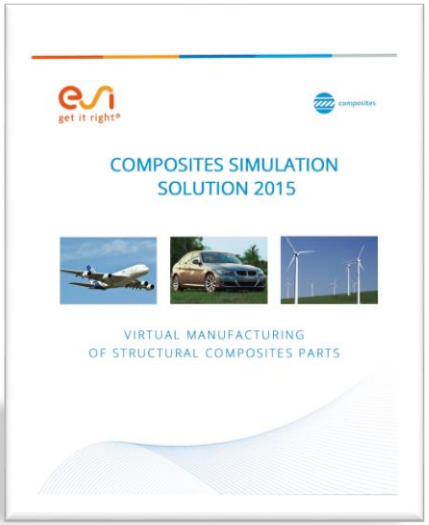
ESI's Composites Simulation Solution

Integrated solution to simulate the manufacturing of structural composites components



Dr. Xiaoshi Jin
November 2015

ESI's Composites Simulation Solution

What is it?

FEA Solution to define and Optimize process parameters

- Dedicated to composites structural components made of continuous fibers

Dedicated to automated processes

- For mass production
- For full control on costs, delays and reproducibility

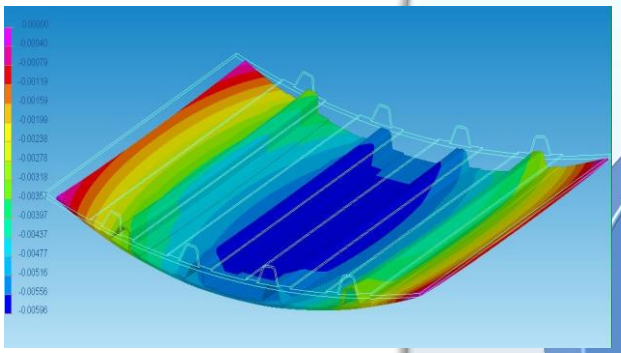
Address a wide range of materials

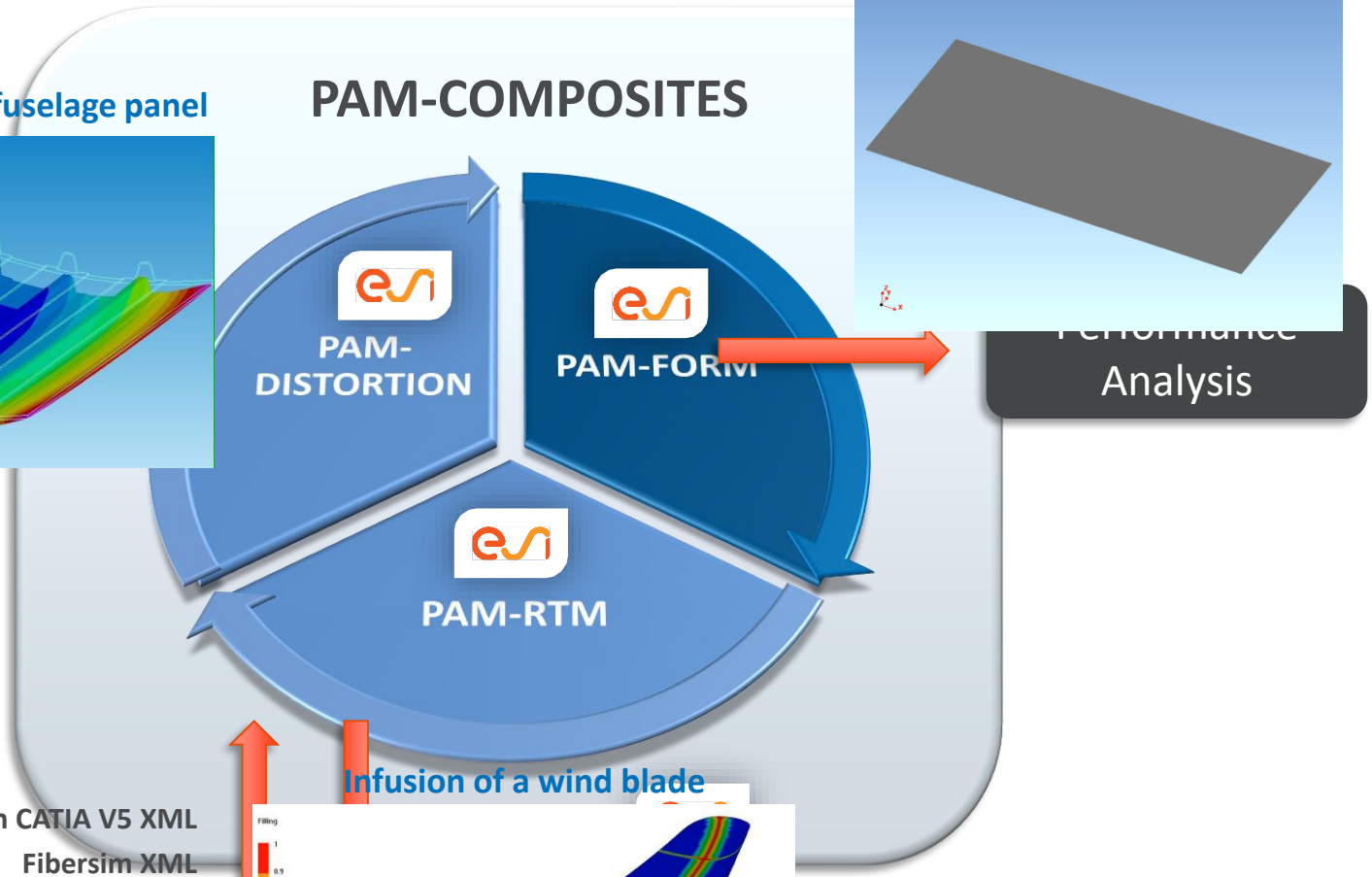
- Carbon, Glass and natural fibers
- Thermoplastic and thermoset resins
- Including core, inserts
- Woven fabrics, NCF, UD…
- Prepregs or dry textiles

ESI's Composites Simulation Solution

Thermoforming of organosheets

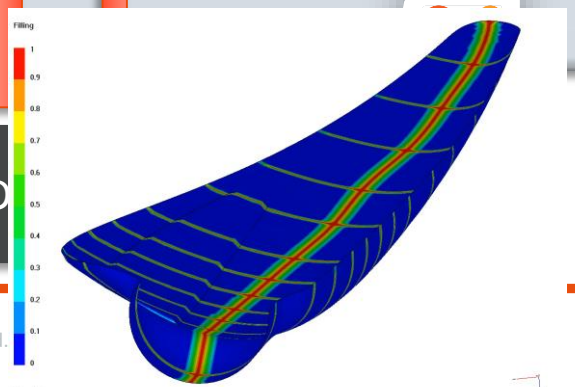
Post-cure distortion of a fuselage panel





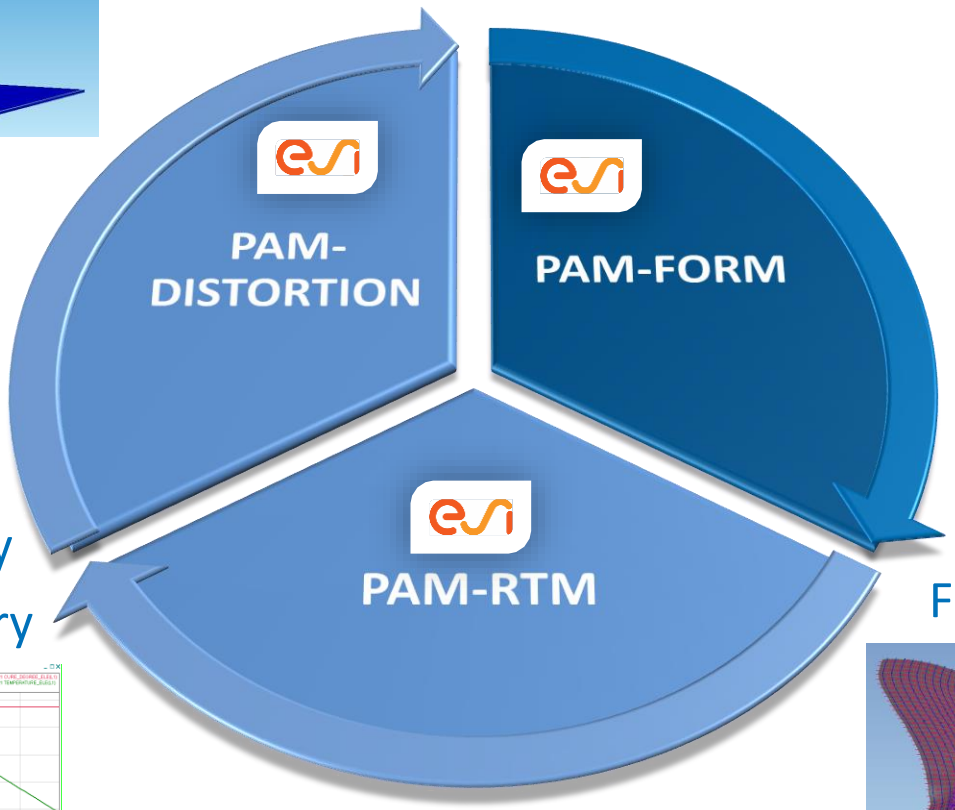
CPD-to-ESI in CATIA V5 XML
Fibersim XML

Infusion of a wind blade



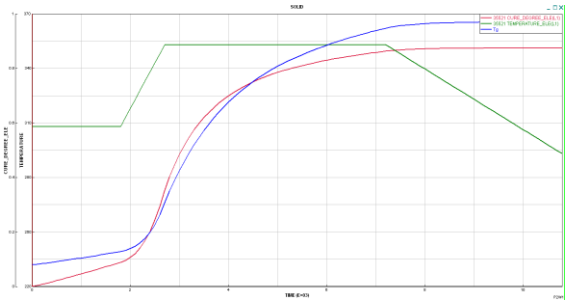
ESI's Composites Simulation Solution

Compensated mold (CATIA RSO)

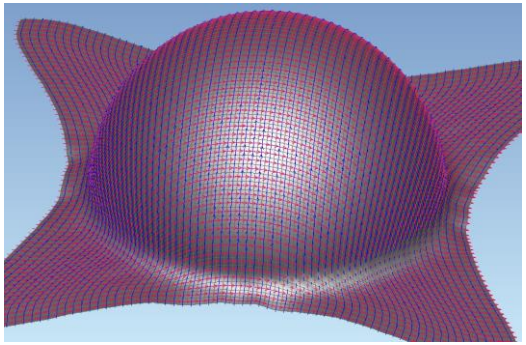


Temperature history

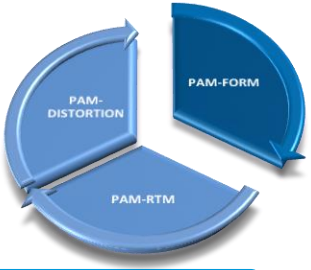
Degree of cure history



Fiber orientations



PAM-FORM Simulation
What for?



