Simulation numérique des procédés d'élaboration des composites

Elaboration des CMO

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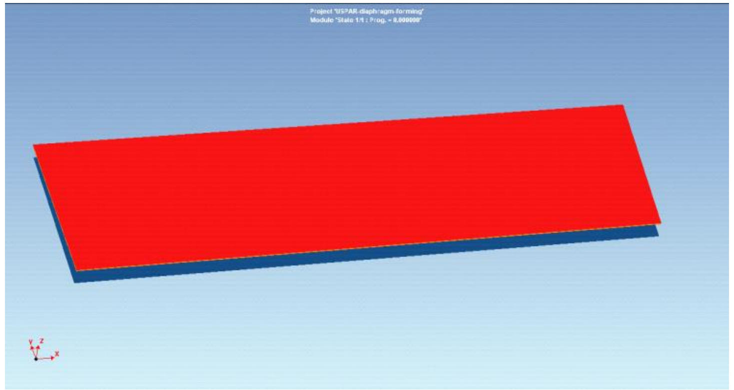
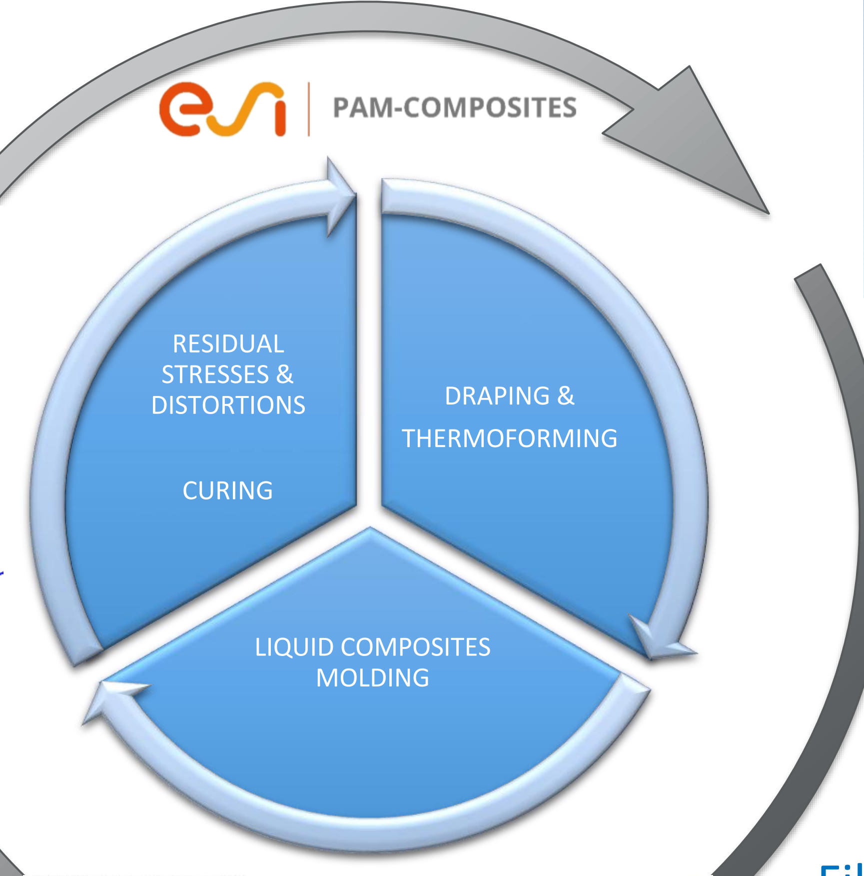
- **Cyril Dedieu** (Presenter)
- Arnaud Dereims
- Mustapha Ziane
- Marta Perez Miguel

ESI’s PAM-COMPOSITES

Compensated mold



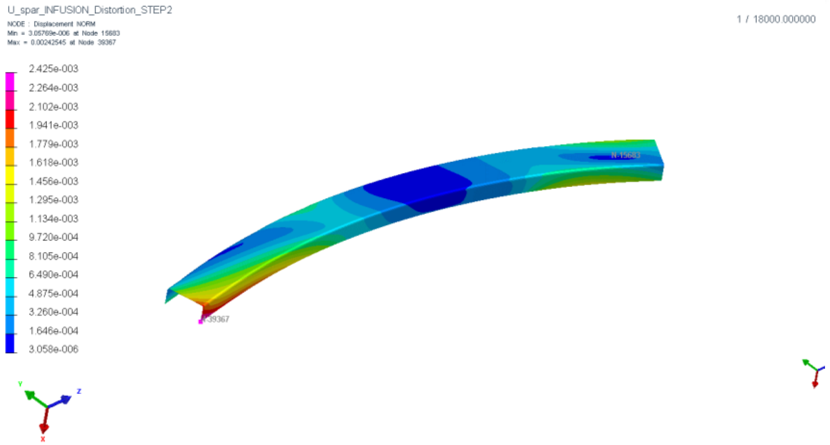


RESIDUAL STRESSES & DISTORTIONS

CURING

DRAPING & THERMOFORMING

LIQUID COMPOSITES MOLDING



Temperature history

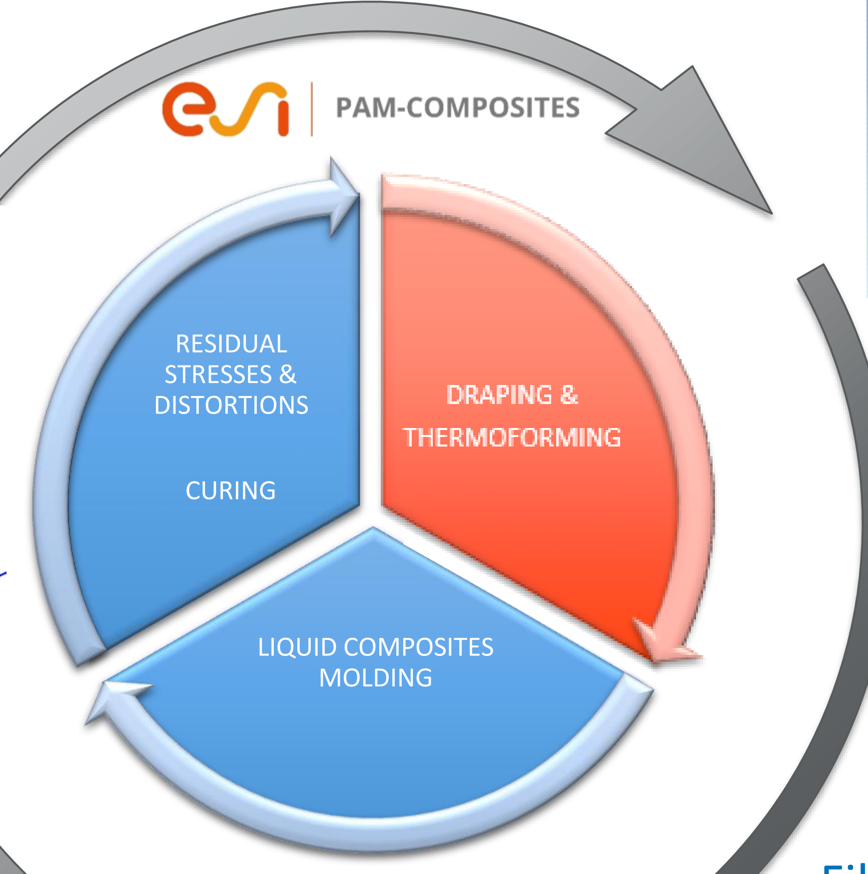
Degree of cure history

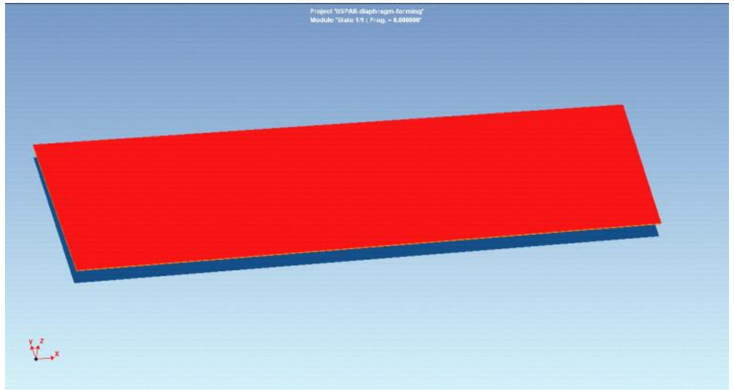
Fiber direction

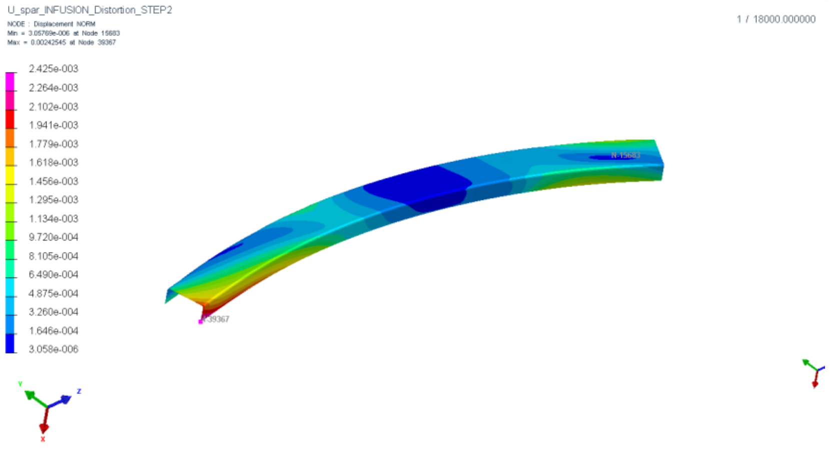
Thickness variation

ESI's PAM-COMPOSITES

Compensated mold







Temperature history

Degree of cure history

Fiber direction

Thickness variation

get it right®

DRAPING & THERMOFORMING

What for ?

Dry & pre-impregnated reinforcements can be draped over moulds that have complex shapes

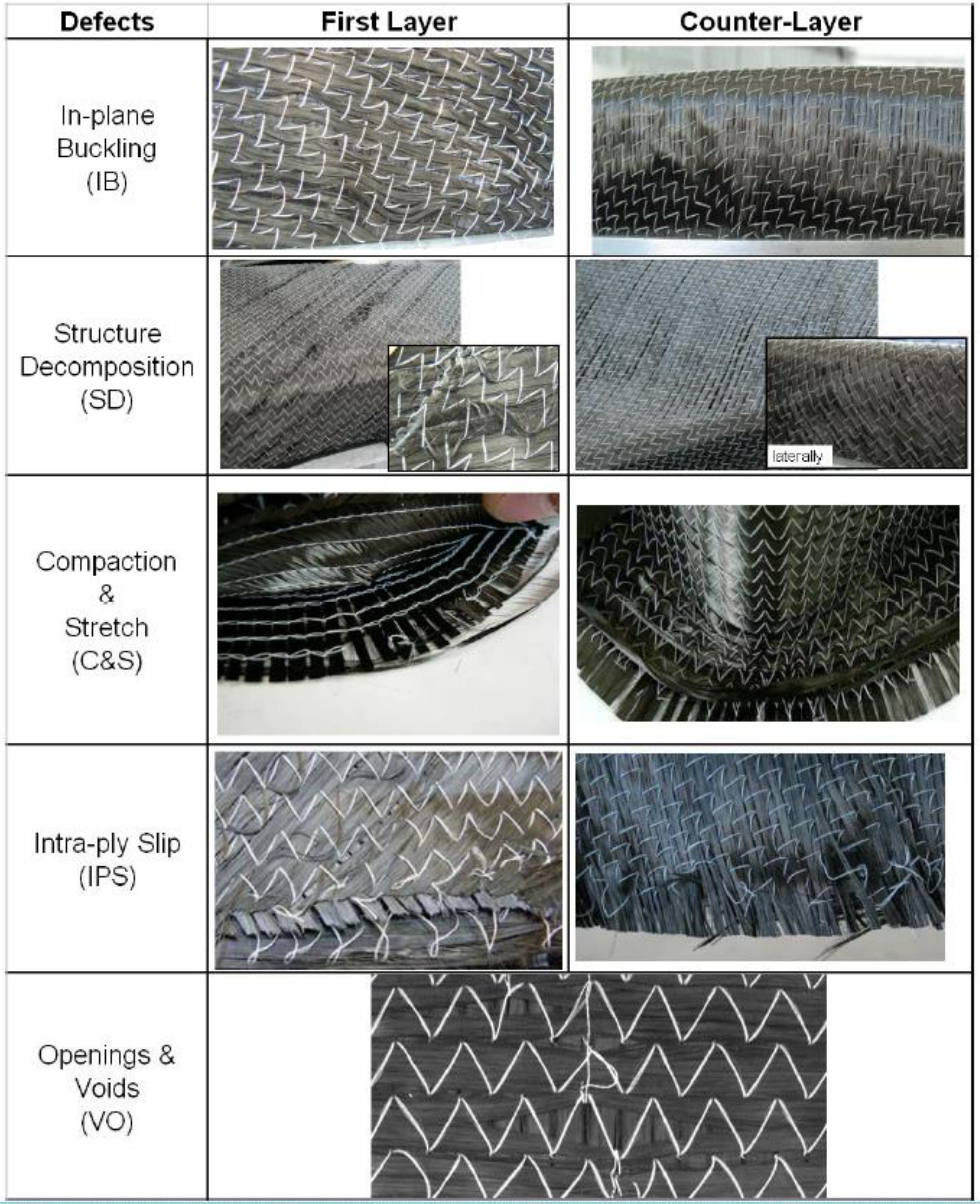
- Preforming of dry textiles (woven fabrics, NCF, UD, mats, tapes…)
- Draping of thermoset prepregs (woven fabrics, NCF, UD, mats, tapes…)
- Thermoforming of organosheets (woven fabrics, NCF, UD, mats, tapes…)

DRAPING & THERMOFORMING

Some issues


Unweaving

Examples of some **defects** related to dry textiles preforming (before LCM processes)



Defects	First Layer	Counter-Layer
In-plane Buckling (IB)		
Structure Decomposition (SD)		
Compaction & Stretch (C&S)		
Intra-ply Slip (IPS)		
Openings & Voids (VO)		

Poor part quality

Wrinkling

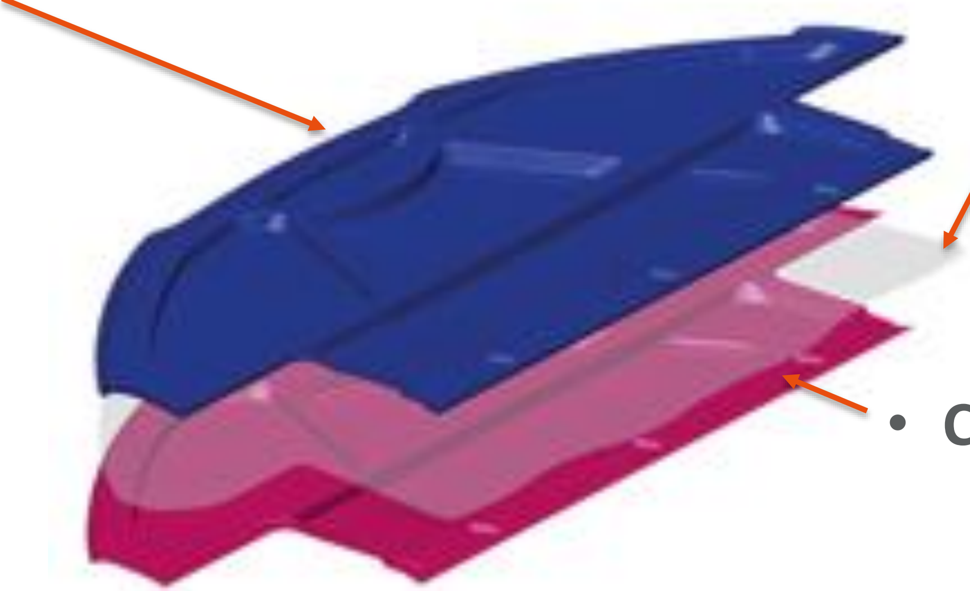
Unweaving

Examples of some defects related to dry textiles preforming (before **LCM processes**)

Need to know the **fibre content** and **fibre orientation**, that strongly influence the **permeability** field

DRAPING & THERMOFORMING

Need a simulation tool



- **Process parameters**
  - Tooling kinematics
  - Pressure cycle
  - Temperature cycle
  - Clamping definition
  - Ply definition
  - …

- **Composite material**
  - Material law
  - Stacking sequences
  - Initial flat pattern

- **Contact & friction**
  - Ply to ply
  - Tool to ply

To evaluate

Defects

- Wrinkles
- Bridging

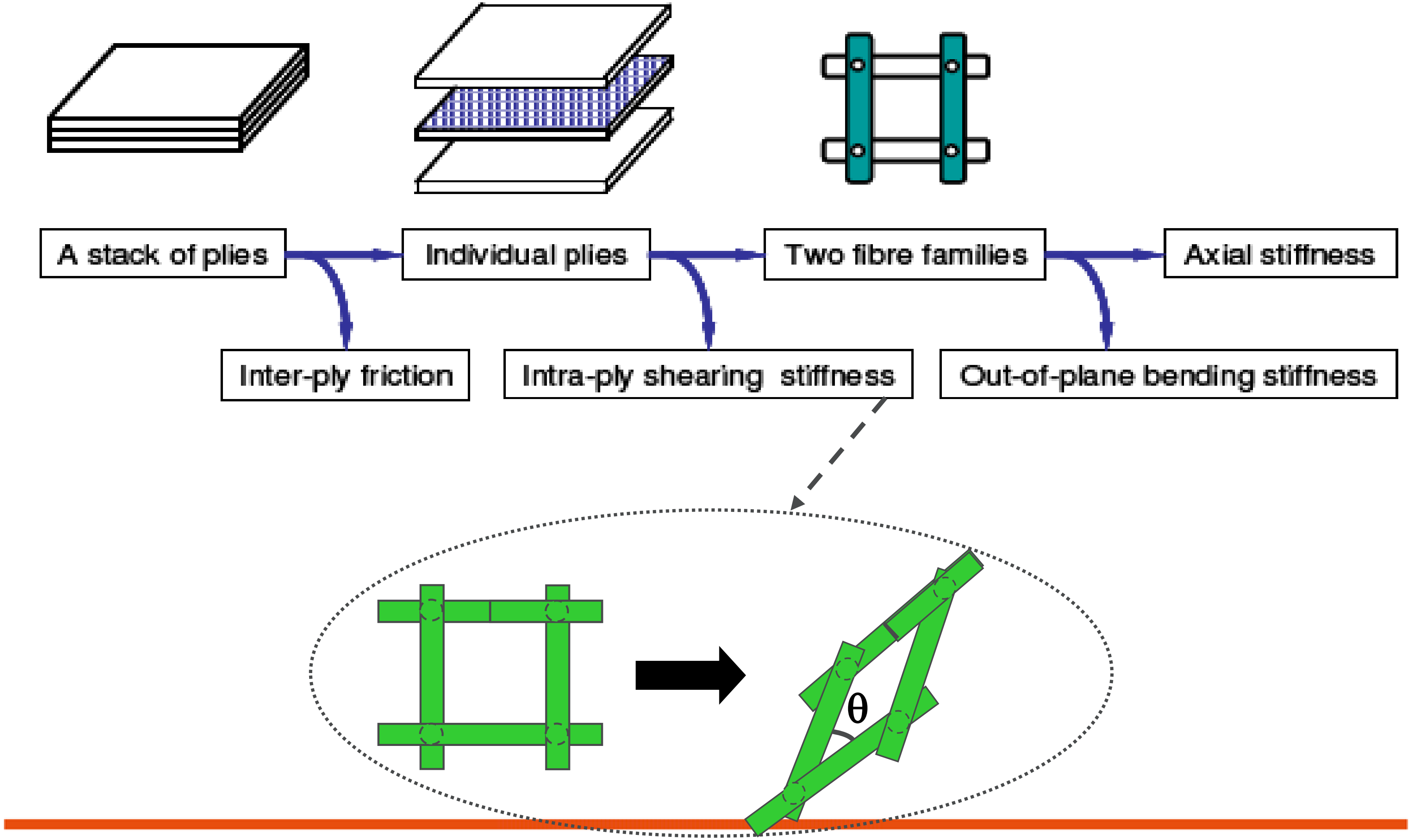
Quantities of interest

- Pressure on the mold
- Fibers orientation
- Fiber content
- Thickness distribution

DRAPING & THERMOFORMING

Composite material behaviour

Fabric Deformation Mechanisms



A stack of plies

Individual plies

Two fibre families

Axial stiffness

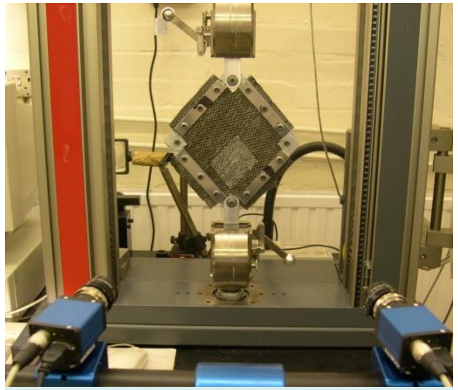
Inter-ply friction

Intra-ply shearing stiffness

Out-of-plane bending stiffness

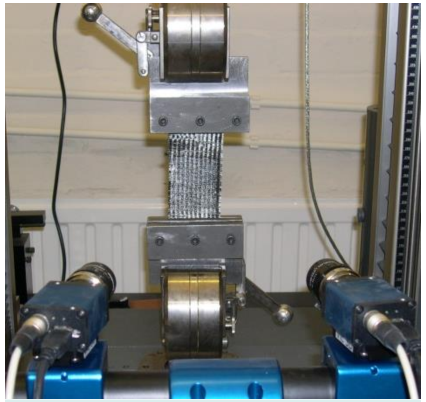
Material characterisation

Picture frame test



- Shear stiffness
- Interlocking angle

Tensile test



- E_{fibre}
- E_{stitch}

Friction test

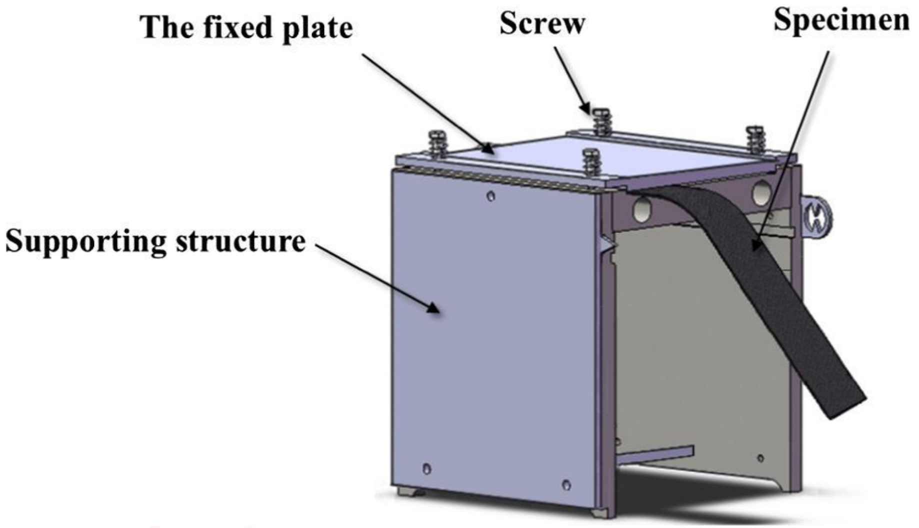
- Friction law

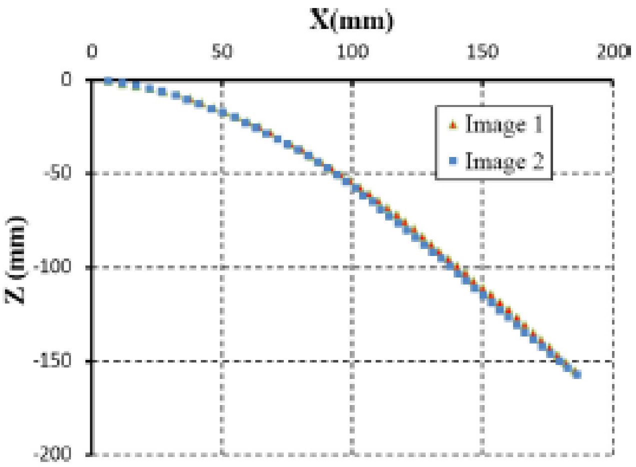
Each fabric = one material model

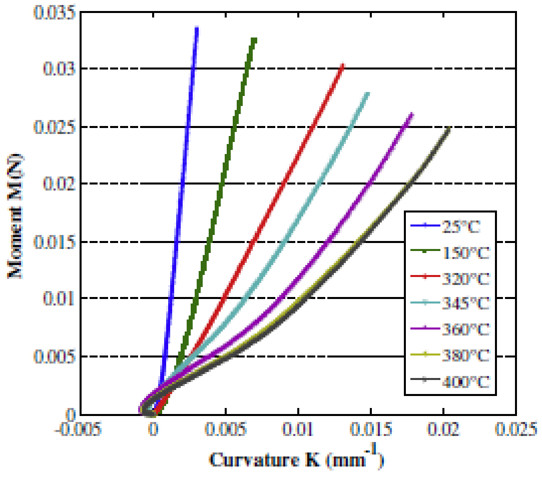
- Characterisation tests are **modelled** to fit **experimental data** in the material model

Material characterisation

- **Bending, can be temperature dependent**
  - Cantilever test
    - 2 fiber direction
    - 2 face position (positive and negative curvature)
    - 2 possibilities to use results:
      - Measure deflection and recover it with simulation
      - Use optical measurement that captures the deflection shape and discretize it with many points. Analytical tool is used to compute bending moment/stiffness and curvature on all these points for a direct input in PAM-FORM

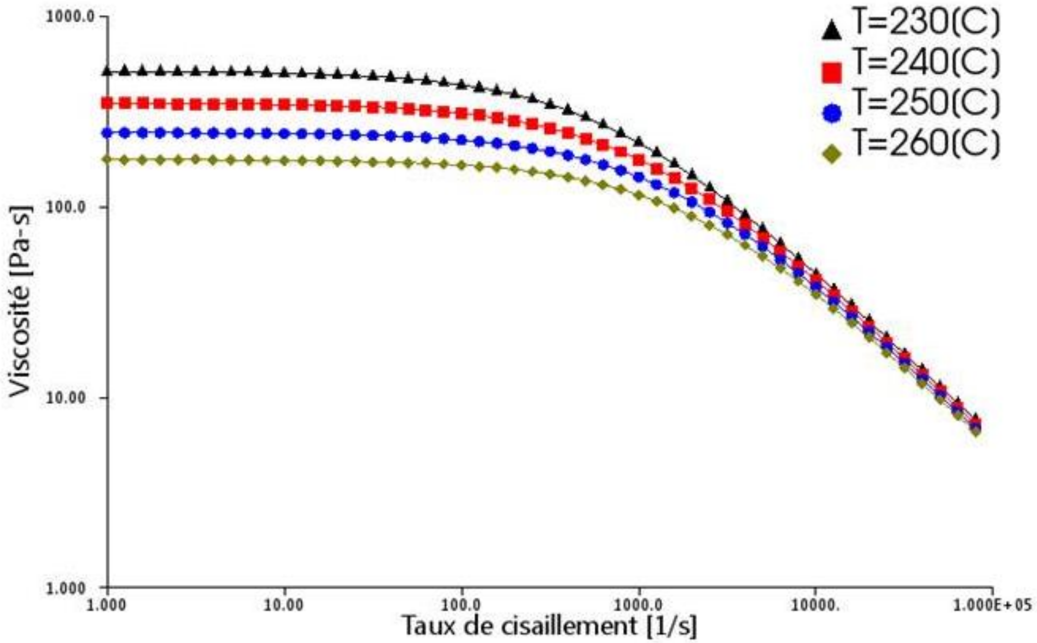






Material characterisation

- **Viscous friction, can be temperature dependent**
  - Dynamic viscosity (Pa.s) of resin for prepregs, or binder for dry fabrics
    - Rheometer equipment is used
    - Viscosity for thermoset prepregs and binder
    - Viscosity = f(shear rate) for thermoplastic prepregs



Material characterisation

- **Friction test, can be temperature dependent**

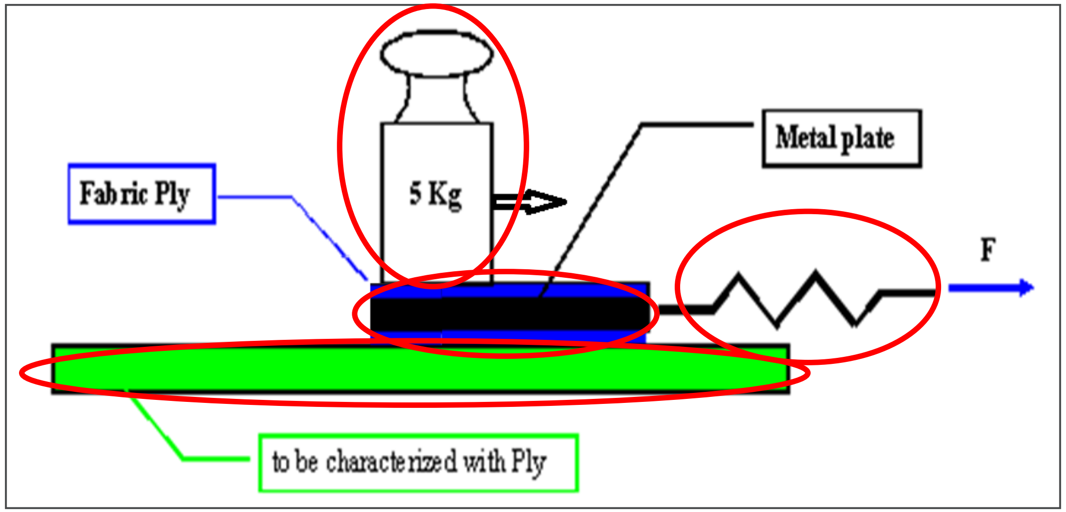


Figure 10 : Friction test trial

Balance spring

- ❖ Placed horizontally
- ❖ Manually extended until the plate begins to move.

Fabric

- ❖ Wrapped around a metal plate
- ❖ Dimensions: 100mm×175mm
- ❖ Placed on the surface of the metallic material

The static friction coefficient : $\mu_s = \frac{F_s}{W}$

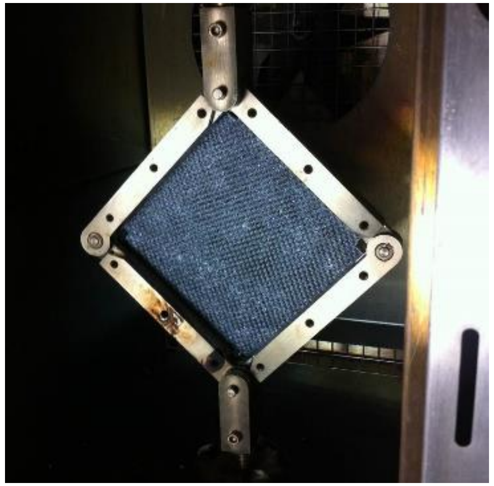
The dynamic friction coefficient: $\mu_d = \frac{F_d}{W}$

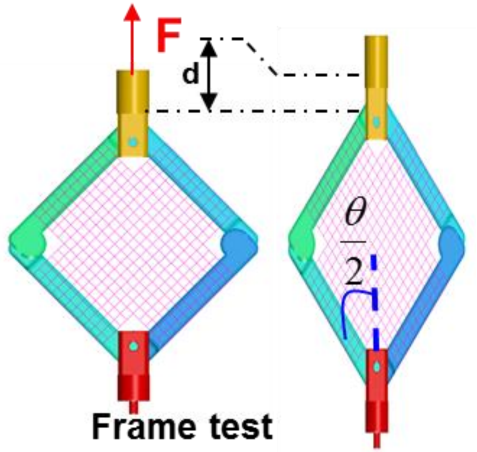
5 Kg Mass

- ❖ Placed upon the fabric

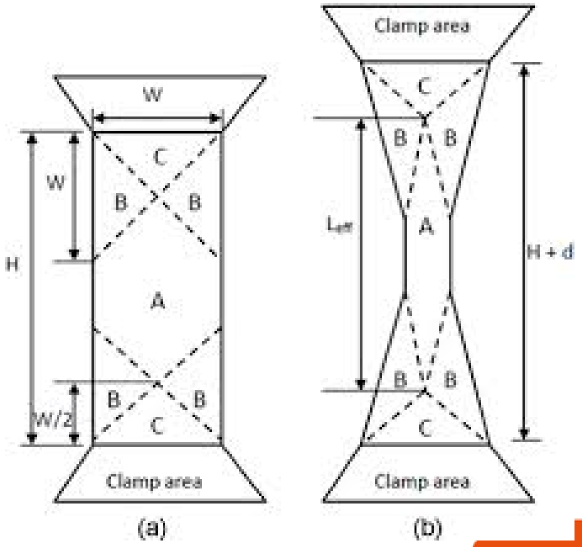
Material characterisation

- **In-plane shear (can be temperature dependent)**
  - Picture frame test
    - For NCF or woven fabric
      - NCF usually requires test for positive and negative shear since behavior is usually not symmetric due to stitching

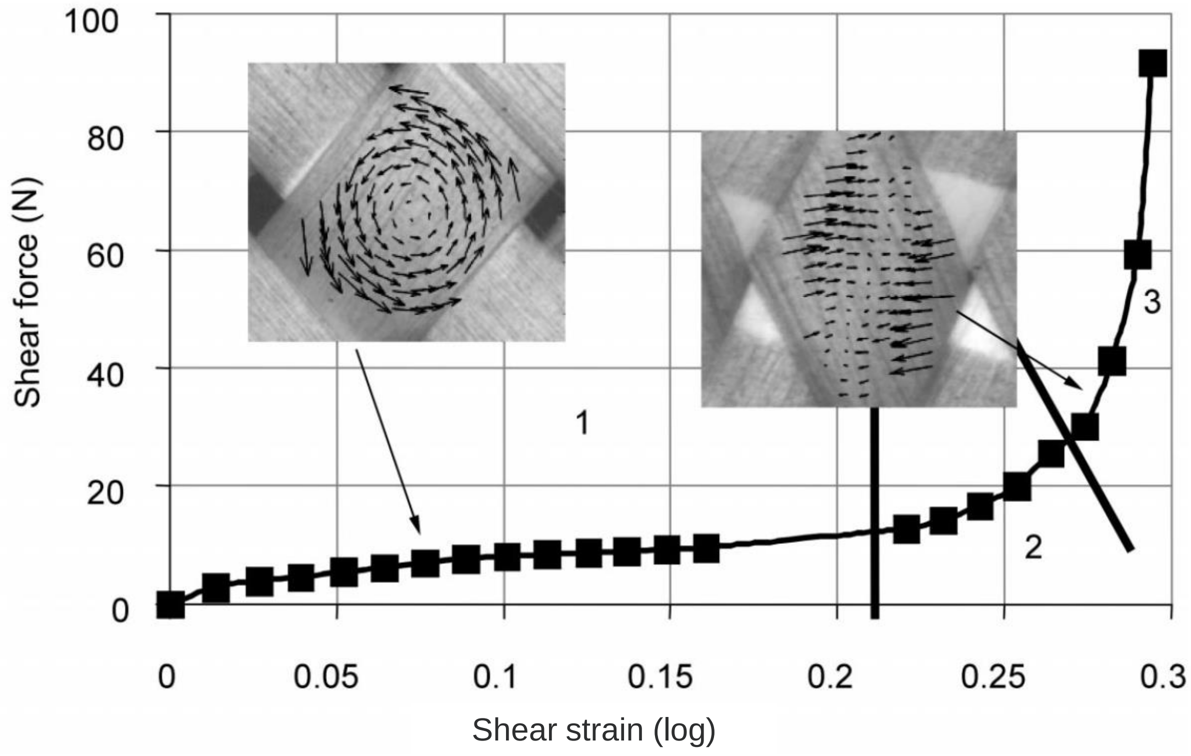




  - Bias extension test
    - Coupons with ratio of 3 between length and width
    - For woven fabric



Material characterisation

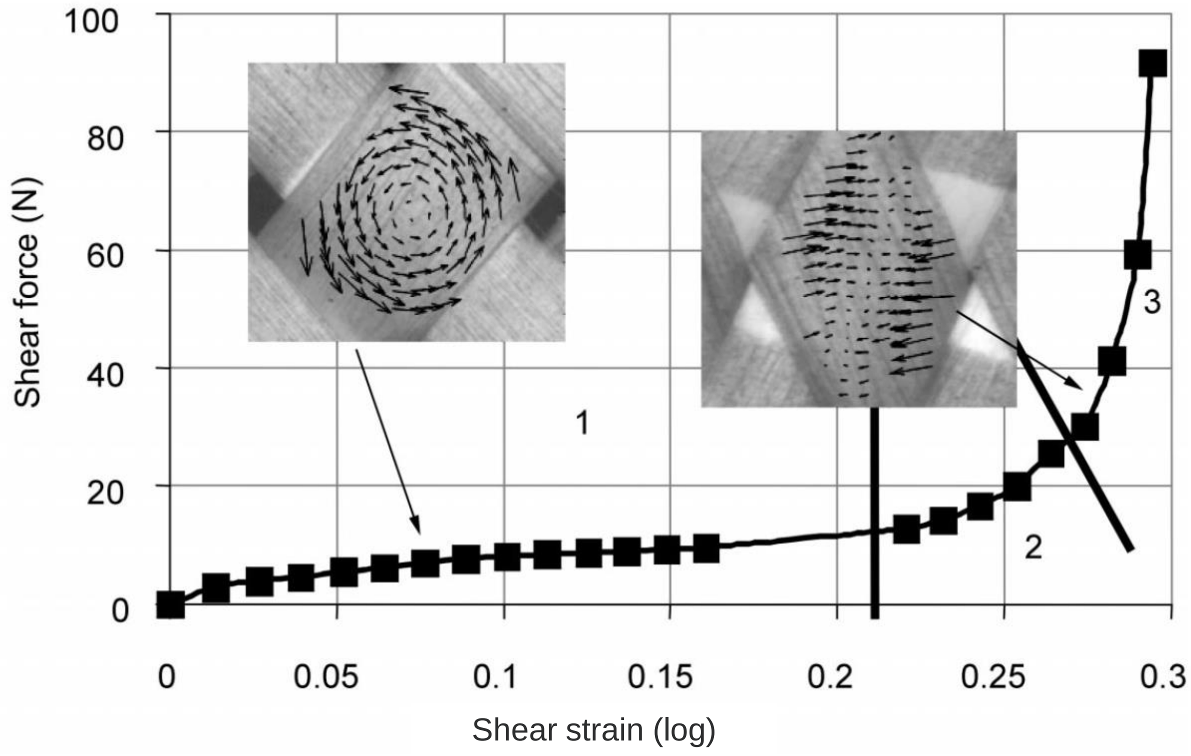


3.16 Shear curve and optical analysis (Dumont, 2003). *(2)*

- **Picture frame test - glass plain weave**
  - Strain computed with image correlation
  - **Zone 1** : small load - yarn submitted to rotation
  - Shear-locking angle: beginning of zone 2
  - The contact networks develop, partial (**Zone 2**) and total (**Zone 3**) lateral compression

(2) Composites forming technologies. Chapter 3: Finite element analysis of composite forming, P. Boisse.

