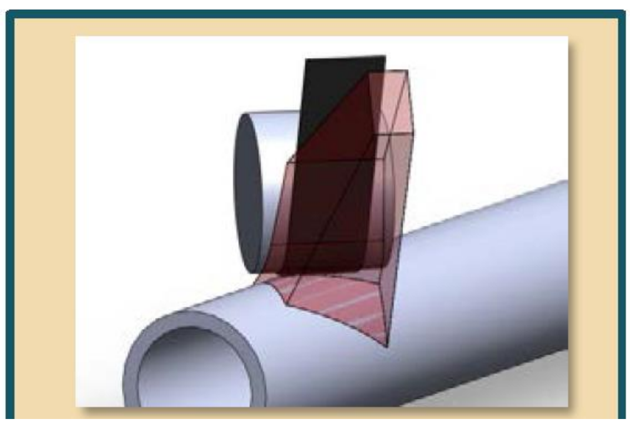
Optical model
How / where does the laser heat the tape?

Temperature

Bonding model
Consolidation?
Crystallinity?

Quality





LATW process simulation tool

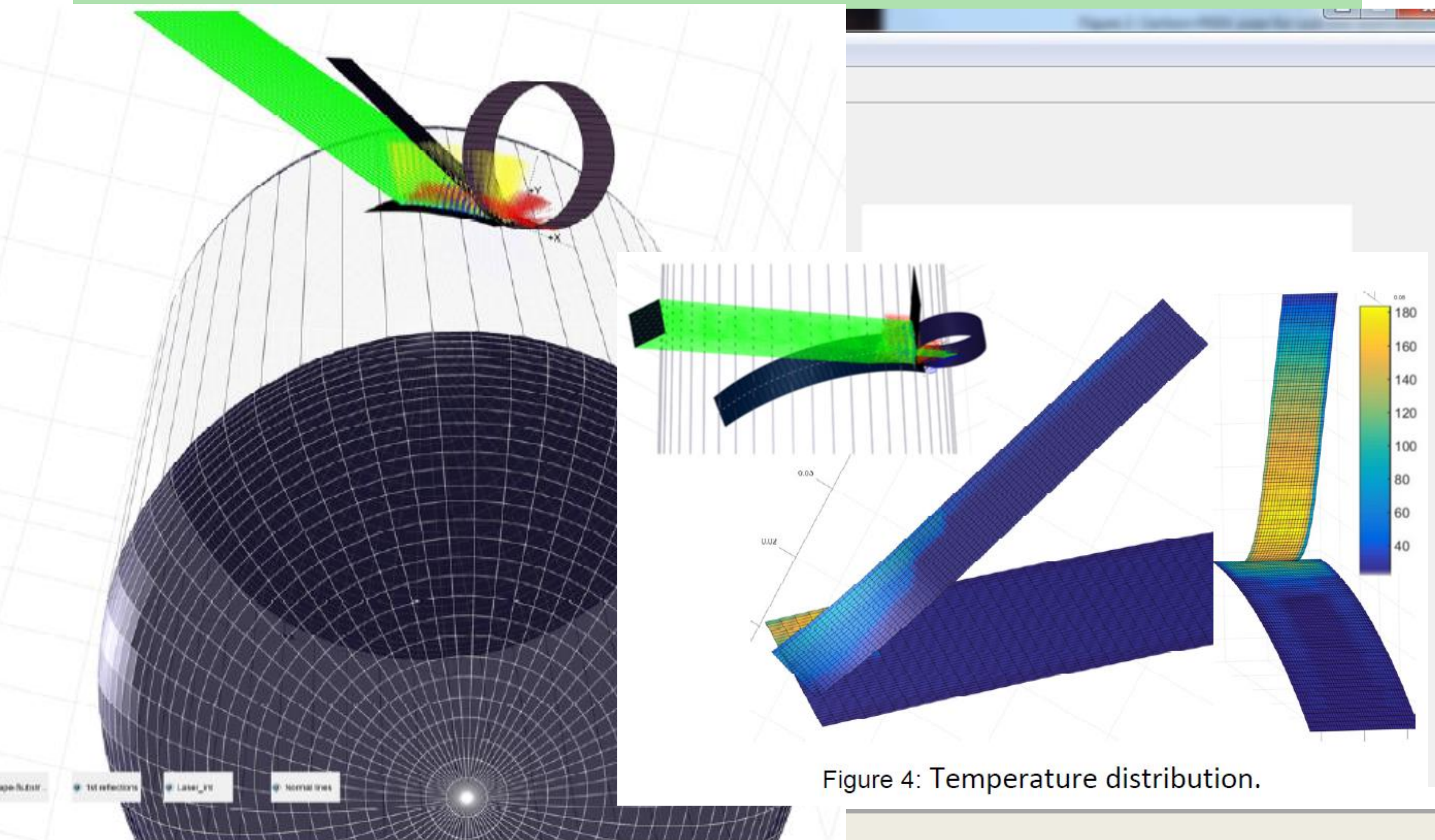
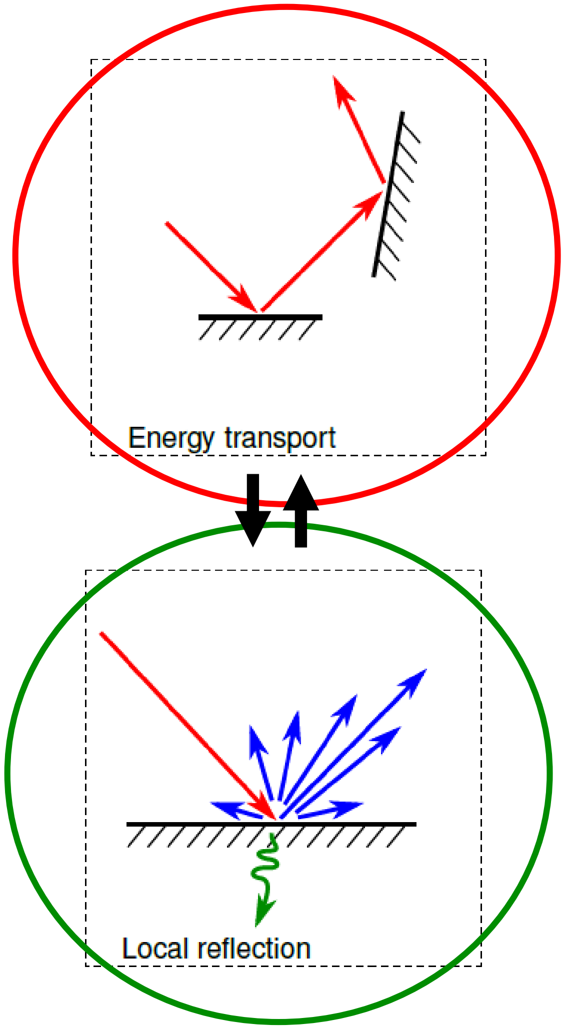
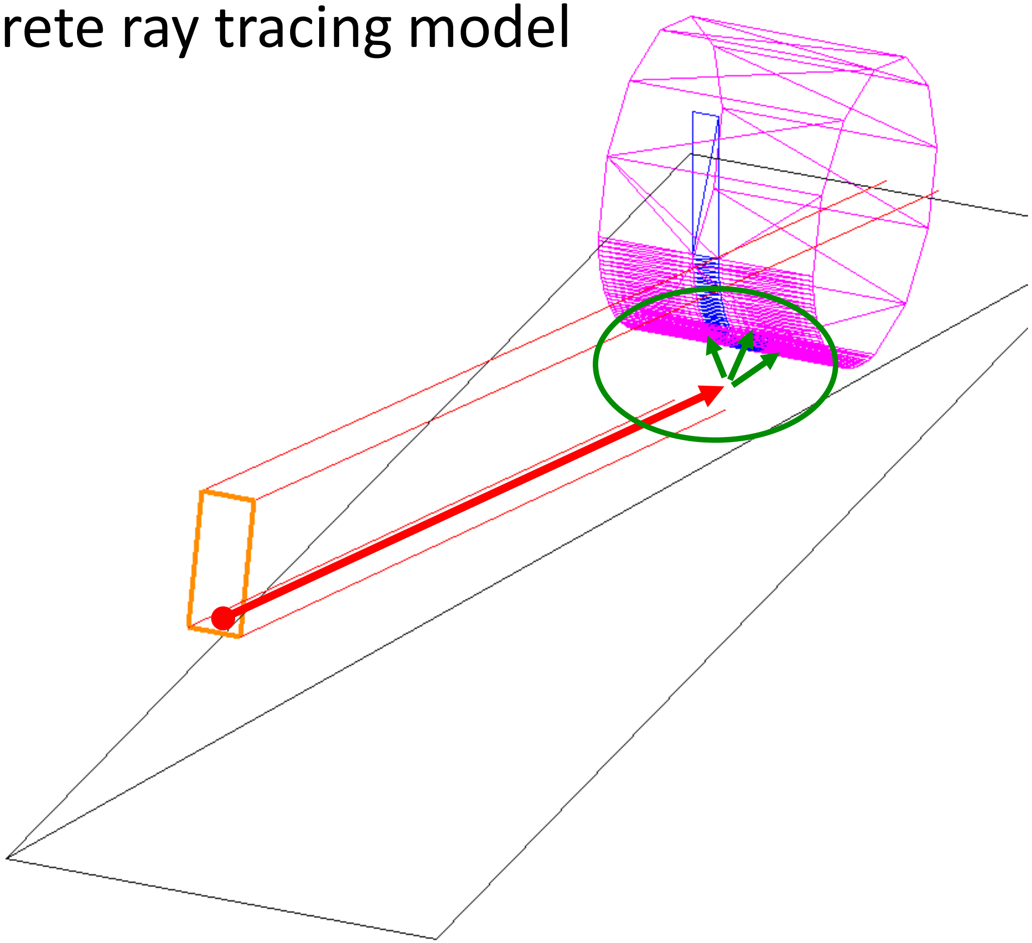


Figure 4: Temperature distribution.