To Simulate

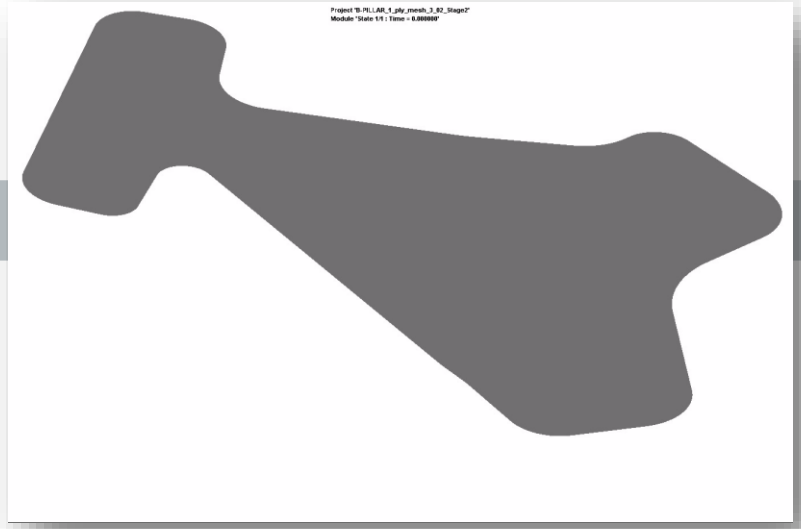
- Preforming
- Draping of thermoset prepregs
- Thermoforming of Organosheet

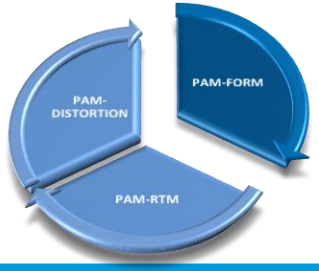
To Determine and Optimize process parameters such as:

- Kinematic of the tools
- Temperature cycle
- Pressure cycle
- Clamping conditions
- Clamping forces
- Initial flat pattern

Through the prediction of

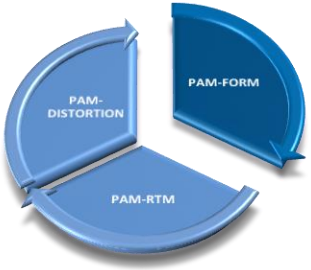
- Wrinkles
- Thicknesses
- Bridging
- Strains (shearing and in fibers)
- Stresses (Shearing and in fibers)
- Fibers orientation





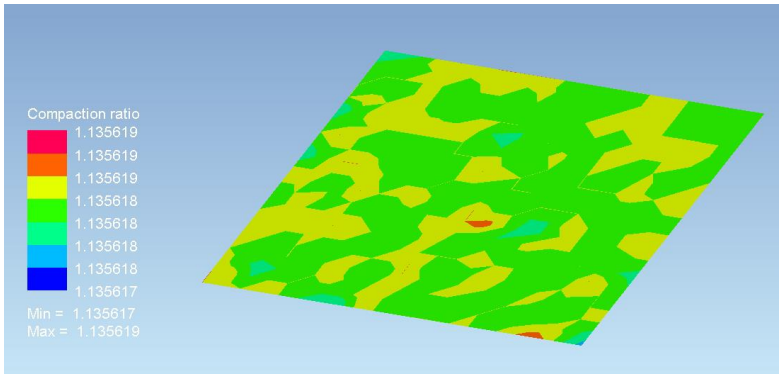
Non-linear elasto-plastic material with damage

- Possible **Temperature**, **Strain rate** and **Curvature** dependency
- Behavior defined through following input:
  - **Tension and Compression deformation** in fiber directions
    - Tension is elastic with damage or plastic (transverse direction of UD)
    - Compression is elastic
  - **In-plane shear** deformation
    - Elastic with damage or plastic
  - **Bending deformation** in fiber directions
  - **Thickness deformation** through normal pressure



Material compressibility

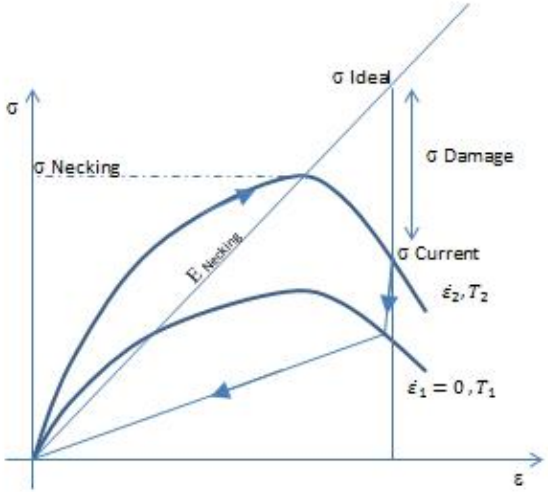
- Whether the material is defined as **incompressible**
  - The volume of each element remains constant during the simulation: epsilon1+epsilon2+epsilon3=0
- Whether the material is defined as **compressible**
  - Thickness is then dependant of the shear deformation and/or pressure
  - Possibility to visualize compaction ratio (=initial volume of element/final volume of element) as an output



Elastic damage behavior

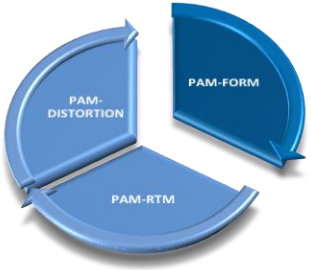
- Damage behavior is **automatically activated after each necking** point detected in the stress-strain curves
- Computed damage amount **express the broken fiber ratio**
  - It is approximated as the ratio between the damaged stress amount and the assumed ideal tensile stress when no damage

$$\delta = Max\left(\frac{\sigma_{damage}}{\sigma_{ideal}}\right)$$



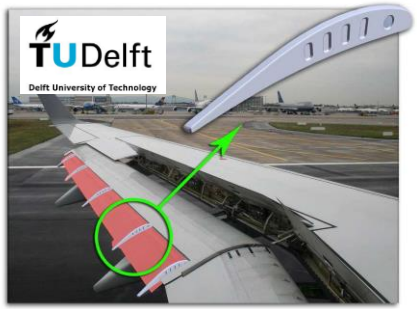
PAM-FORM Simulation

Thermal modeling



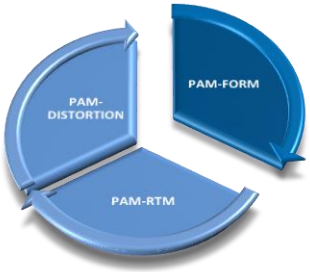
Thermal phenomena coupled to mechanical analysis

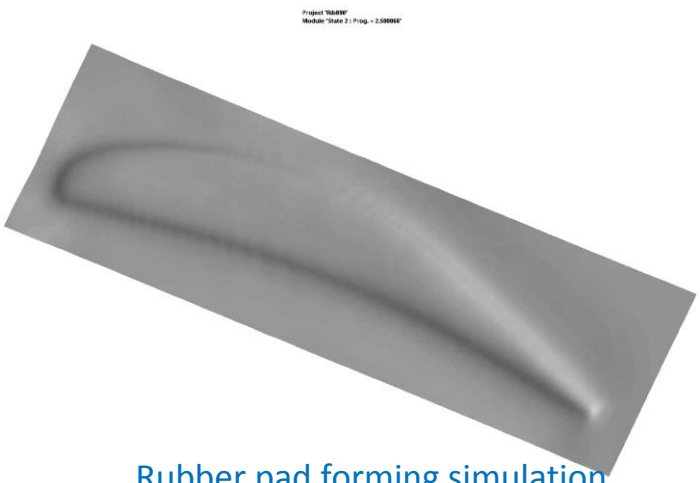
- Interesting when **thermal dependency in material properties** (prepreg materials)
- The following phenomena can be taken into account:
  - Conductivity in the composites material
  - Conductivity in the tools
  - Heat transfer between composites layers
  - Heat transfer between composites and tools
  - Convection exchanges
  - Radiation exchanges