Material characterisation



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- **MULTISCALE** nature of the material

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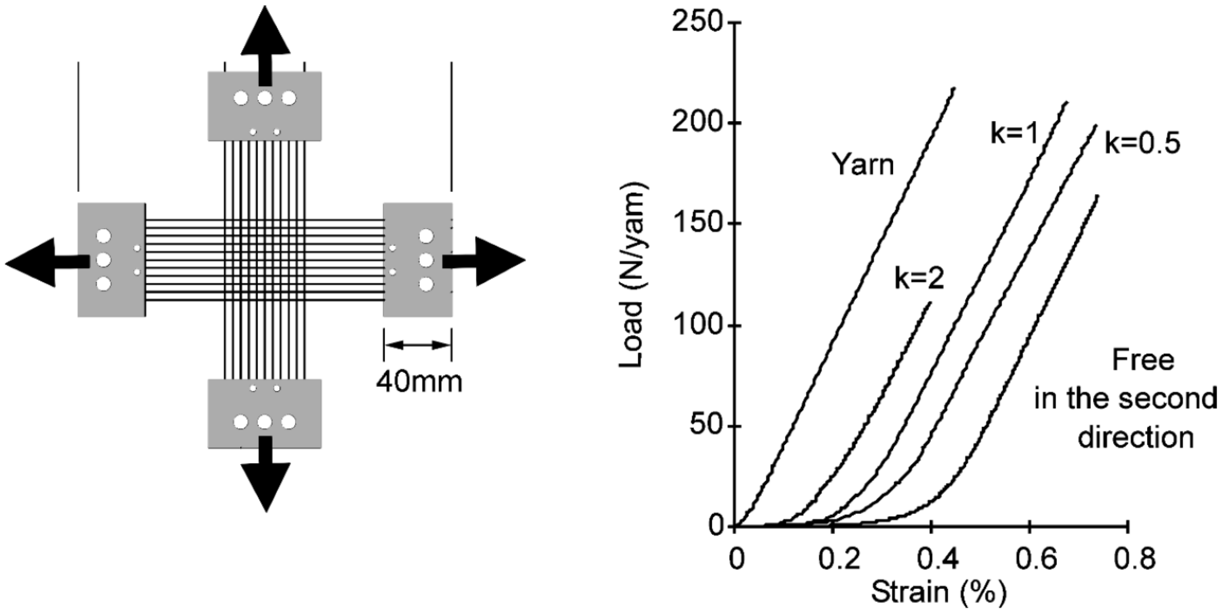
Material characterisation



* *3.13* Cross shape specimen and tensile curves for different warp weft strain ratios k.

- **Biaxial tensile test**
  - Different strain ratio between warp and weft directions
  - **Non-linear** response, **coupling** between both directions

- **MULTISCALE** nature of the material

* *Composites forming technologies. Chapter 3: Finite element analysis of composite forming, P. Boisse.*

DRAPING & THERMOFORMING

Models & Constitutive law*

Discrete methods

- Mapping - geometrical models, fishnet
- Particle based methods - interacting **particles** via an energy function
- Truss based methods - periodic arrangements of fibre bundles

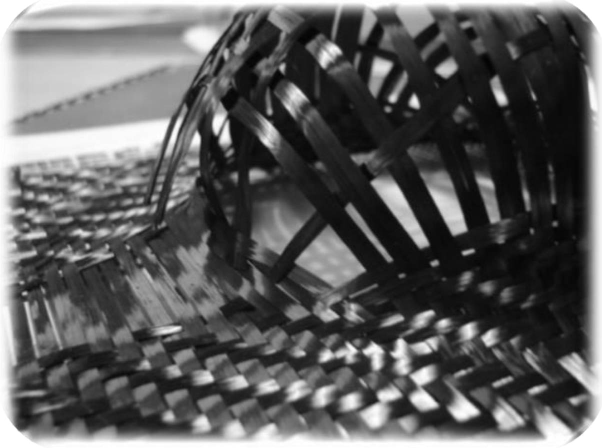
Continuous methods

- Elastic - many models in the literature, **solid**
- Viscous models - inextensible **fluid**
- Both

** Composites forming technologies. Chapter 2: Constitutive modelling for composite forming. R. Akkerman, EAD. Lamers.*

Continuous approach

Continuous approach



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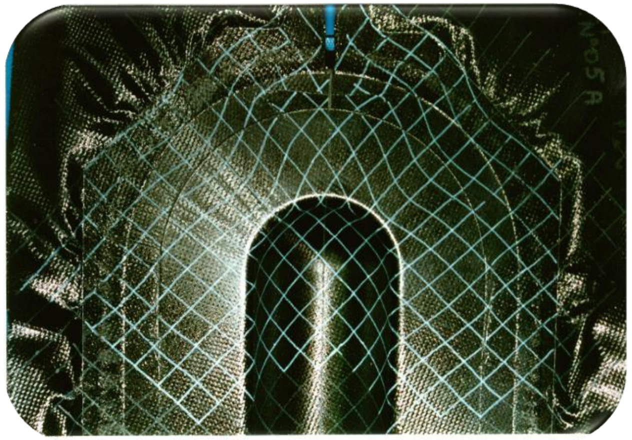


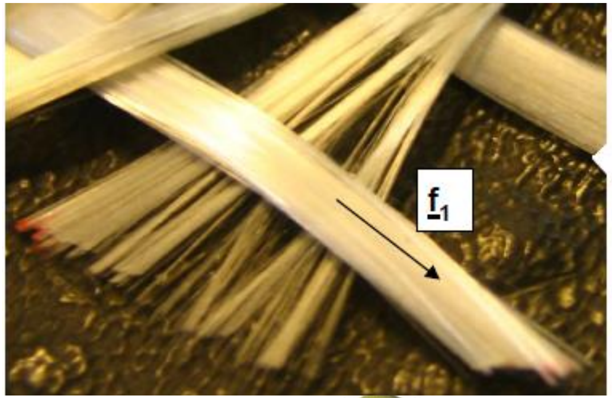
HYPOELASTIC MODEL

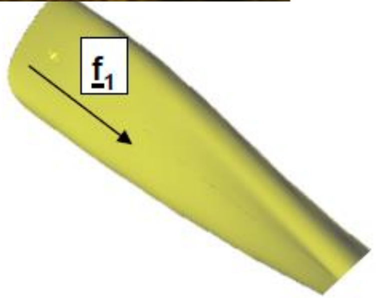
Hypoelastic models

- Constitutive law (fibrous reinforcements):

$$\boldsymbol{\sigma}^{\nabla} = \mathbb{C} : \mathbf{D}$$

$\mathbf{D}$: strain rate tensor
$\boldsymbol{\sigma}^{\nabla}$: objective stress rate tensor

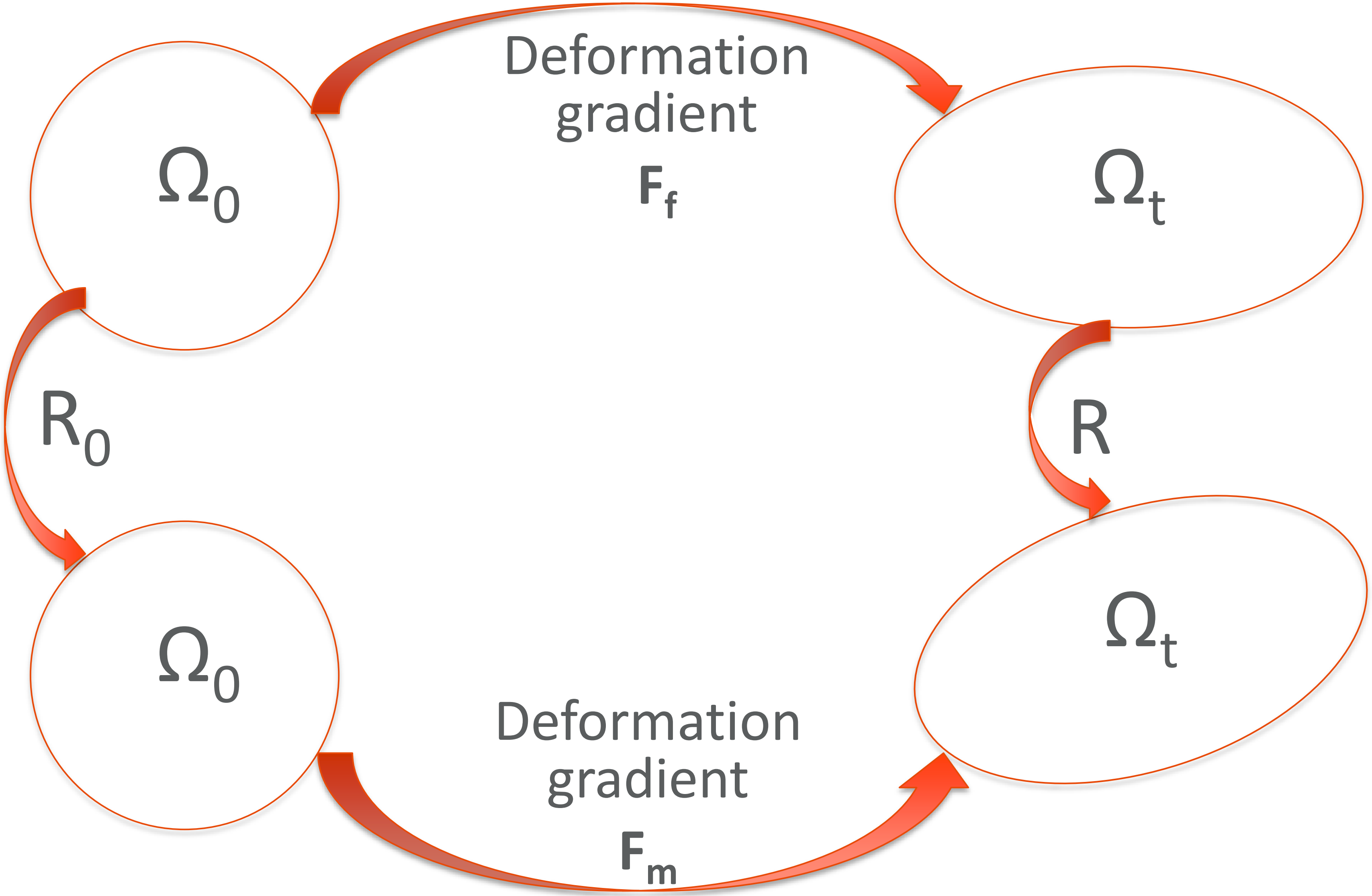




✓ Objectivity

  - Frame invariance principle: the stress rate should not depend on the frame definition !
  - A rigid body motion should not imply a stress rate

Hypoelastic models



Fixed frame

R_f

Another frame

R_m

(rigid body motion // R_f)

(1) Visco-élasticité des polymers fondus. Cours de DEA, Rapport interne n°146, 1993. ENS Cachan, L. Chevalier, A. Poitou.

Hypoelastic models

Fixed frame

R_f

$$\begin{tikzcd}
\Omega_0 \arrow[r, bend left, "F_f"] \arrow[d, bend right, "R_0"] & \Omega_t \arrow[d, bend right, "R"] \\
\Omega_0 \arrow[r, bend right, "F_m"'] & \Omega_t
\end{tikzcd}$$

$$F_m = R F_f R_0^T$$

Another frame

R_m

(rigid body motion // R_f)

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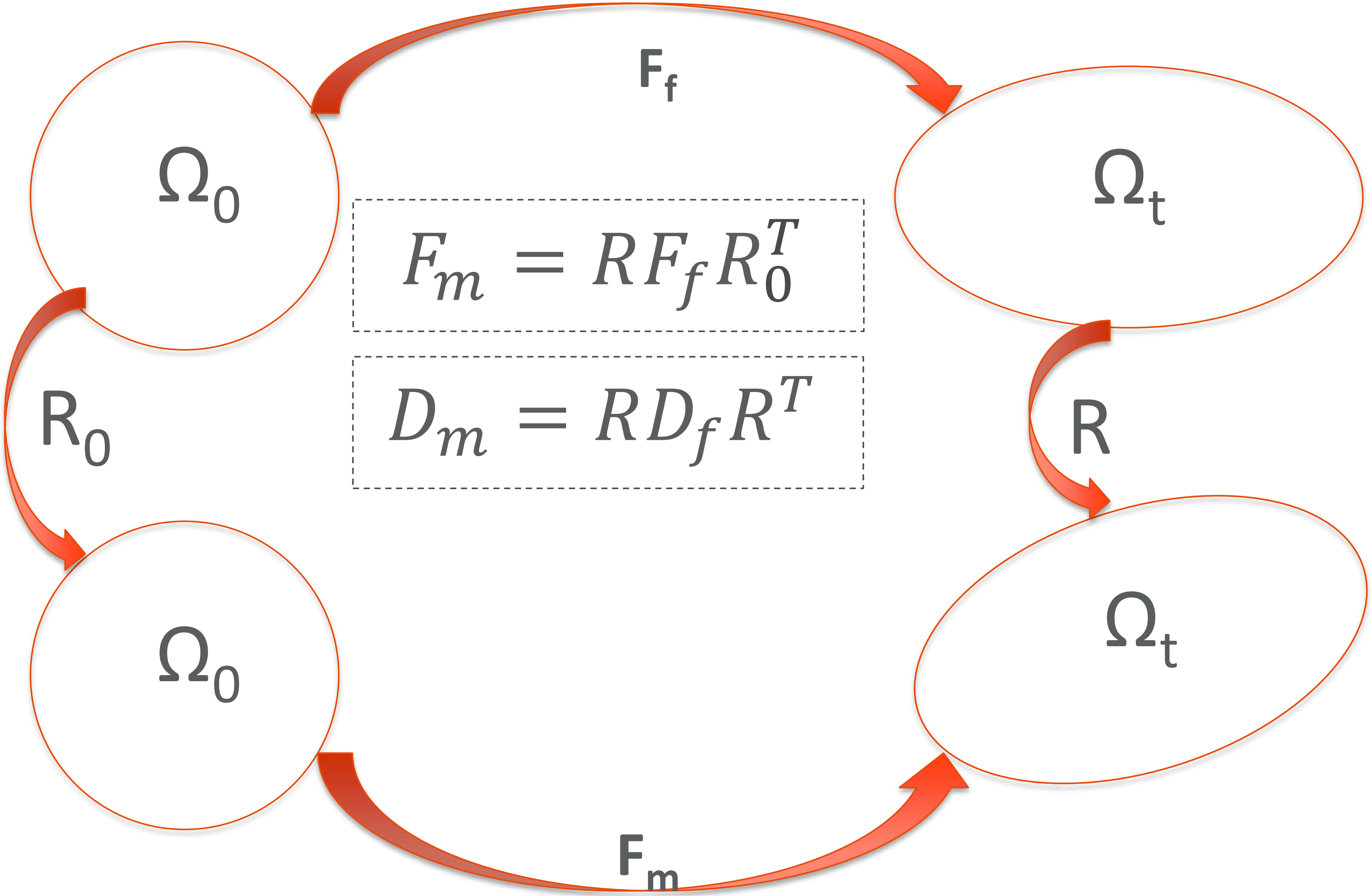
Hypoelastic models



Fixed frame

R_f

Ω_0

F_f

Ω_t

$$F_m = R F_f R_0^T$$

$$D_m = R D_f R^T$$

R_0

R

Another frame

R_m

(rigid body motion // R_f)

Ω_0

Ω_t

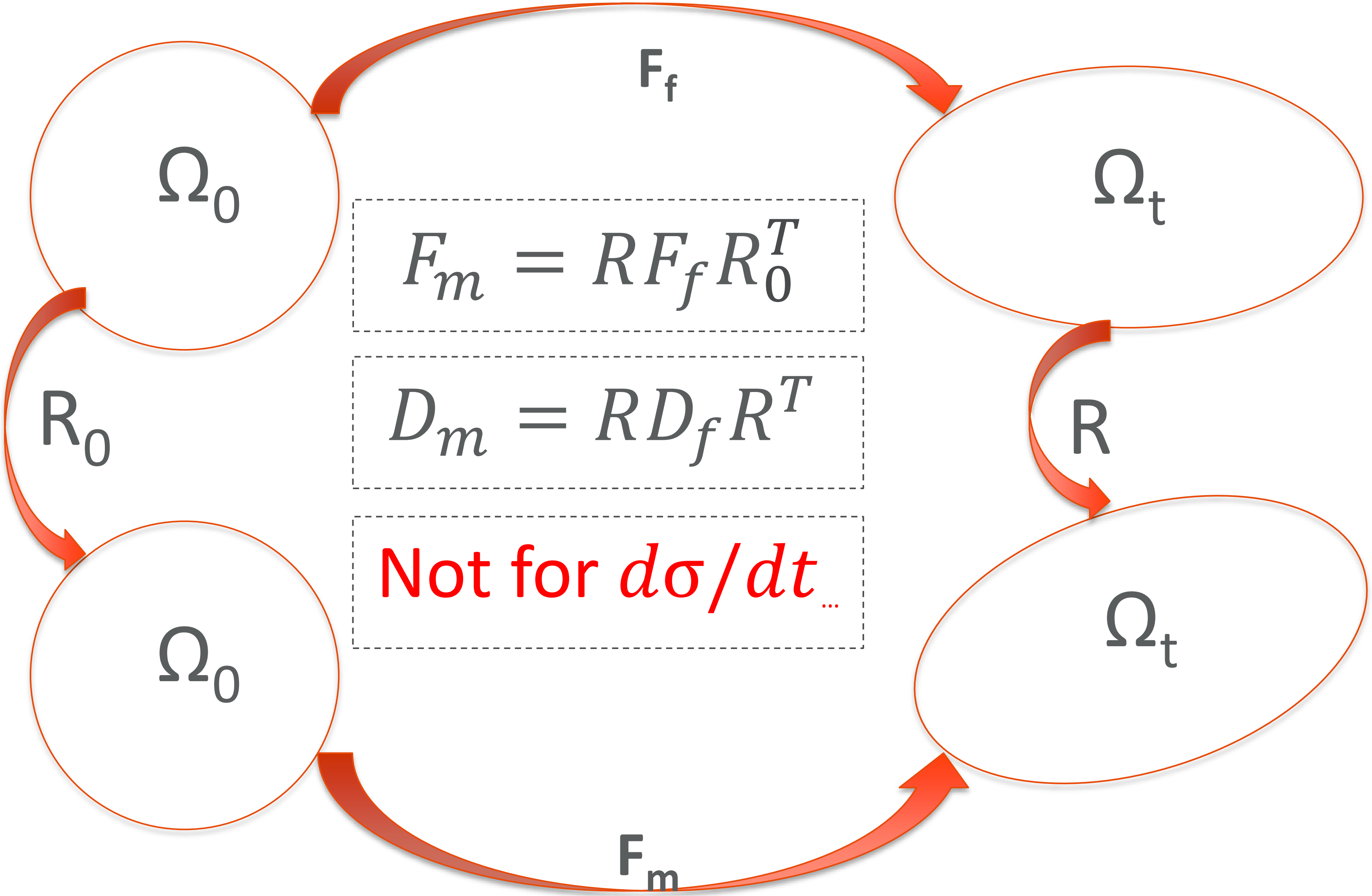
F_m

(1) Visco-élasticité des polymers fondus. Cours de DEA, Rapport interne n°146, 1993. ENS Cachan, L. Chevalier, A. Poitou.

Hypoelastic models

Fixed frame

R_f



Ω_0

$\mathbf{F_f}$

Ω_t

R_0

R

$$F_m = R F_f R_0^T$$

$$D_m = R D_f R^T$$

Not for $d\sigma/dt$ …

Ω_0

Ω_t

$\mathbf{F_m}$

Another frame

R_m

(rigid body motion // R_f)

(1) Visco-élasticité des polymers fondus. Cours de DEA, Rapport interne n°146, 1993. ENS Cachan, L. Chevalier, A. Poitou.

Hypoelastic models

Classic objective derivatives (Jaumann, Green-Nagdhi, …)

$$\boldsymbol{\sigma}^{\nabla} = \dot{\boldsymbol{\sigma}} + \boldsymbol{\sigma}\cdot\boldsymbol{\Omega} - \boldsymbol{\Omega}\cdot\boldsymbol{\sigma}$$

With: $\boldsymbol{\Omega} = \dot{\mathbf{Q}}.\mathbf{Q}^T$ (rigid body rotation)

$\mathbf{Q}$: corotational frame rotation (rigid body rotation)

$\dot{\mathbf{Q}}$: rotation rate

- Consequences
  - Orthotropic axes updated by the rotation **Q**
  - But **Q** is not exactly the local material rotation, the orthotropic axes are not aligned with the fibre direction
  - When shear deformation is important the orthotropic axes are far from being aligned with the fibre direction
  - This is why non-orthogonal model have been developed*

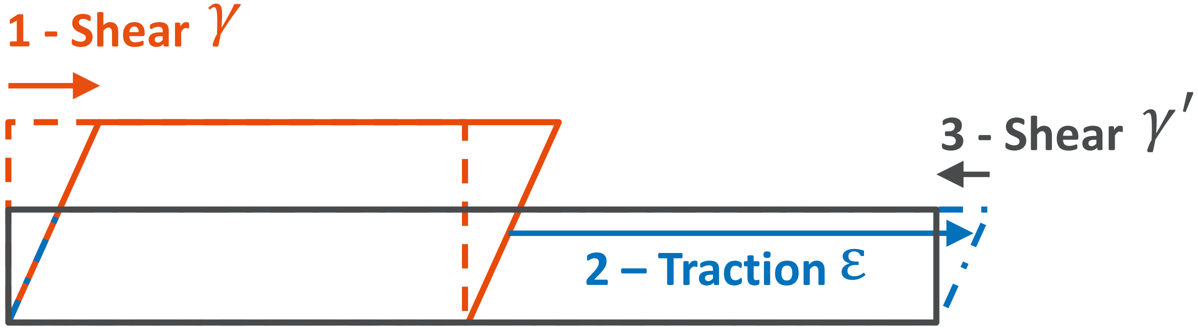
** Simulation and tomography analysis of textile composite reinforcement deformation at the mesoscopic scale. Badel et al. 2009.*

Hypoelastic models

- Constitutive law (fibrous reinforcements):

$$\boldsymbol{\sigma}^{\nabla} = \mathbb{C} : \mathbf{D}$$

Why **hypo**elastic ?



It can be shown that the stress state depends on the **loading path** (1)

- ❖ The initial configuration can be recovered **without** or **with** stresses
- ❖ The stresses can be cancelled without recovering the initial configuration

- Constitutive law (fibrous reinforcements):

$$\boldsymbol{\sigma}^{\nabla} = \mathbb{C} : \mathbf{D}$$

Why **hypo**elastic ?

It can be shown that the stress state depends on the **loading path** (1)

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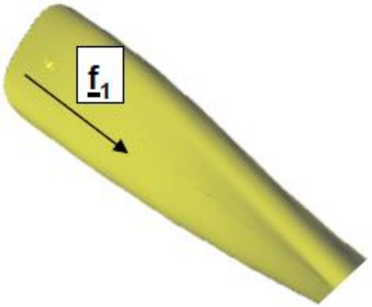
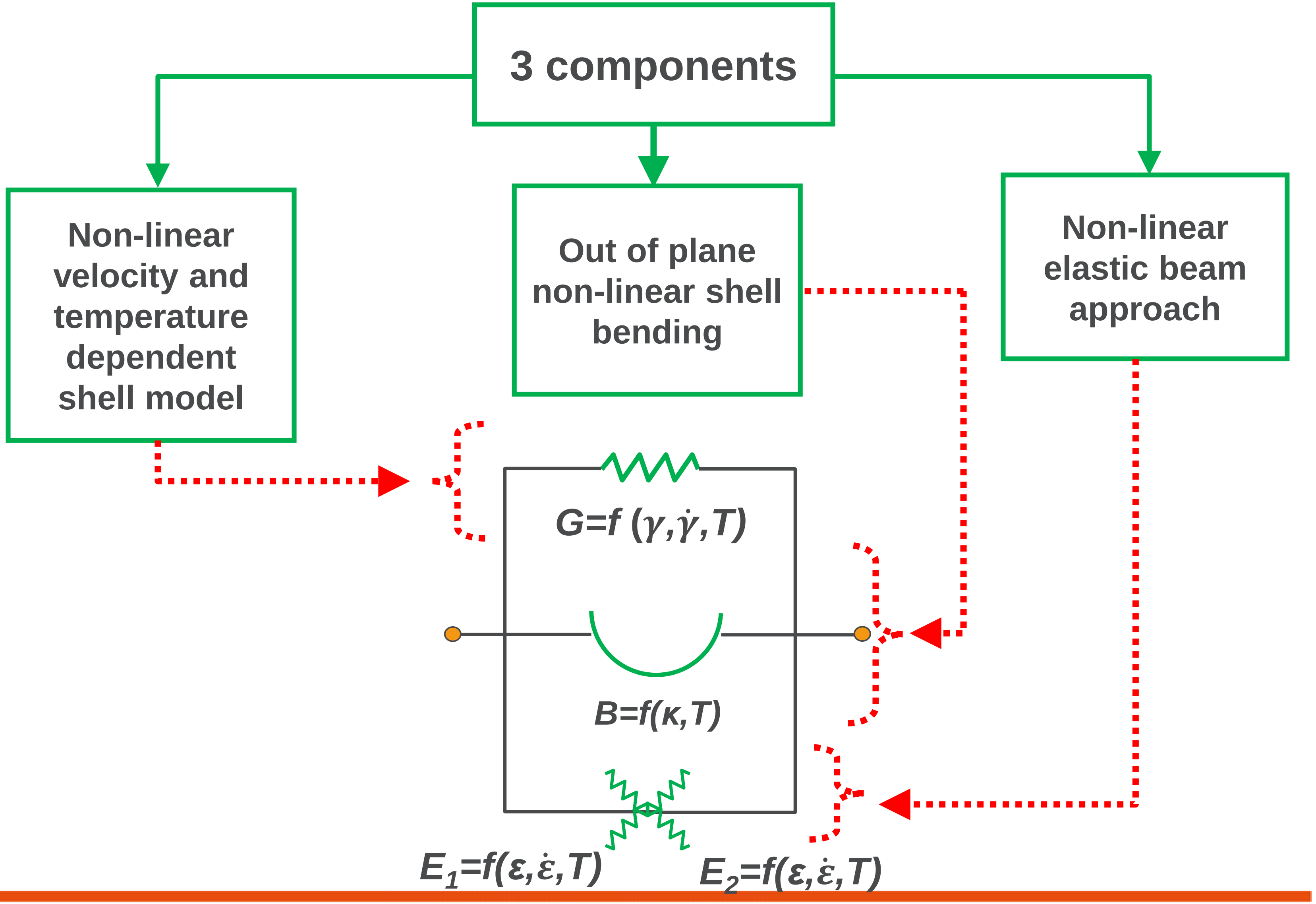


(1) Visco-élasticité des polymers fondus. Cours de DEA, Rapport interne n°146, 1993. ENS Cachan, L. Chevalier, A. Poitou.

Approche continue



3 components

Non-linear velocity and temperature dependent shell model

Out of plane non-linear shell bending

Non-linear elastic beam approach

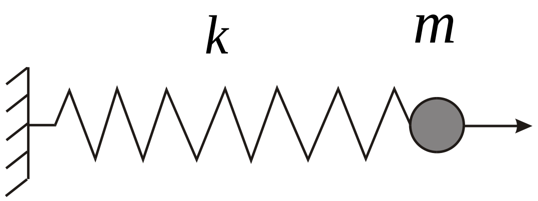
$G=f(\gamma,\dot{\gamma},T)$

$B=f(\kappa,T)$

$E_1=f(\varepsilon,\dot{\varepsilon},T)$

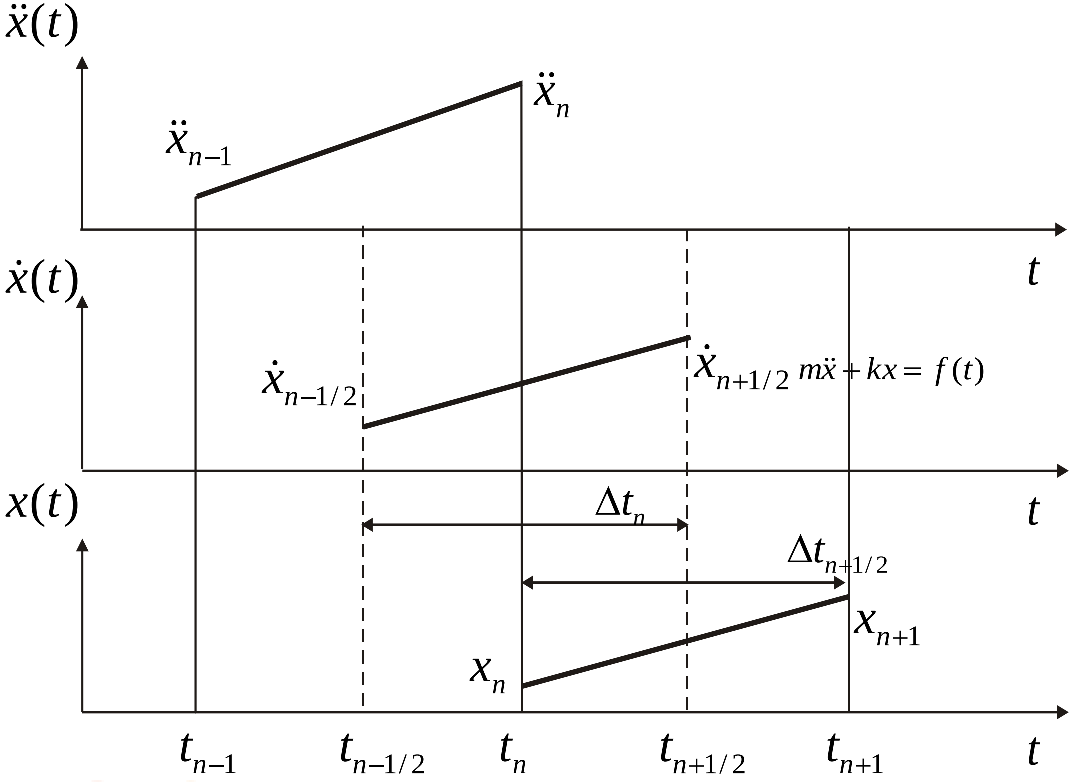
$E_2=f(\varepsilon,\dot{\varepsilon},T)$

The explicit integration scheme



x: displacement

$$m\ddot{x}_n + kx_n = f_n(t)$$



(1) $\ddot{x}_n = m^{-1}(f_n - kx_n)$

(2) $\dot{x}_{n+1/2} = \dot{x}_{n-1/2} + \Delta t_n \ddot{x}_n$

(3) $x_{n+1} = x_n + \Delta t_{n+1/2} \dot{x}_{n+1/2}$

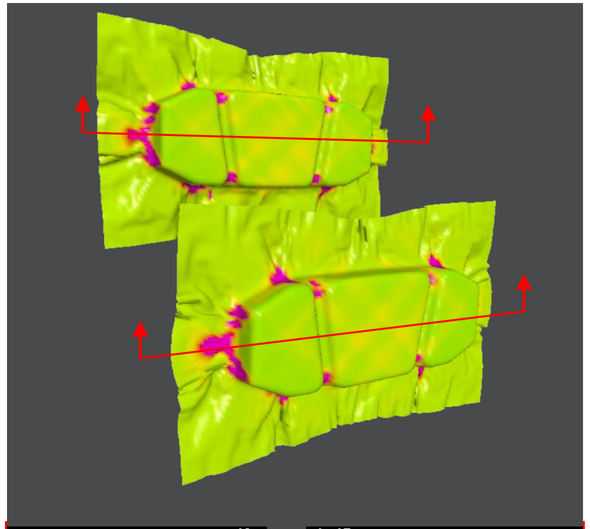
DRAPING & THERMOFORMING

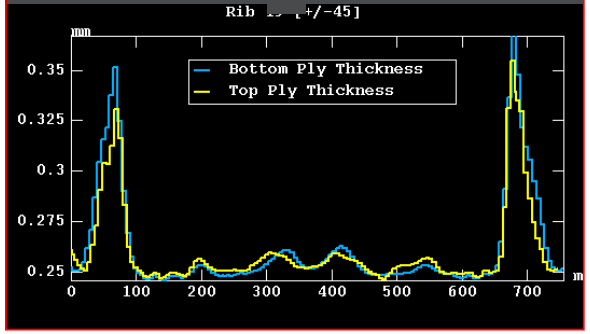
Simulations Examples

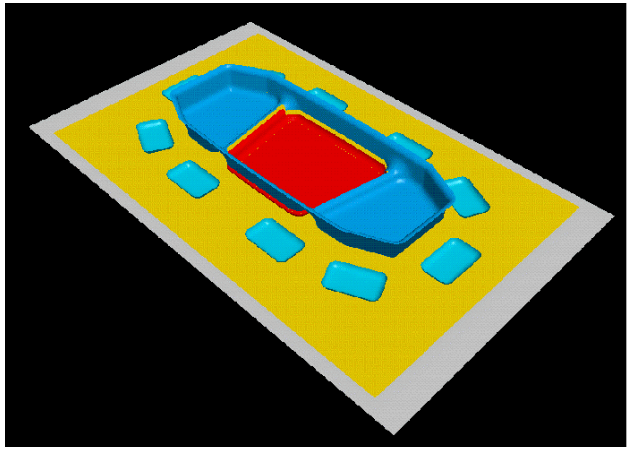
ESI PAM-COMPOSITES

Thermoplastic forming application: **Wing box thermoforming**

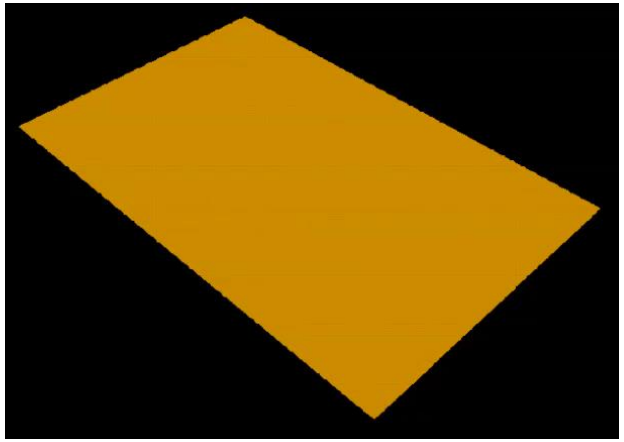
Thickness per ply





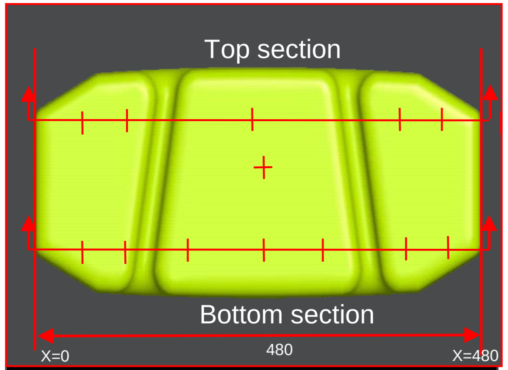


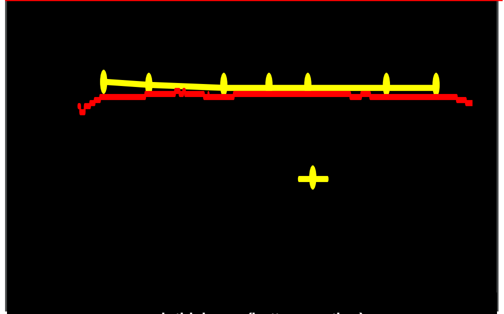
Process animation

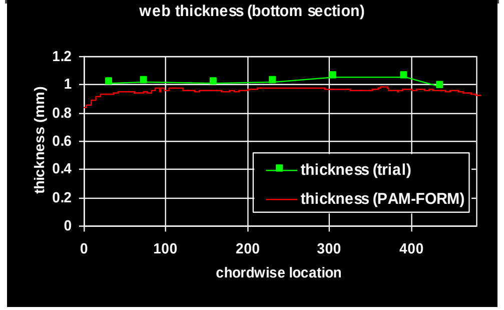


Laminate thickness

Ultrasonic measurement versus simulation







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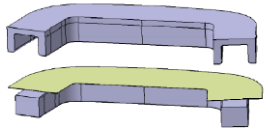
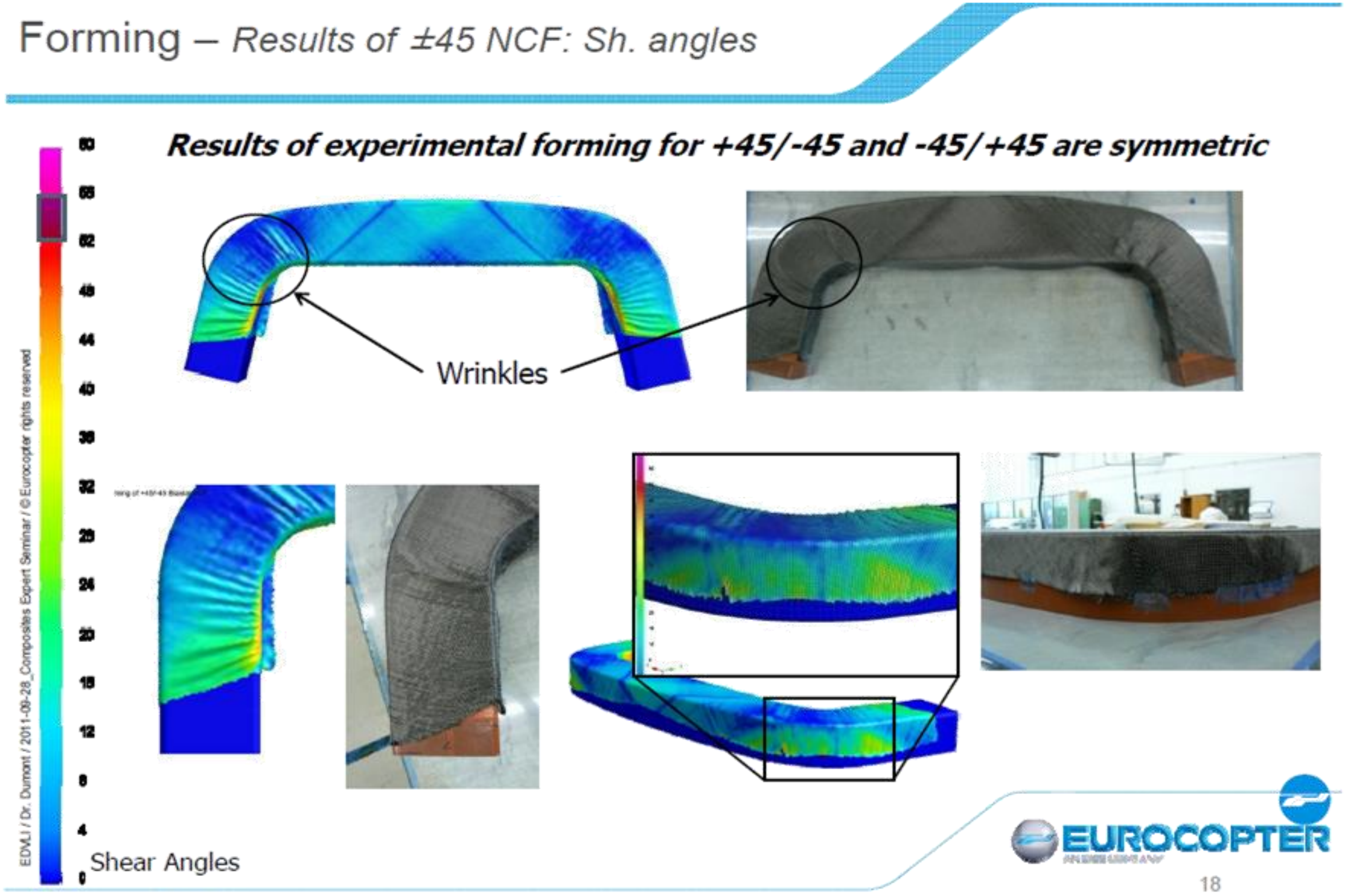