LATW laser light reflection

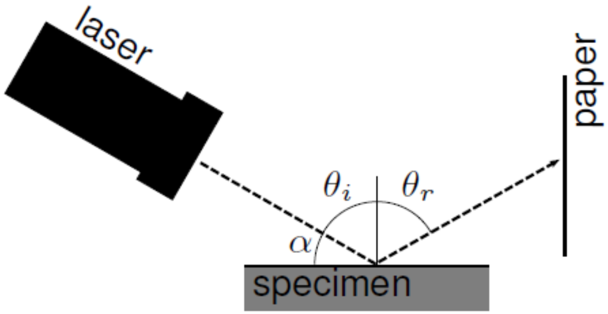


Discrete ray tracing model

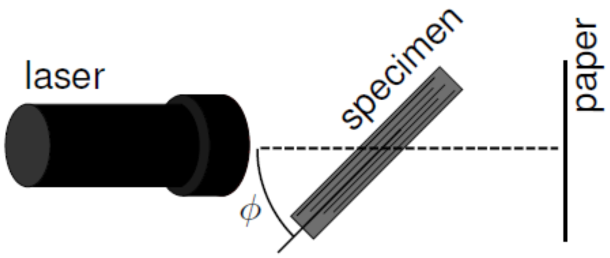


LATW non-specular reflection

Experiment:



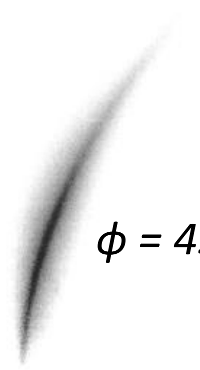
(a) Side view



(b) Top view

Result:

ϕ = 0°

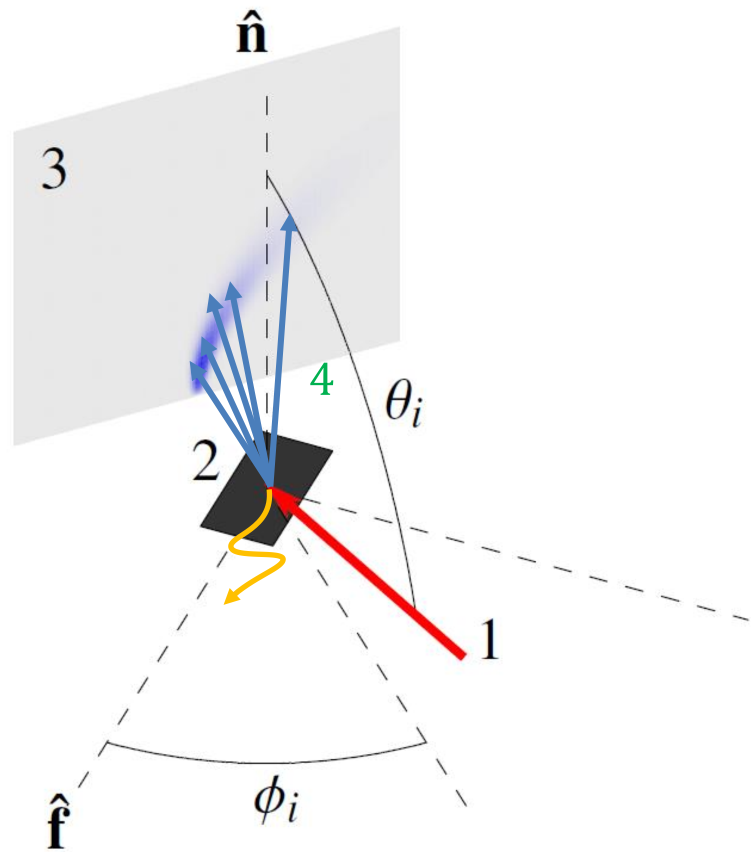


ϕ = 45°

ϕ = 90°

LATW optical model (non-specular reflection)

(1) Incident light ray
(2) Piece of material, fibre orientation $\hat{\mathbf{f}}$
(3) Reflected light on screen
(4) Reflected rays + absorption