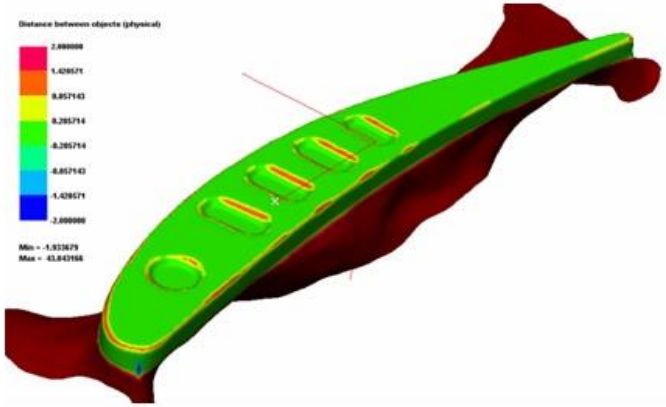
Thermoplastic forming Application

Flap rib thermoforming

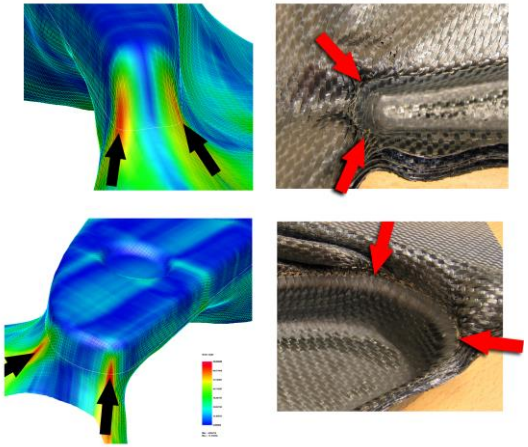




Rubber pad forming simulation



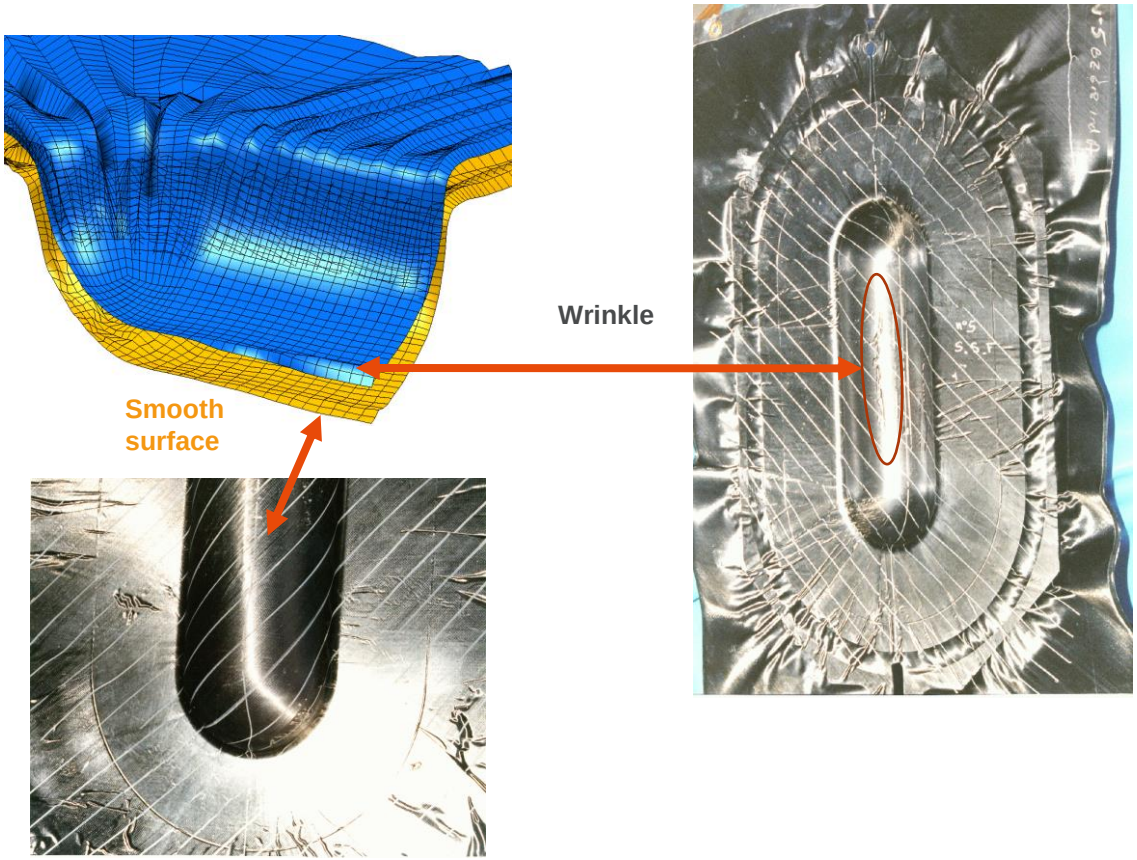
Bridging effect



Fiber Shearing

Thermoplastic forming Application

Wrinkling prediction

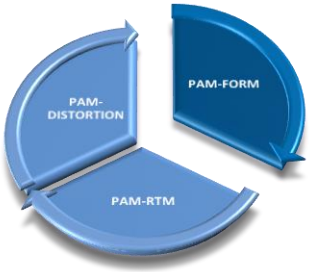


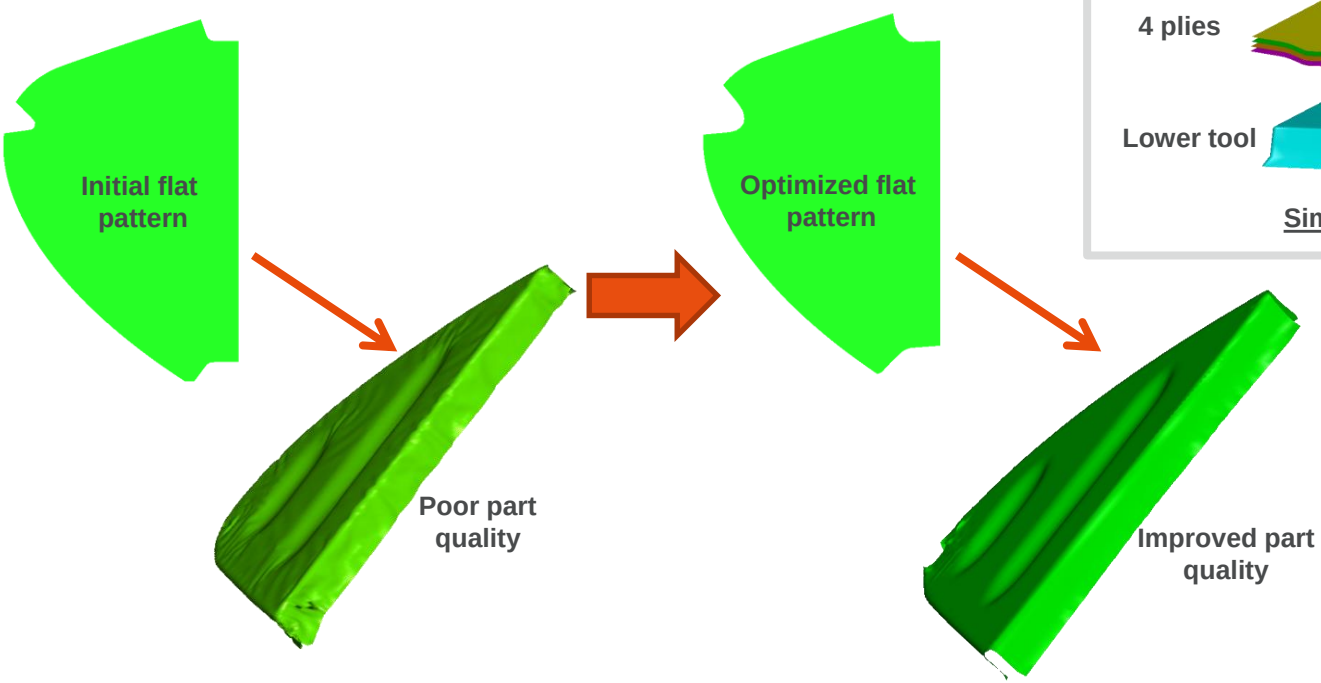
Wrinkling prediction

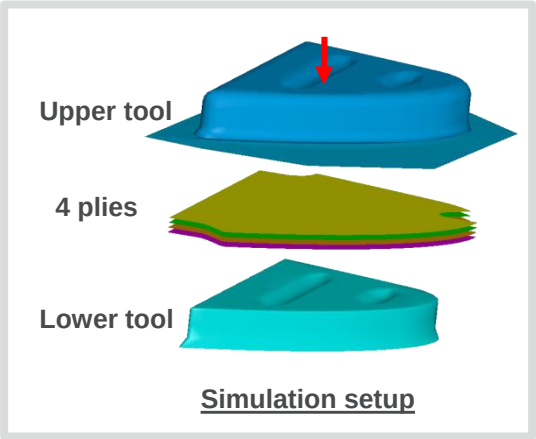
20 plies carbon UD / APC2-AS4

Thermoplastic forming Application

Flat pattern optimization





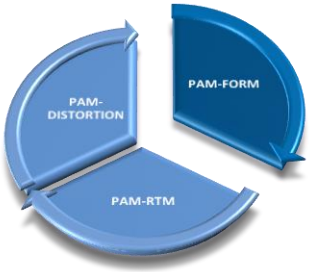


Flat pattern optimisation
4 plies / thermoplastic matrix

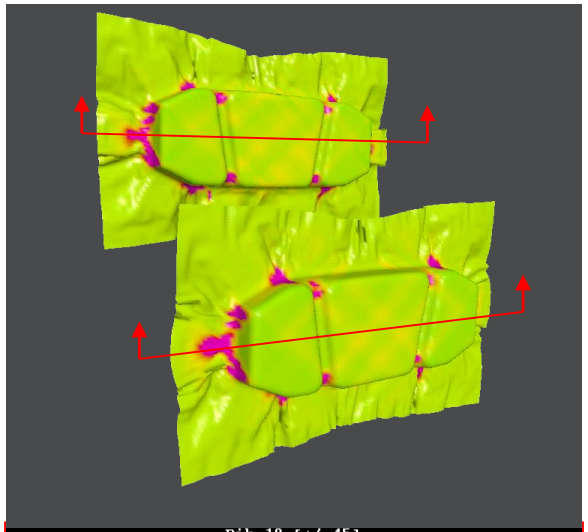
AIRBUS

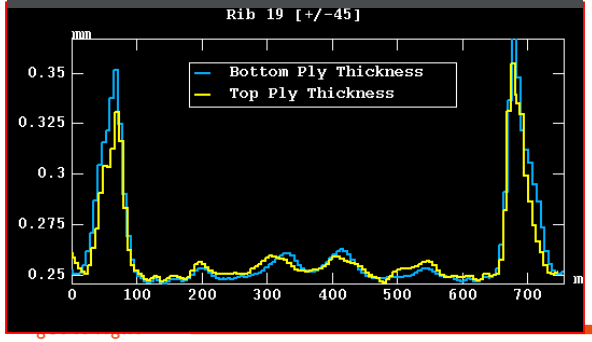
Thermoplastic forming Application

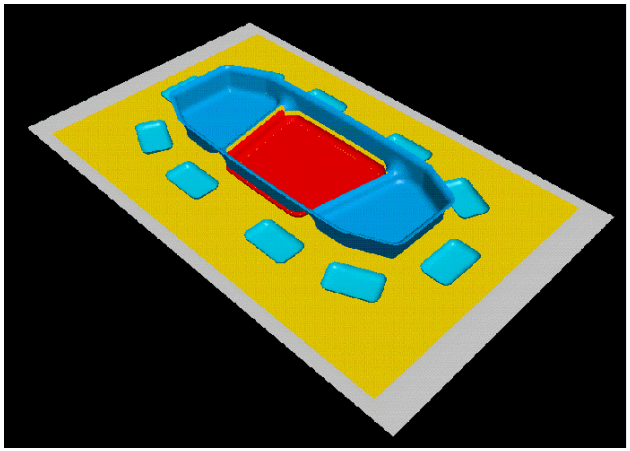
Wing box thermoforming



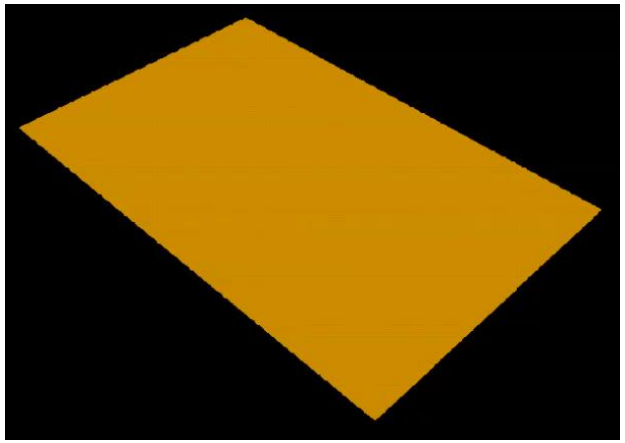
Thickness per ply





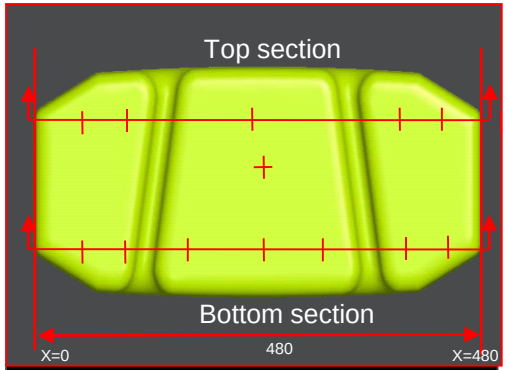


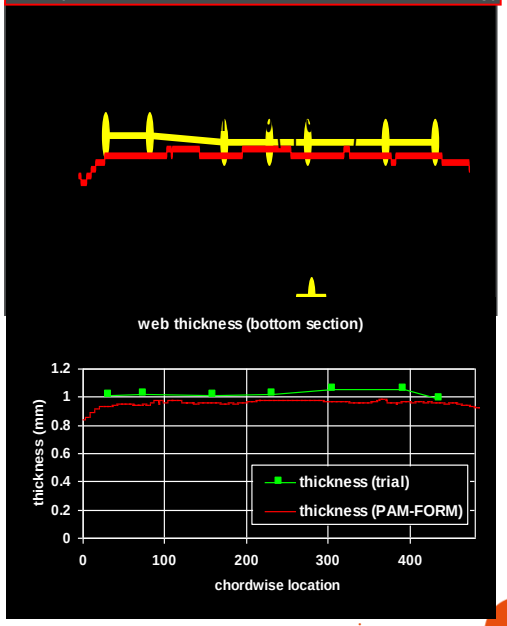
Process animation



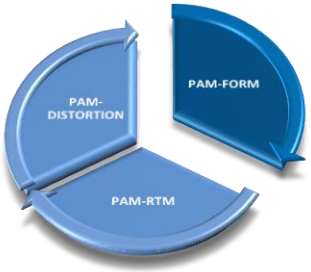
Laminate thickness

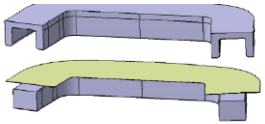
Ultrasonic measurement versus simulation