Stamping tools and reinforcement

Preforming application: **Fabric shearing and wrinkle prediction**


Forming – *Results of ±45 NCF: Sh. angles*

Results of experimental forming for +45/-45 and -45/+45 are symmetric

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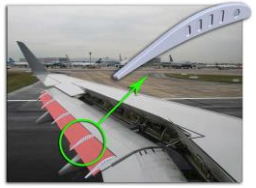
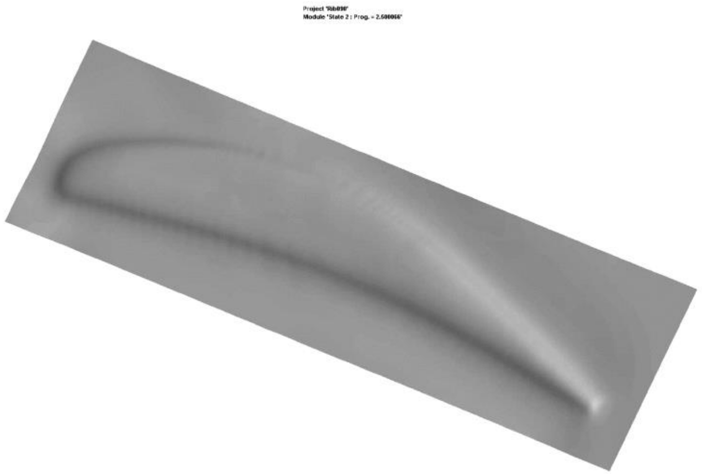
ESI PAM-COMPOSITES

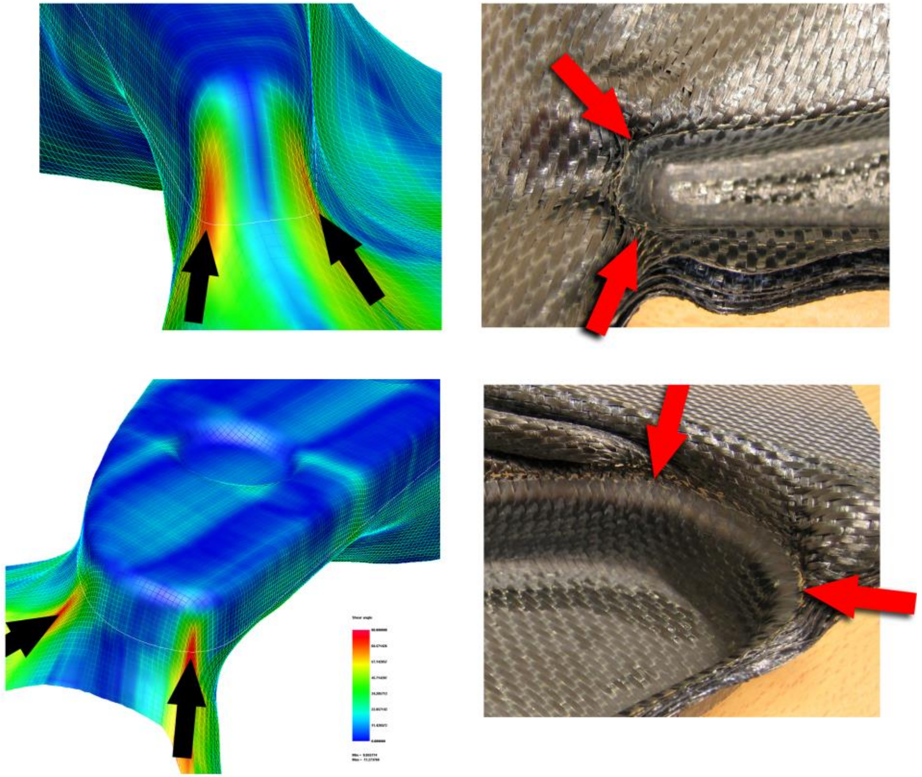


Delft University of Technology

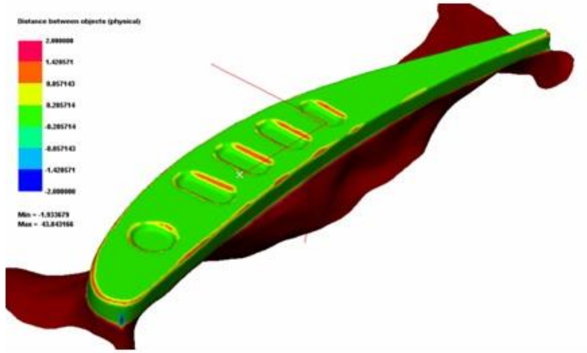
Thermoplastic forming application: Flap rib Rubber Pad Forming



Rubber pad forming simulation



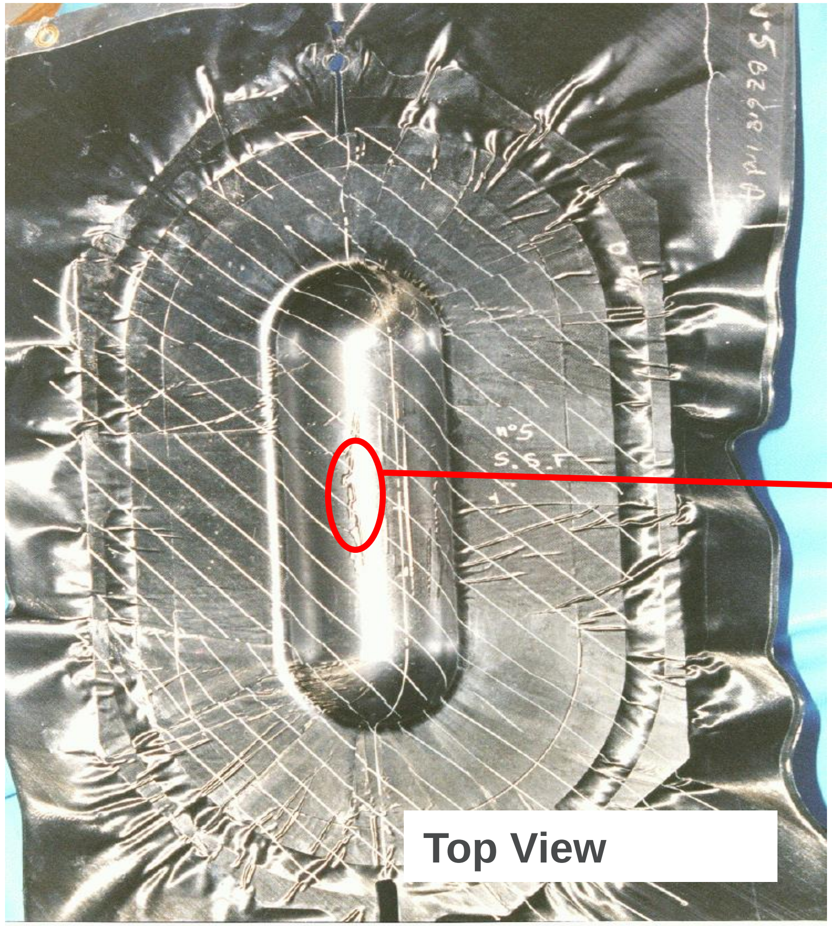
Fabric shearing

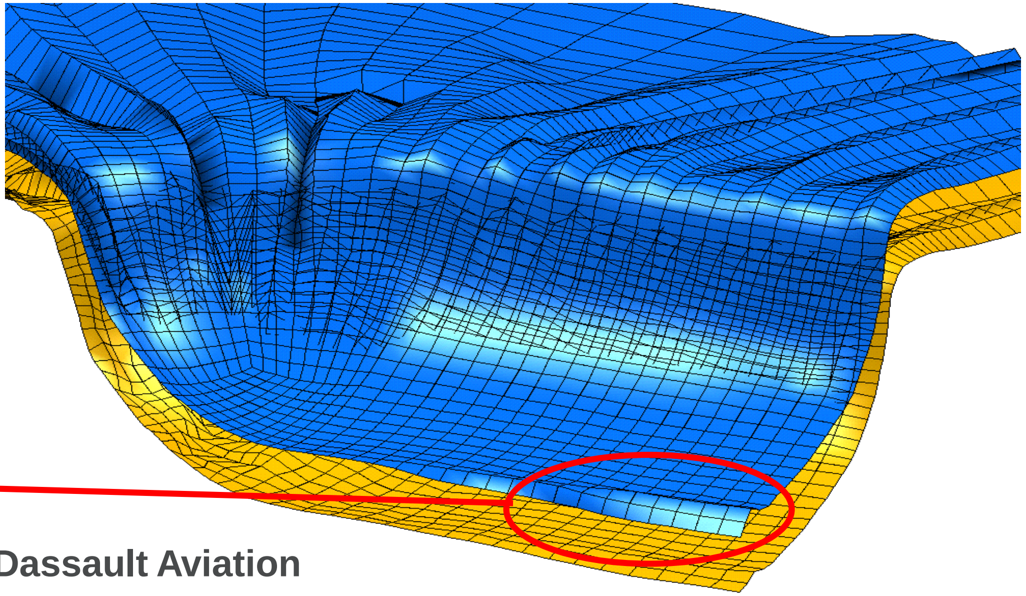


Bridging effect

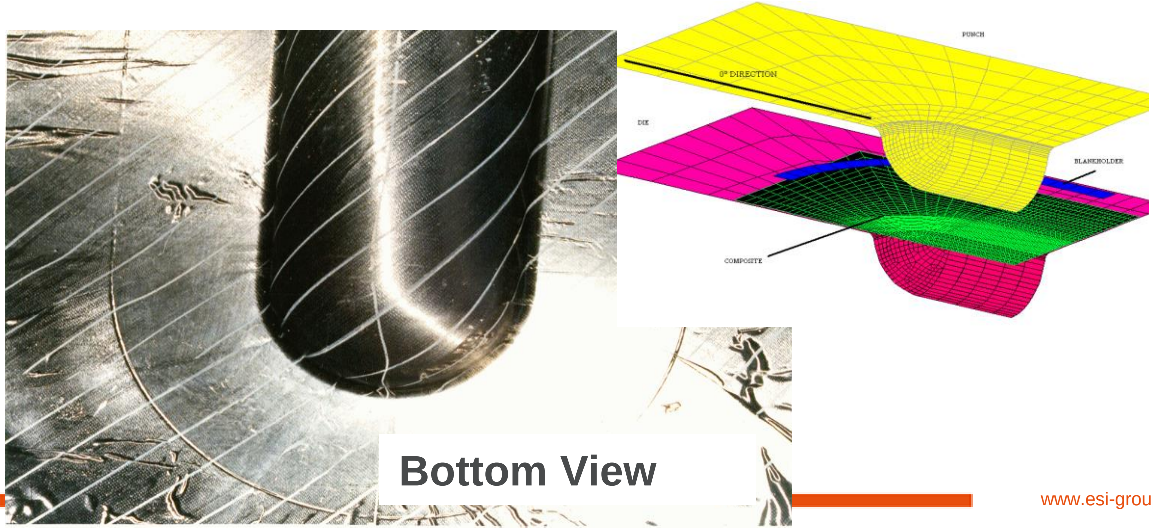
get it right®

UD Thermoforming





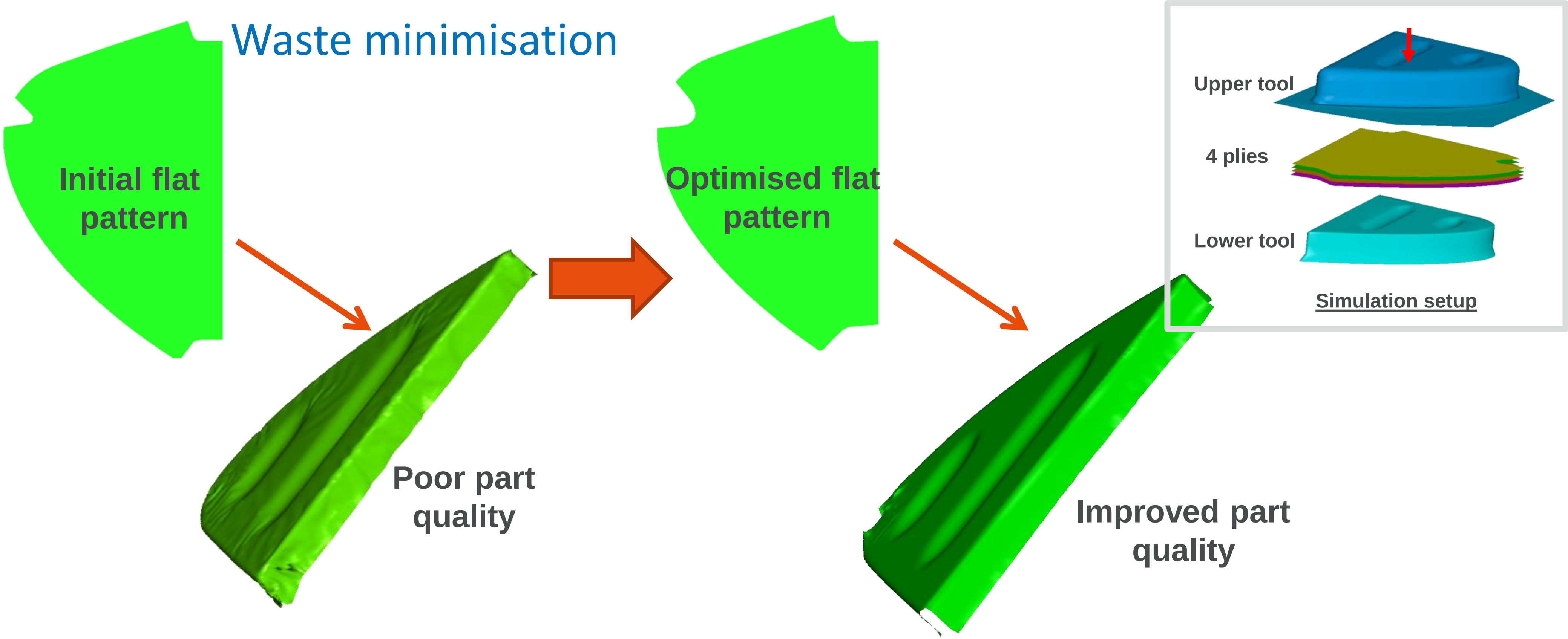
Dassault Aviation



20 plies, APC2-AS4 (thermoplastic matrix, carbon unidirectional reinforcement), Quasi-Isotropic lay-up

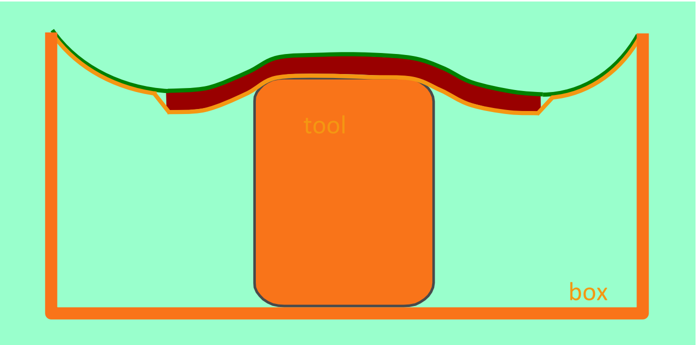
ESI PAM-COMPOSITES

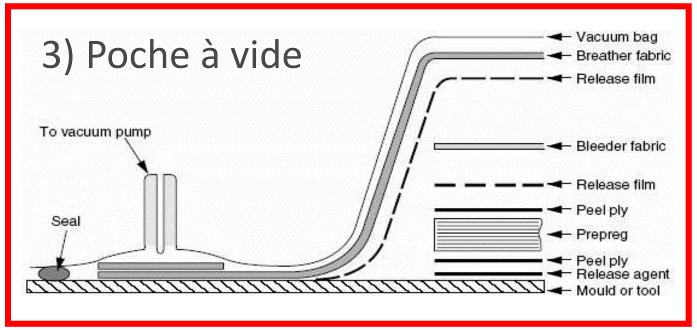
Thermoplastic forming application: **Flat pattern optimization**



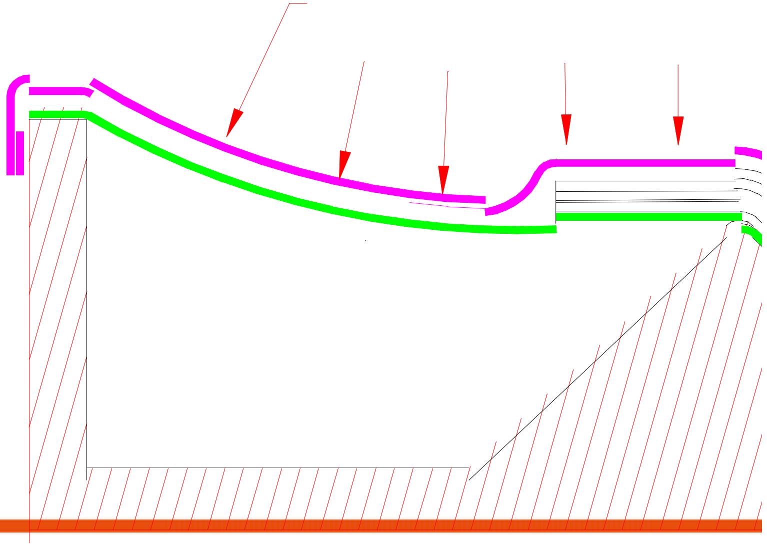
Flat pattern optimization
4 plies / thermoplastic matrix

Double diaphragm forming





Avant formage

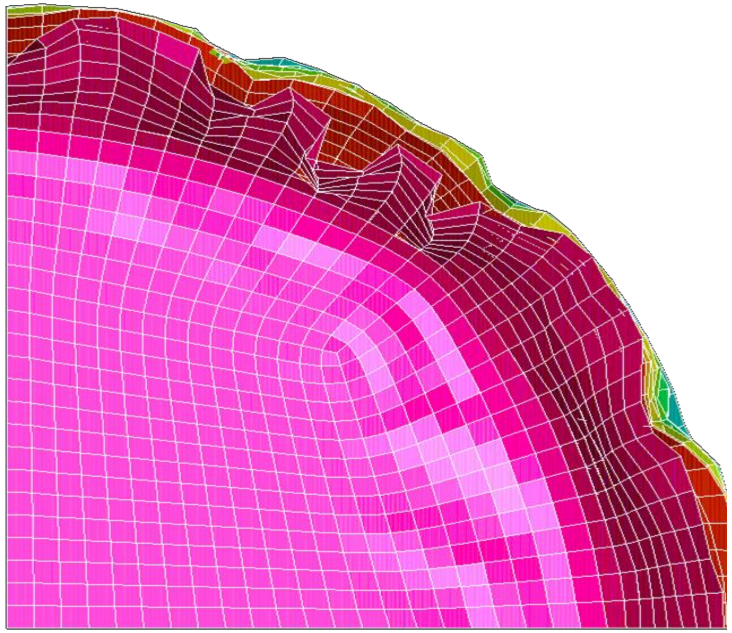


Chauffage pour assouplir la matrice

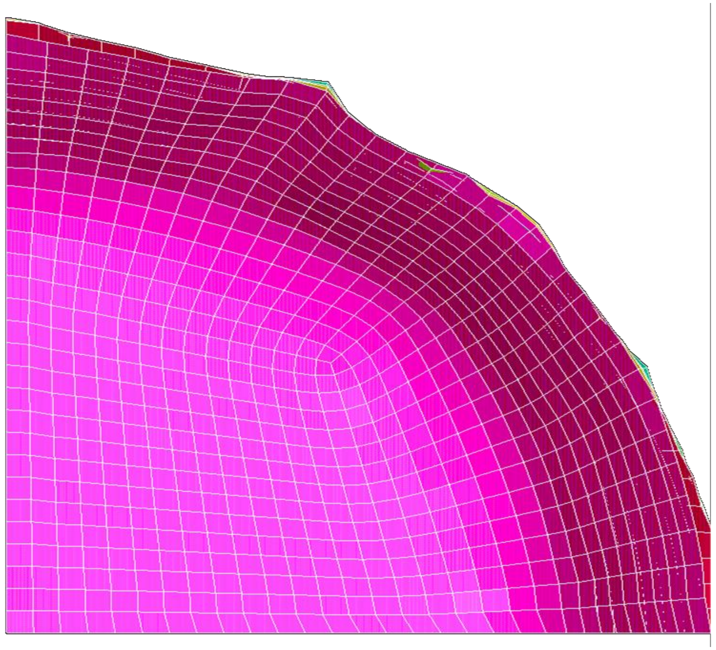
Example of what the results can tell us

- Comparison between two forming strategies

Use of one single diaphragm
=> **wrinkles**

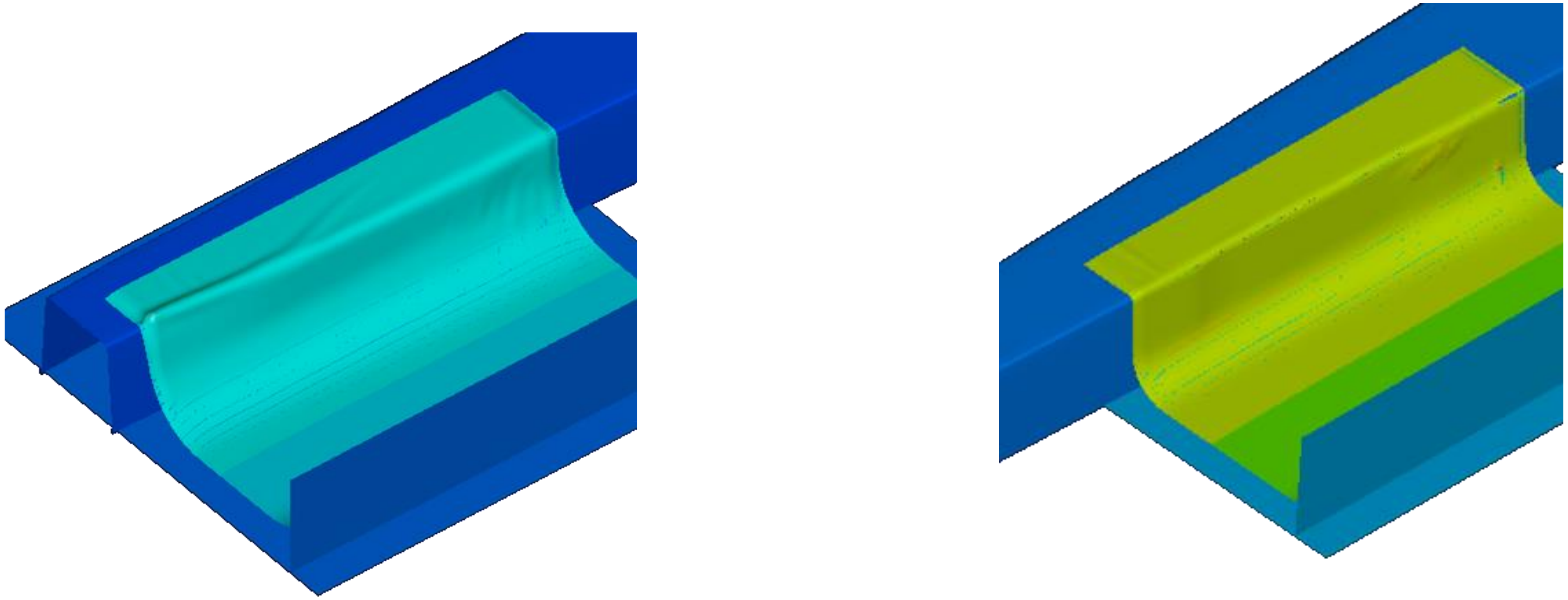


Use of two diaphragms
=> **No wrinkle**



Courtesy: CRC–ACS

Forming of a composite stringer
Double diaphragm forming

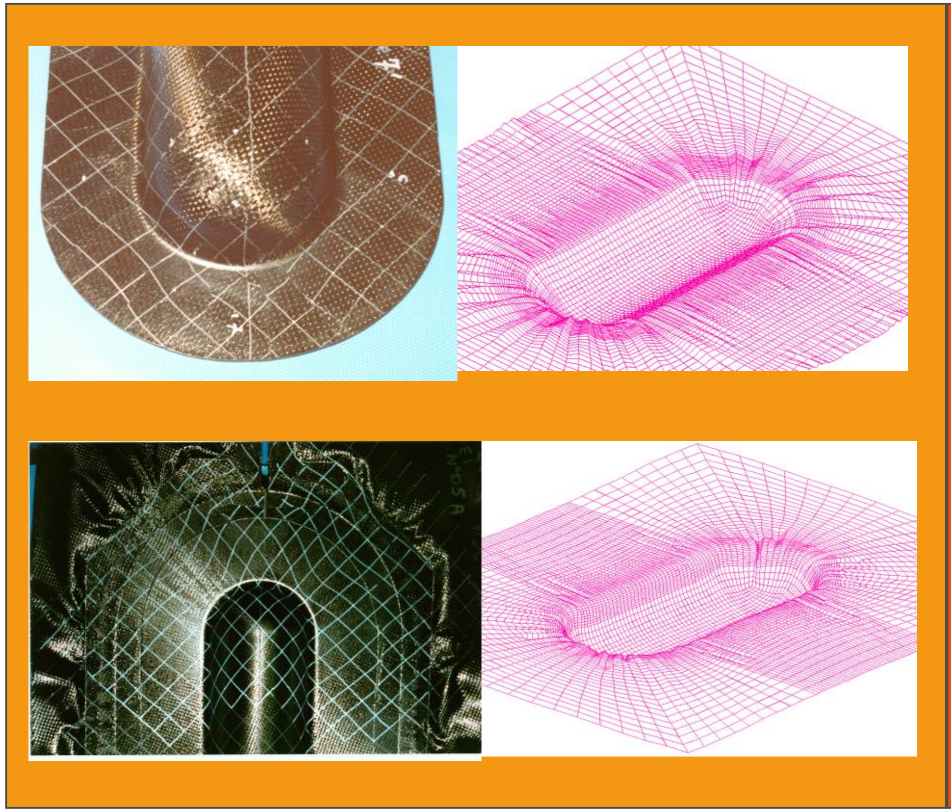


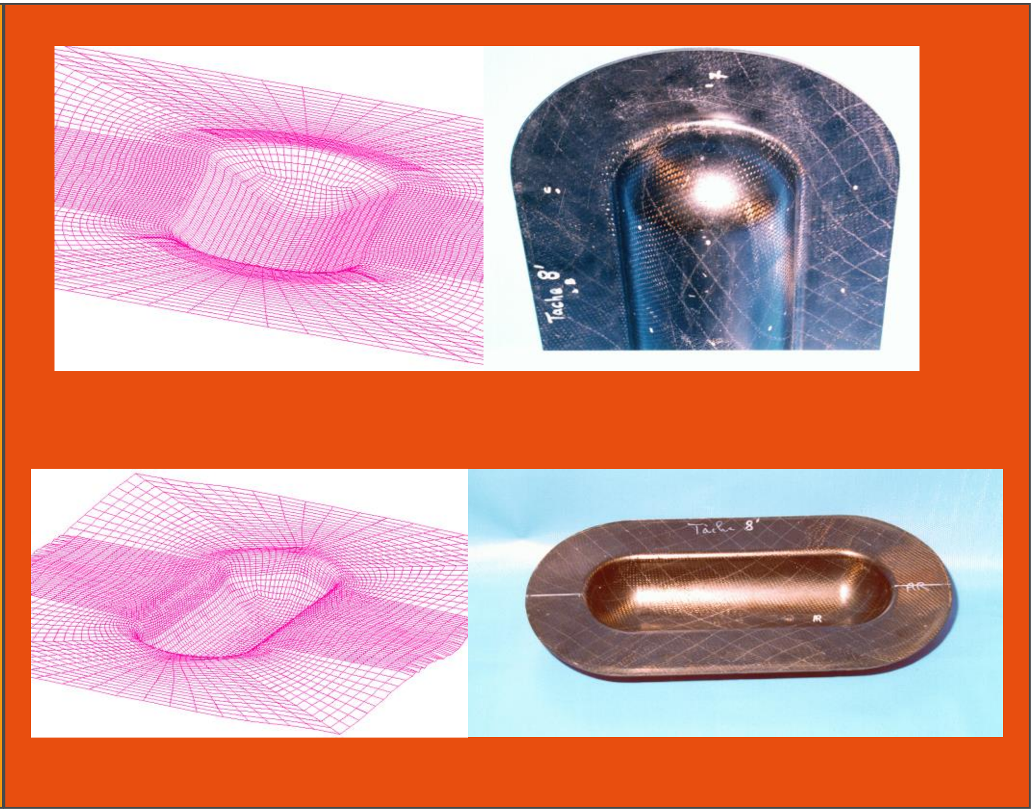
- The number of plies has an influence on the laminate deformation

Woven Fabrics Thermoforming

- Punch velocity selection

Dassault Aviation





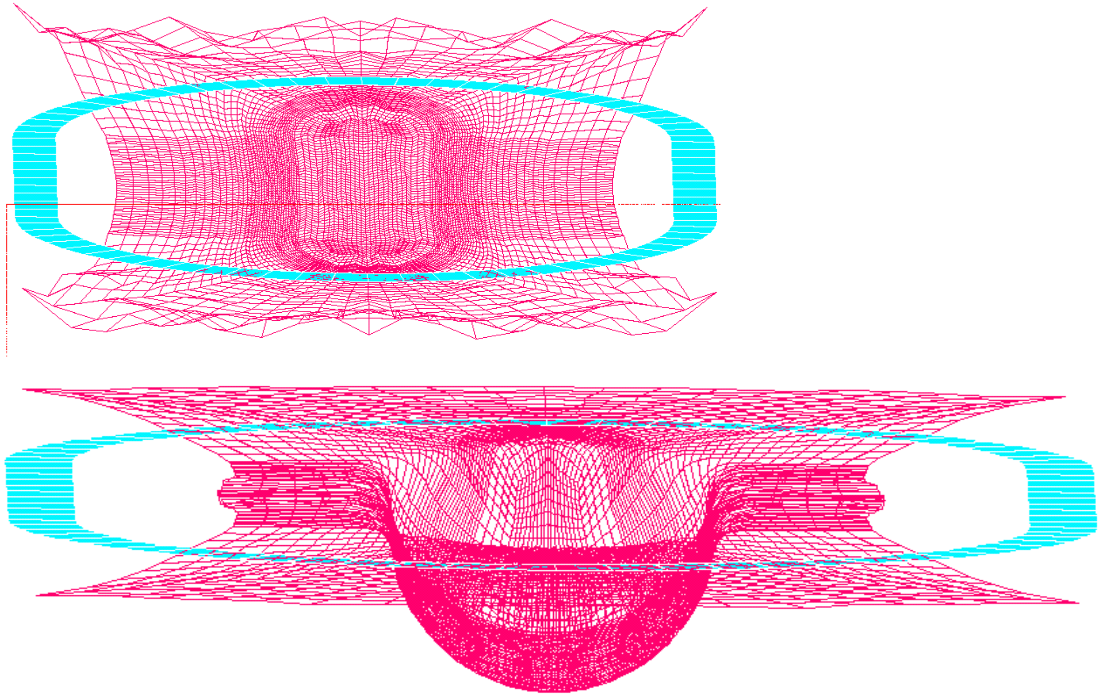
PUNCH VELOCITY=40.mm/s

PUNCH VELOCITY= 5.mm/s

(PEI-CETEX; 8 plies)

Simulation
Woven Fabrics Thermoforming

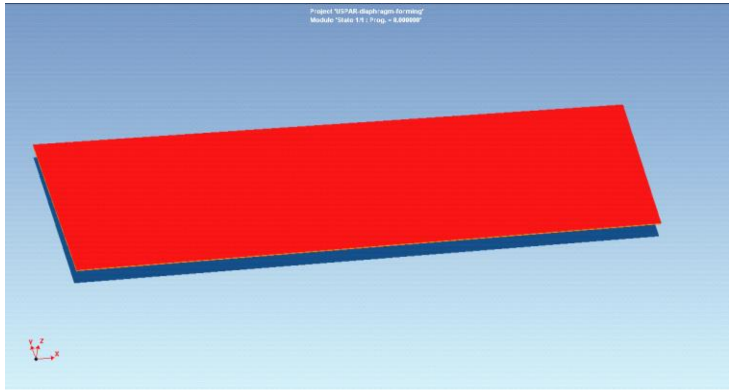
- Clamping system definition
- Laminate definition

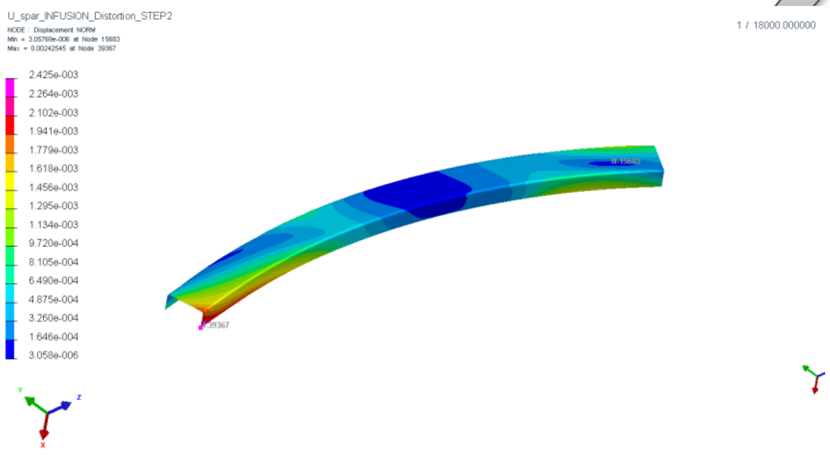


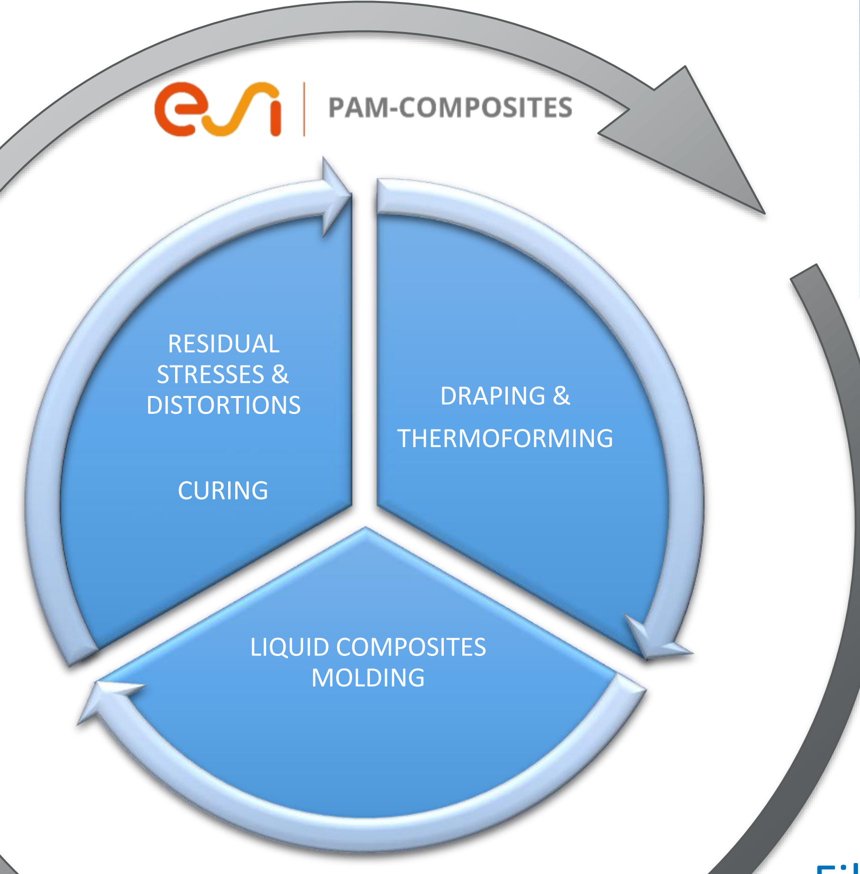
Dassault Aviation

ESI's PAM-COMPOSITES

Compensated mold







RESIDUAL STRESSES & DISTORTIONS

CURING

DRAPING & THERMOFORMING

LIQUID COMPOSITES MOLDING

Temperature history

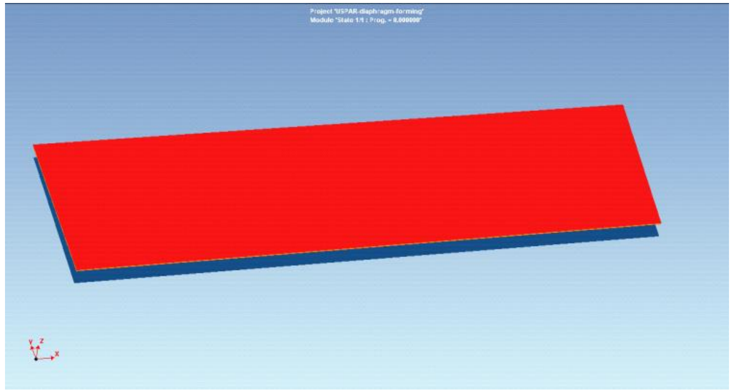
Degree of cure history

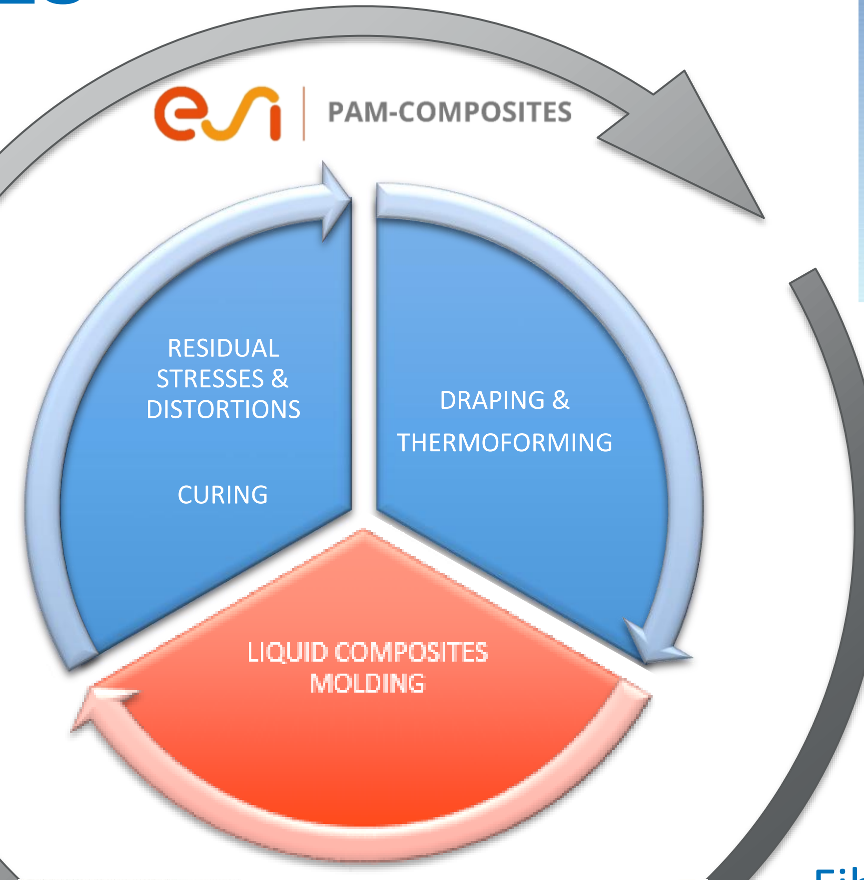
Fiber direction

Thickness variation

ESI's PAM-COMPOSITES

Compensated mold





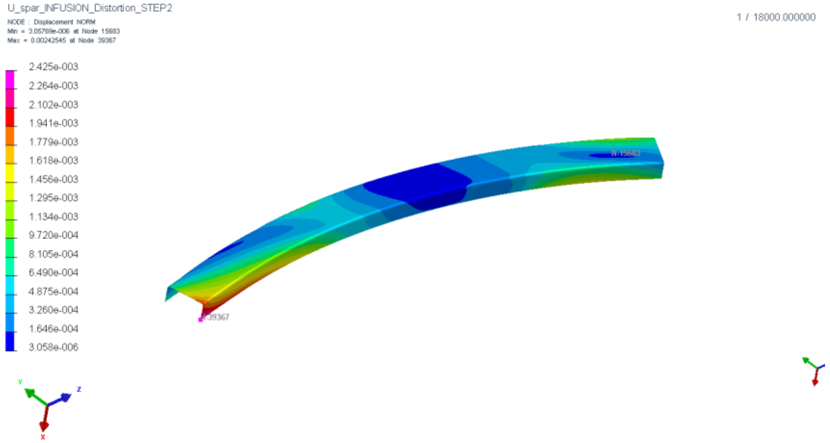
PAM-COMPOSITES

RESIDUAL STRESSES & DISTORTIONS

CURING

DRAPING & THERMOFORMING

LIQUID COMPOSITES MOLDING



Temperature history

Degree of cure history

Fiber direction

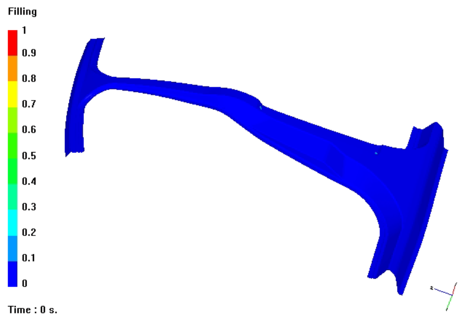
Thickness variation

Liquid Composite Moulding

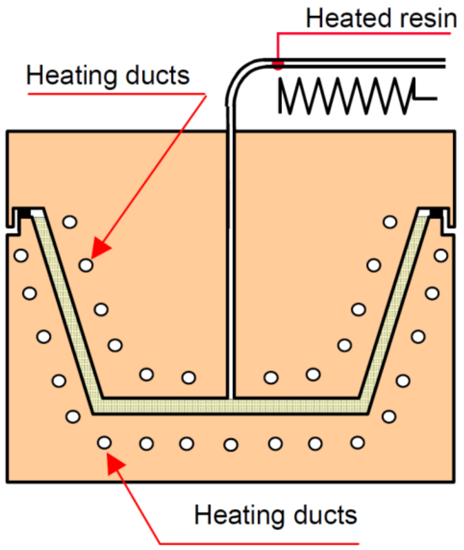
What for ?