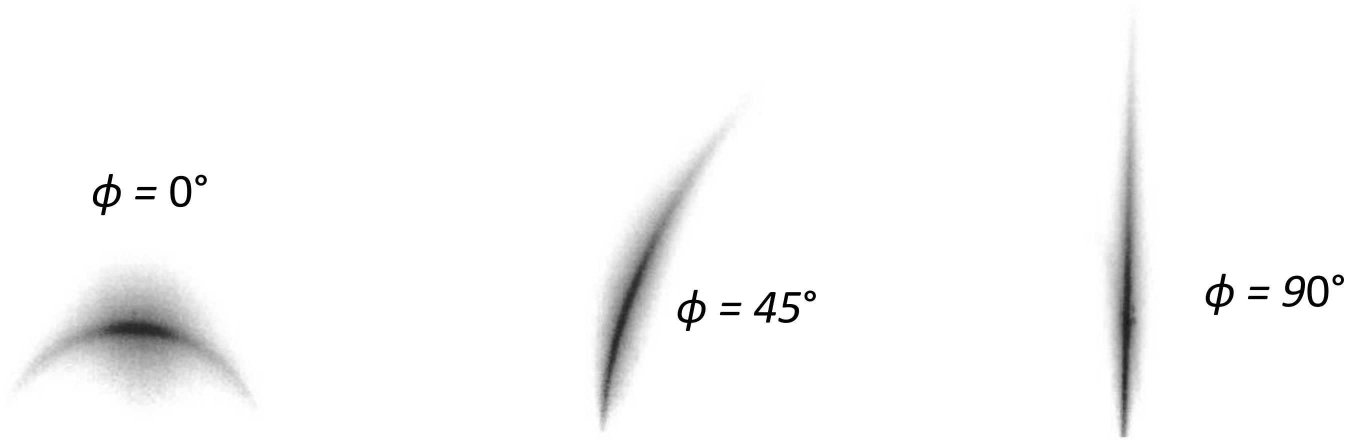


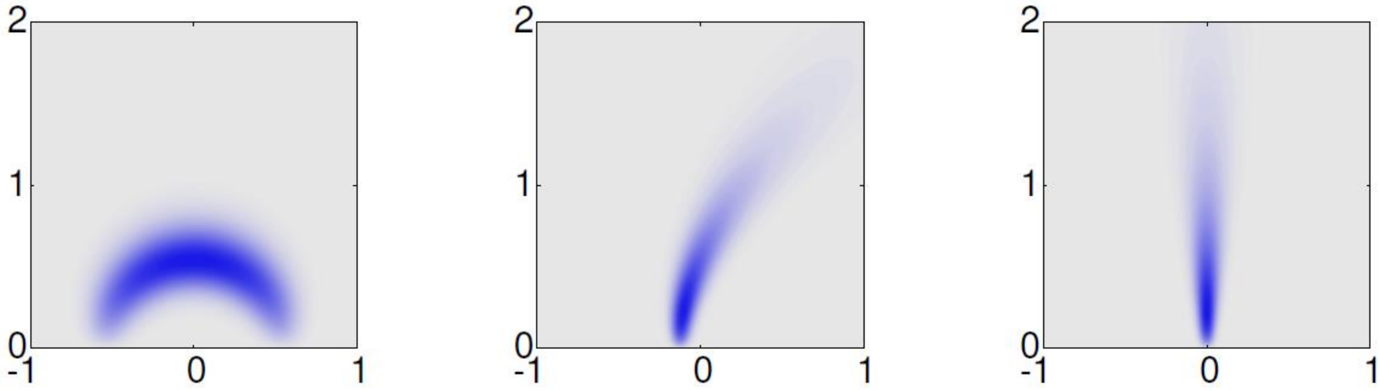
Microfacet-based Bidirectional Reflectance Distribution Function (BRDF) with microfacet probability distribution:

$$p(\hat{\mathbf{h}}) = p(\theta, \phi) = \exp\left(-\tan^2\theta \left(\frac{\cos^2\phi}{2\sigma_f^2} + \frac{\sin^2\phi}{2\sigma_t^2} \right) \right)$$

In preparation for publication

LATW optical model (non-specular reflection)



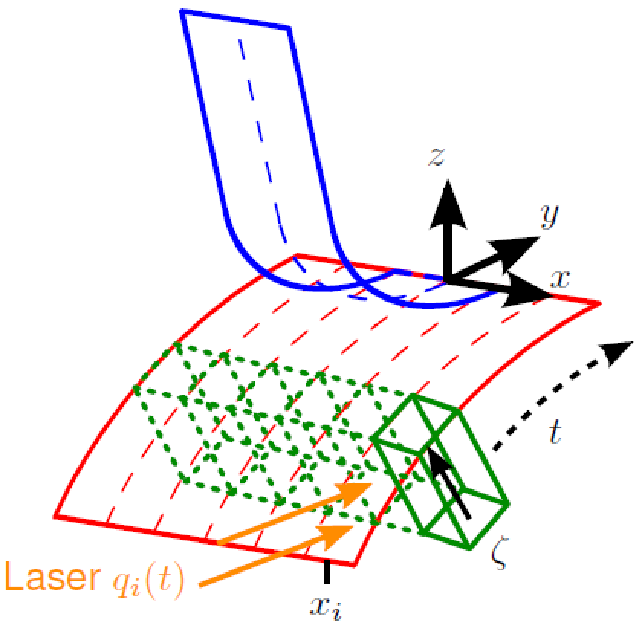


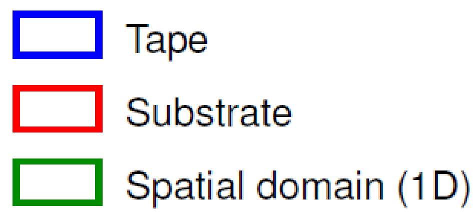
(a) Reflection for $\phi_i = 0°$ (b) Reflection for $\phi_i = 45°$ (c) Reflection for $\phi_i = 90°$

In preparation for publication

LATW thermal model

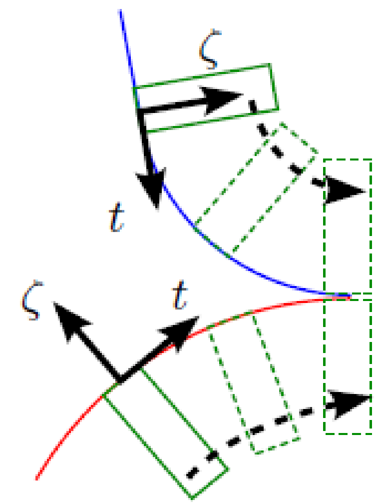
- 1D transient heat transfer model
- 2D Lagrangian domain (BCs)
- 2D →3D: row of *independent* domains (in transverse direction)