Preforming Application
Fiber shearing



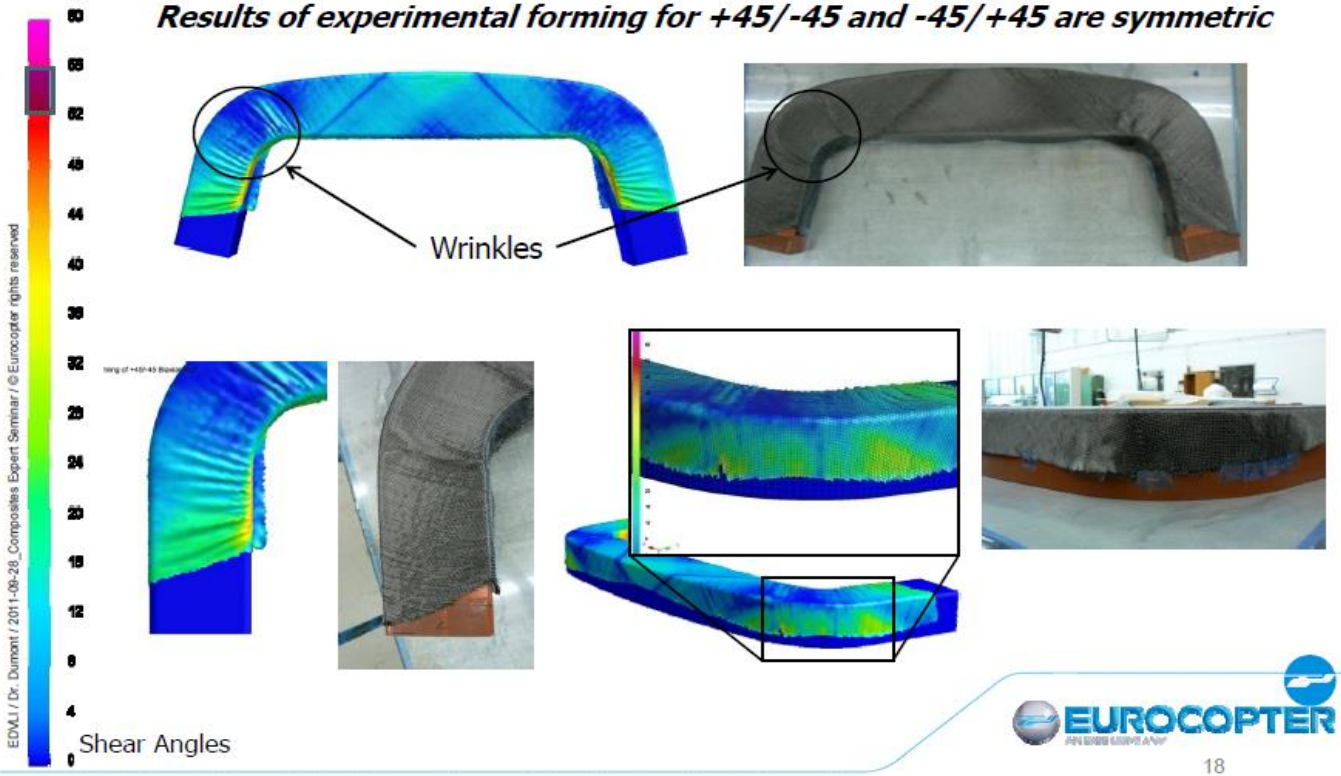


Stamping tools and reinforcement

thinking without limits

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

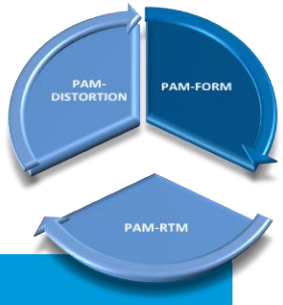
Results of experimental forming for +45/-45 and -45/+45 are symmetric



EUROCOPTER

18

PAM-RTM Simulation
What for?



To Simulate

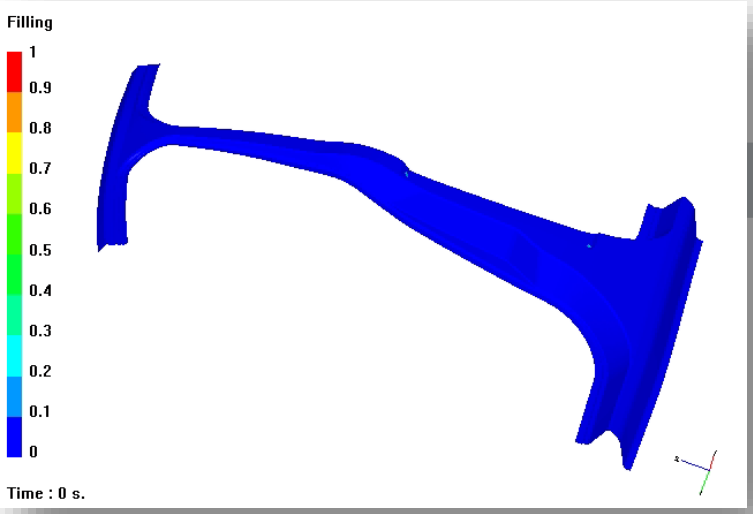
- RTM
- VARI
- Light RTM
- C-RTM
- Curing

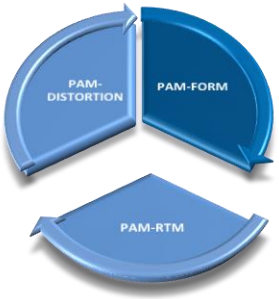
To Determine and Optimize process parameters such as:

- Location of injection gates
- Location of vents
- Position and size of flow media
- Heating of the mold
- Cure cycle

Through the prediction of

- Air traps
- Micro porosity
- Injection time
- Curing time
- Temperature evolution
- Degree of cure evolution
- Pressure in the mold





Darcy's law

- Darcy's law:

$$\vec{V} = -\frac{K}{\mu}\vec{\nabla}P$$

K : permeability tensor
μ : viscosity of the resin
V : Darcy's velocity
P : pressure

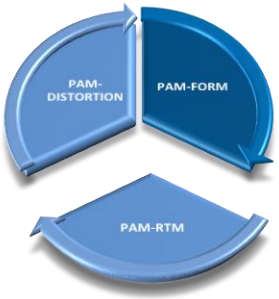
- Resin mass conservation:

$$\nabla.\vec{V} = 0$$

$$\boxed{\nabla.\left(\frac{K}{\mu}\nabla P\right) = 0}$$

Boundary conditions required to solve the equation:
- imposed pressure
- or imposed flow rate at the inlet

PAM-RTM Simulation
Thermal phenomena



Temperature of the resin

- Governs the reactivity of the **polymerization reaction**
- Influences the filling since the **viscosity of the resin** is temperature dependent

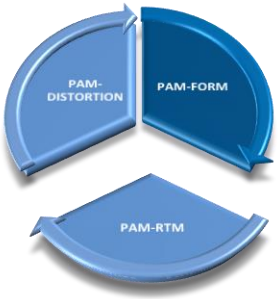
- Temperature field is governed by following equation:

$$\rho C_p \frac{\partial T}{\partial t} + \rho_r c_{pr} \vec{V} \bullet \nabla T = \vec{\nabla} \bullet \{k \bullet \nabla T\} - \rho_r \Delta h \frac{D\alpha}{Dt}$$

where T denotes the temperature, t denotes the time, ρ is the density, C_p is the specific heat, k is the heat conduction coefficient tensor, the subscript r designates the resin, Δh is the total enthalpy of the polymerization of the resin, α is the resin cure.

PAM-RTM Simulation

Material data



Permeability of the reinforcements

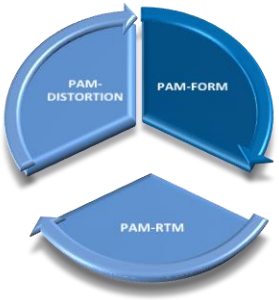
- Permeability is **fiber volume content** dependent (degree of compaction)
- It also depends on the **draping** of the reinforcements (fiber “shearing”)
- Fiber volume content and draping results can be computed with PAM-FORM and imported in PAM-RTM

Viscosity of the resin

- It is **temperature** and **degree of conversion** dependent

Kinetics of the resin

- Defined through pre-defined **Kamal-Sourour** models or **User defined models**