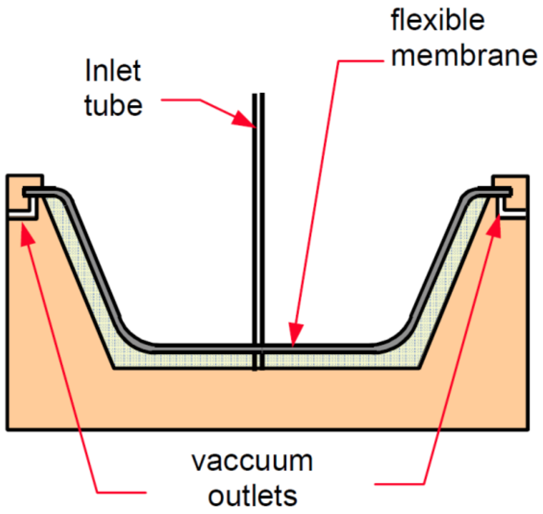
Liquid Composite Moulding

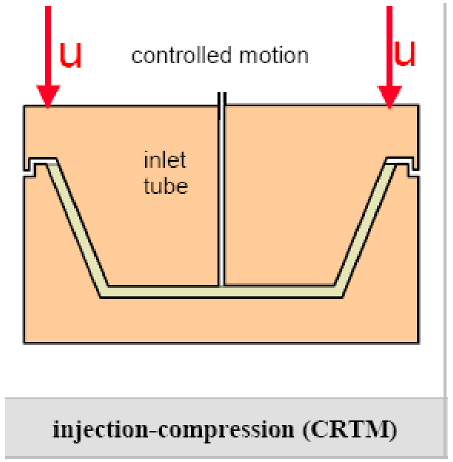
What for ?



Impregnation of dry preform with resin and curing







injection-compression (CRTM)

- **RTM**
- **Infusion**
- **C-RTM**

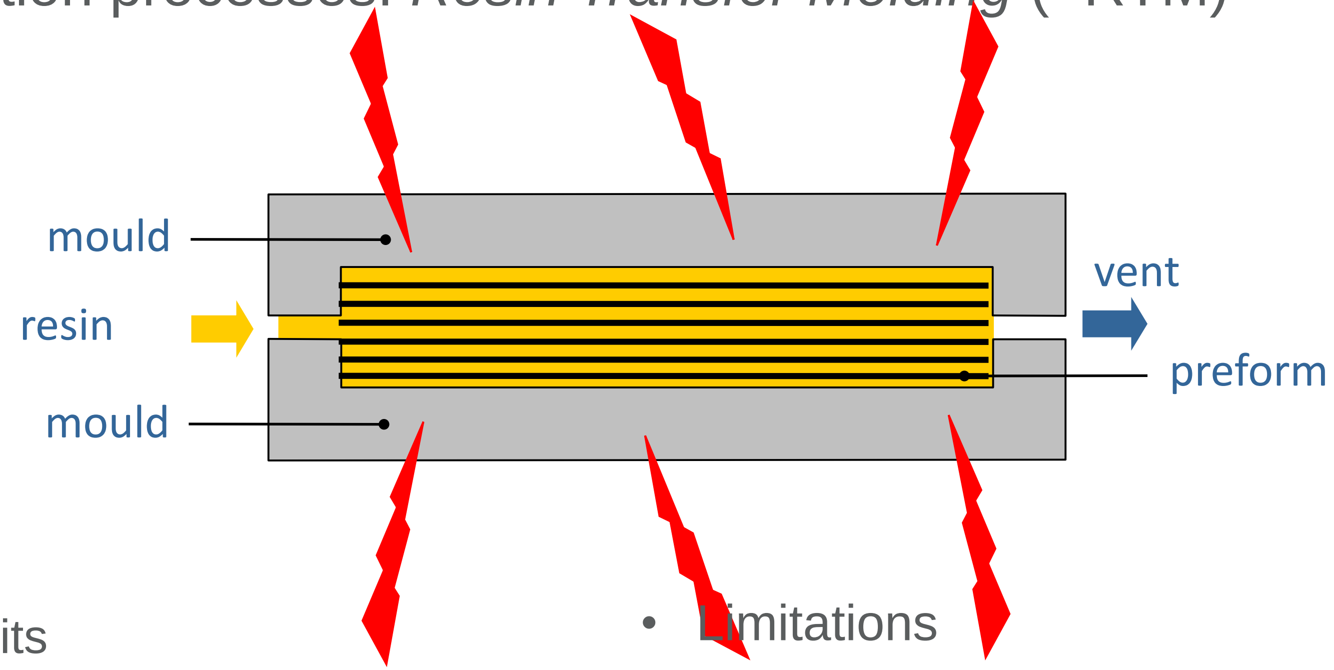
- **HP-RTM**
- **Curing**
- **…**

Liquid Composite Moulding

What for ? Resin Transfer Moulding

LCM process (=Liquid Composite Molding)

- Injection processes: *Resin Transfer Molding* (=RTM)

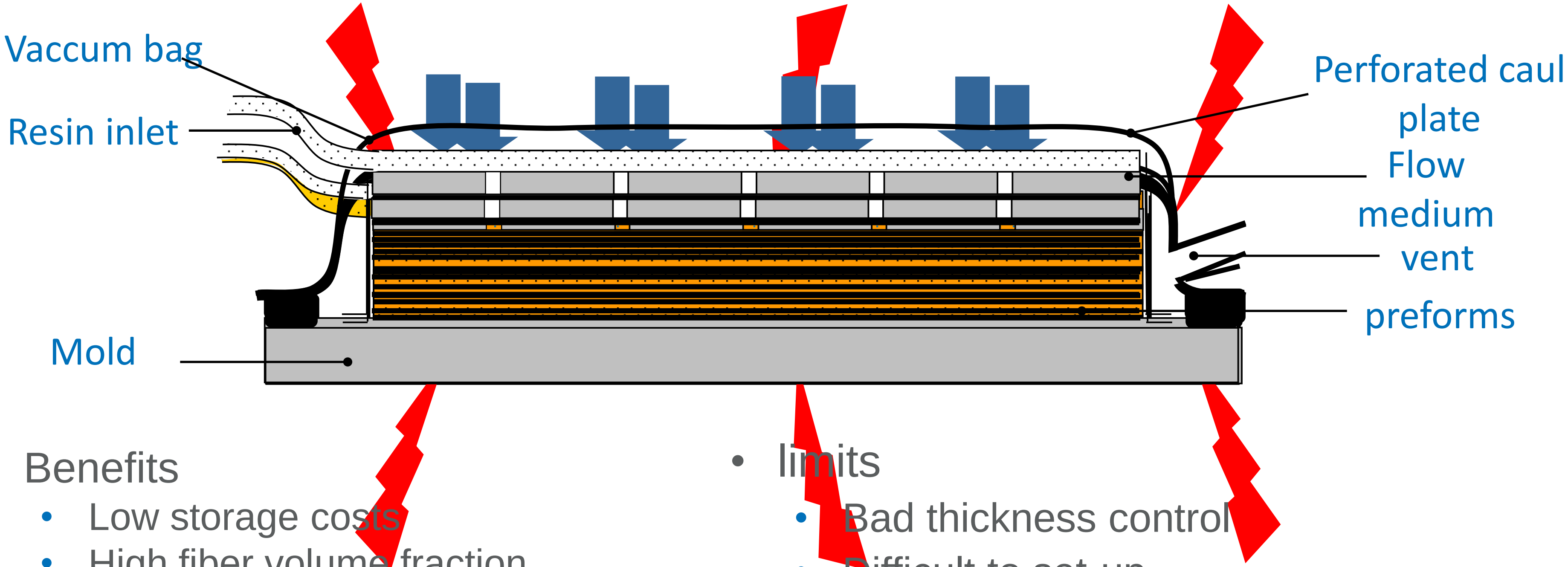


- Benefits
  - Low storage costs
  - Good geometrical properties
  - High fiber volume fraction
- Limitations
  - Mould cost
  - Small parts
  - Impregnation difficulties for complex shapes

Liquid Composite Moulding

What for ? Liquid Resin Infusion

- Flexible tooling + throught thickness impregnation

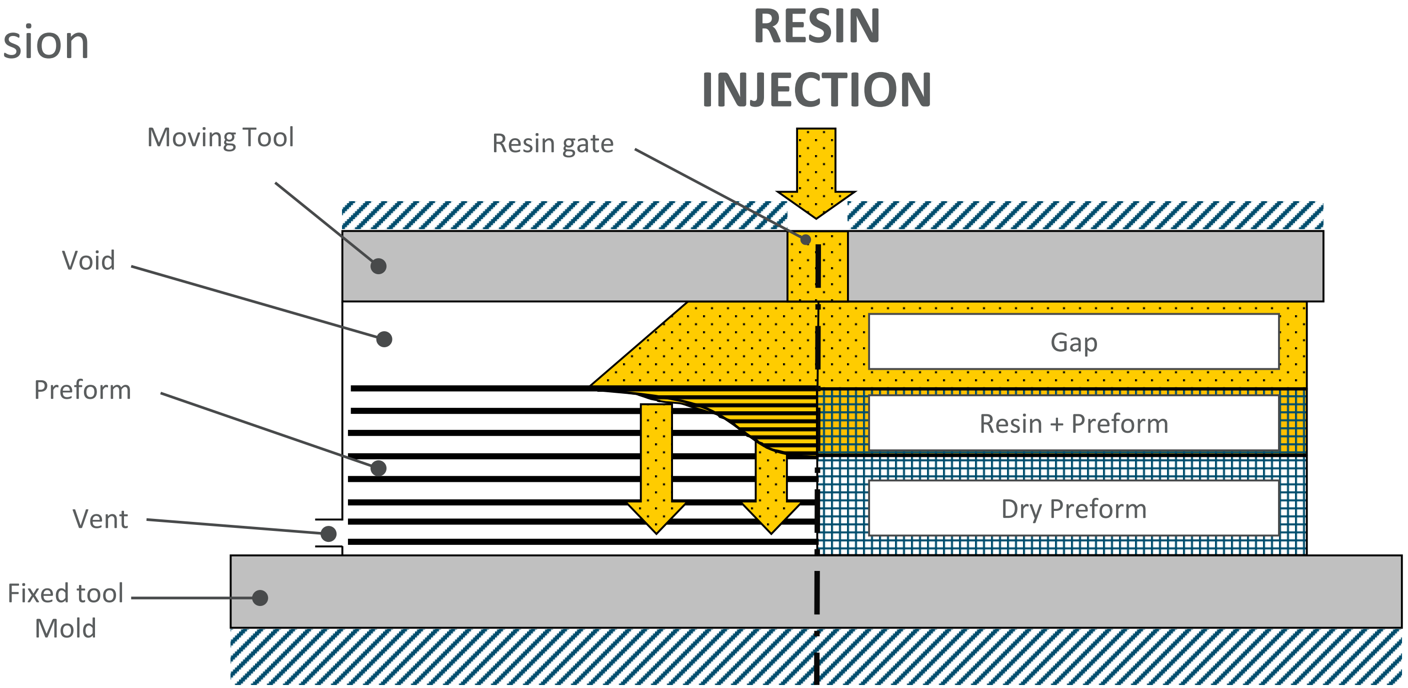


- Benefits
  - Low storage costs
  - High fiber volume fraction
  - Low mold cost
  - Big parts
  - Good impregnation
- limits
  - Bad thickness control
  - Difficult to set-up

Liquid Composite Moulding

What for ? Compression Resin Transfer Molding (C-RTM)

- Process is split in 2 stages
  - **Injection**
  - Compression



Liquid Composite Moulding

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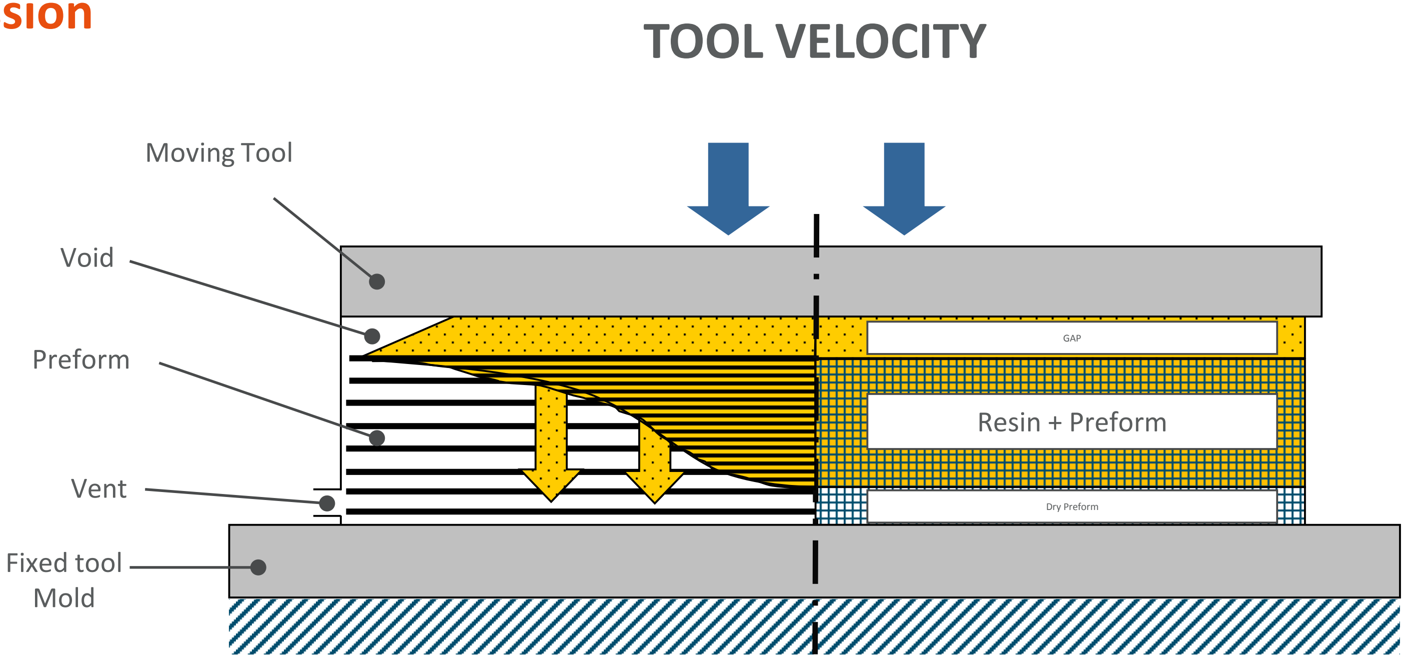

Liquid Composite Moulding

What for ? Compression Resin Transfer Molding (C-RTM)

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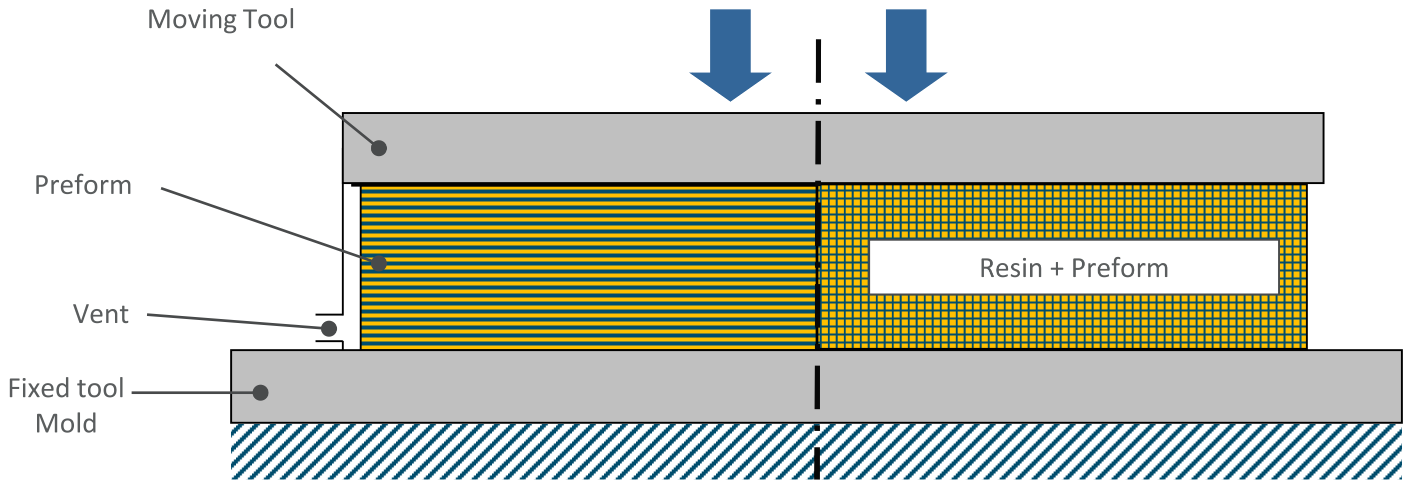
  - **Compression**

TOOL VELOCITY



Liquid Composite Moulding

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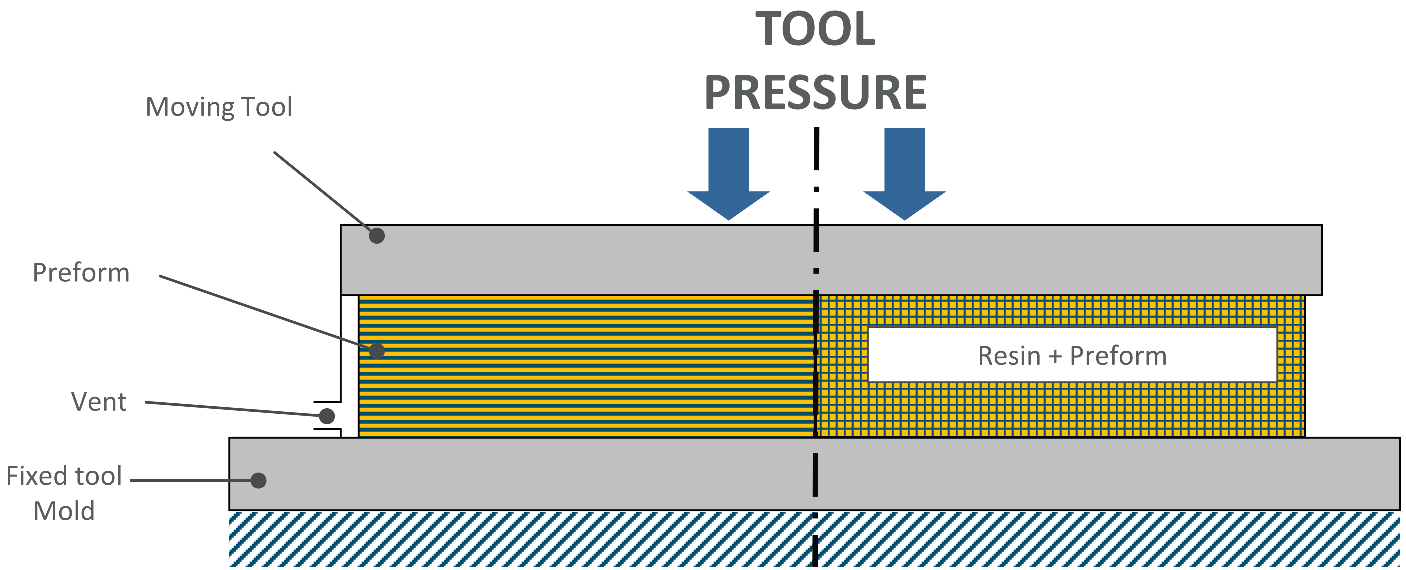


Liquid Composite Moulding

Industrial issues

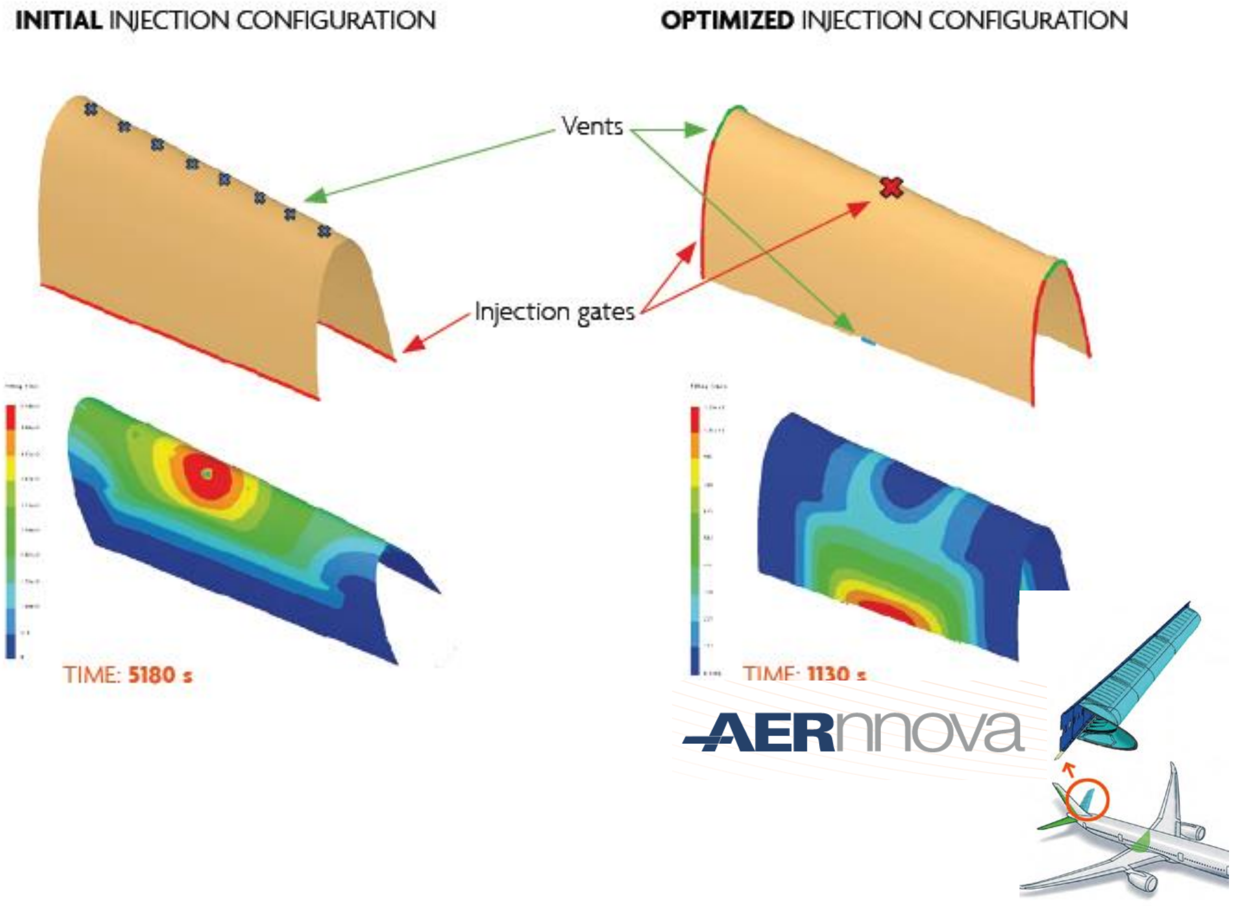
Liquid Composite Moulding

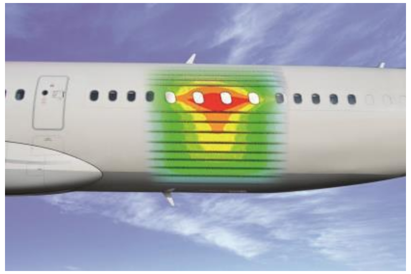
Industrial issues : Aeronautic industry

Simulation time divided by 5 thanks to simulation

Better quality parts with less scraps (better reproducibility)

- Medium to large parts
- Main constraints:
  - Part design cannot be modified easily
    - Processability of the designed part
    - Process design cost
  - Manufactured part quality (very few porosity, no distortion…)
- New constraints:
  - Manufacturing time and cost





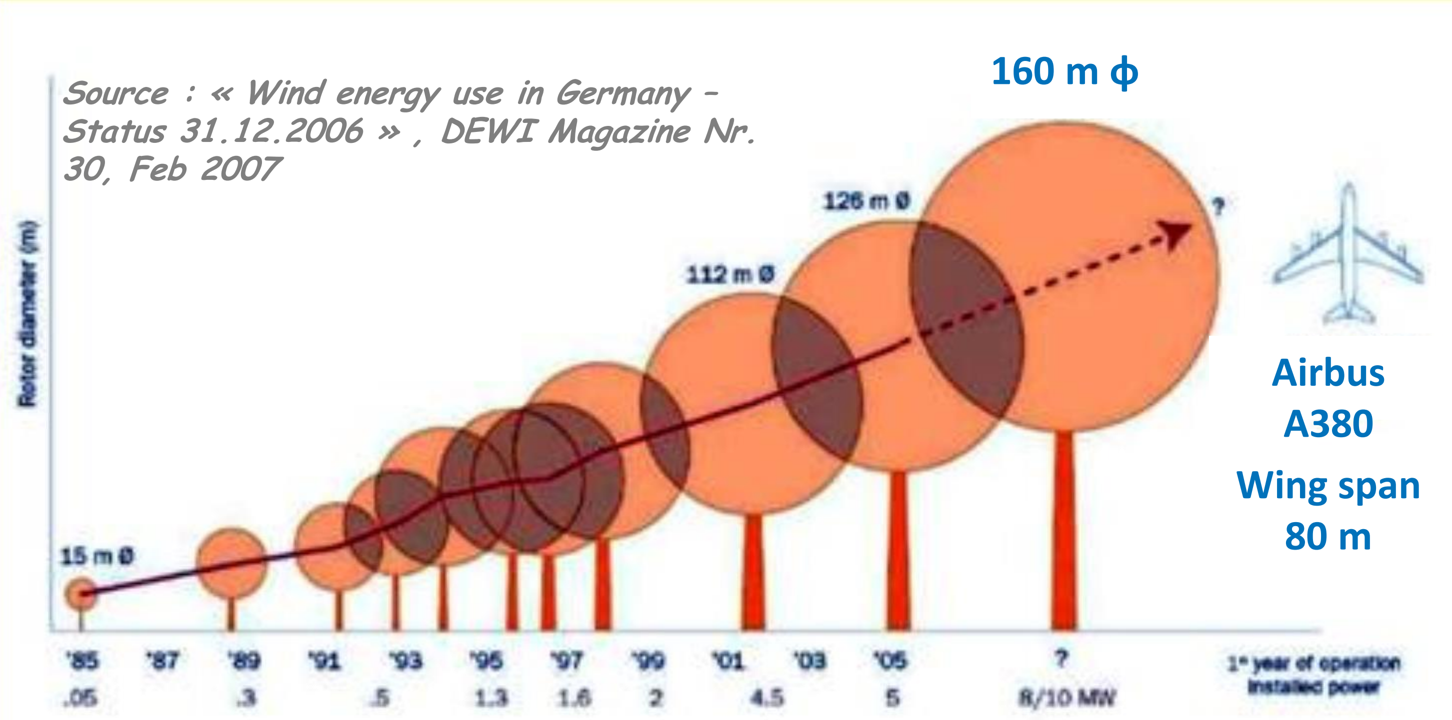
G_MKT_RL_10_345, Courtesy of EADS Innovation Works, Infusion simulation of a fuselage panel with PAM-RTM

G_MKT_R_L_13_255, Courtesy of VZLÚ

Liquid Composite Moulding

Industrial issues : Wind industry

- Large to very large parts
- Some region very thick (> 10 cm)
- Main constraints:
    - Size of the parts:
        - Processability of the designed part
        - Process design cost
    - Manufactured part quality for the critical structural part (spar)
    - Manufacturing and material cost

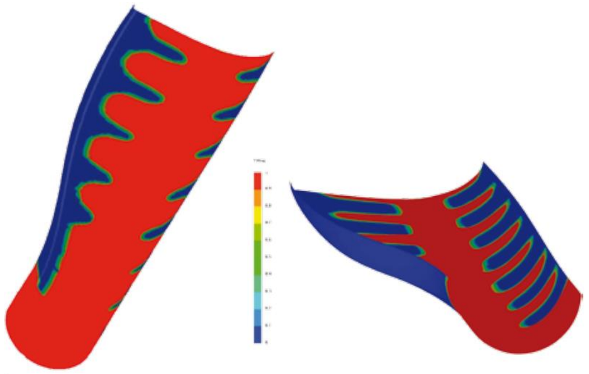


Source : « Wind energy use in Germany – Status 31.12.2006 » , DEWI Magazine Nr. 30, Feb 2007

160 m ϕ

Airbus A380

Wing span 80 m



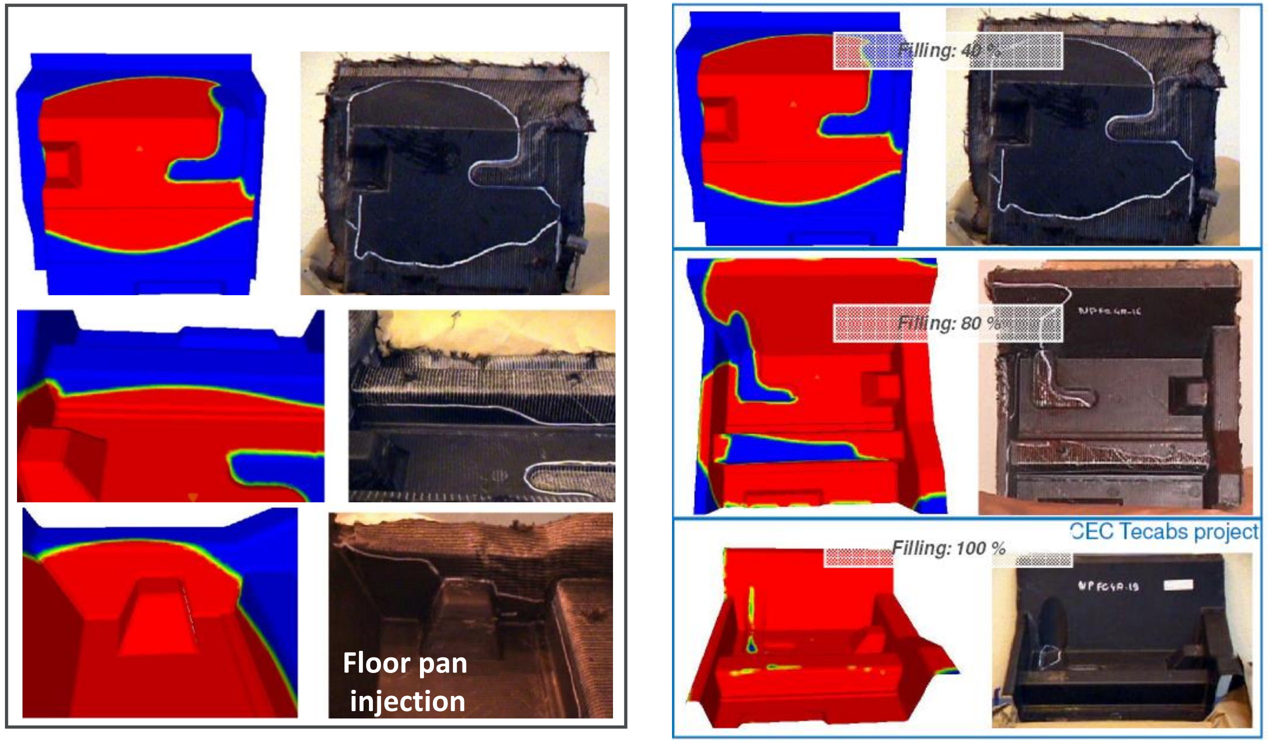
An 81.6 meter long offshore wind turbine rotor blade & Analysis of several injection strategies with PAM-RTM on the root of the rotor blade

G.MKT.R.L14.625

Liquid Composite Moulding

Industrial issues : Automotive industry

- Small to medium parts
- Main constraints:
  - Material cost
  - Manufacturing **time** window (< 2-3’) and **cost**
    - Processability of the designed part
    - Process design cost



RTM application: Automotive floor panel

Liquid Composite Moulding

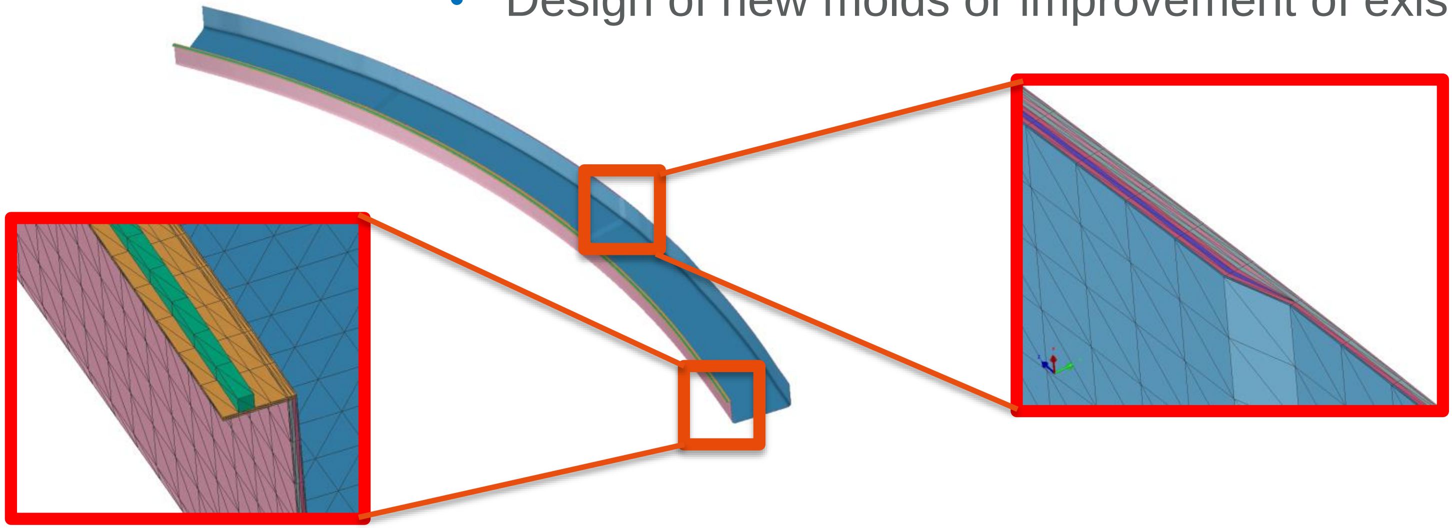
How to simulate and Why

Why simulate LCM process ?