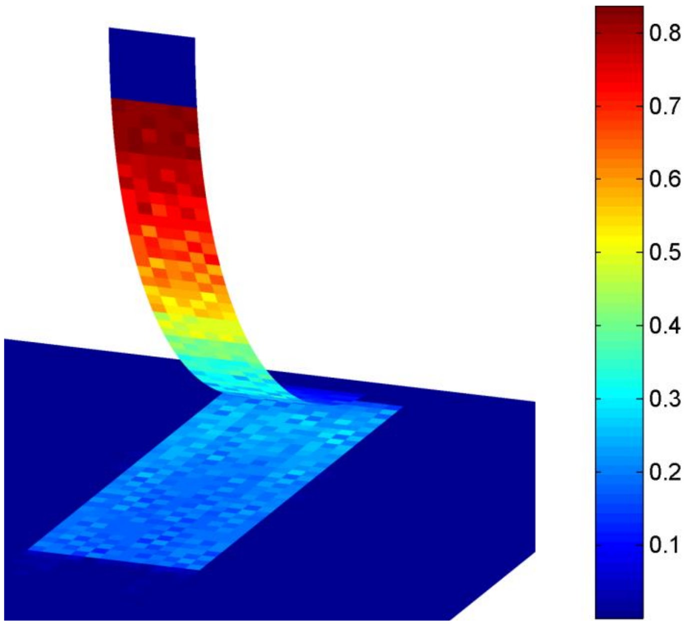
$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial \zeta^2}$$

$$\alpha \equiv \frac{k}{\rho c_p}$$

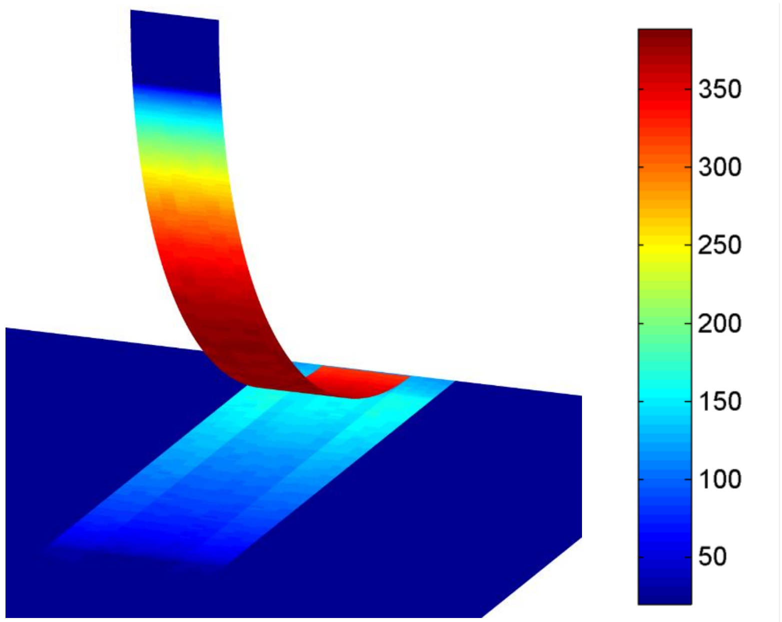


LATW model results

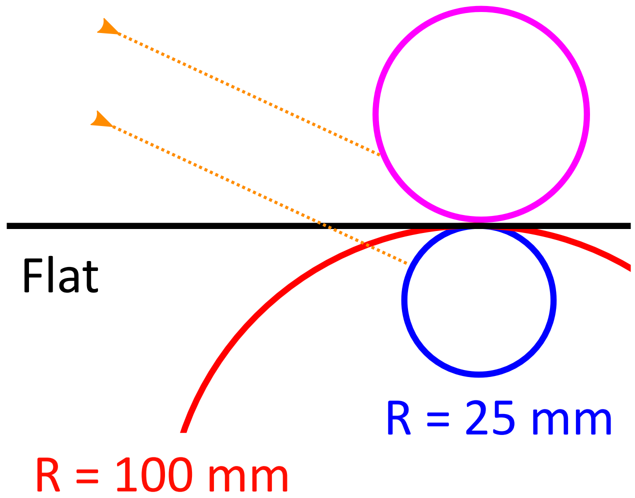
Optical model output:
Normalized laser intensity