Coupling of physical phenomena

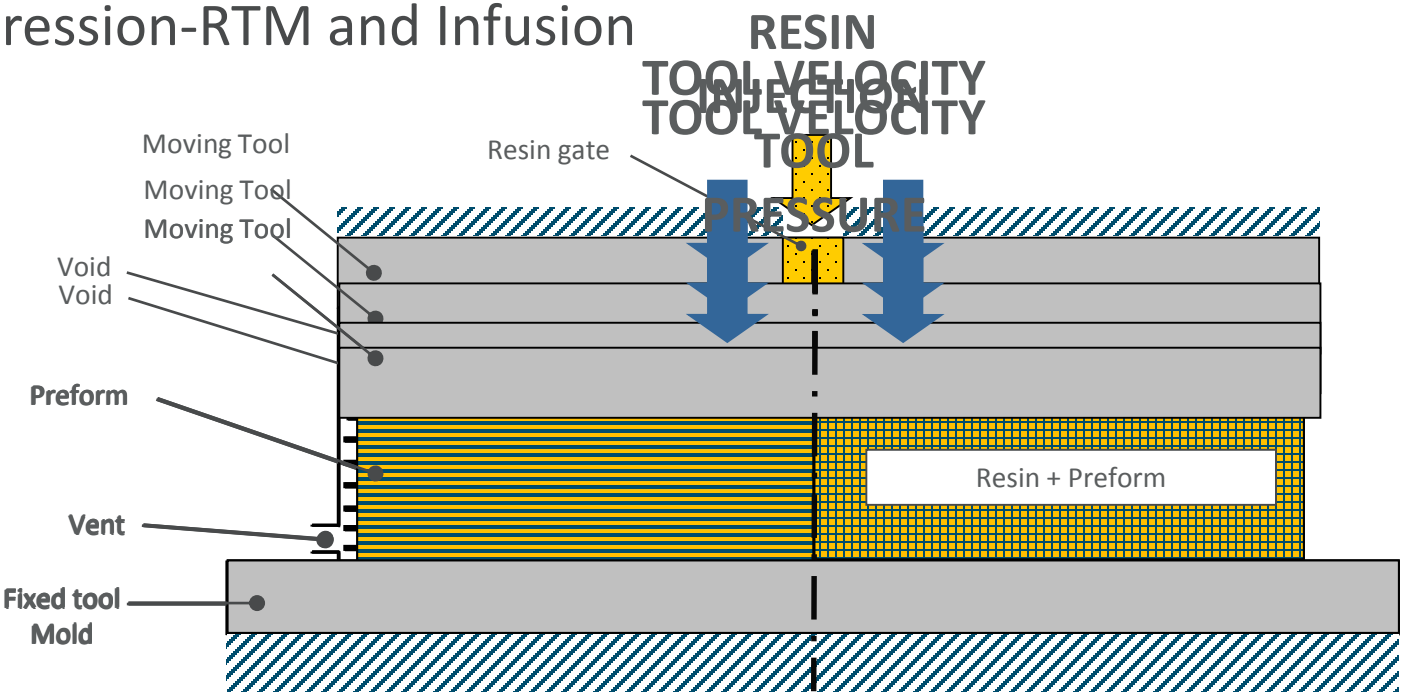
Category	Phenomenon	Mathematical model
Rheologic	Resin flow in a porous medium Variations of viscosity	Darcy's law Constitutive law
Thermal	**Mold**: conduction, loss in surface **Part**: conduction, convection, generation of heat, superficial heat loss	Heat equation, transfer coefficient (convection-radiance) Equation of convection-diffusion with source term, model with one temperature
Chemical	Transport of chemical species, diffusion, polymerization	Equation of convection-diffusion with source term, kinetic model (Kamal-Sourour)

PAM-RTM Simulation

To be released in 2016

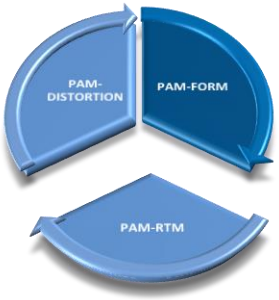
Fluid-Mechanics coupling solver

- Includes Navier-Stokes law
- Introduced to treat in a more accurate way processes as Compression-RTM and Infusion

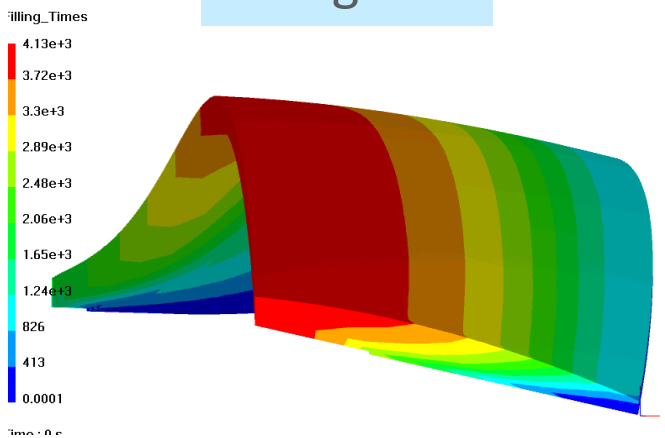


Infusion Application

Large dimensions parts

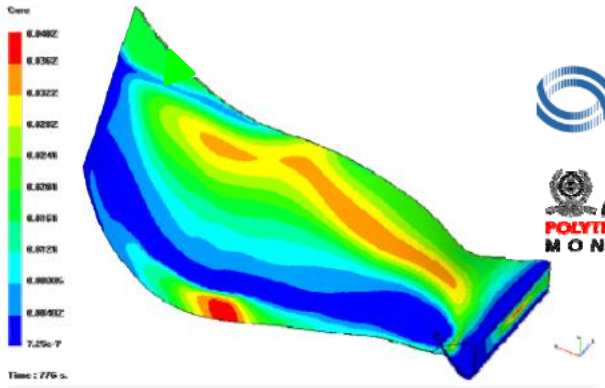


Filling time



30 meters wind spar cap infusion

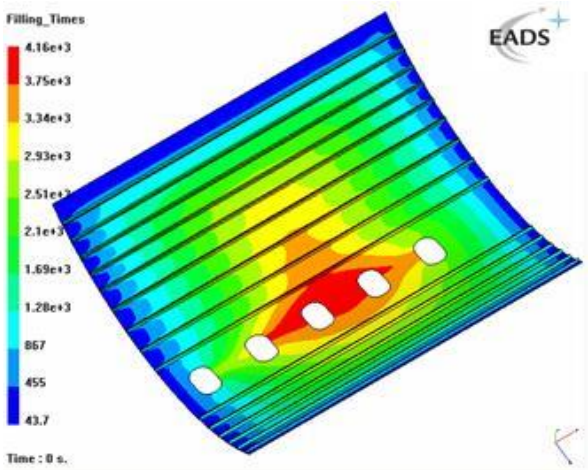
Curing time



Snecma SAFRAN Group

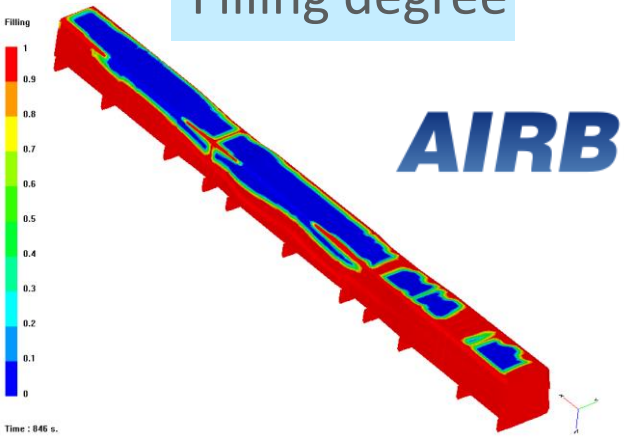
ÉCOLE POLYTECHNIQUE MONTRÉAL

Fan blade of an aircraft engine RTM



Fuselage panel infusion

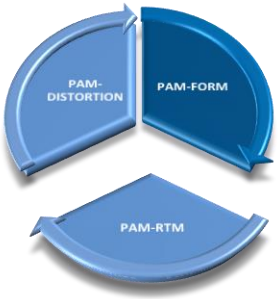
Filling degree



AIRBUS

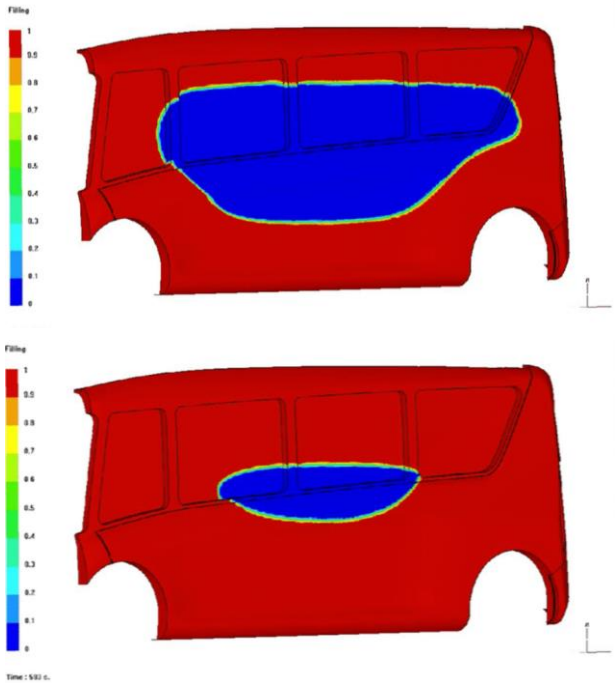
Light RTM Application

Bus body side



"In this project, the RTM simulation helped us to secure and to optimize the process. Today, we are using ESI's PAM- RTM not only to assess process parameters, including injection time and pressure in mold, but also to fine-tune mold design."

Jérôme RAYNAL
Sales and Export Director
Pôle de Plasturgie de l'Est



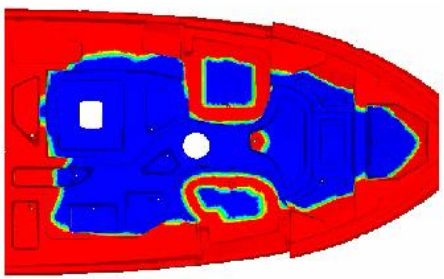
Optimum resin flow pattern computed with PAM-RTM

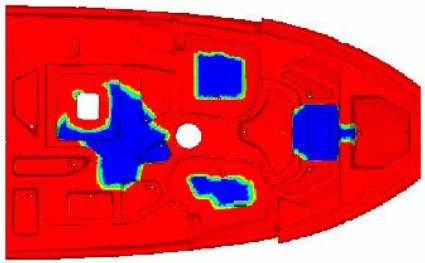
Infusion Application

Inner liner for hull reinforcement

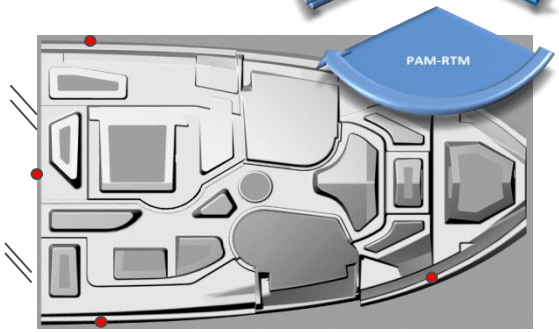
Very complex part including high shapes (1.2m)
Injection analysis allows determination of injection strategy (injection points/channels and vents location as well as open/closing sequence)
to minimize:

- Dry spots
- Filling and curing times
- Fiber washing
- Pressure in the mold

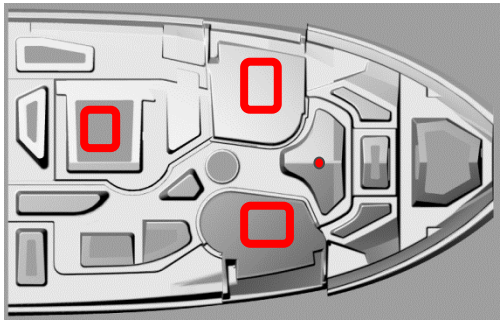




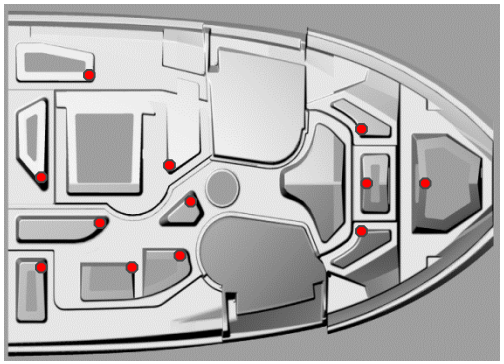
Flow front during injection



Initial injection points



Secondary injection points/channels

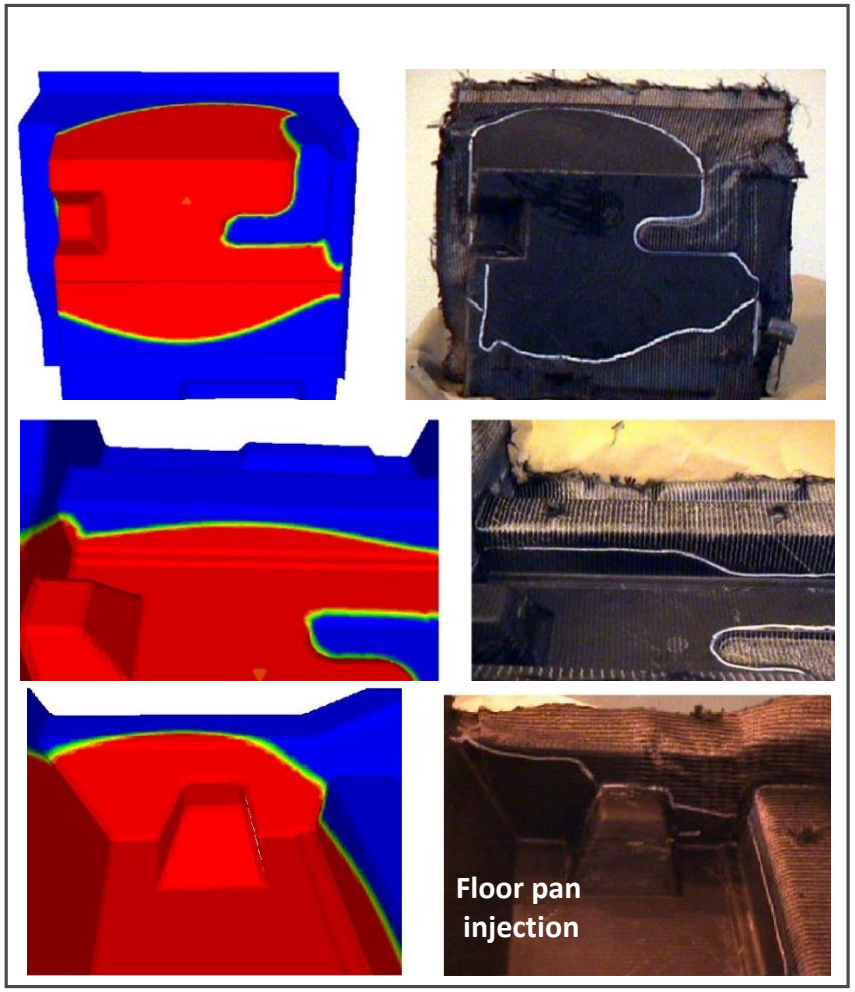


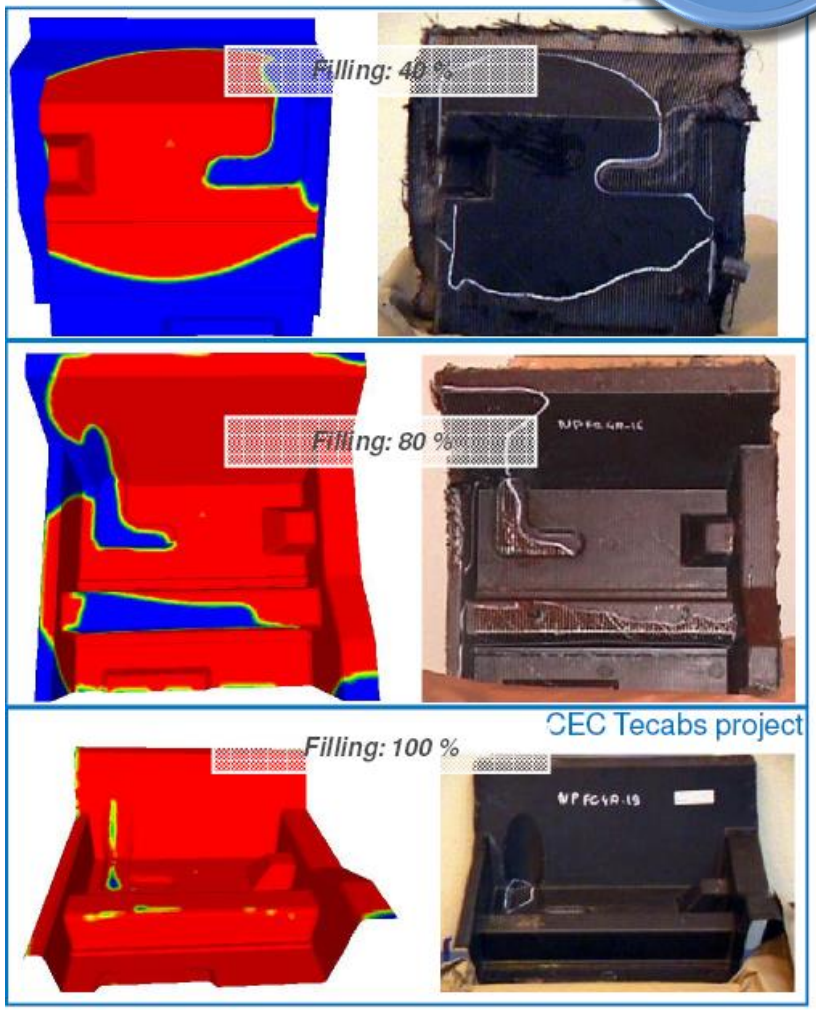
Vents location

TECABS project
Renault – Mines de Douai

RTM Application

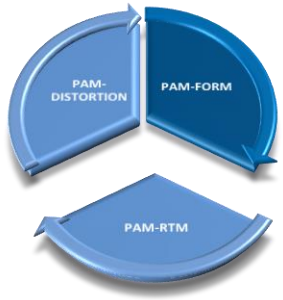
Automotive floor panel

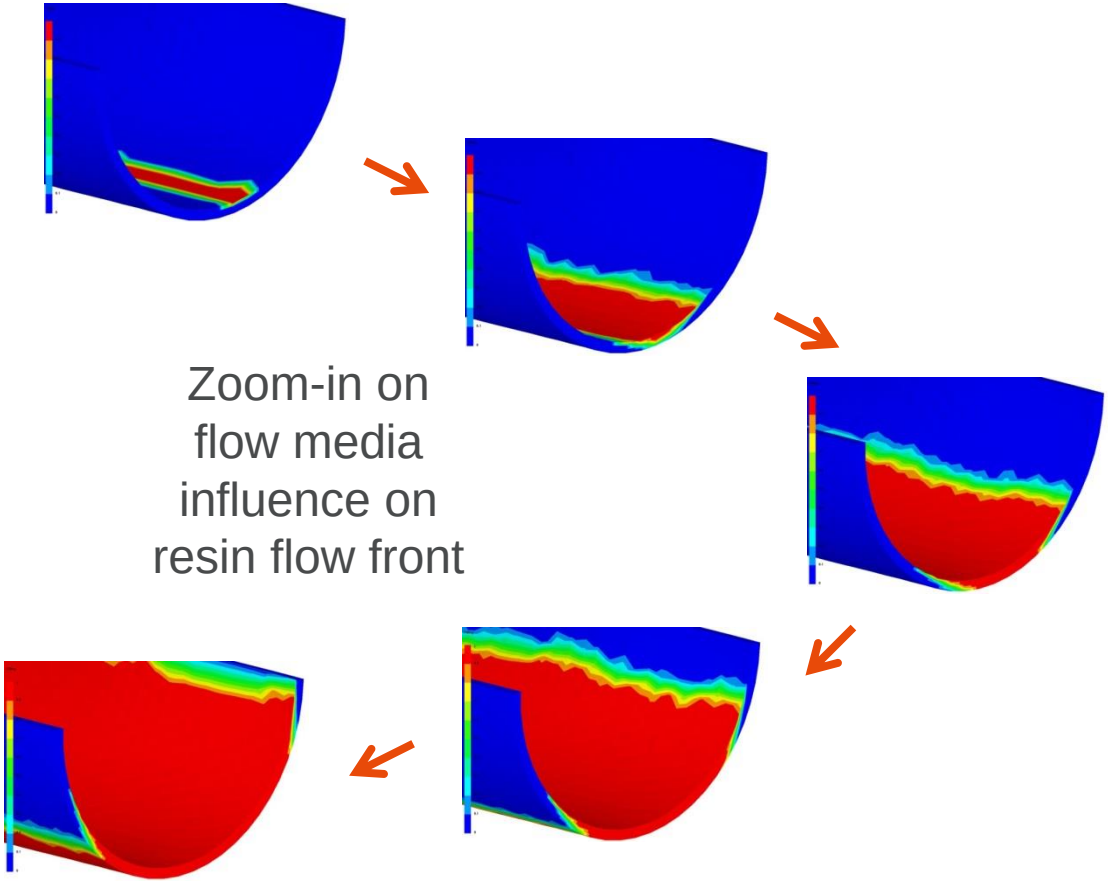




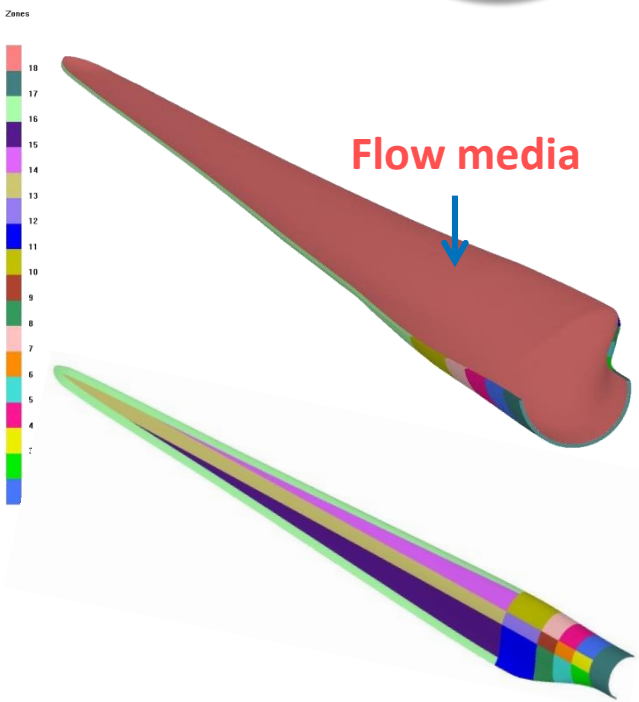
Infusion Application

Wind blade



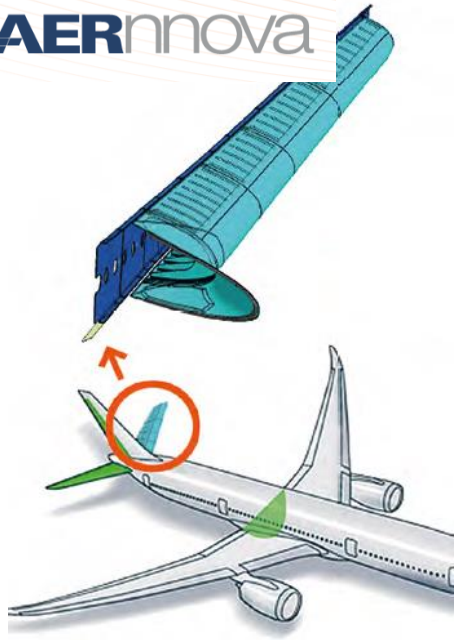


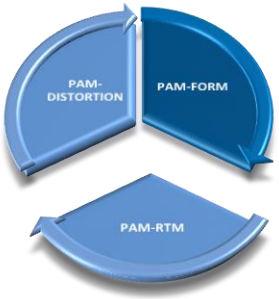
Zoom-in on flow media influence on resin flow front