To Determine and Optimize process parameters such as:

- **Process parameters:**
  - locate injection gates and vents
  - Flow rates or pressure
  - Vacuum
  - Temperature cycle

- **Material / Design**
  - Material behavior f(T, t)
  - Ply book
  - Design of new molds or improvement of existing molds



Through prediction of:

- Air traps
- Micro porosity
- Injection time

- Temperature evolution
- Degree of cure evolution
- Pressure in the mold

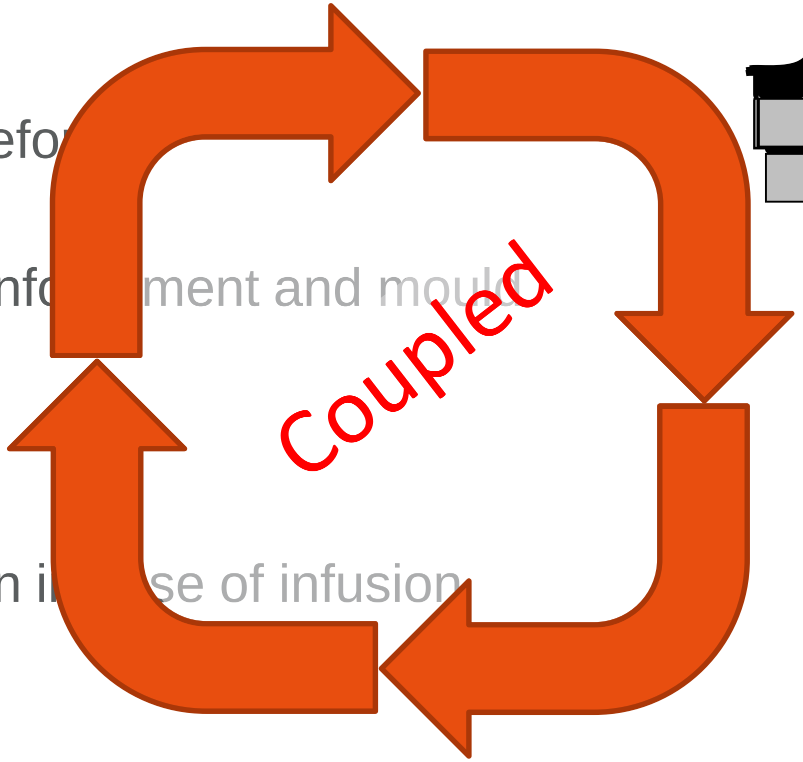
Liquid Composite Moulding

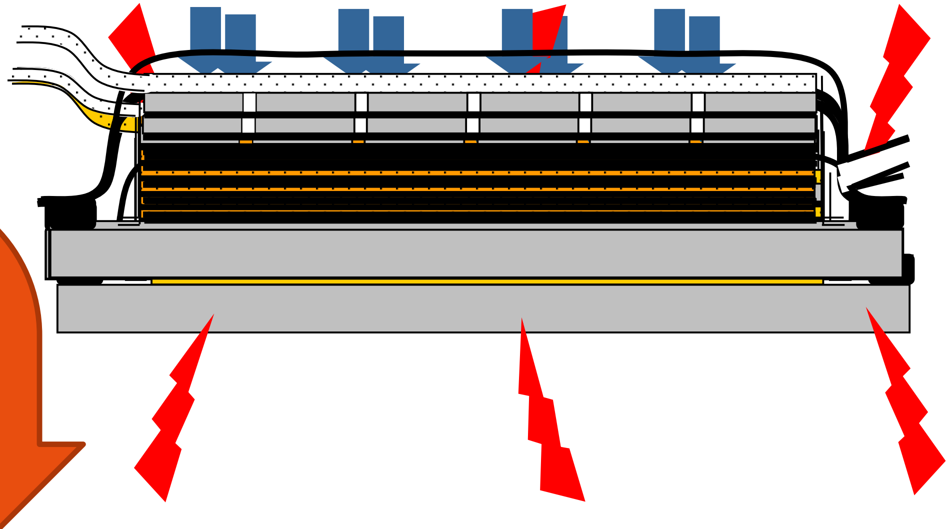
Physics involved

Liquid Composite Moulding

Physics involved: Modelling

- Four physical phenomena are modeled
  - Flow of resin inside the prefo
  - Heat exchanges inside reinfo ment and mould
  - Chemical reaction of resin
  - Reinforcement deformation i se of infusion





Liquid Composite Moulding

Physics involved: reinforcement modelling

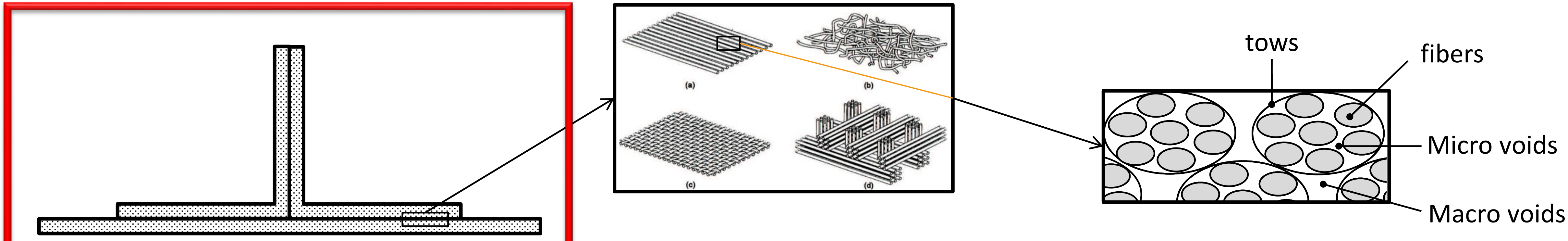
Fibres

+

Organic Matrix

Liquid Composite Moulding

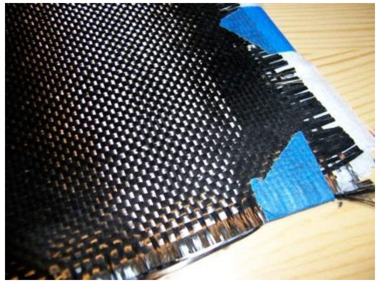
Physics involved: Preform modelling

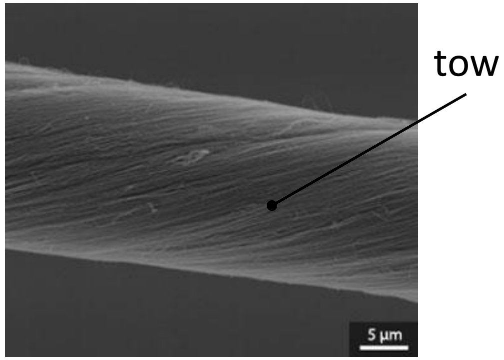


Macroscopic

Meso-scopic

Microscopic



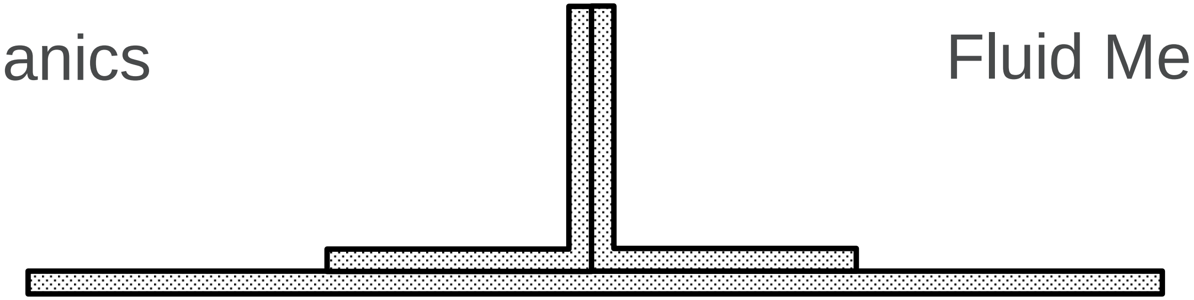


Preform modelling

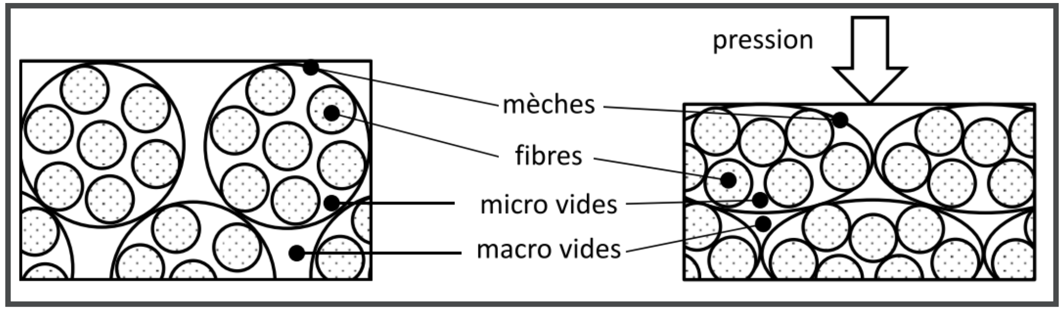
Physics involved: Preform modelling

Solid Mechanics

Fluid Mechanics

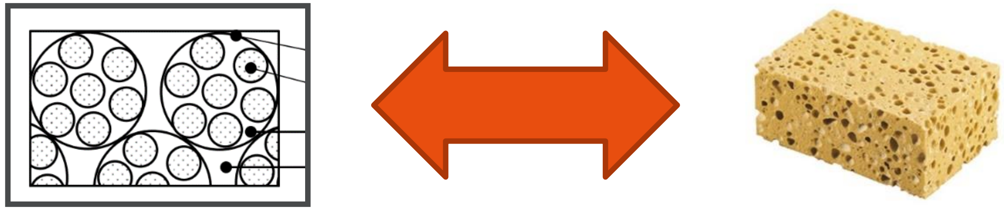


Macro-scale



deformable preform made of undeformable filaments

$$J(\vec{x}, t+\Delta t)\, v_f(\vec{x}, t+\Delta t) = J(\vec{x}, t)\, v_f(\vec{x}, t)$$



Porous medium approximation

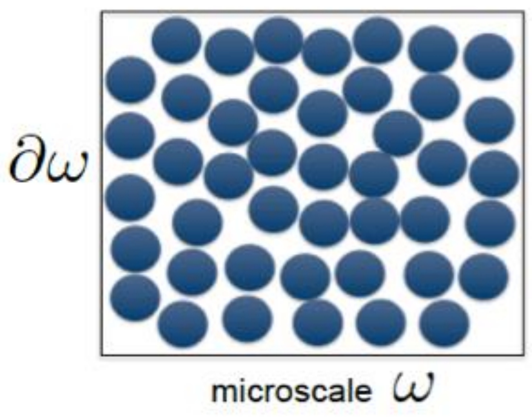
Darcy law / permeability

Fluid Mechanics in porous medium

Physics involved: Darcian permeability : origin?

Single-phase flow (saturated), negligible inertia (creeping flow), no-slip condition on fibers, single-scale porosity medium, stationary fiber bed, linear & incompressible fluid of constant viscosity

Fluid = Continuum



microscale

Upscaling

Fiber bed + fluid
= Continuum

macroscale

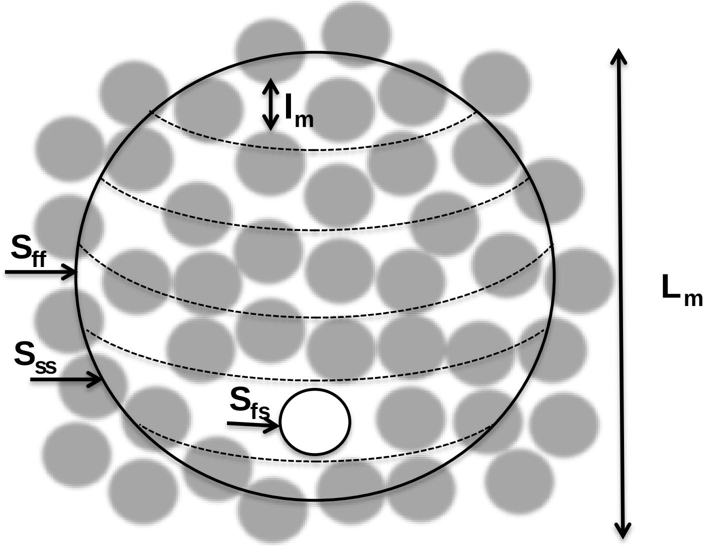
$$\nabla P_{\mathrm{f}} + \eta \nabla^2 \boldsymbol{v}_{\mathrm{f}} = 0$$

$$\nabla \cdot \boldsymbol{v}_{\mathrm{f}} = 0$$

?

Fluid Mechanics in porous medium

Physics involved: Darcian permeability : origin?



$$l_m << L_m$$

$$\langle \tau_f \rangle = \frac{1}{V} \int_{V_f} \tau_f \, dV \quad (2)$$

$$\langle P_f \rangle^f = \frac{1}{V_f} \int_{V_f} P_f \, dV$$

Upscaling of Stokes equation :

$$\nabla \cdot \langle \boldsymbol{\tau}_f \rangle - \underbrace{\phi_f}_{\text{Porosity}} \nabla \langle P_f \rangle^f - \boldsymbol{f}_d = 0 \quad (1)$$

Where :

$$\boldsymbol{\tau}_f = \eta \left[\nabla \boldsymbol{v}_f + (\nabla \boldsymbol{v}_f)^T \right] = 2\eta \boldsymbol{D}_f \quad (3)$$

Extra-stress tensor

$$\underbrace{\boldsymbol{f}_d}_{\text{Drag force}} = -\frac{1}{V} \int_{S_{fs}} \boldsymbol{\sigma}_f \cdot \boldsymbol{n}_{fs} \, dS + \nabla \phi_f \langle P_f \rangle^f \quad (4)$$

$$\boldsymbol{\sigma}_f = -P_f \mathbf{I} + 2\eta \mathbf{D}_f \quad (5)$$

Total stress tensor for linear fluid

Fluid Mechanics in porous medium

Physics involved: Darcian permeability : origin?

At large scale $\nabla \phi_\mathrm{f} \approx 0 \Rightarrow$ Statistically homogeneous porous media

Then : $\boldsymbol{f}_\mathrm{d} = -\dfrac{1}{V}\displaystyle\int_{S_\mathrm{fs}} \boldsymbol{\sigma}_\mathrm{f} \cdot \boldsymbol{n}_\mathrm{fs}\,\mathrm{d}S$ (6)

$$\boldsymbol{f}_\mathrm{d} = \frac{\phi_\mathrm{f}\eta}{\boldsymbol{K}}\langle \boldsymbol{v}_\mathrm{f} \rangle \quad (7)$$

Permeability tensor

$\nabla \cdot \langle \boldsymbol{\tau}_\mathrm{f} \rangle << \boldsymbol{f}_\mathrm{d}$ if velocity gradients varies smoothly

$$\boldsymbol{K} = \frac{\phi_\mathrm{f}\eta}{-\frac{1}{V}\int_{S_\mathrm{fs}} \boldsymbol{\sigma}_\mathrm{f} \cdot \boldsymbol{n}_\mathrm{fs}\,\mathrm{d}S}\langle \boldsymbol{v}_\mathrm{f} \rangle \quad (8)$$

where $\langle \boldsymbol{v}_\mathrm{f} \rangle = \dfrac{1}{V}\displaystyle\int_{V_\mathrm{f}} \boldsymbol{v}_\mathrm{f}\,\mathrm{d}V$

Darcy's law : $\langle \boldsymbol{v}_\mathrm{f} \rangle = -\dfrac{\boldsymbol{K}}{\eta} \cdot \nabla \langle P_\mathrm{f} \rangle^\mathrm{f}$

Fluid Mechanics in porous medium

Physics involved: resin viscosity

Fibres

\+

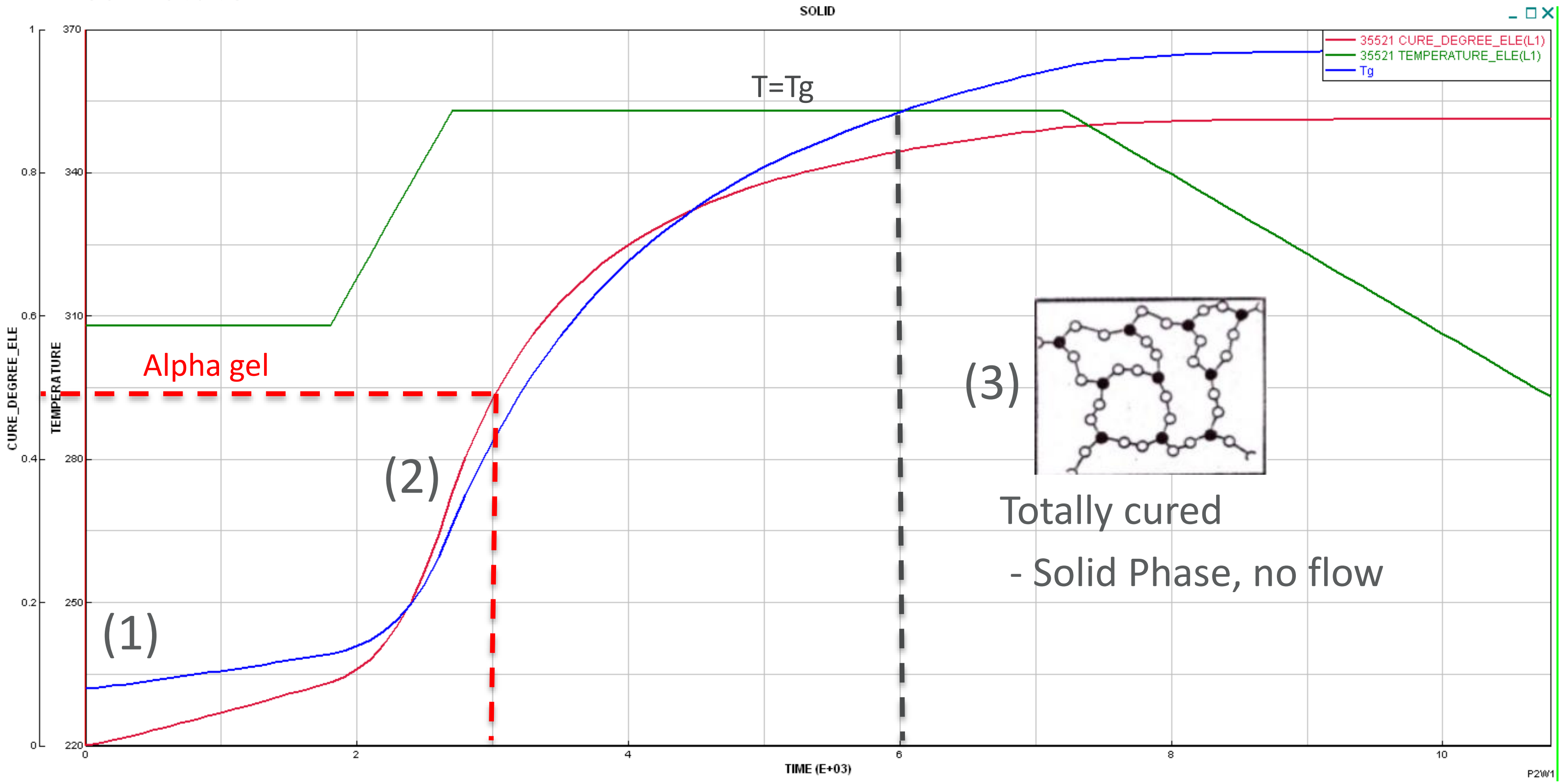
Organic Matrix

- Thermoset
- Thermoplastic

Fluid Mechanics in porous medium

Physics involved: Resin Viscosity of thermoset

Resin state



(3)

Totally cured

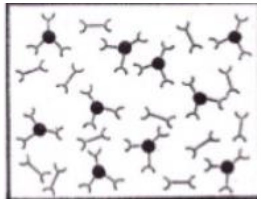
- Solid Phase, no flow

Resin is liquid

Resin is rubbery

Resin is glassy

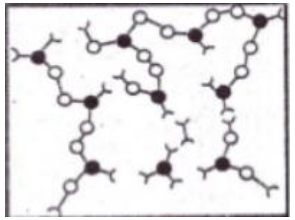
(1)



Monomers / Oligomers

- low viscosity
- Newtonian fluid, $\eta=f(T)$

(2)



Partially cured

- Viscosity increases rapidly
- liquid phase: Newtonian behavior, $\eta=f(T;\ \alpha)$
- rubbery phase: too high viscosity

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Liquid Composite Moulding

Modelling the infusion process in PAM-RTM

Infusion modelling

Resin Modelling

- Reactive incompressible Newtonian fluid

$$\eta = f(T;\alpha)$$

$$\rho = cte \Longleftrightarrow \operatorname{div} \vec{v} = 0$$

Properties evolution due to chemical reaction (polymerisation, crystallization or reticulation)

Infusion modelling

Fluid and Mechanics equations

Fluid Mechanics

$$\left|\begin{array}{l} \vec{v} = -\dfrac{\overline{\overline{K}}}{\eta}\left(\vec{\nabla}p - \rho\vec{g}\right) \\ \mathrm{div}\vec{v} = 0 \end{array}\right.$$

$$\Downarrow$$

$$\mathrm{div}\left(\frac{\overline{\overline{K}}}{\eta}\vec{\nabla}p\right) = 0$$

Linear finite element method with non-conforming elements

Solid Mechanics

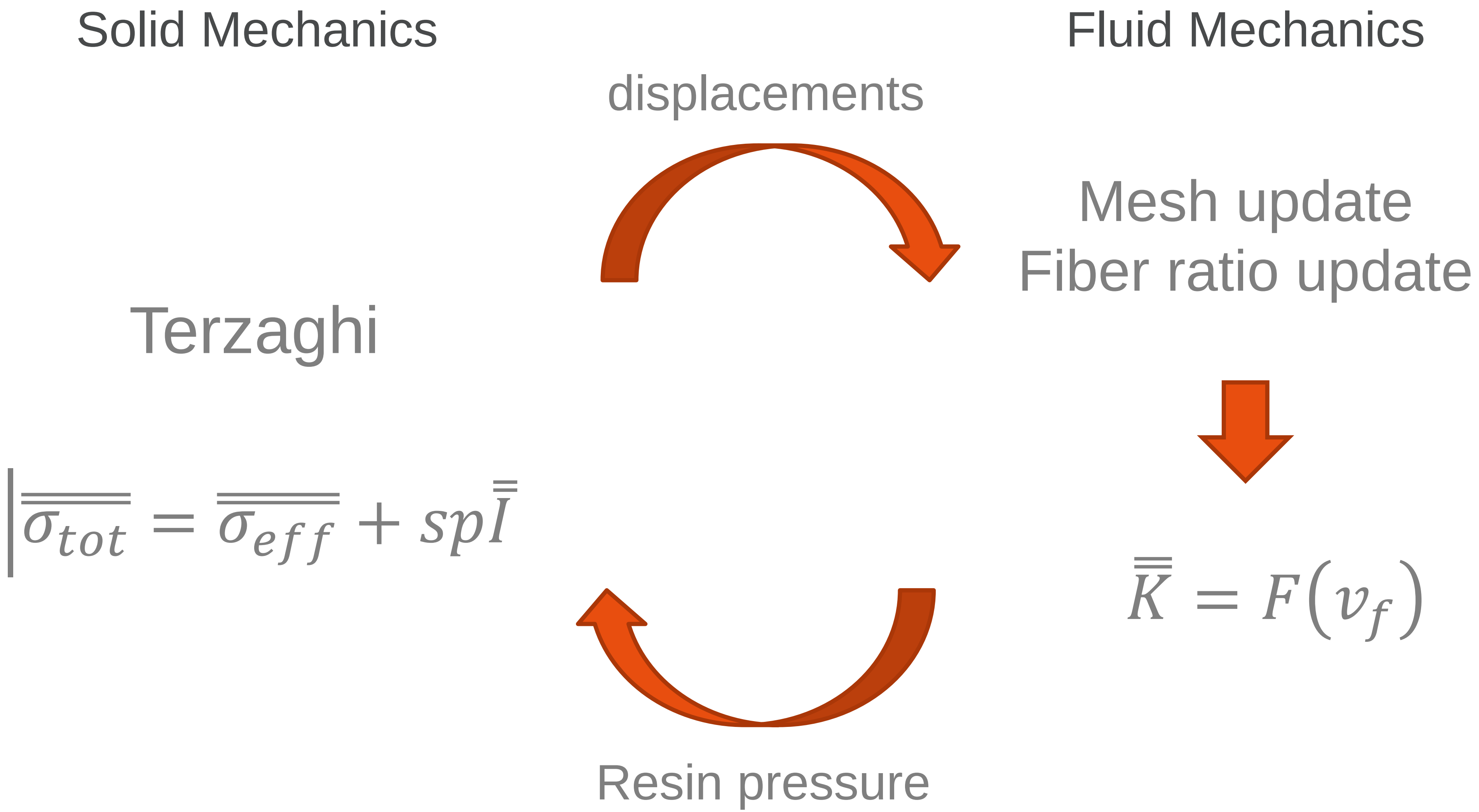
$$\underline{\mathrm{div}}\ \underline{\underline{\sigma}} = \underline{f}_v$$

→ Non linear elastic tranversally isotropic behaviour

Implicit non linear finite element method

Infusion modelling

Fluid and Mechanics equations



Solid Mechanics

Fluid Mechanics

displacements

Mesh update
Fiber ratio update

Terzaghi

$$\overline{\overline{\sigma_{tot}}} = \overline{\overline{\sigma_{eff}}} + sp\overline{\overline{I}}$$

$$\overline{\overline{K}} = F(v_f)$$

Resin pressure

Infusion modelling

Thermal Equation

→ Resin flow

→ chemical exothermic reaction

$$\rho C_p \frac{\partial T}{\partial t} + \boxed{\rho_r C_{pr} \vec{v} \cdot \vec{\nabla} T} = \mathrm{div}\left(\bar{\bar{\kappa}} \cdot \vec{\nabla} T\right) \boxed{+ S}$$

C_p: specific heat of the porous medium (J·kg^{-1}·K^{-1})

ρ : volumetric mass density of the porous medium (Kg.m $^{-3}$)

C_{pr}: specific heat of the resin(J·kg^{-1}·K^{-1})

ρ_r: volumetric mass density of the resin (Kg.m^{-3})

$\vec{v}$: resin velocity (m.s^{-1})

T: temperature (K)

$\bar{\bar{\kappa}}$: thermal conductivity tensor (W·m^{-1}·K^{-1})

S: source term (W·m^{-3})

Infusion modelling

Chemical Reaction Modeling: kinetic law

generic law representing the degree of completion of a several chemical sub-reactions

$$\frac{d\alpha}{dt} = \sum_i w_i(t)\frac{d\alpha_i}{dt} = \sum_i w_i(t) f_i(T,\alpha)$$

Example of thermosetting resin reticulation

Kamal-Sorrour model: $$\frac{D\alpha}{Dt} = \tilde{K}_i\, \alpha_i^{n_i}(1-\alpha_i)^{p_i}$$

Arrhénius law: $$\tilde{K}_i = A_i e^{-\frac{E_i}{RT}}$$

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Liquid Composite Moulding

Material characterization

ESI PAM-COMPOSITES

Material characterization for **RTM module (Isothermal filling)**

Density of the resin

- Resin supplier

Viscosity of the resin = f(time)

- Rheometer measurement of the viscosity evolution as a function of time at injection temperature

Permeability tensor of the reinforcements

- In-plane values for shell models
- In-plane and transverse values for solid models

EASYPERM permeability bench:

https://www.youtube.com/watch?v=YTS0ihjBy_Y&feature=youtu.be&list=PLEm2vnZ25o0YUxDvXF0su1wFhK68PycG3

ESI PAM-COMPOSITES

Material characterization for **RTM module (Heated filling)**

Viscosity of the resin = f(degree of cure, temperature)

- Rheometer measurement of the viscosity evolution as a function of time at different temperatures

Kinetic and enthalpy of the resin

- DSC measurements at different temperatures

Specific heat of the resin

- Resin supplier

Conductivity of the resin

- Resin supplier

Density of the resin

- Resin supplier

Conductivity tensor of the reinforcement

- Computed analytically from fiber conductivity

Specific heat of the fiber

- Fiber supplier

Density of the fiber

- Fiber supplier

Permeability tensor of the reinforcements

- In-plane and transverse values

ESI PAM-COMPOSITES

Material characterization for **Thermal module (Pre-heating & Curing)**

PREHEATING (solids only)

- **Conductivity tensor of the reinforcement**
  - Computed analytically from fiber conductivity
- **Specific heat of the fiber**
  - Fiber supplier
- **Density of the fiber**
  - Fiber supplier

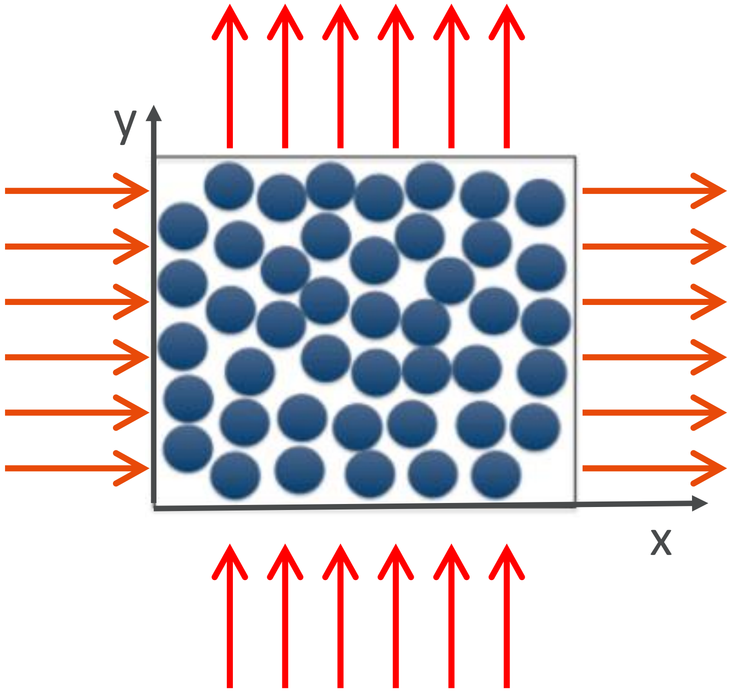
CURING (solids only)

- **Kinetic and enthalpy of the resin**
  - DSC measurements at different temperatures
- **Specific heat of the resin**
  - Resin supplier
- **Conductivity of the resin**
  - Resin supplier
- **Density of the resin**
  - Resin supplier
- **Conductivity tensor of the reinforcement**
  - Computed analytically from fiber conductivity
- **Specific heat of the fiber**
  - Fiber supplier
- **Density of the fiber**
  - Fiber supplier

Fluid Mechanics in porous medium

Numerical characterization: Methods to predict K from microstructural data

1/ Identification from Darcy's law : single-scale porous medium

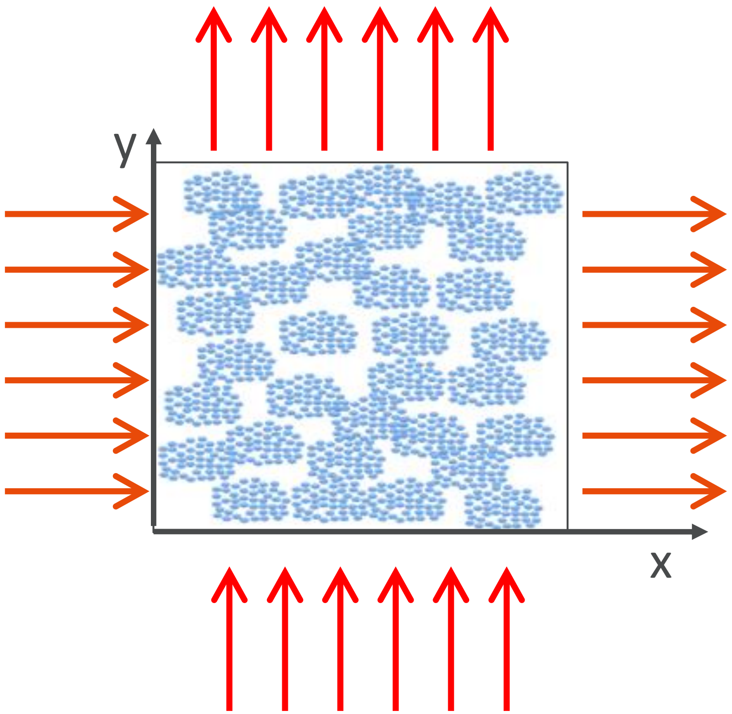


- Impose appropriate periodic BC (e.g. a given velocity of pressure in the direction i)
- Solve for v_i and P using in the fluid domain $\nabla P_\mathrm{f} + \eta \nabla^2 \boldsymbol{v}_\mathrm{f} = 0$
- Compute $\langle \boldsymbol{v}_\mathrm{i} \rangle = \dfrac{1}{A} \displaystyle\int_{S_\mathrm{f}} \boldsymbol{v}_\mathrm{f} \boldsymbol{n} \mathrm{d}S$
- Compute $K_\mathrm{i} = \dfrac{\langle \boldsymbol{v}_\mathrm{i} \rangle \eta}{A \nabla P}$

Fluid Mechanics in porous medium

Numerical characterization: Methods to predict K from microstructural data

1/ Identification from Darcy's law : double-scale porous medium



- Get the permeability tensor **K** of fiber tows
- Impose appropriate periodic BC (e.g. a given velocity of pressure in the direction i)

- Solve for v_i and P using the Brinkman Eq.

$$-\phi_{\mathrm{f}}\nabla\langle P_{\mathrm{f}}\rangle^{\mathrm{f}} + \eta\nabla^2\langle \boldsymbol{v}_{\mathrm{f}}\rangle - \phi_{\mathrm{f}}\eta\boldsymbol{K}_{tow}^{-1}\cdot\langle \boldsymbol{v}_{\mathrm{f}}\rangle = 0$$

- Compute $\langle \boldsymbol{v}_{\mathrm{i}}\rangle = \frac{1}{A}\int_{S_{\mathrm{f}}} \boldsymbol{v}_{\mathrm{f}}\boldsymbol{n}\mathrm{d}S$

- Compute $K_{\mathrm{i}} = \frac{\langle \boldsymbol{v}_{\mathrm{i}}\rangle\eta}{A\nabla P}$

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Fluid Mechanics in porous medium

Numerical characterization: Methods to predict K from microstructural data

Example

SEM image

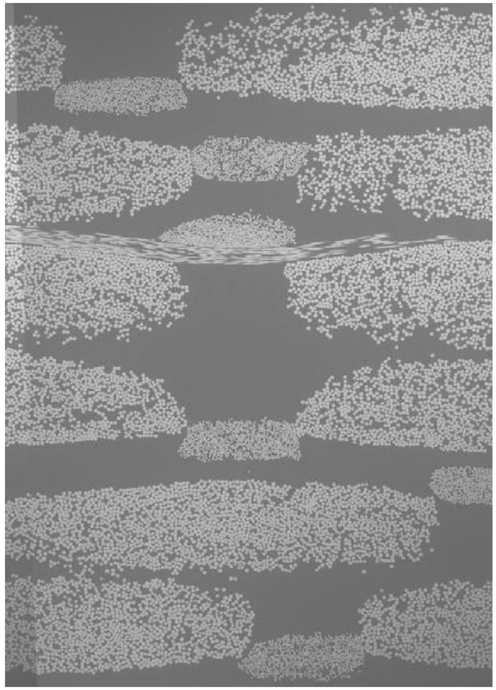


Image with segmented fibrous regions

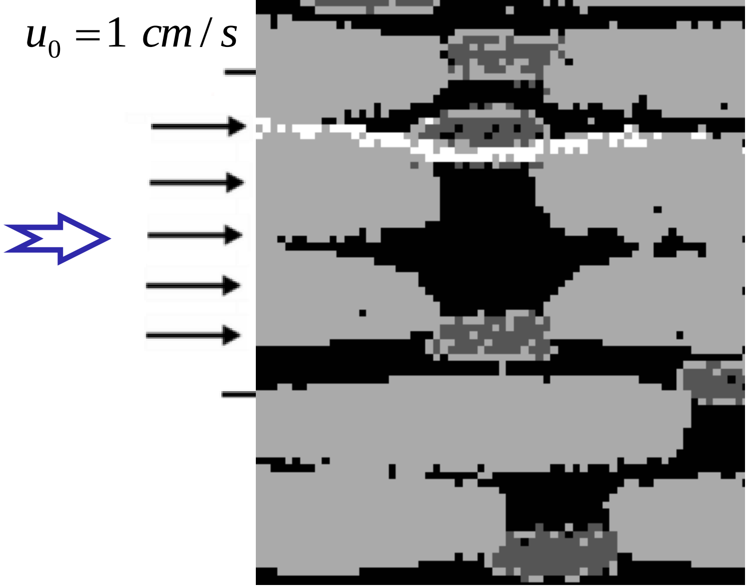
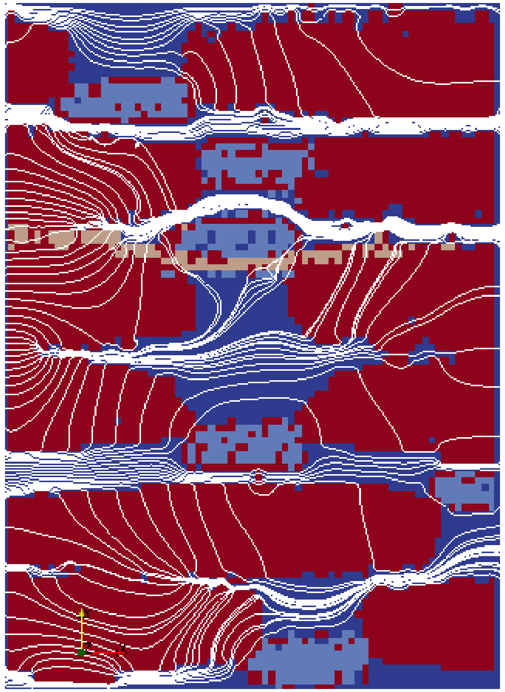


Image with segmented regions and calculated flow (streamlines)



3 fiber tows regions (white, dark grey and light gey) :

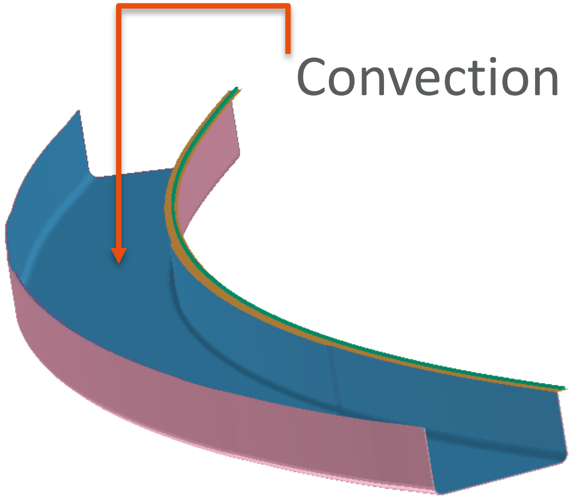
$$\mathbf{K}_1 = \begin{bmatrix} K_\perp^1 & 0 \\ 0 & K_\perp^1 \end{bmatrix} \quad \mathbf{K}_2 = \begin{bmatrix} K_{//}^2 & 0 \\ 0 & K_\perp^2 \end{bmatrix} \quad \mathbf{K}_3 = \begin{bmatrix} K_\perp^2 & 0 \\ 0 & K_\perp^2 \end{bmatrix}$$