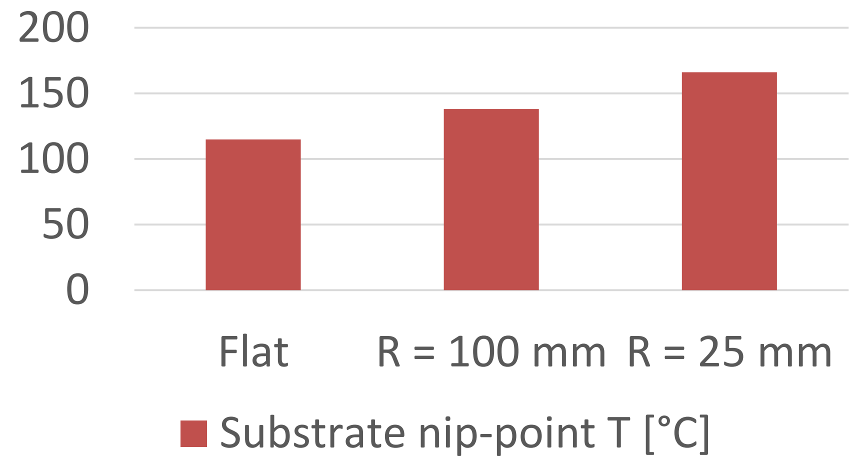
Thermal model output:
Surface temperature [°C]

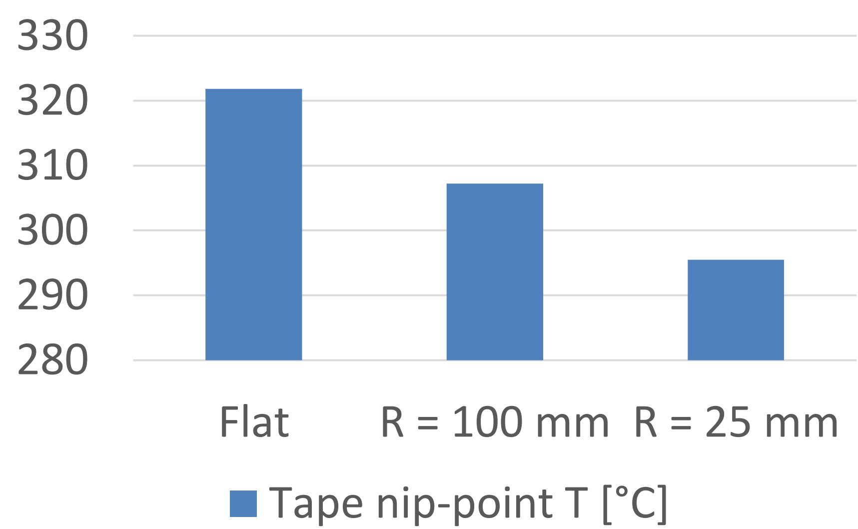


LATW effect of geometry



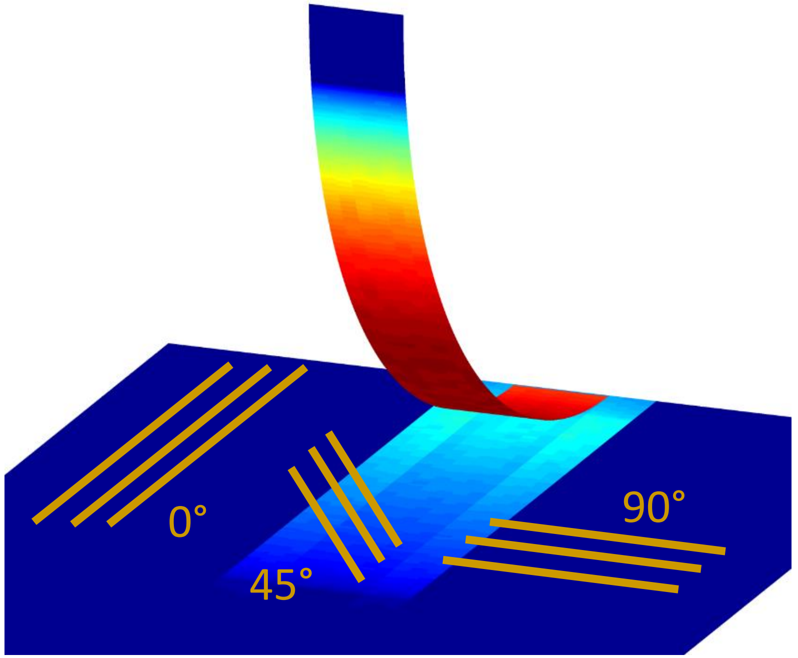
- Substrate curvature is important



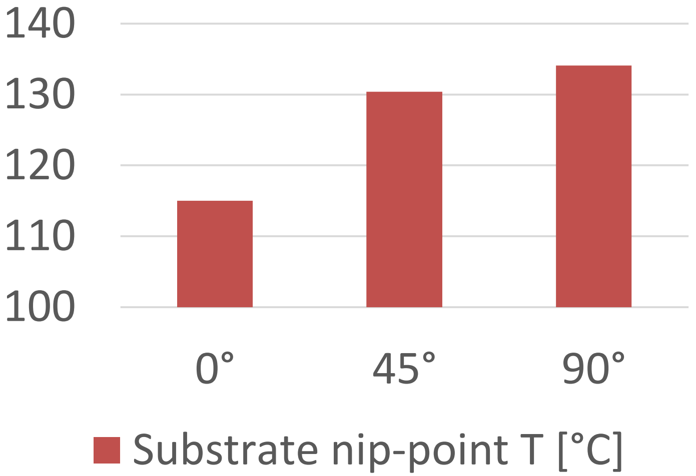


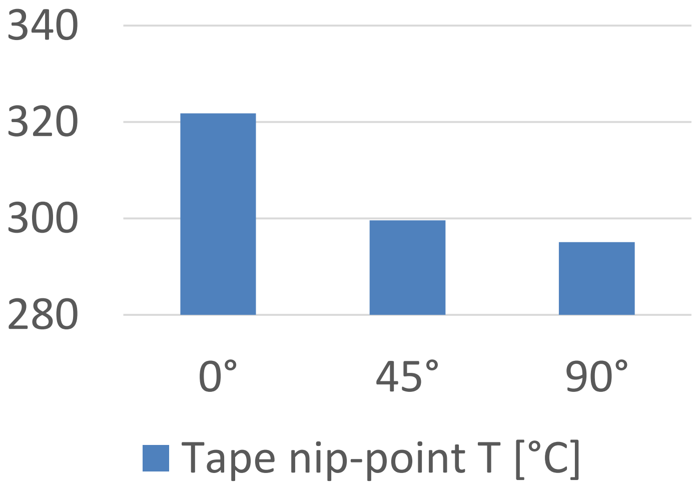
Reichardt, Baran and Akkerman. *ECCM17* (2016)
Zaami, Baran and Akkerman. *ESAFORM* (2017)

LATW effect of fiber orientation



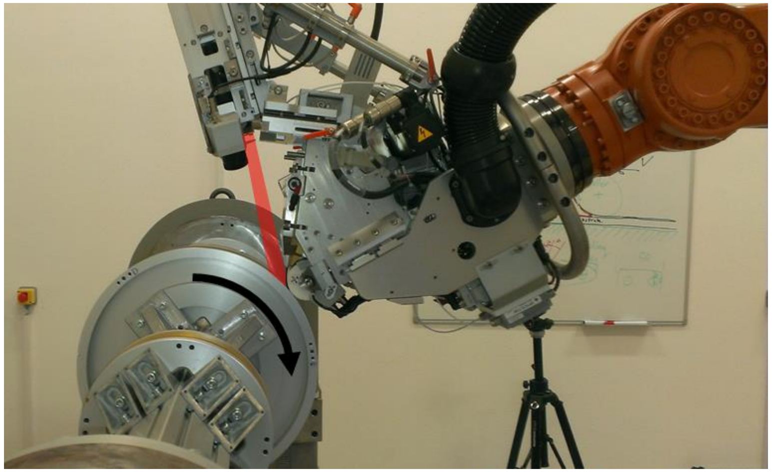
- Fibre orientation is important

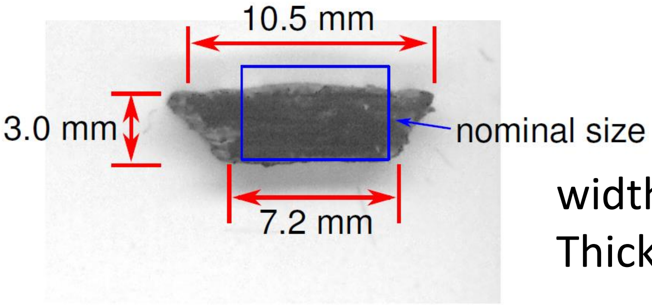


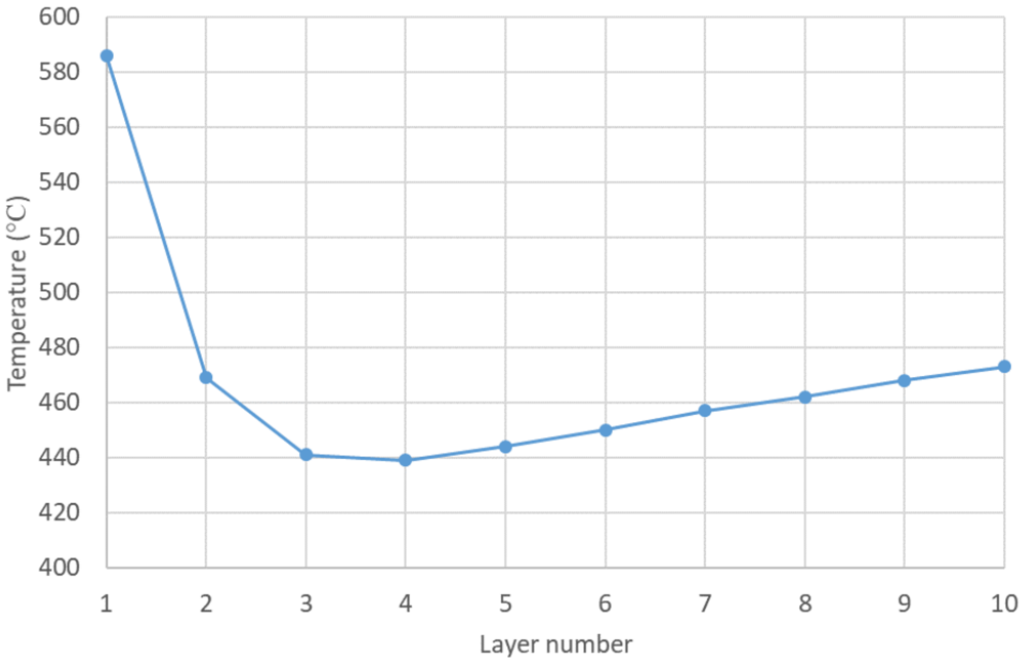


Reichardt, Baran and Akkerman. *ECCM17* (2016)