Liquid Composite Moulding

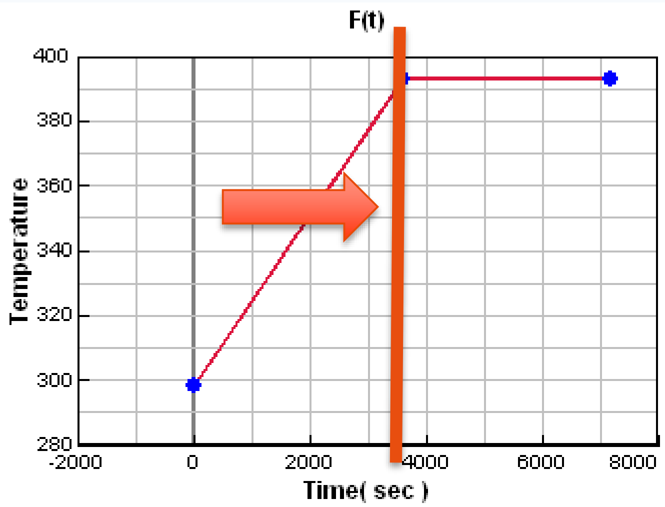
Examples

C Spar

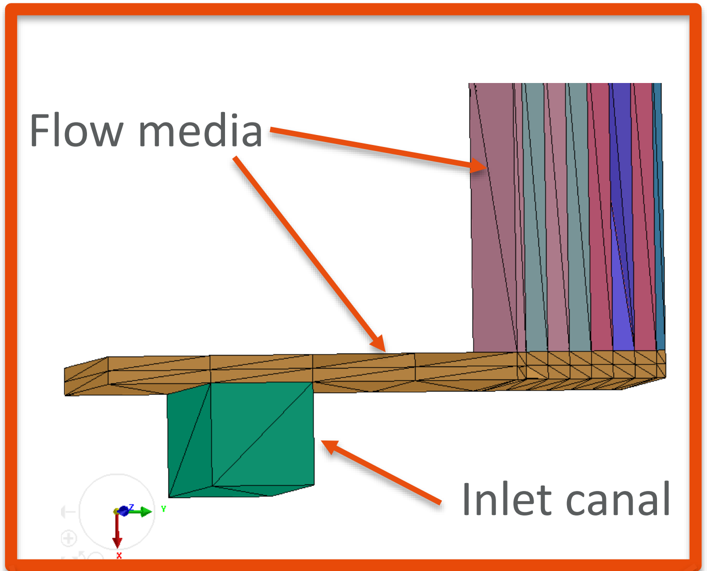
Pre-heating model



Convection composite / mold inside skin

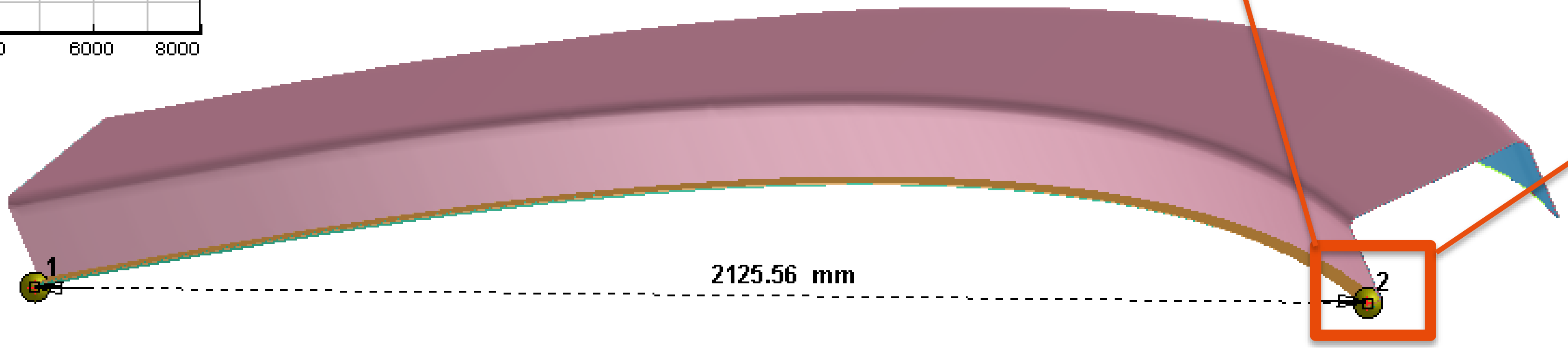


Imposed temperature on the top



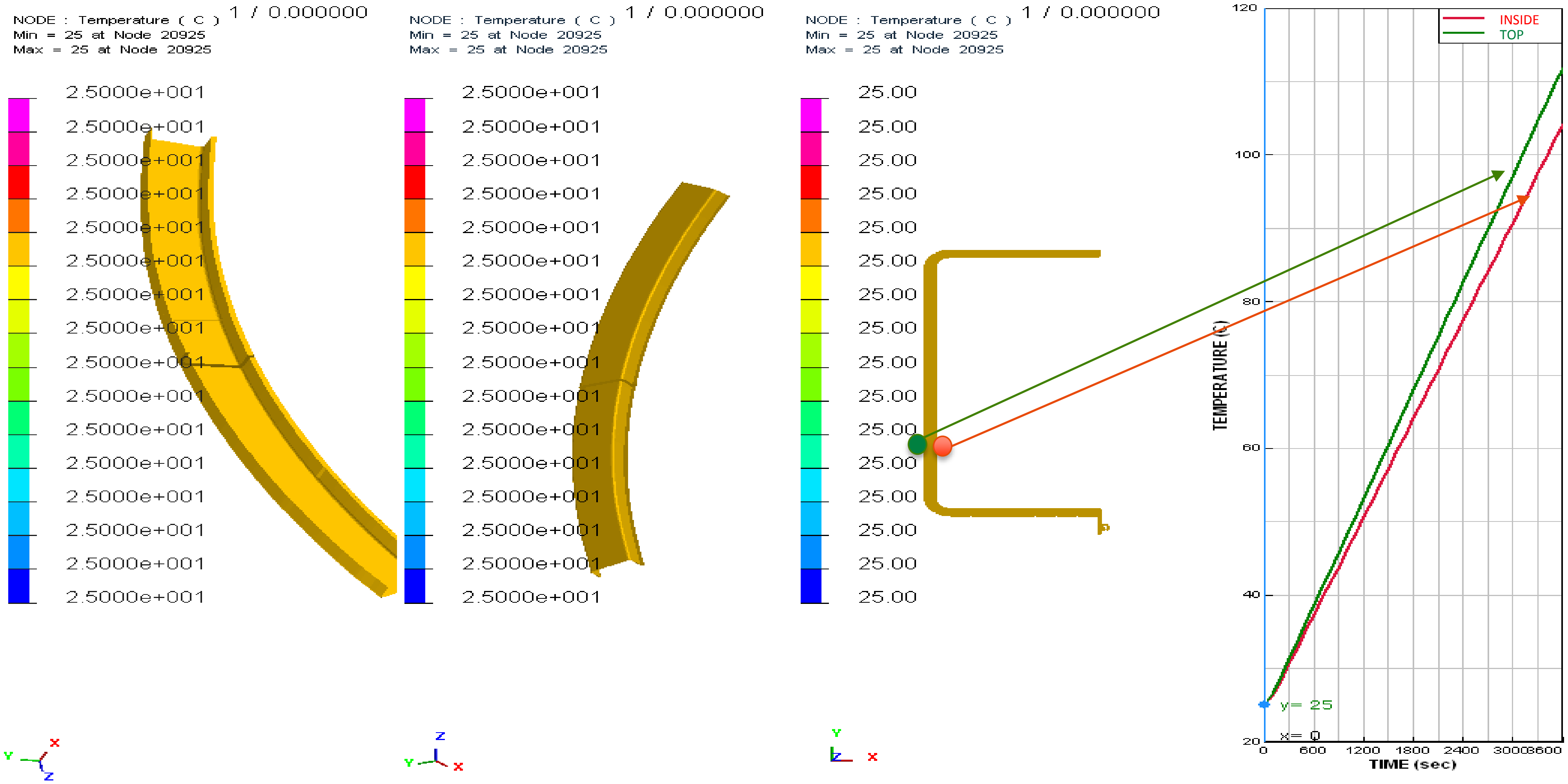
Flow media

Inlet canal



C Spar

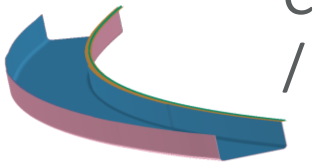
Pre-heating simulation



C Spar

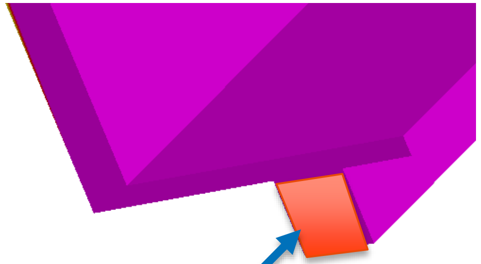
Heated filling model

Temperature BC



Convection composite / mold inside skin

Imposed temperature on the top



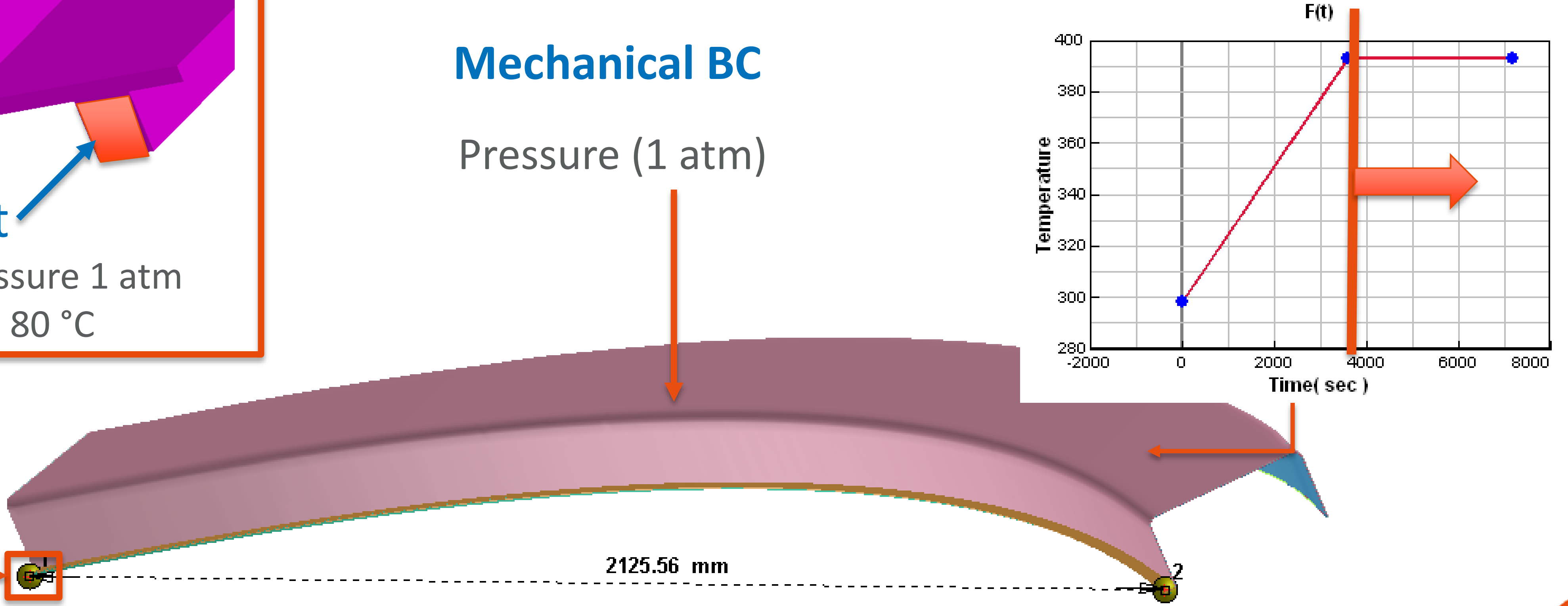
Flow Inlet

Imposed pressure 1 atm

Resin temp = 80 °C

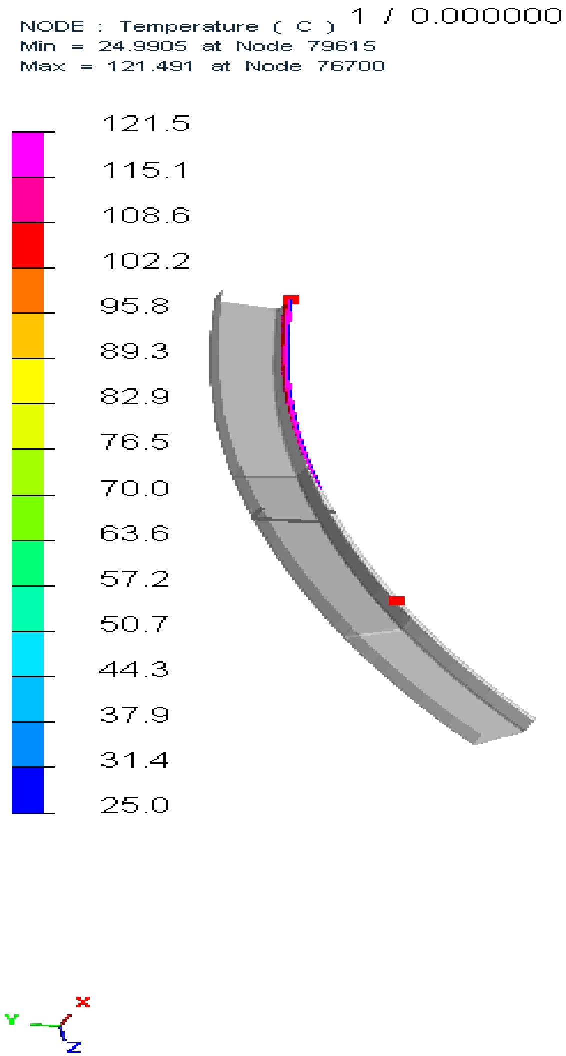
Mechanical BC

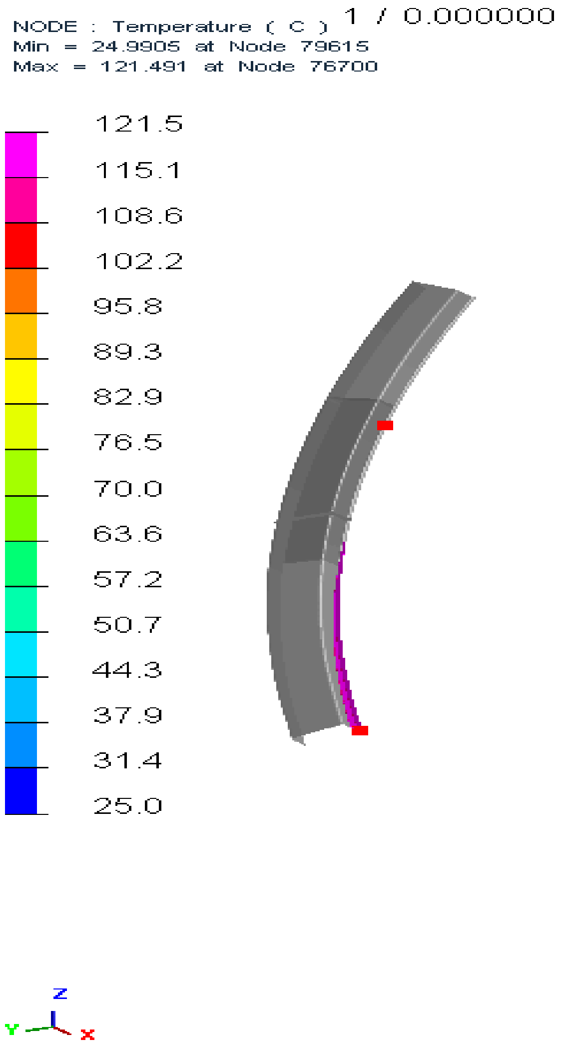
Pressure (1 atm)

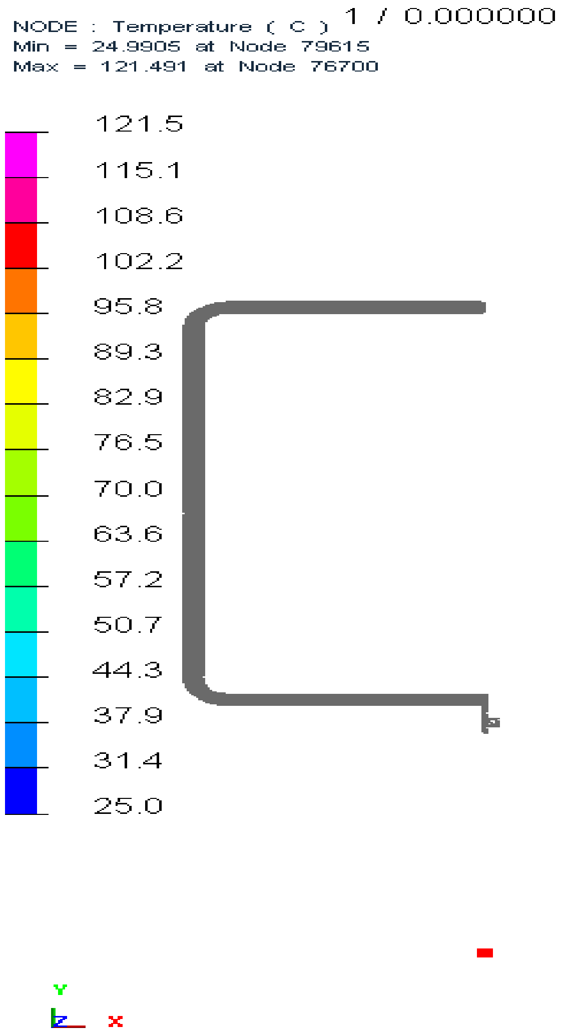


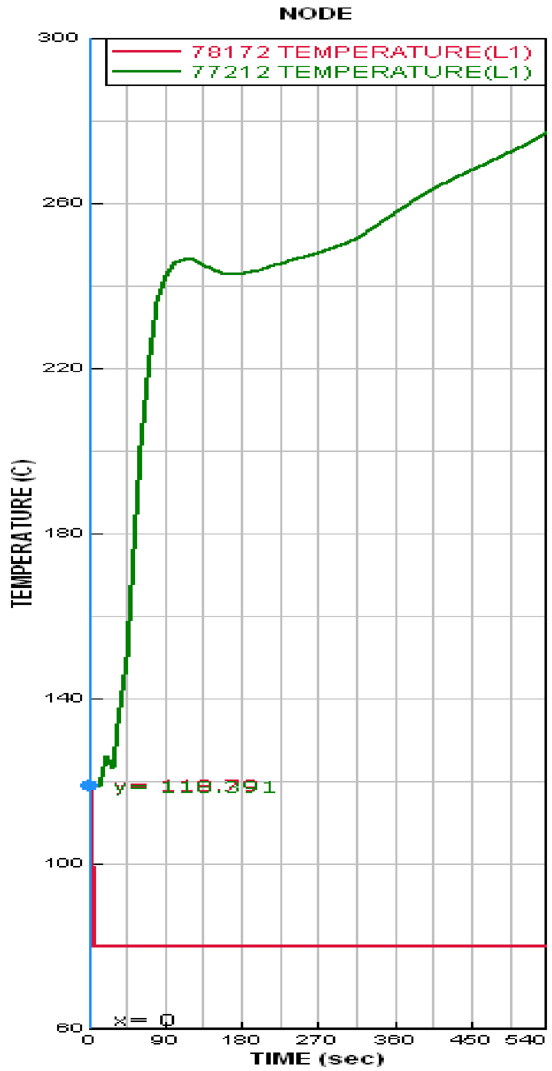
C Spar

Heated filling simulation



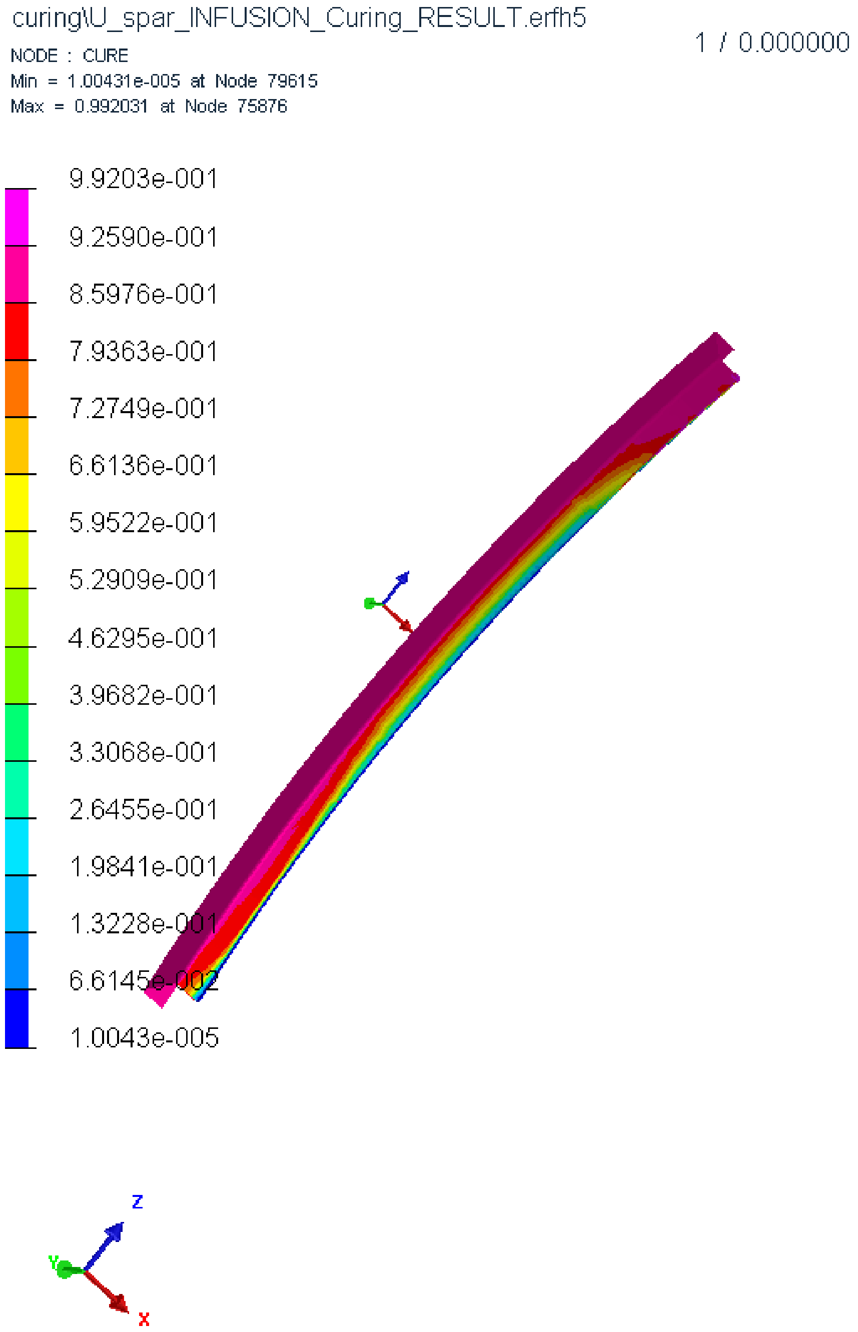






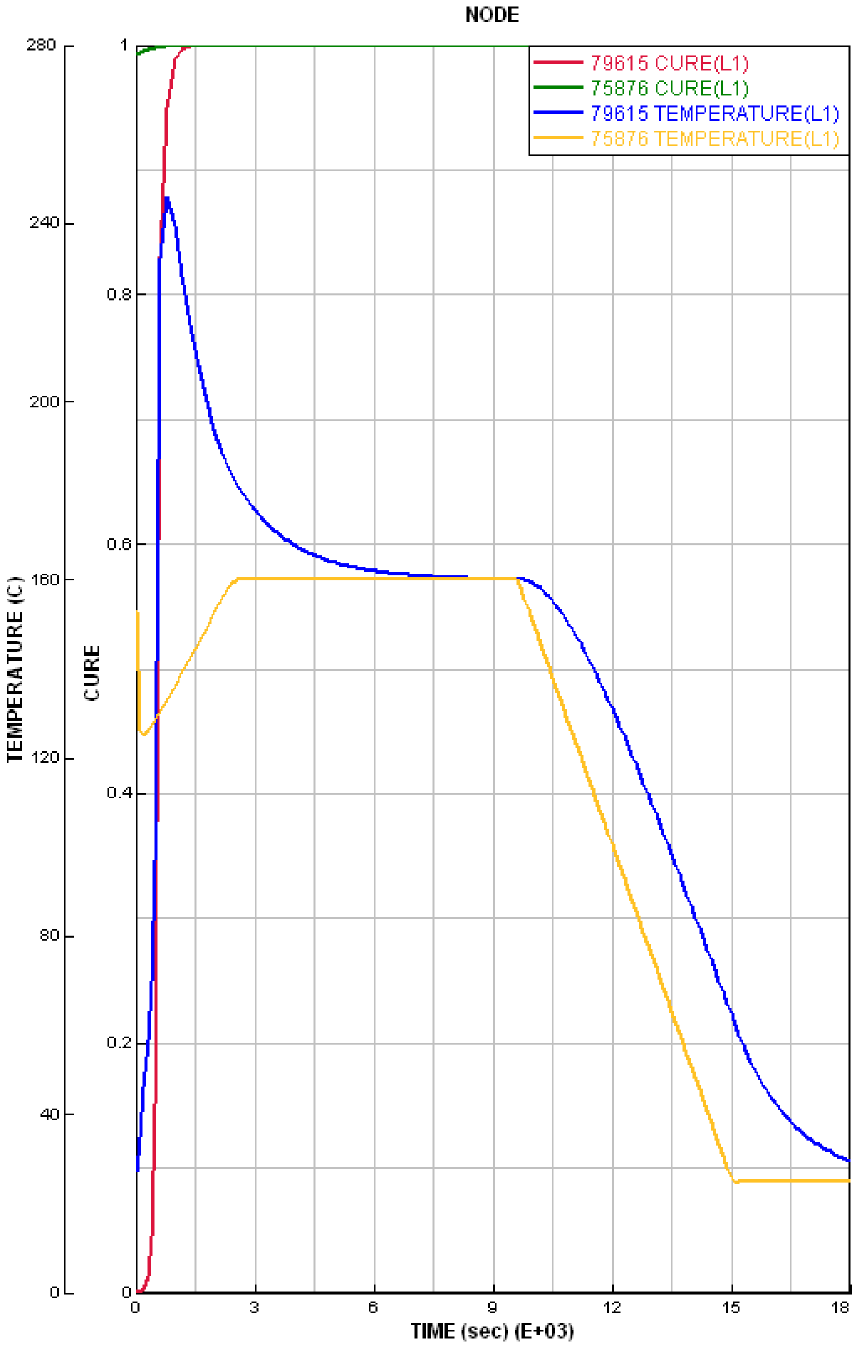
C Spar

Curing simulation



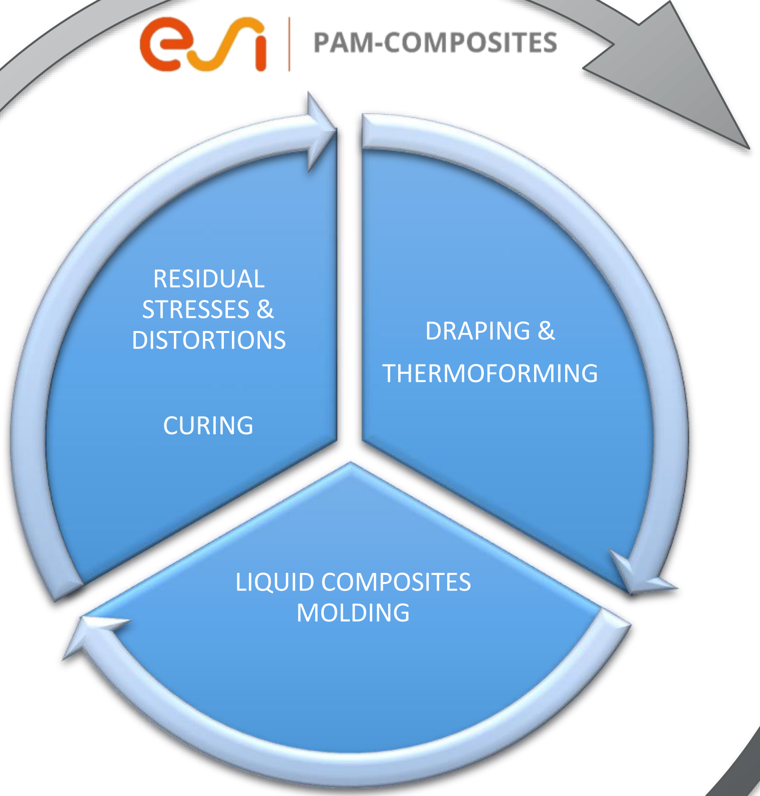
curing\U_spar_INFUSION_Curing_RESULT.erfh5

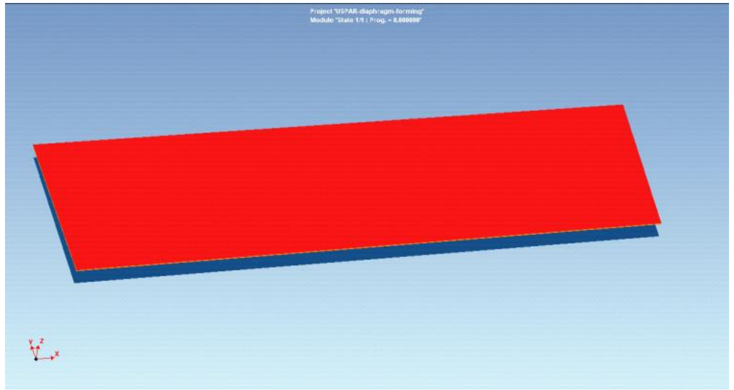
NODE : CURE
Min = 1.00431e-005 at Node 79615
Max = 0.992031 at Node 75876

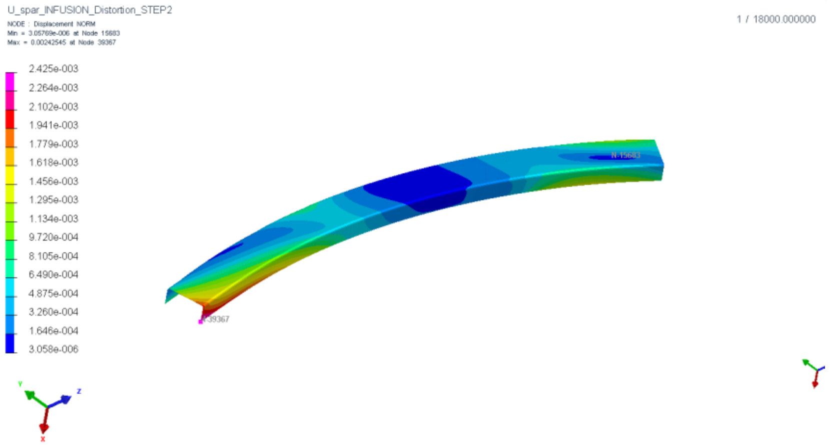


ESI’s PAM-COMPOSITES

Compensated mold







Temperature history

Degree of cure history

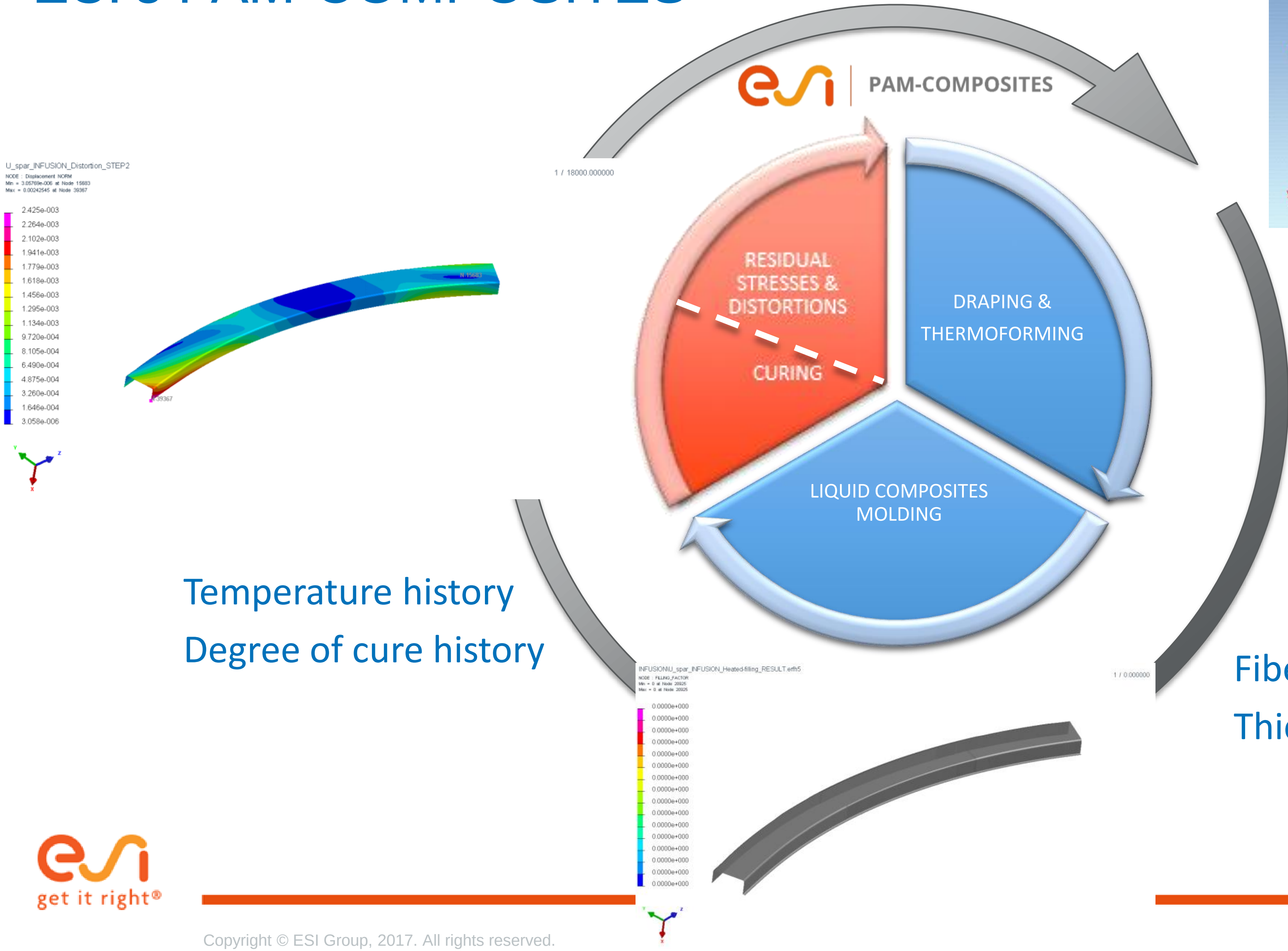
Fiber direction

Thickness variation

get it right®

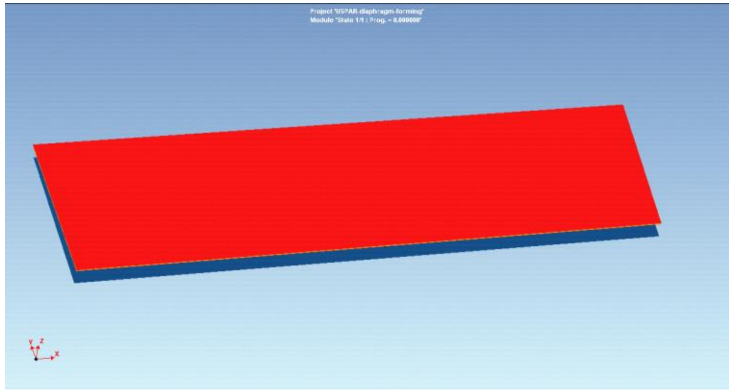
ESI’s PAM-COMPOSITES

Compensated mold



Temperature history

Degree of cure history



Fiber direction

Thickness variation

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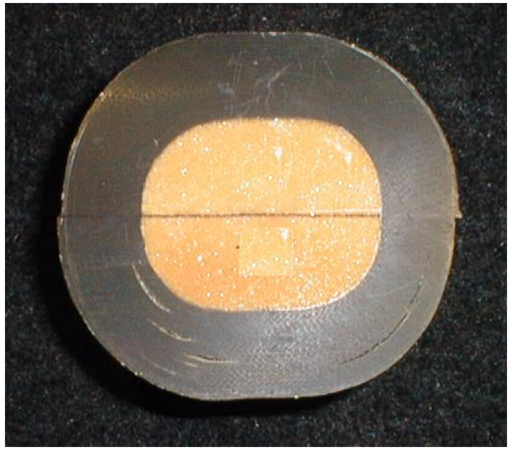
CURING & DISTORTION

Industrial issues

Industrial problematic

Problem Faced in Manufacture: **assembling problems** and **delamination**

Seattle Times pictures



Courtesy: SWEREA SICOMP

- How to avoid or minimise distortions and residual stresses ?
- What parameter do I need to modify ?
  - Material
  - Stacking sequences
  - Tooling
  - Temperature history

CURING OF THERMOSETS & DISTORTION

Why shall we model it ?

CURING	With the defined process, is the part going to be fully cured ? Are the costs optimised ?
DISTORTION	How much does the part deform after tooling removal ? How to minimise these deformations ? How to quantify the residual stresses ?

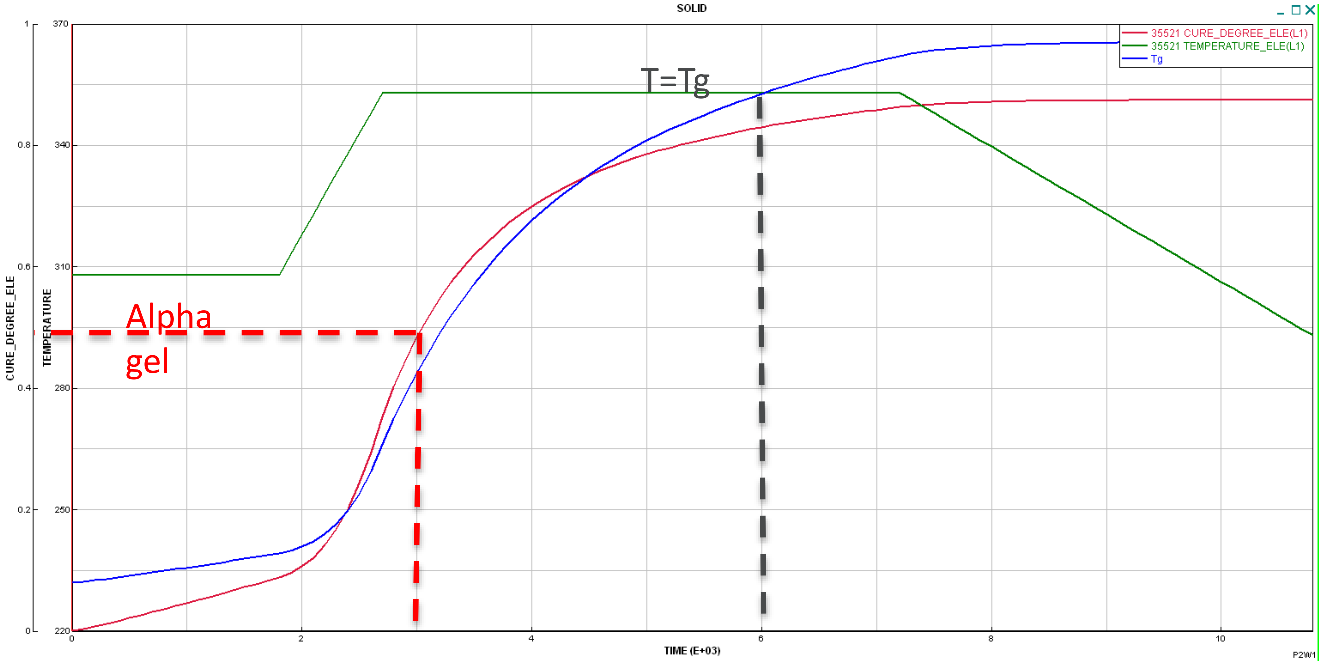
CURING & DISTORTION

Material state evolution

PAM-DISTORTION

Resin state

- Initially, the resin is a **liquid**. The cross-linking (or **curing**) reaction leads it to a **rubbery** state (after the **gel point**).
- Below the glass transition temperature (T_g), the resin is in a **glassy** state.
- The T_g depends on the degree of cure (α).



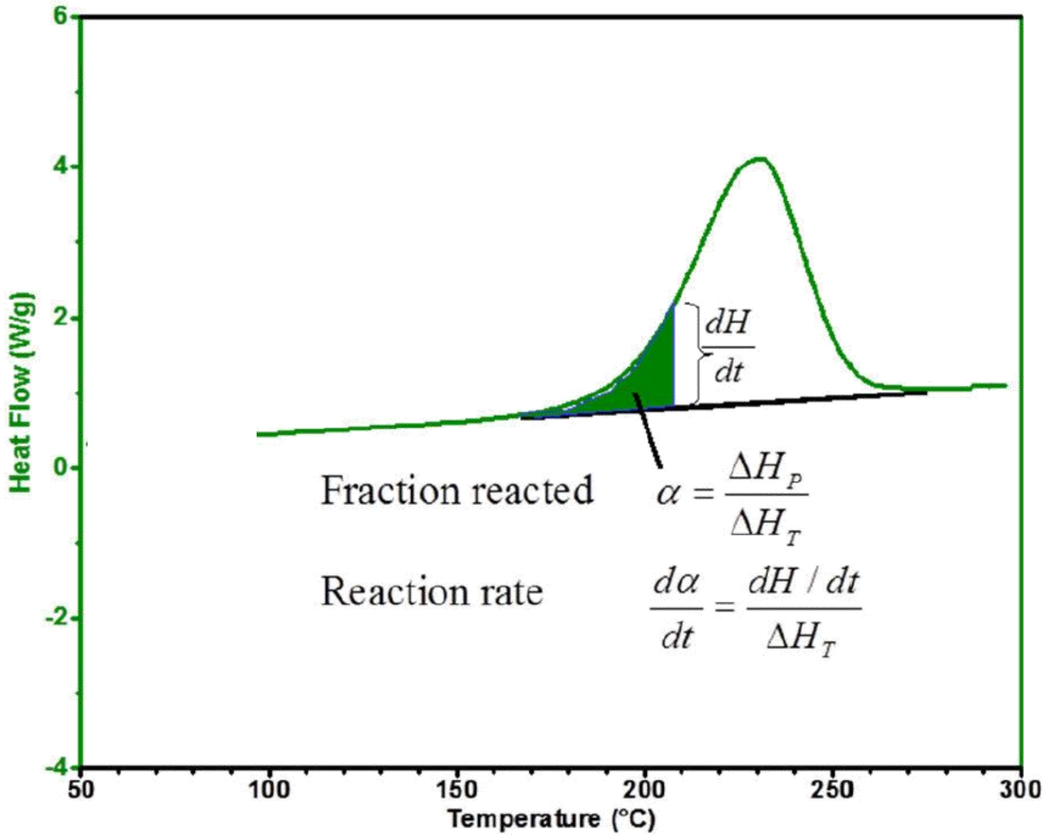
Resin is liquid

Resin is rubbery

Resin is glassy

PAM-DISTORTION

Differential Scanning Calorimetry



- Gives **α** and **dα/dt** as functions of time and temperature.
- The cure kinetics can thus be **modelled** (Kamal-Sourour and other models…)

$$\frac{d\alpha}{dt} = f(\alpha, t)$$

- DSC measurements also provide the **T$_g$**

Di Benedetto $$\frac{T_g - T_{g0}}{T_{g\infty} - T_{g0}} = \frac{\lambda\alpha}{1 - (1 - \lambda) \cdot \alpha}$$

T_{g0}: Glass transition temperature of the uncured system ($\alpha = 0$)
$T_{g\infty}$: Glass transition temperature of the fully cured system ($\alpha = 1$)
λ: Material constant

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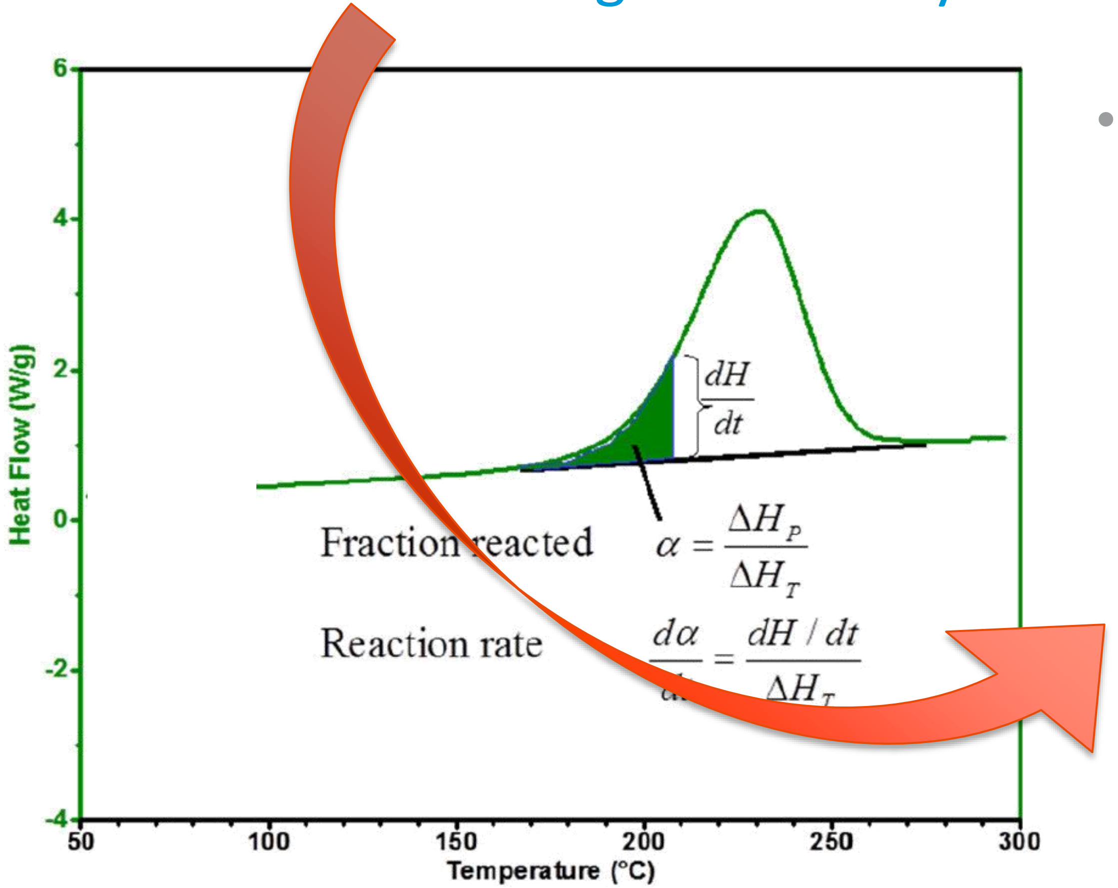
PAM-DISTORTION

Differential Scanning Calorimetry



- Gives **α** and **dα/dt** as functions of time and temperature.
- The cure kinetics can thus be **modelled** (Kamal-Sourour and other models…)

$$\frac{d\alpha}{dt} = f(\alpha, t)$$

- To reduce drastically the **processing time** (for example **the automotive industry**), some **highly reactive resin** are developed, and the curing time can be **below the minute** !
- Accurate characterisation is therefore crucial

CURING & DISTORTION

Mechanical behaviour

PAM-DISTORTION

Linear Viscoelasticity

- For an **isotropic linear viscoelastic** material, in the 1D case

$$\sigma(t) = \int_0^t E(\alpha, T, t-\tau) : \frac{d}{d\tau}\left[\varepsilon^{total}(\tau) - \varepsilon^{tc}(\tau)\right] d\tau$$

With ε^{tc} the addition of the thermal **expansion strains** and the **chemical strains (shrinkage)** assumed to be linear

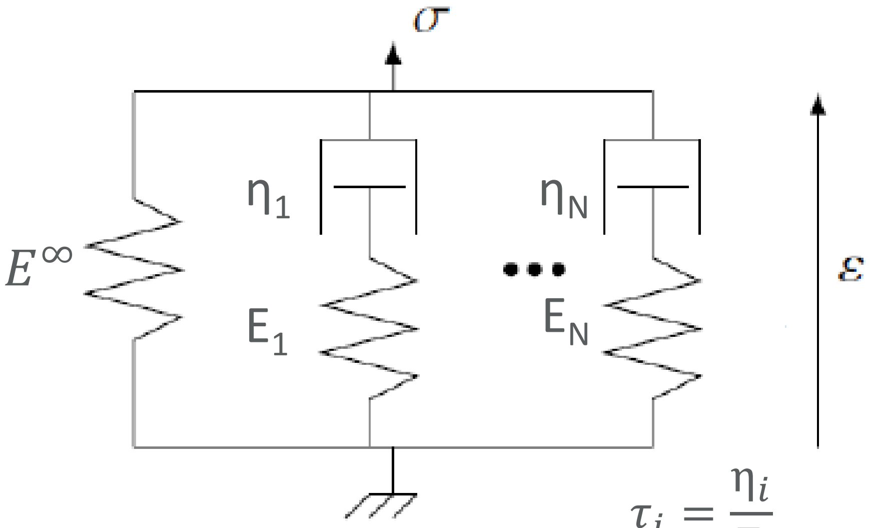
- **Time-temperature superposition** method, sometimes extended to the cure advancement,

$$\sigma(t) = \int_0^t E(\xi(t) - \xi'(\tau)) : \frac{d}{d\tau}\left[\varepsilon^{total}(\tau) - \varepsilon^{tc}(\tau)\right] d\tau$$

With the **reduced time variable** $\xi(t) = \int_0^t \frac{1}{a_T(\alpha, T)} dt$

PAM-DISTORTION

Linear Viscoelasticity



$$\tau_i = \frac{\eta_i}{E_i}$$

***Fig.** Generalised Maxwell model*

- For example* for an epoxy resin characterised with **stress relaxation** tests with **DMA**

$$E(\alpha,\xi) = E^\infty(\alpha) + [E^u(\alpha) - E^\infty(\alpha)]\sum_{i=1}^{N} W_i(\alpha)\exp[\frac{-\xi(\alpha,T)}{\tau_i(\alpha)}]$$

- Note that this is not a general model that can represent a priori **ANY** viscoelastic behaviour**.
- Let us assume that this is possible.
- Then, **homogenisation** is needed to estimate the **composite** viscoelastic properties.
- Still **complex** and **costly**: example of numerical homogenisation based on the Laplace-Carson transform ***

• *Kim YK, White SR. Stress relaxation behaviour of 3501-6 epoxy resin during cure. 1996.*

** *Bouleau N. Viscoelasticity and Lévy processes. Springer Verlag, 1999.*

*** *Lévesque M. et al. Numerical inversion of the Laplace-Carson transform applied to homogenization of randomly reinforced linear viscoelastic media. Comput. Mech 2007.*

CURING & DISTORTION

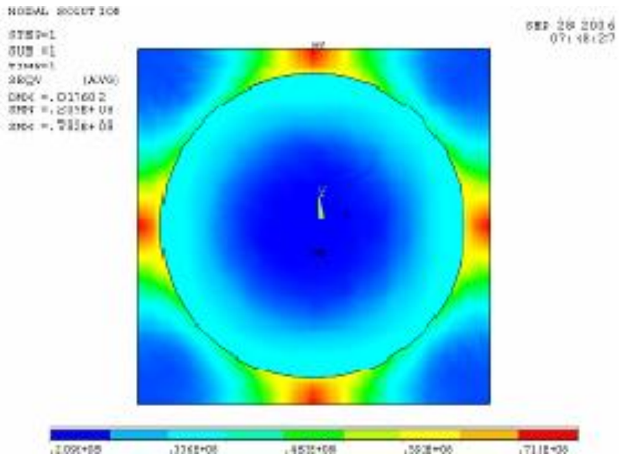
Identified physical phenomena*

- *Composites formiong technologies. Chapter 7: Understanding composite distortion during processing, Wisnom, Potter. 2007.*

CURING & DISTORTION

Identified physical phenomena

- **Thermal expansion**
  - Fibre // matrix CTEs
  - Anisotropic CTE at a ply level
  - Unsymmetric laminates

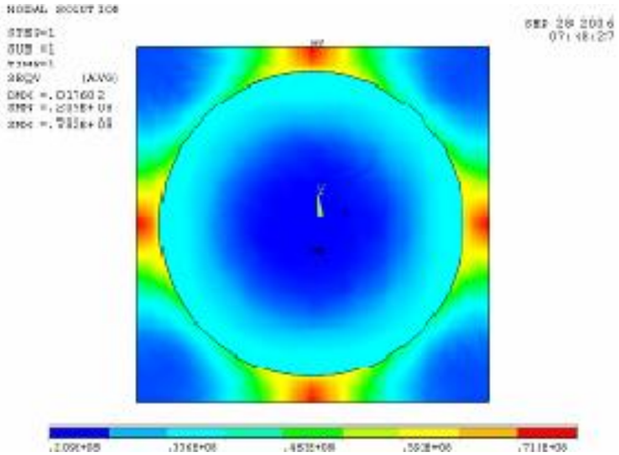


7.4 Curvature in (0/90) unsymmetric laminate due to residual thermal stresses.

CURING & DISTORTION

Identified physical phenomena

- **Thermal expansion**
  - Fibre // matrix CTEs
  - Anisotropic CTE at a ply level
  - Unsymmetric laminates



7.4 Curvature in (0/90) unsymmetric laminate due to residual thermal stresses.

- **Chemical shrinkage**

(typically about 7% for an epoxy resin)

CURING & DISTORTION

Identified physical phenomena

- **Thermal expansion**
  - Fibre // matrix CTEs
  - Anisotropic CTE at a ply level
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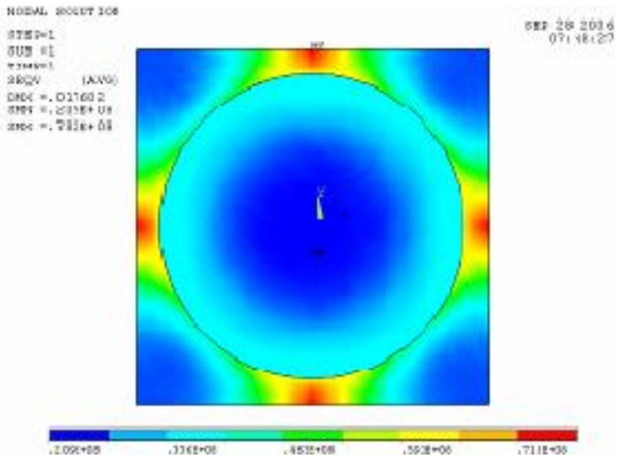
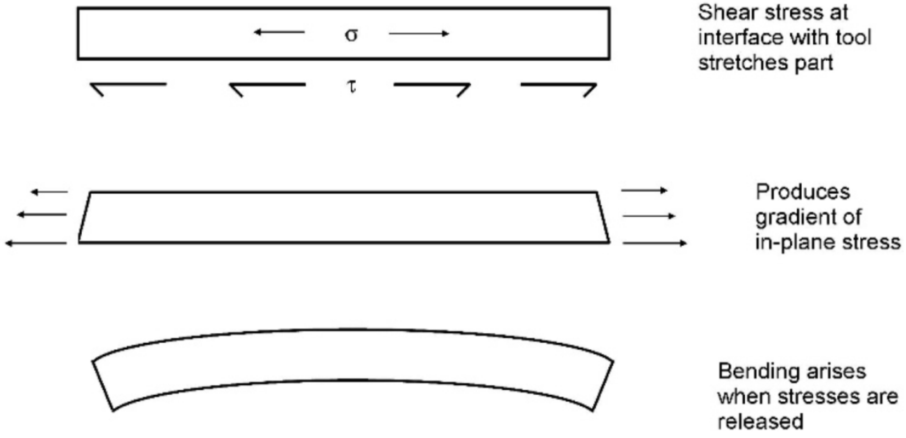
7.4 Curvature in (0/90) unsymmetric laminate due to residual thermal stresses.



- **Chemical shrinkage**

(typically about 7% for an epoxy resin)

- **Tool part interaction**
  - Frictional forces
  - Different CTEs

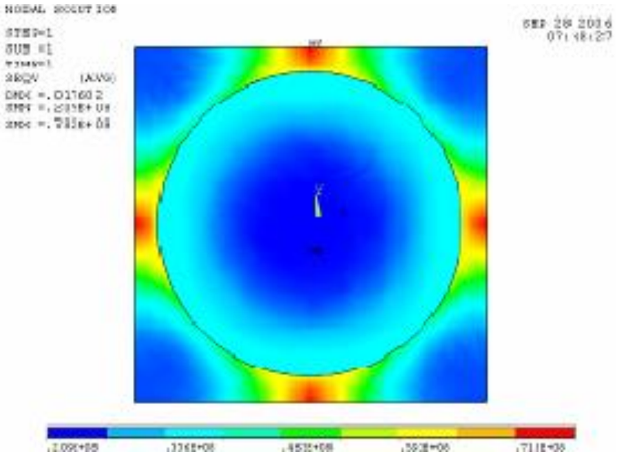


7.7 Distortion due to shear interaction at tool interface.

CURING & DISTORTION

Identified physical phenomena

- **Thermal expansion**
  - ❖ Fibre // matrix CTEs
  - ❖ Anisotropic CTE at a ply level
  - ❖ Unsymmetric laminates

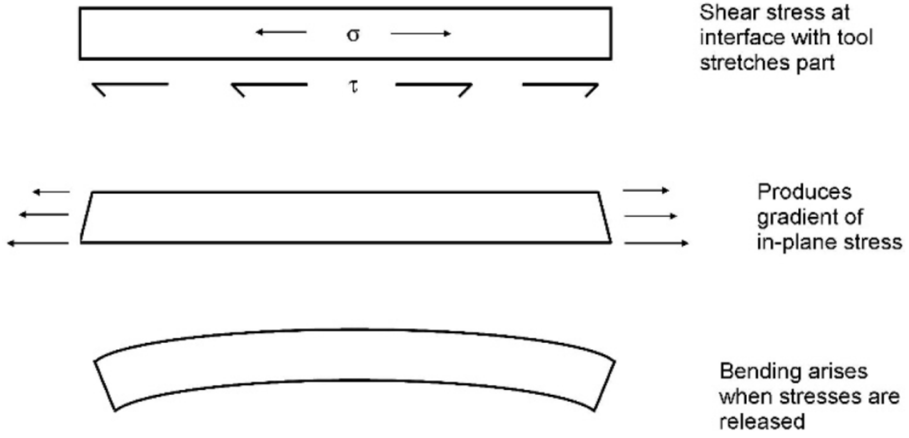


7.4 Curvature in (0/90) unsymmetric laminate due to residual thermal stresses.

- **Chemical shrinkage**

(typically about 7% for an epoxy resin)

- **Tool part interaction**
  - ❖ Frictional forces
  - ❖ Different CTEs



7.7 Distortion due to shear interaction at tool interface.

- **Others…** (thick parts lead to gradients, heterogeneous fibre content, manufacturing …)

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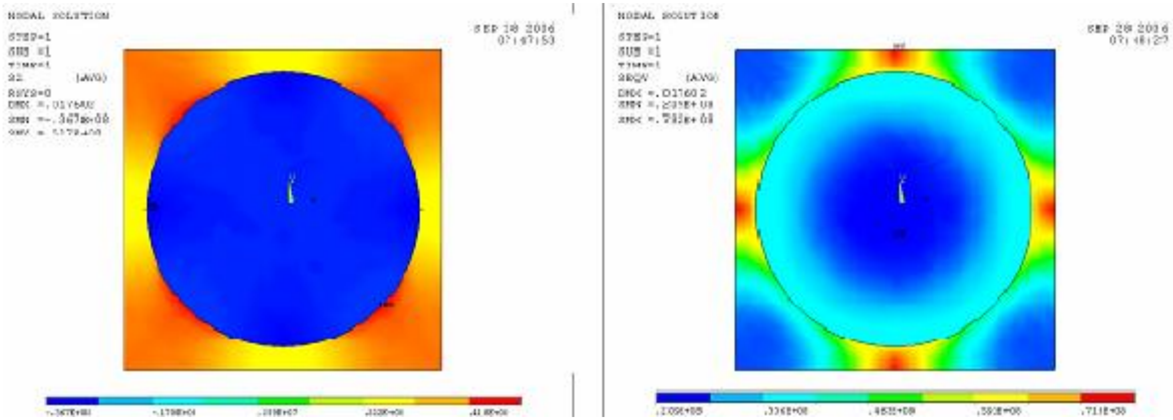
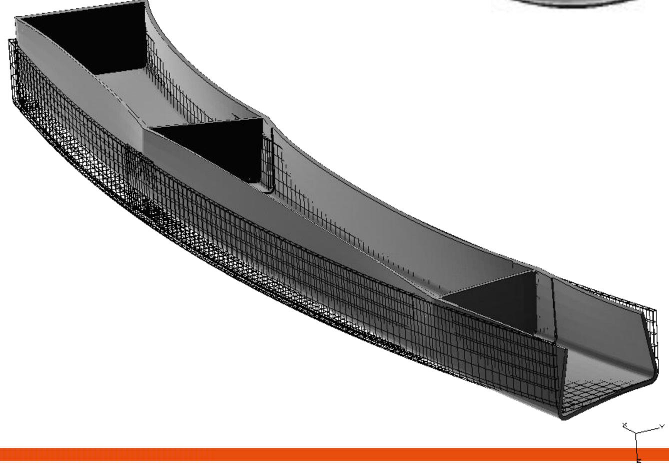
A **multiscale** nature of the problem

- **Micro (Fibre/matrix)**



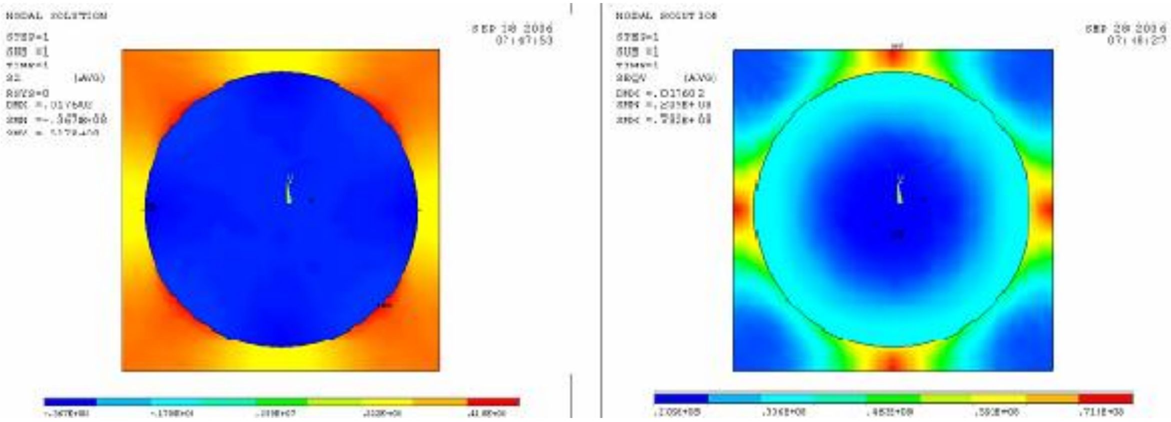
- **Meso (Ply)**

- **Macro (Laminate)**



A **multiscale** nature of the problem

- **Micro (Fibre/matrix)**



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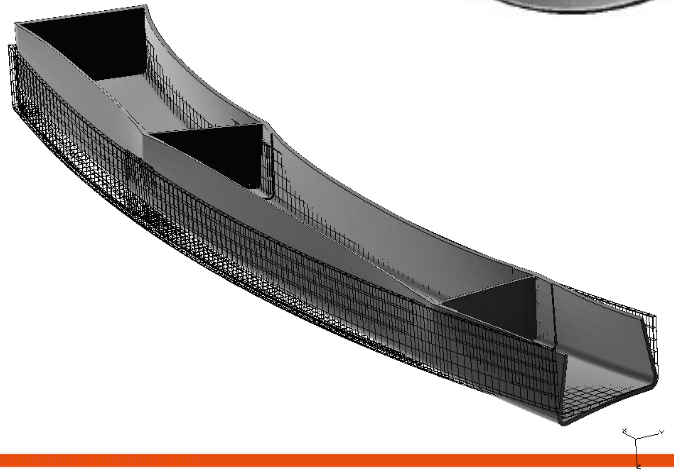
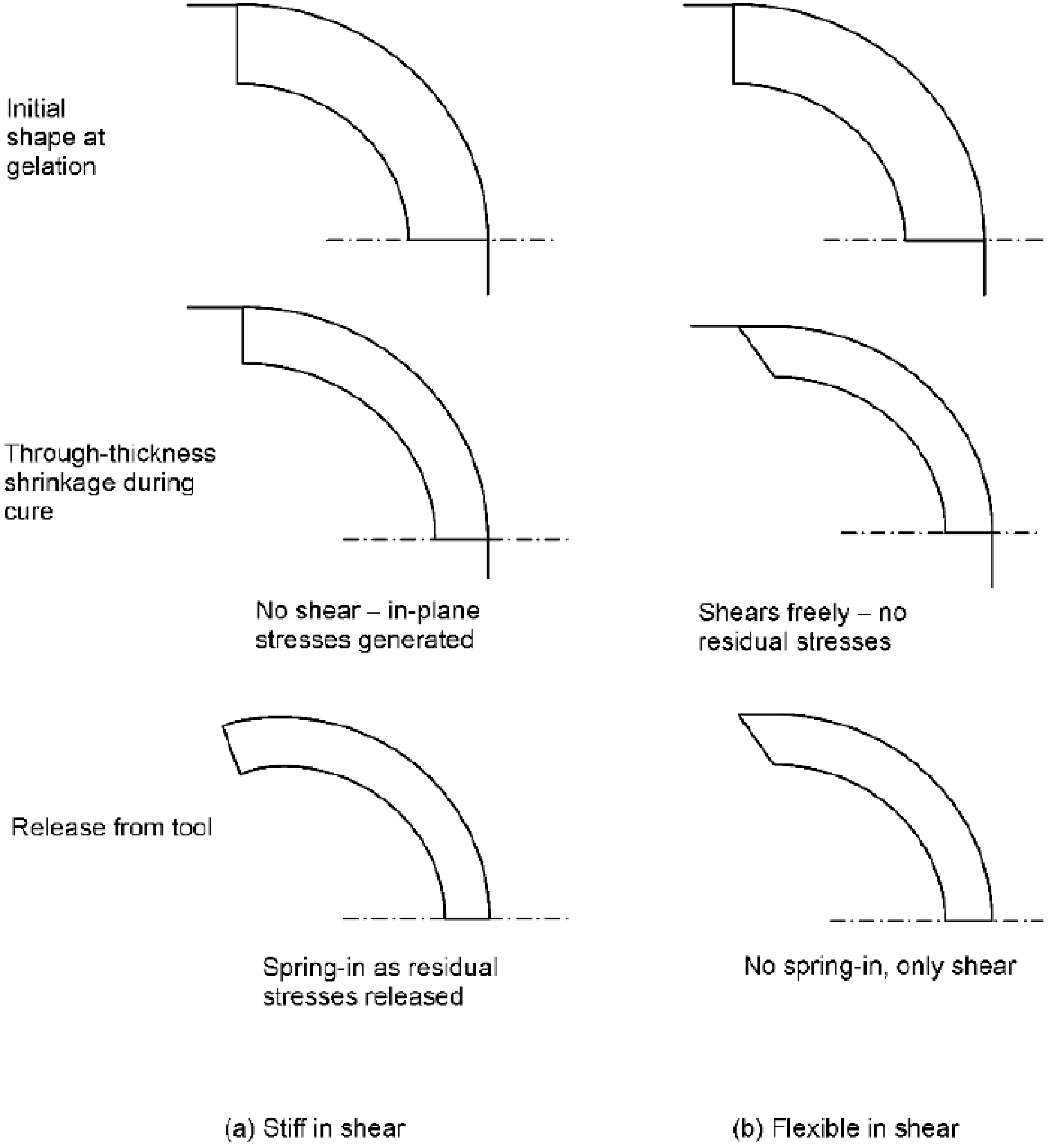


Spring in of curved parts

In the **elastic case**, **without chemical shrinkage**,

$$\frac{\Delta\theta}{\theta} = (\alpha_I - \alpha_T)\Delta T$$

Where Δθ is the change in angle θ, and the α's are the CTEs (in-plane and through-thickness).



7.10 Change of angle due to a through-thickness contraction.

Pictures extract from "High Performane Composites"

CURING & DISTORTION

Modelling the composite material behaviour

Constitutive law

- **Elastic Models**
  - based on CTE orthotropy
  - Material stiffness is constant
  - Offer good insight in general, but are not sophisticated enough to become accurate

$$\sigma = C : \varepsilon$$

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- **CHILE Models** (Cure Hardening Instantaneously Linear Elastic)
  - Incrementally elastic
  - Material stiffness function of temperature and degree of cure
  - Easy to characterise and to implement

$$\sigma(t) = \int_0^t C\big(T(\tau), \alpha(\tau)\big) : \frac{d\varepsilon}{d\tau}\, d\tau$$

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- **Viscoelastic Models**
  - Known as polymer behaviour. Especially pronounced for partially cured polymers at high temperatures in a cure cycle.

$$\sigma(t) = \int_0^t C(t-\tau) : \frac{d\varepsilon}{d\tau} d\tau$$

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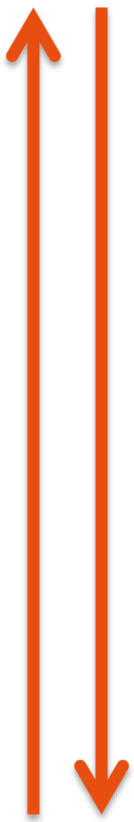
Constitutive law



Attractive

Computational cost

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Global Accuracy

Constitutive law

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  - Incrementally elastic
  - Material stiffness function of temperature and degree of cure
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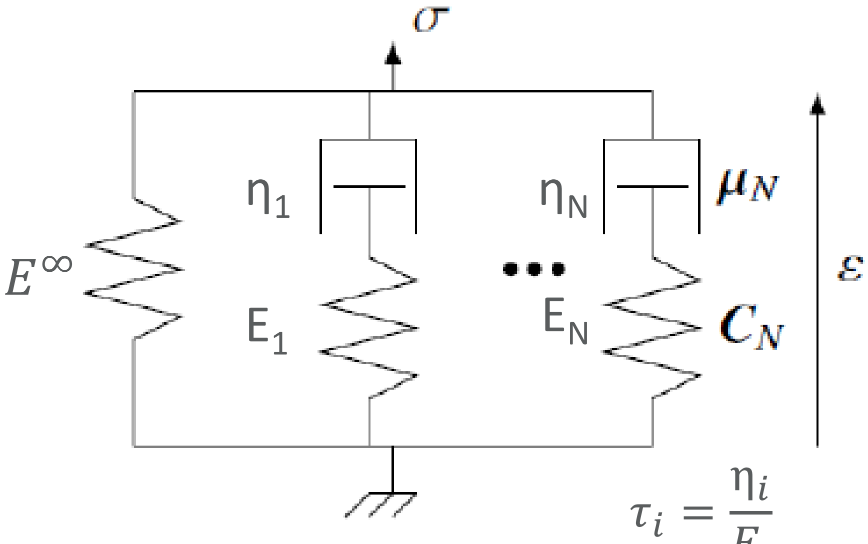
PAM-DISTORTION → **Simplified viscoelastic formulation**

$$\sigma(t) = \int_0^t C\big(T(\tau), \alpha(\tau)\big) : \frac{d\varepsilon}{d\tau}\, d\tau$$

- **Viscoelastic Models**
  - Known as polymer behaviour. Especially pronounced for partially cured polymers at high temperatures in a cure cycle.

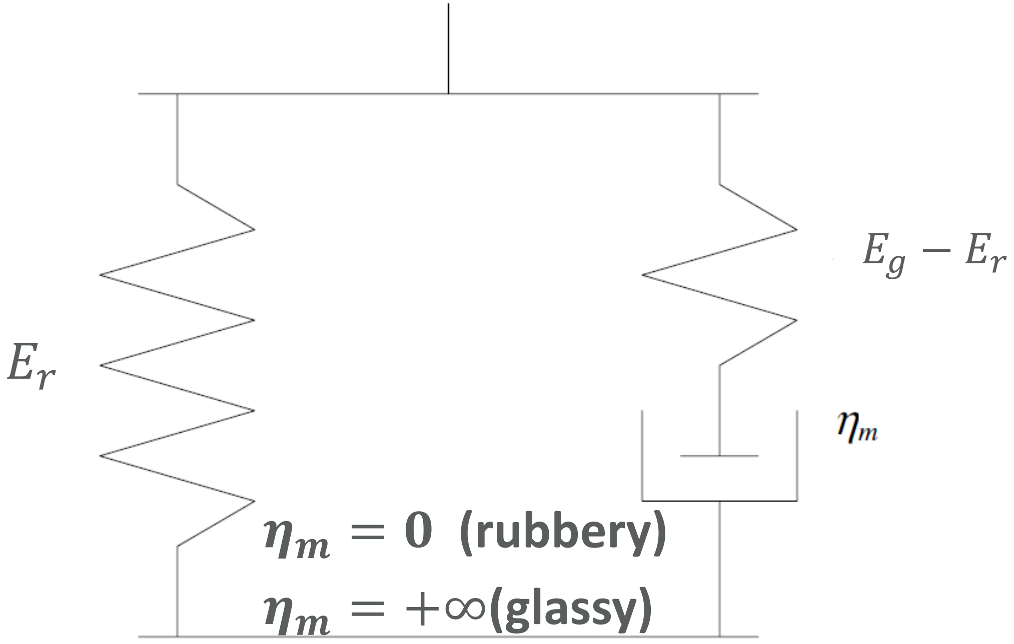
$$\sigma(t) = \int_0^t C(t - \tau) : \frac{d\varepsilon}{d\tau}\, d\tau$$

Introduction of a simplified formulation



$\tau_i = \frac{\eta_i}{E_i}$

***Fig.** Generalised Maxwell model*



$\eta_m = 0$ **(rubbery)**

$\eta_m = +\infty$**(glassy)**

***Fig.** Simplified model*

Introduction of a simplified formulation

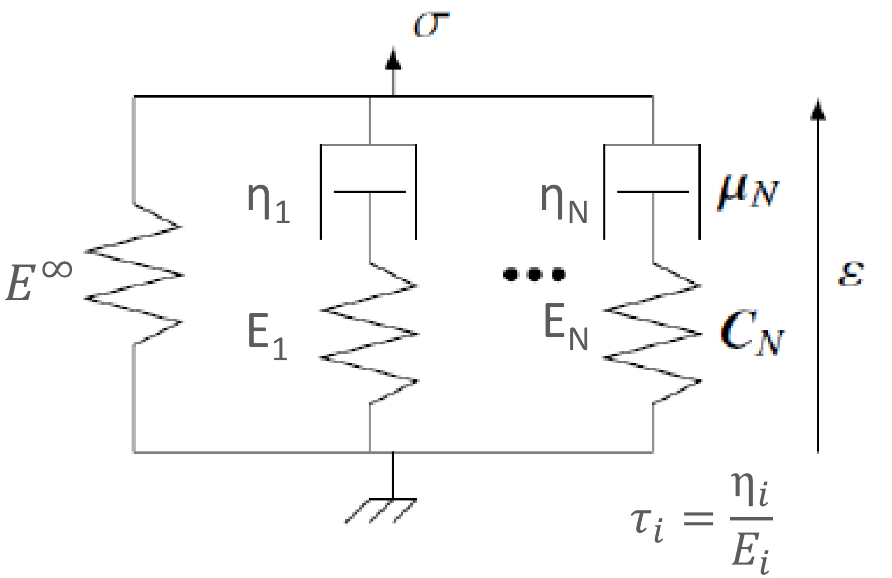
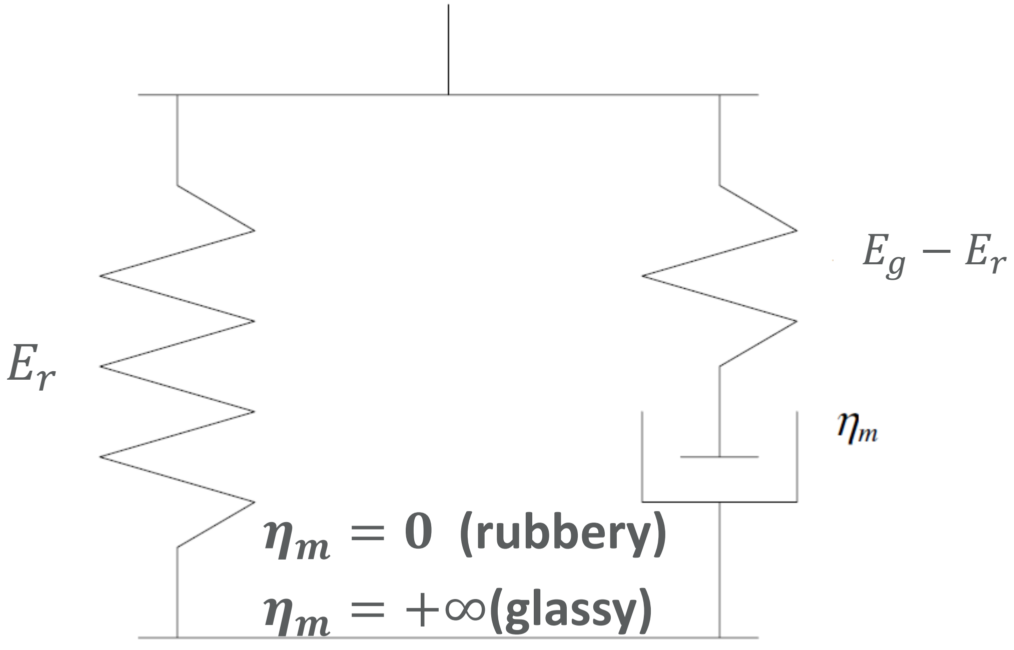


Fig. *Generalised Maxwell model*



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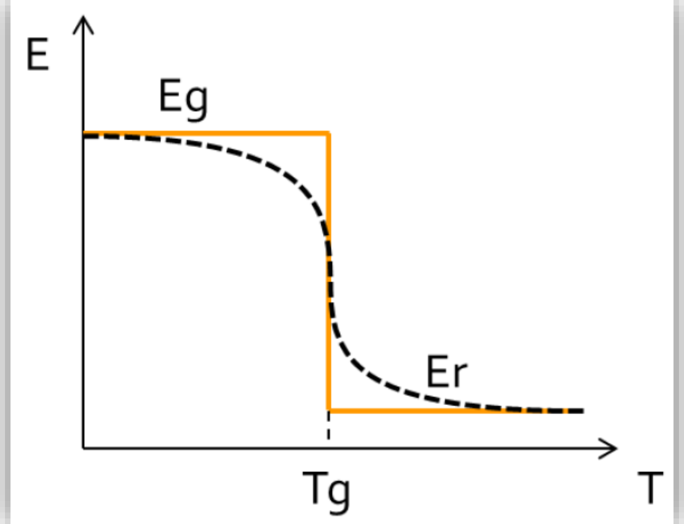
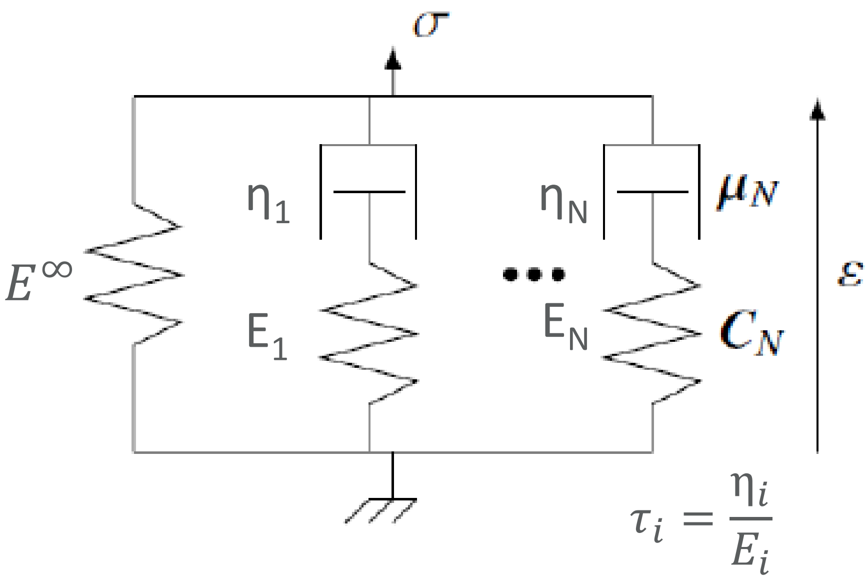


Introduction of a simplified formulation



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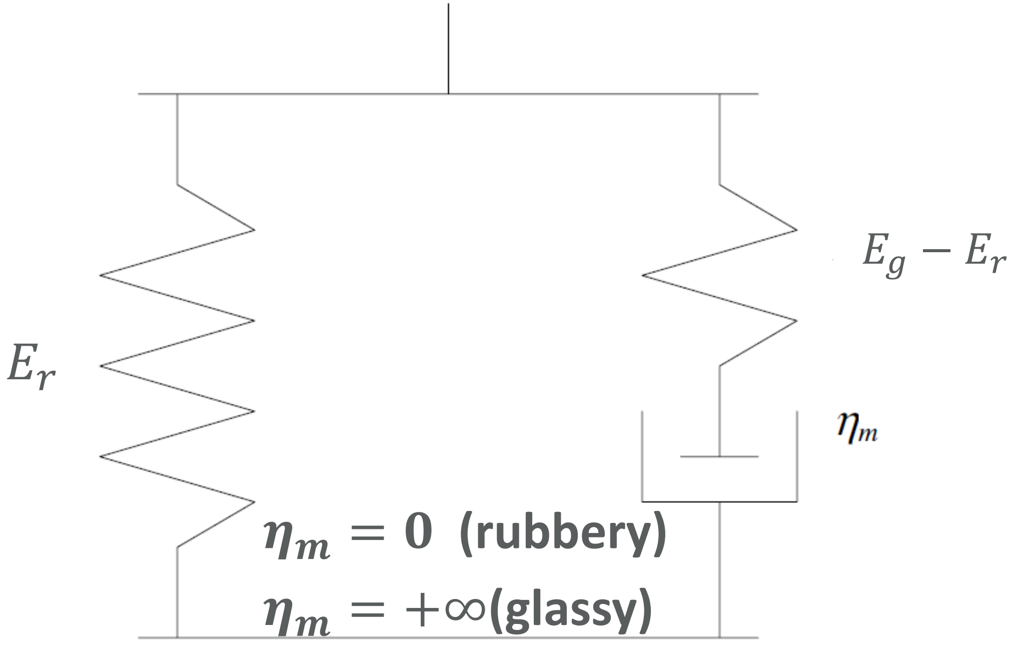