LATW tape widening

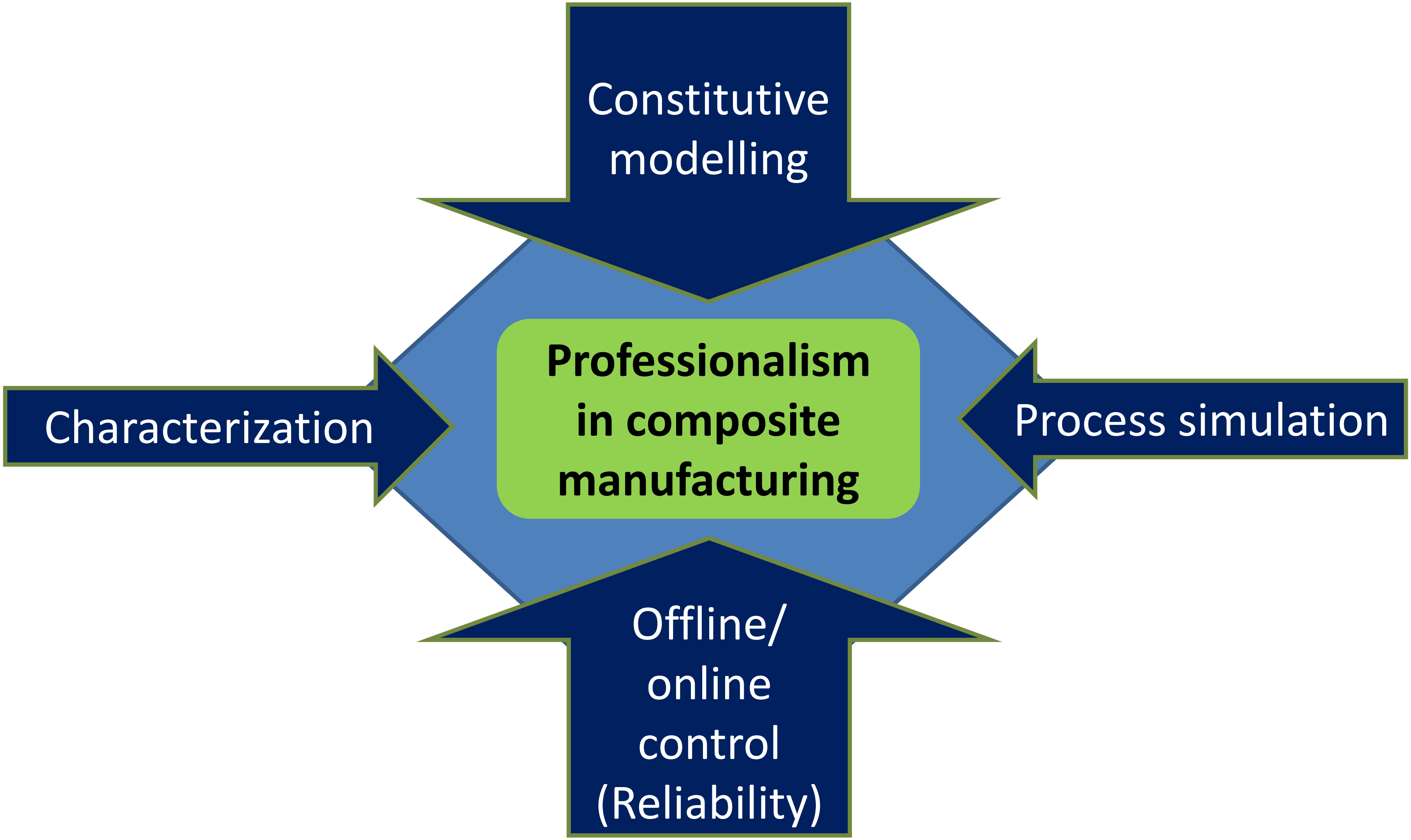






width = 6.35 mm
Thickness = 4.05 mm (27 layers)

Summary


Constitutive modelling
Characterization
Professionalism in composite manufacturing
Process simulation
Offline/ online control (Reliability)

Acknowledgments

Chair of production technology, University of Twente

Process Modelling Group, Technical University of Denmark

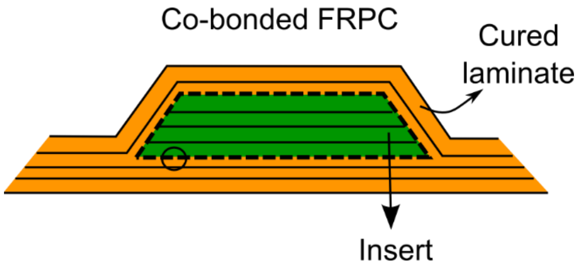
CMG group, KU Leuven


Thank you for your attention!

Recent activities

Pultrusion:
Heat transfer, curing, solid mechanics

Co-bonding/over infusion:
Interface bonding



Laser Assisted Tape Winding (Placement):
Laser optics, irradiation heat transfer