Fig. *Simplified model*

$$\sigma(t) = \int_0^t E(\xi(t) - \xi'(\tau)) : \frac{d}{d\tau}[\varepsilon^{total}(\tau) - \varepsilon^{tc}(\tau)]d\tau$$

$$E(\alpha, \xi) = E^\infty(\alpha) + [E^u(\alpha) - E^\infty(\alpha)] \sum_{i=1}^{N} W_i(\alpha) \exp[\frac{-\xi(\alpha, T)}{\tau_i(\alpha)}]$$

In glassy state

$$\sigma(t) = E_g[\varepsilon^{total} - \varepsilon^{tc}] - (E_g - E_r) \cdot [\varepsilon^{total} - \varepsilon^{tc}]_{vit}$$

In rubbery state

$$\sigma(t) = E_r[\varepsilon^{total} - \varepsilon^{tc}]$$

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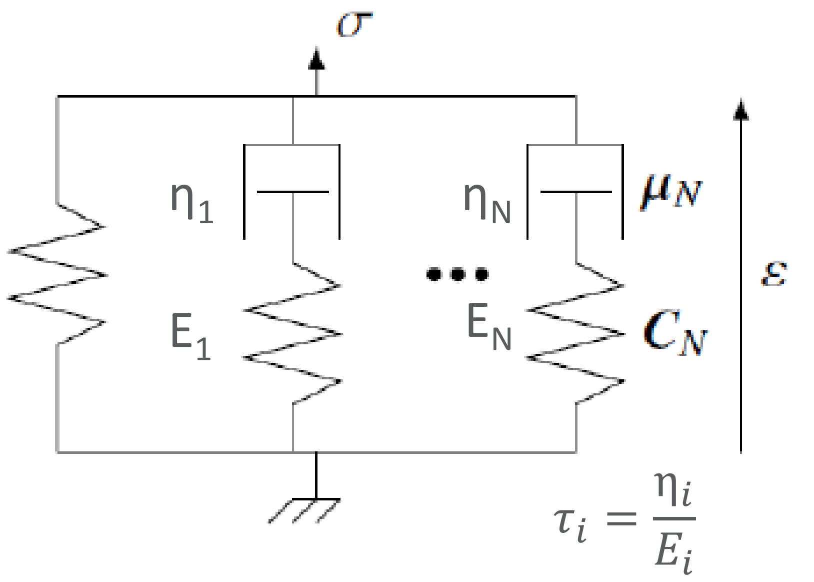
Introduction of a simplified formulation



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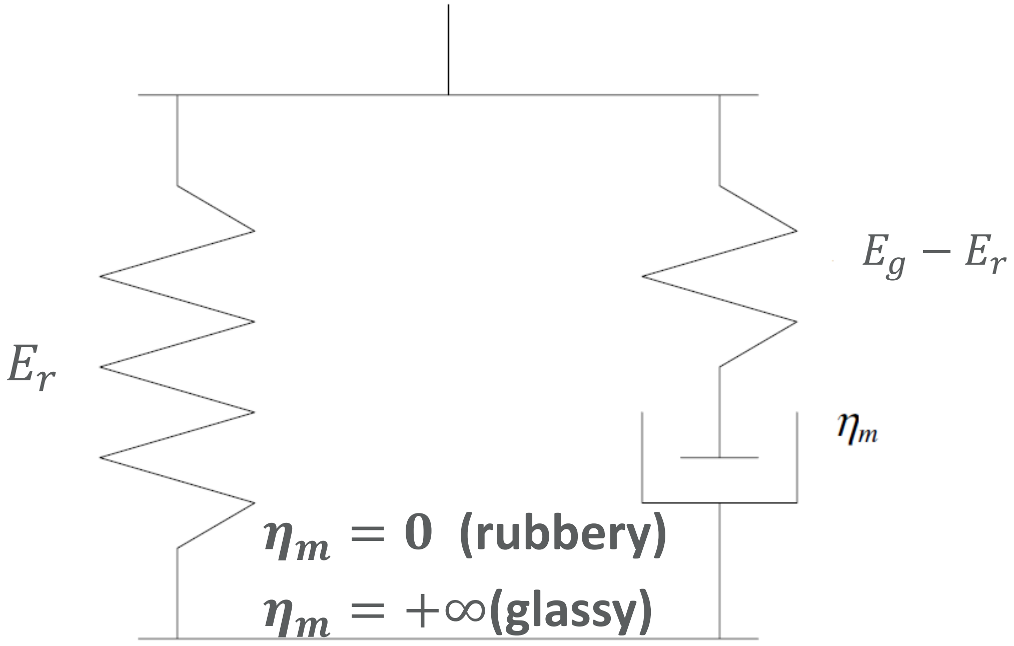

***Fig.** Simplified model*

A fully viscoelastic approach

- Rich model, temperature and degree of cure dependent
- Complex and costly
- Numerically and in terms of material characterisation

ESI pragmatic approach based on Svanberg* formulation

- Simpler formulation with constant moduli
- Processing time assumed very large compared to material characteristic relaxation times
- Much less characterisation needed
- Very large structure simulation affordable

- *Svanberg J.M. Predictions of Manufacturing Induced Shape Distortions. PhD Thesis, Lulea University of Technology, 2002.*

Illustration of a 0D case

- Simulation of a fully constrained block of a characterised polymer

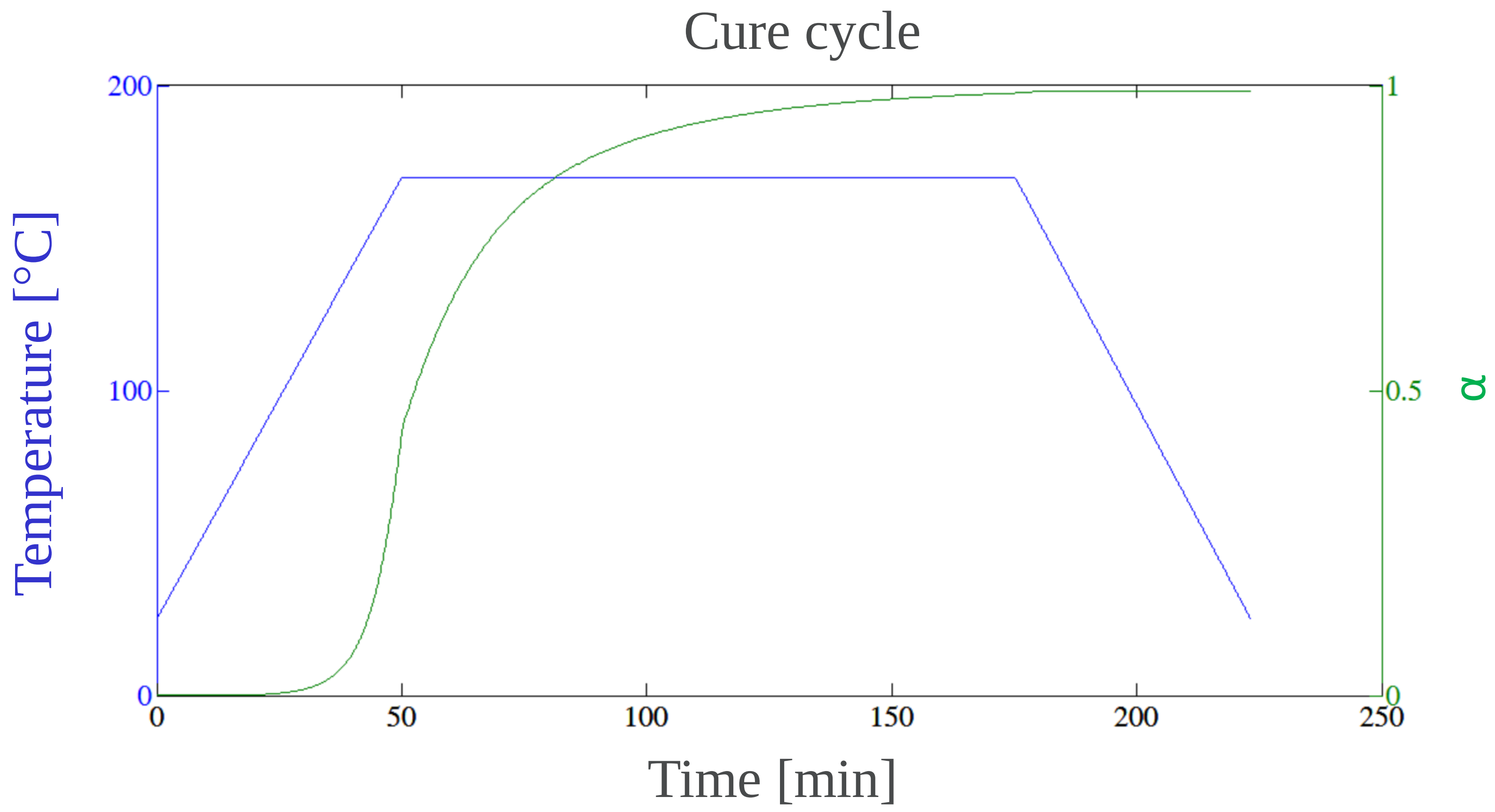

Illustration of a 0D case

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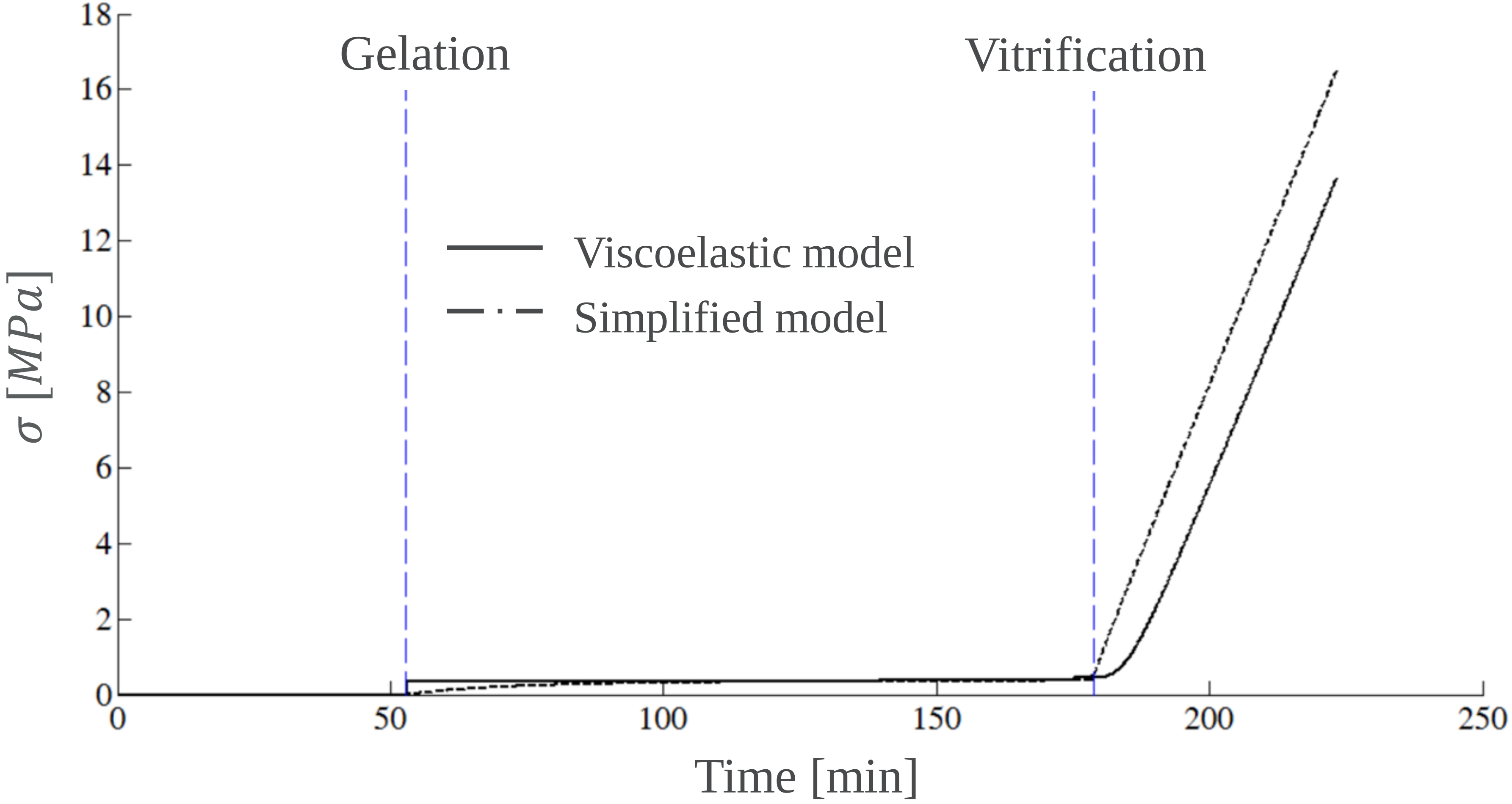

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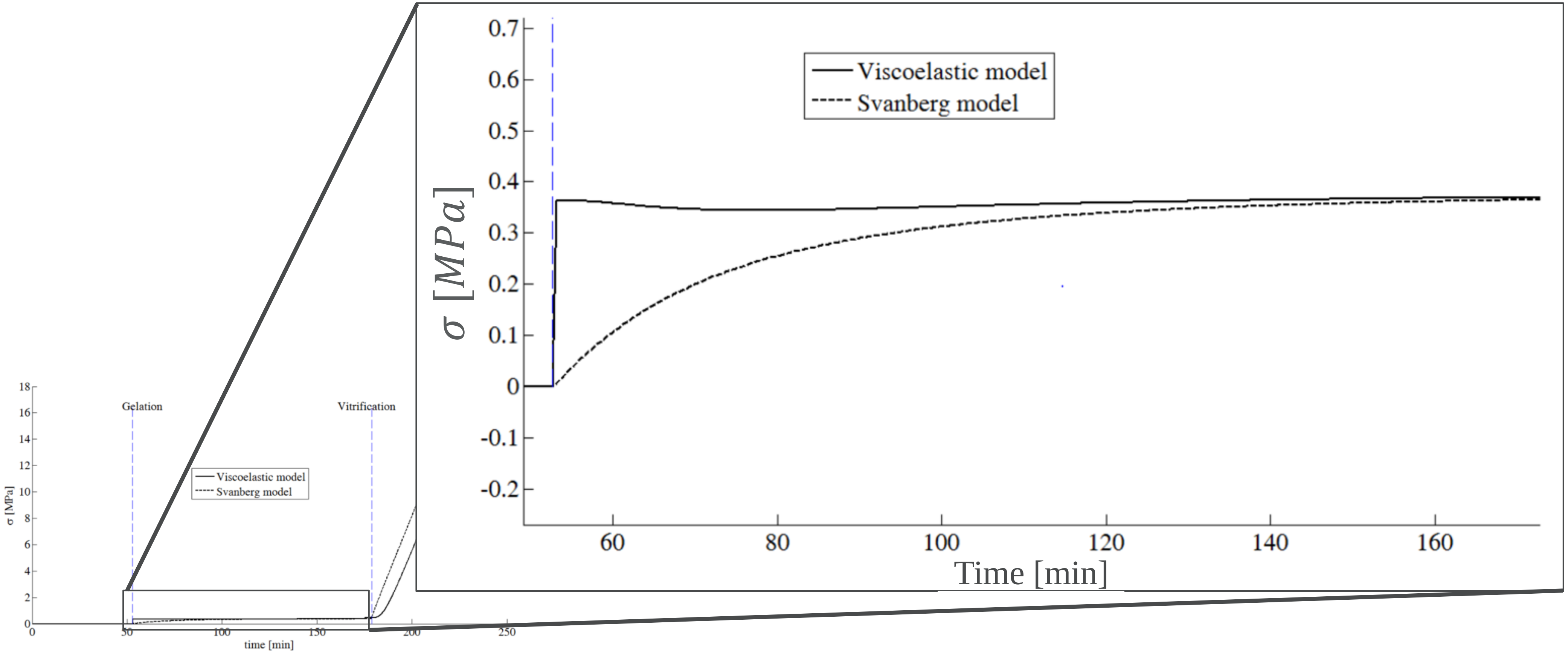
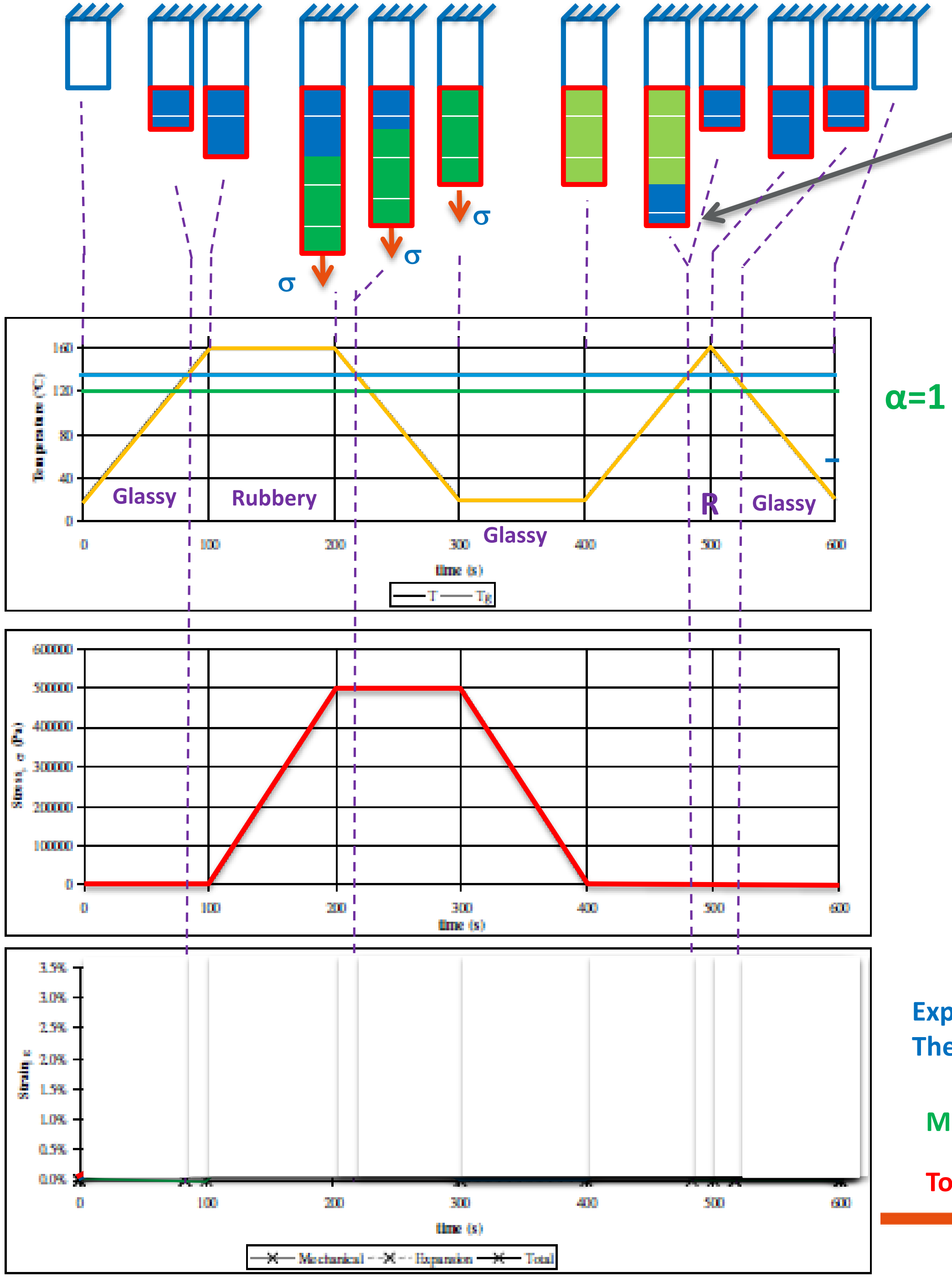


Fully cured rod of **neat resin** subjected to simultaneous **temperatures changes** and **mechanical load**

Applied Temperature

Tg

Applied Stress



Instantaneous Relaxation of frozen strain

Expansion strain

Mechanical strain with

Frozen strain

Total strain

Expansion strain = Thermal strain + Chemical strain (α : 0 ->1)

Mechanical strain

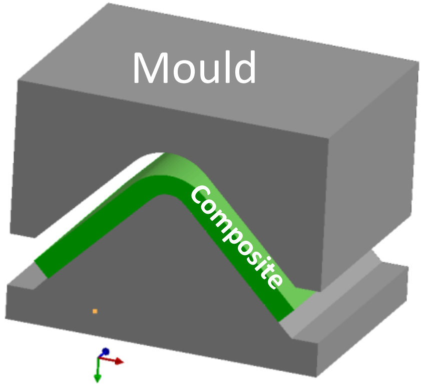
Total strain

CURING & DISTORTION

Simulation workflow

Typical workflow

- After a **curing simulation**, …



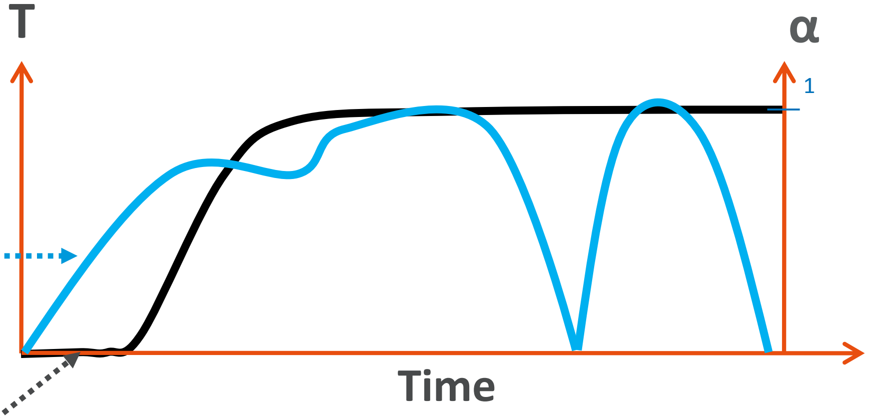
Heat transfer

$$\rho C_p \frac{\partial T}{\partial t} = \underbrace{-\nabla \cdot \left(\overline{\overline{K}}\vec{\nabla} T\right)}_{\text{Orthotropic conduction}} + \underbrace{\rho_m H_{tot} \frac{\partial \alpha}{\partial t}(1 - V_f)}_{\text{Exothermic curing reaction}}$$

Cure kinetics

$$\frac{d\alpha}{dt} = \sum_i w_i(t) \frac{d\alpha_i}{dt} = \sum_i w_i(t) f_i(T, \alpha)$$

Element thermo-chemical history



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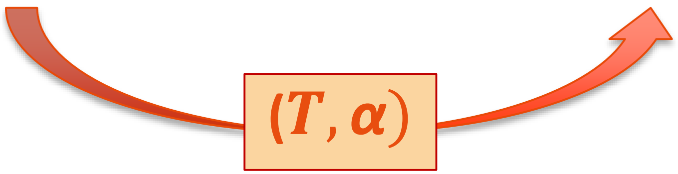
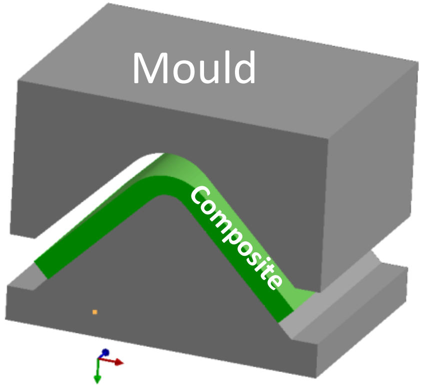
Typical workflow

- After a **curing simulation**, a **distortion simulation** is run





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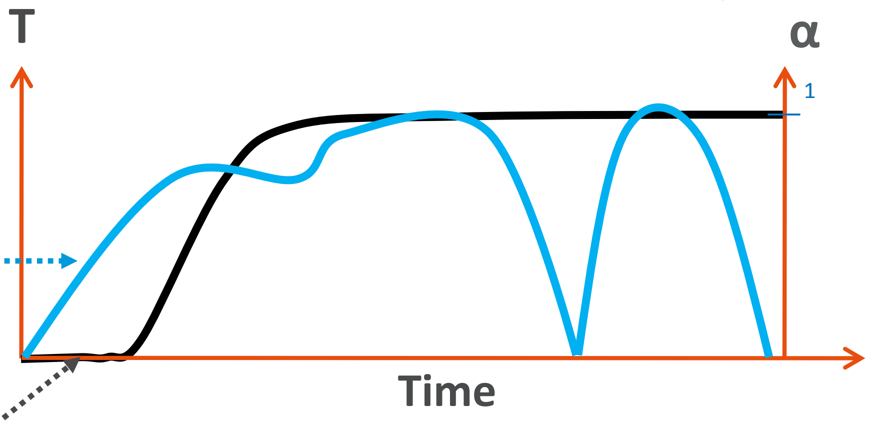
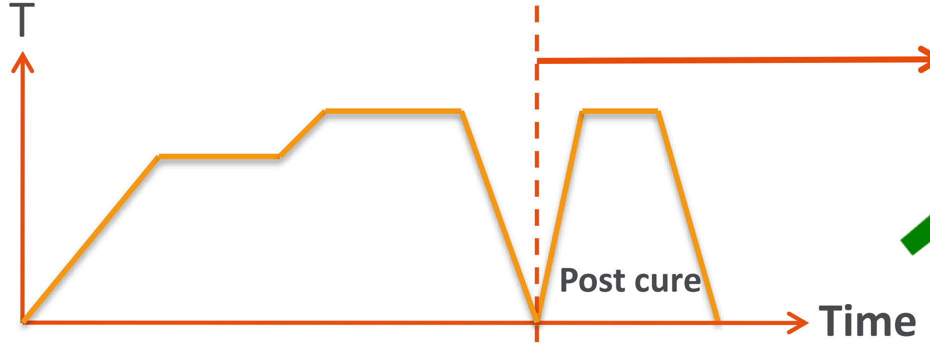
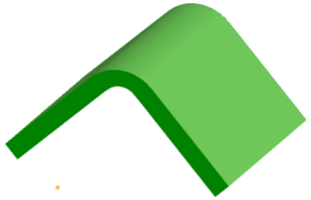


Imposed temperature cycle over part surfaces



Demoulding

Mechanical equilibrium



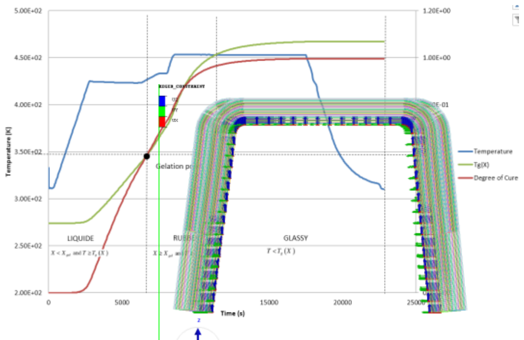
CURING & DISTORTION

Example

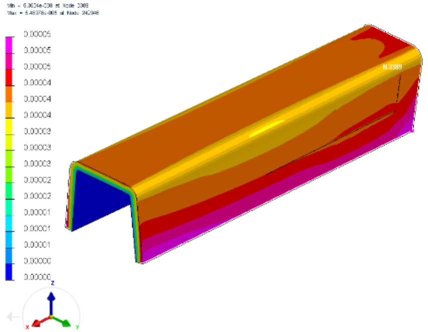
C spar

Distortion analysis

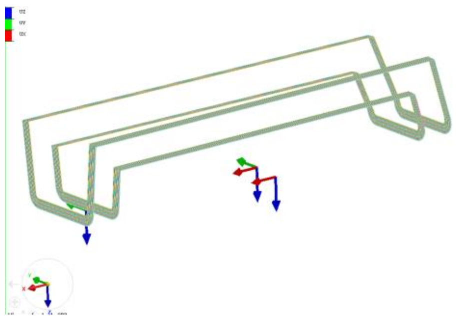
CURING



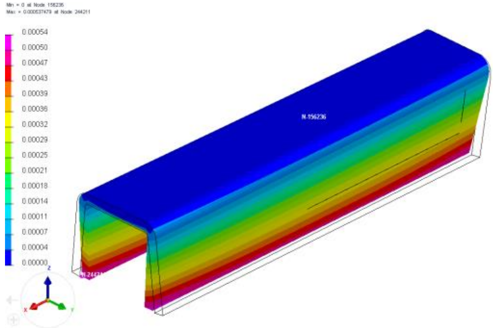
- PHASE1: inner surface of the C-Spar in contact with the mold is fixed during curing



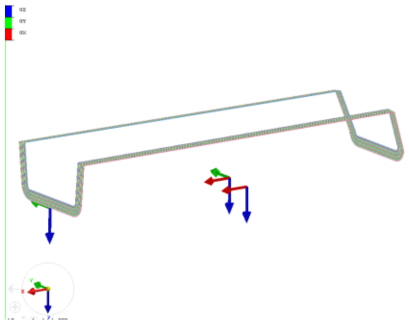
DEMOLDING



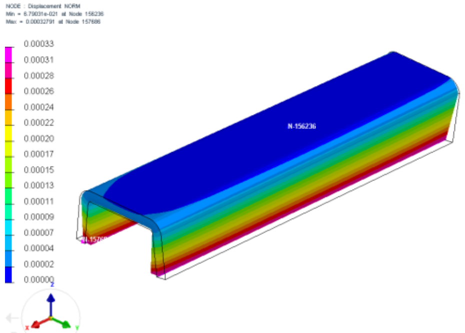
PHASE 2: Isostatic conditions are defined on the upper side of the C-Spar



TRIMMING

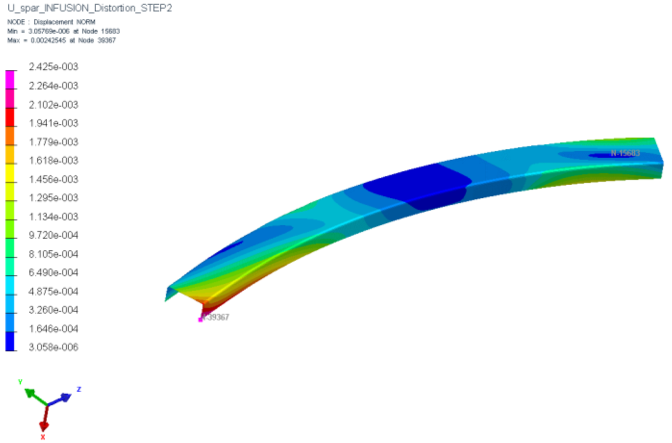


PHASE 3: Isostatic conditions are defined on the upper side of the C-Spar

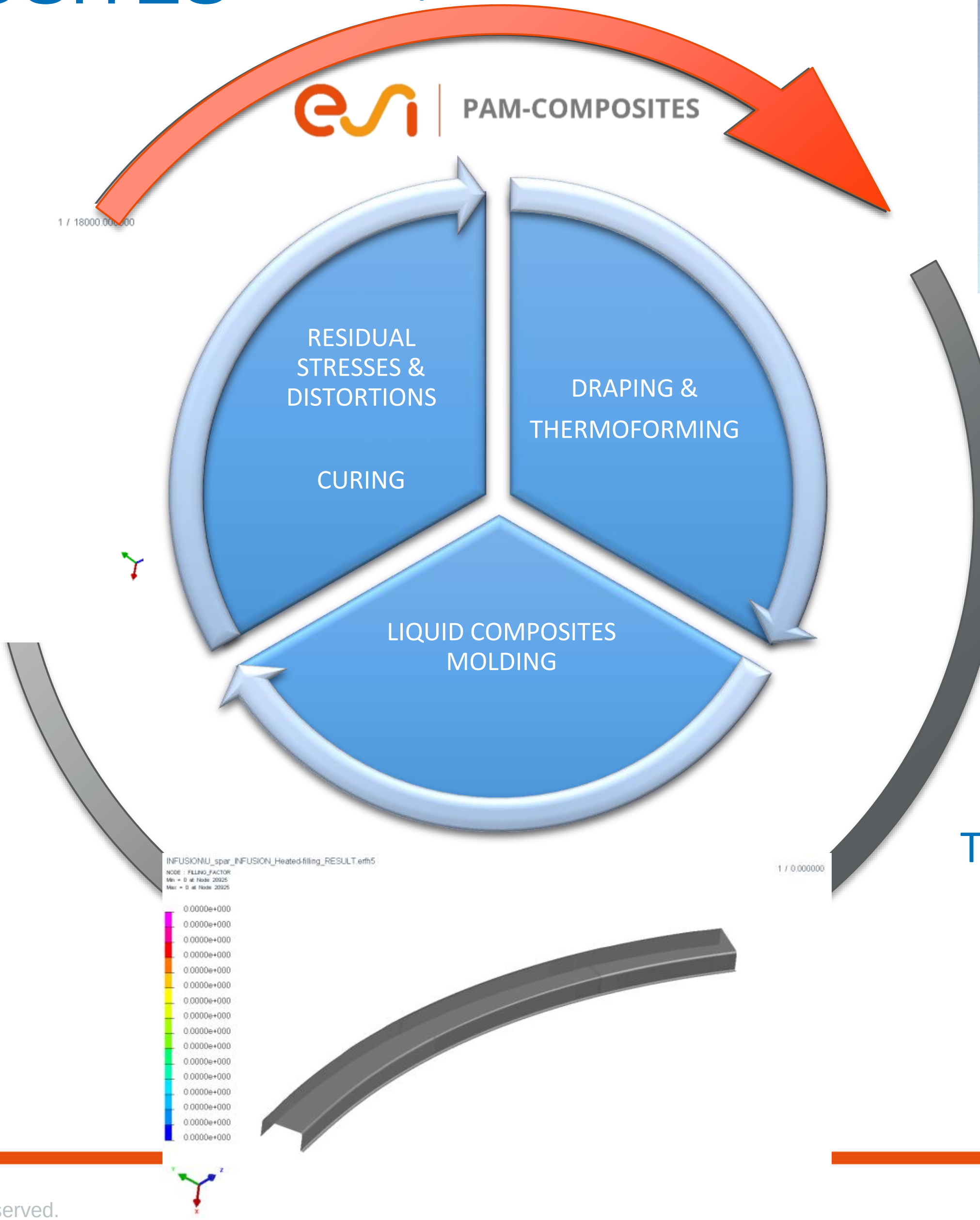


Global displacement of the C-Spar (x20)

ESI's PAM-COMPOSITES



Compensated mold



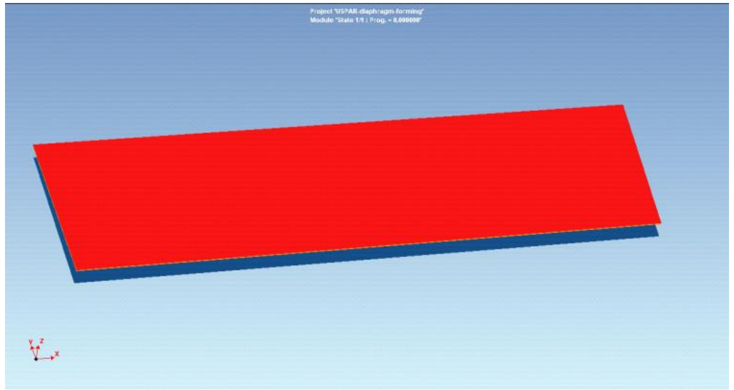
RESIDUAL STRESSES & DISTORTIONS

CURING

DRAPING &

THERMOFORMING

LIQUID COMPOSITES MOLDING



Fiber direction

Thickness variation (Vf)

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Thank you for listening

Do you have any question ?

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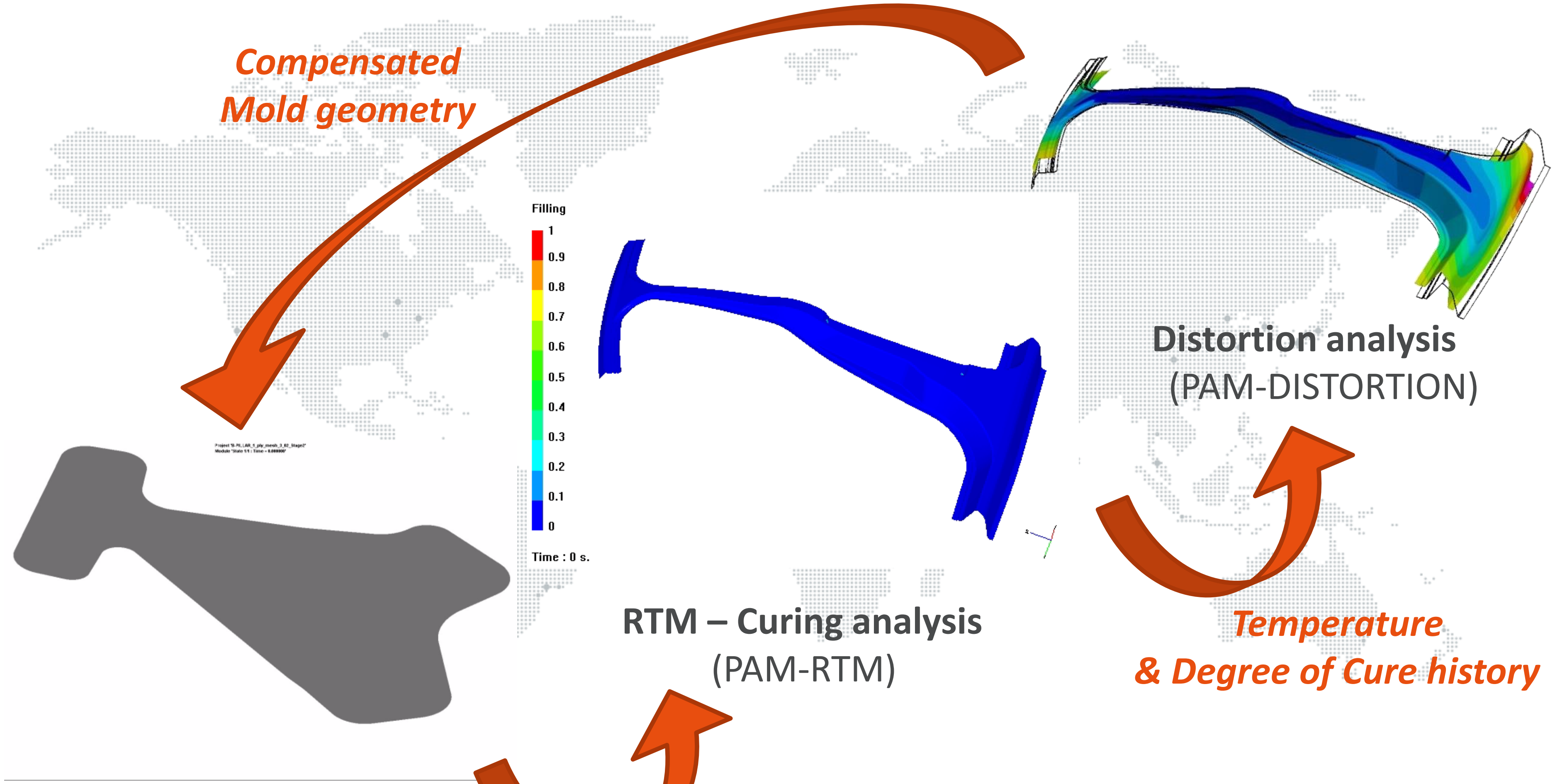

Compensated Mold geometry

Distortion analysis
(PAM-DISTORTION)

RTM – Curing analysis
(PAM-RTM)

Temperature & Degree of Cure history

Pre-forming analysis
(PAM-FORM)

Shearing of fibers