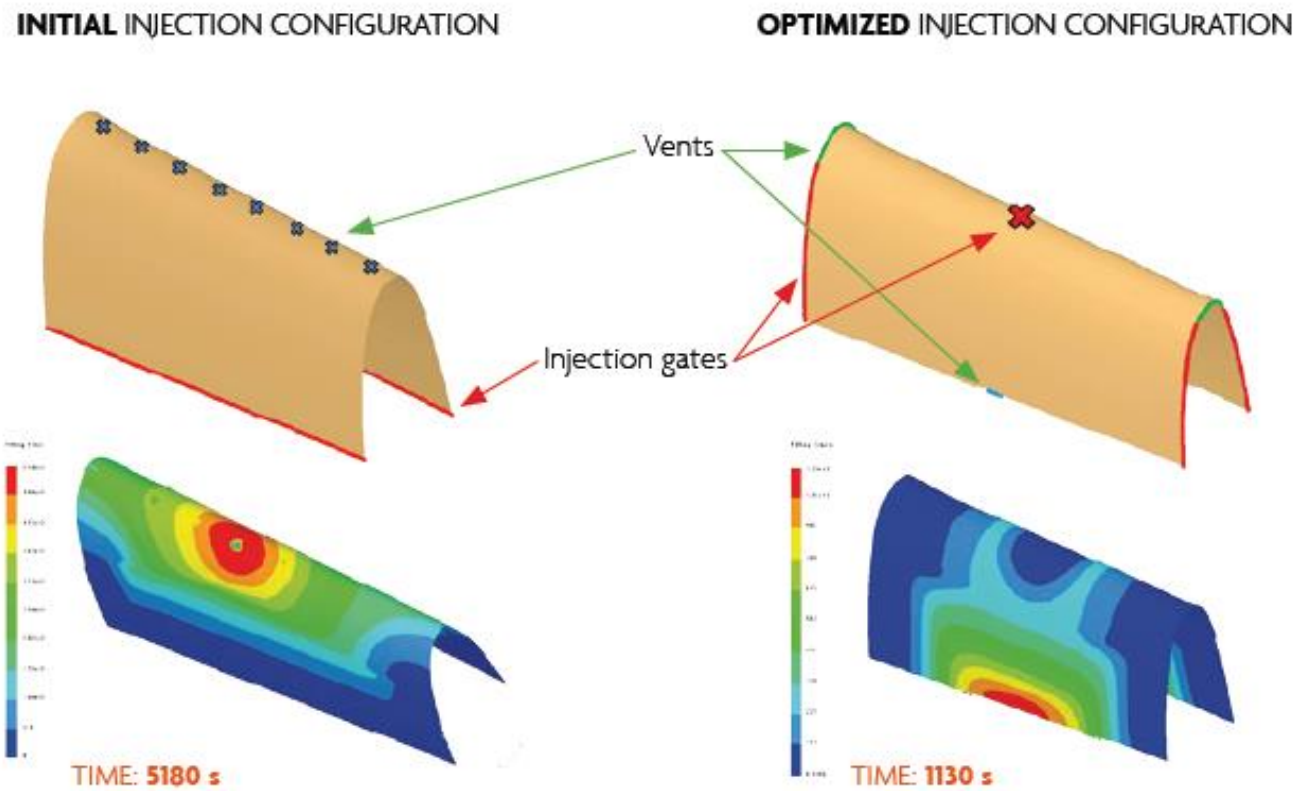
Infusion Application

Aeronautic part





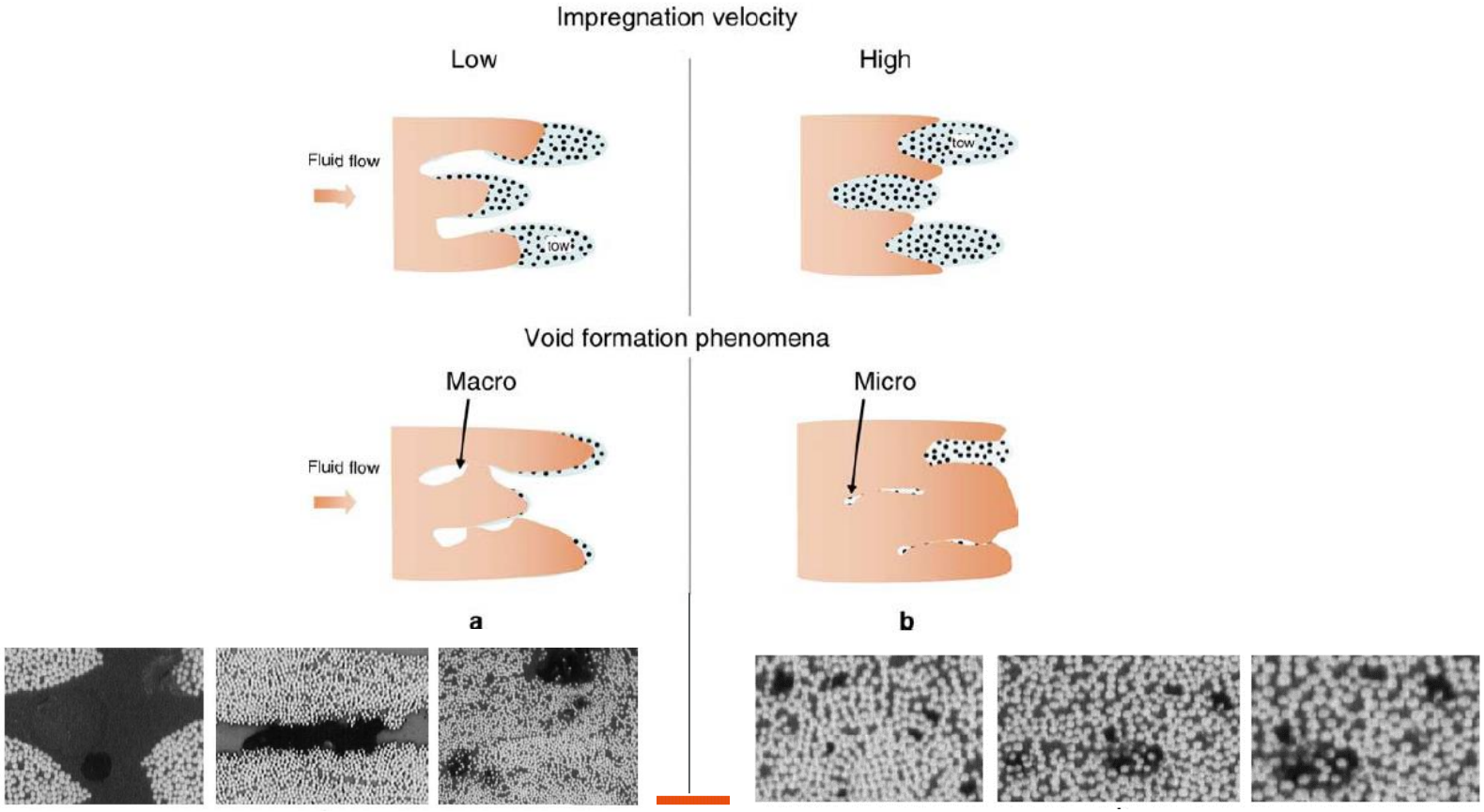
Simulation helped to divide infusion time by almost 5 while producing better quality parts with less scraps (better reproducibility)



RTM Application

Automatic reduction of porosities

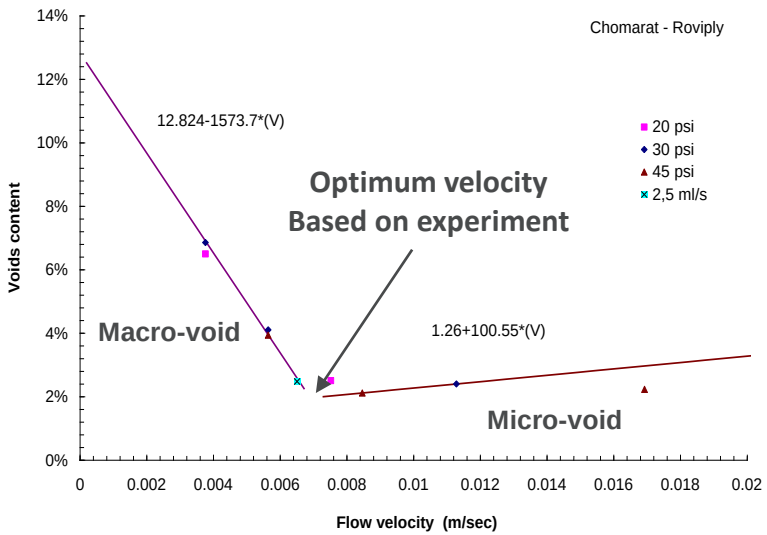
- Porosity prediction and reduction:
  - Principle: Critical impregnation velocity: $\max\left\|\vec{v}_{front}\right\| \leq \left\|\vec{v}_{crit}\right\|$



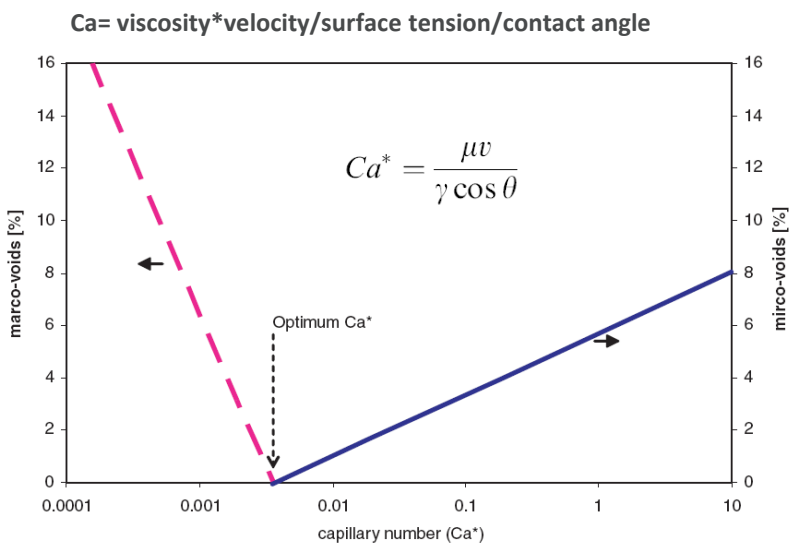
RTM Application

Automatic reduction of porosities

- Porosity prediction and reduction:
  - PAM-RTM input data:



Experimental data

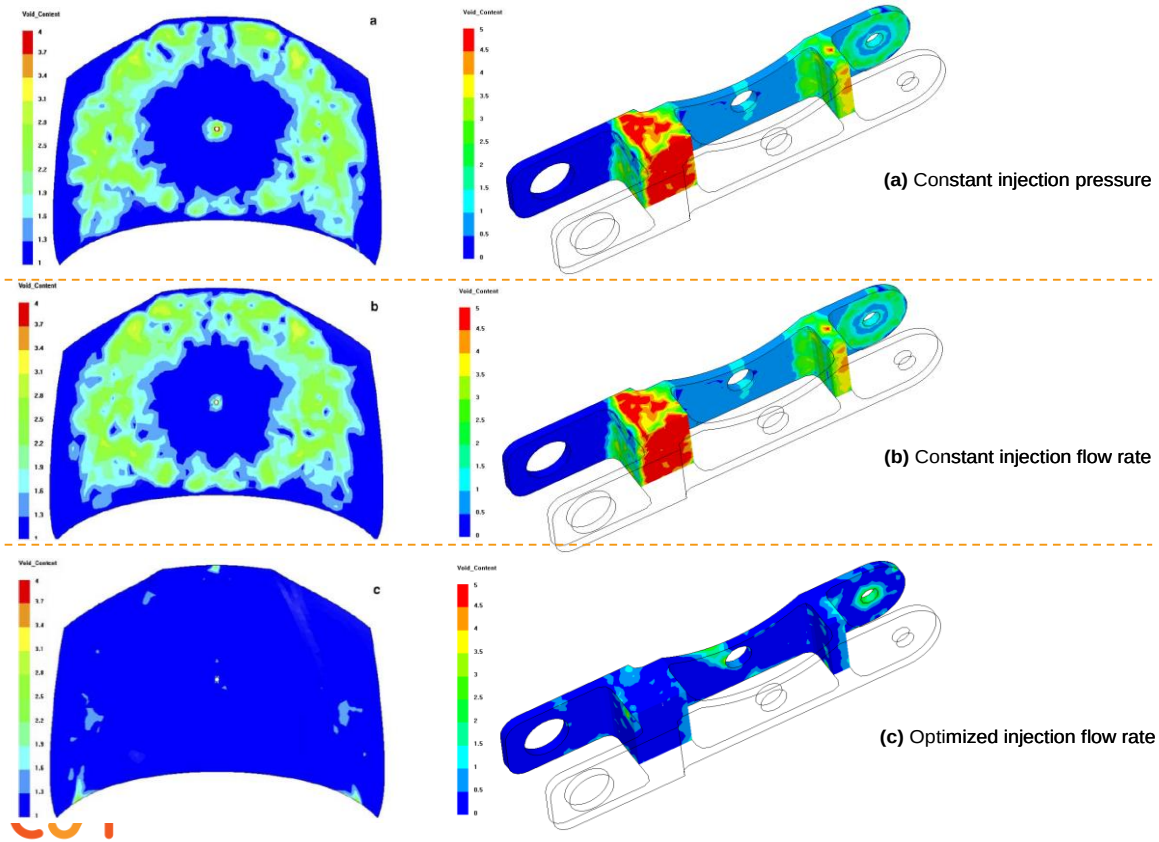


PAM-RTM input curve

RTM Application

Automatic reduction of porosities

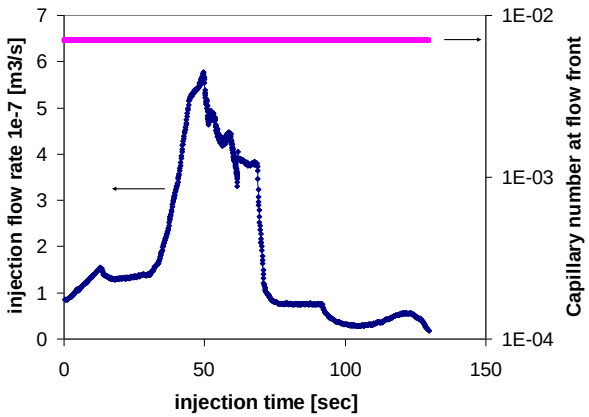
- Porosity prediction and reduction:
  - PAM-RTM output: injection flow rate curve



(a) Constant injection pressure

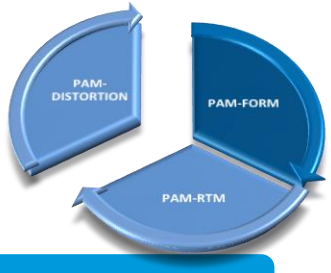
(b) Constant injection flow rate

(c) Optimized injection flow rate



PAM-DISTORTION Simulation

What for?

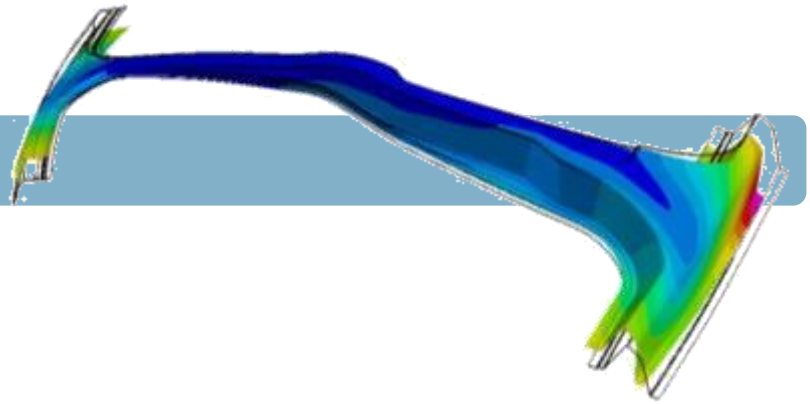


To simulate

- Process induced distortions such as spring-in and warping

To Define and Optimize parameters such as:

- Stacking definition
- Curing cycle
- Mold material and design
- Mold geometrical compensation



Through the prediction of

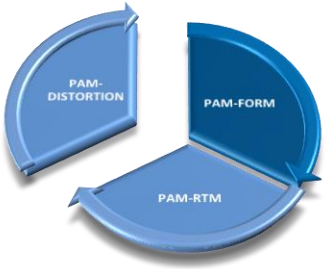
- Internal stresses during curing
- Residual stresses after de-molding
- Deformation during curing
- Deformation after de-molding

Takes into account

- Material history during curing process (temperature and degree of cure)
- Thermal and Mechanical interaction with the mold

PAM-DISTORTION Simulation

Physical phenomena



PAM-DISTORTION computes

- **Thermal strains**

$$Thermal\ strain:\ \varepsilon_{ij}^{T} = \alpha_{ij}\Delta T$$

- αij: Coefficient of thermal expansion tensor
- ΔT: Temperature variation

- **Chemical strains**

$$Chemical\ strain: \varepsilon_{ij}^{C} = \beta_{ij}\Delta\alpha$$

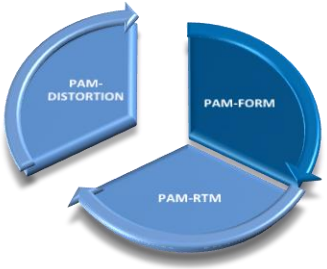
- βij: Coefficient of chemical shrinkage tensor
- Δα: Degree of cure variation

It takes into account resin phase transformation during curing

- Initially the resin is **liquid**: no stress, no strain
- When the resin reaches gelation (alpha=alpha gel) the resin becomes **rubbery**. From this point the resin can sustain stresses.
- When the resin reaches the glass transition temperature (Temperature of the resin = glass transition temperature) the resin becomes **glassy**.
- **Glass transition temperature** evolution is defined using **Di Benedetto** function.

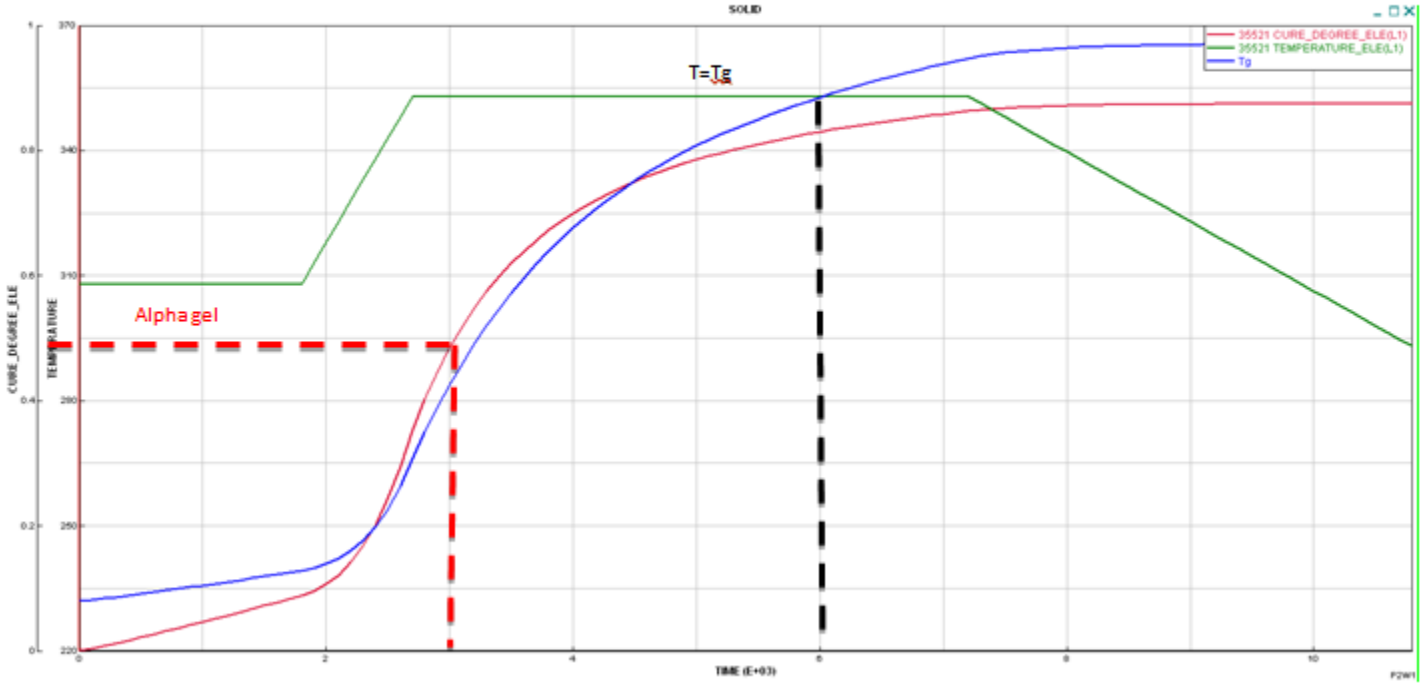
PAM-DISTORTION Simulation

Physical phenomena



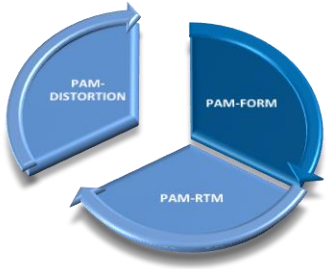
Phases of the resin for 1 element during curing

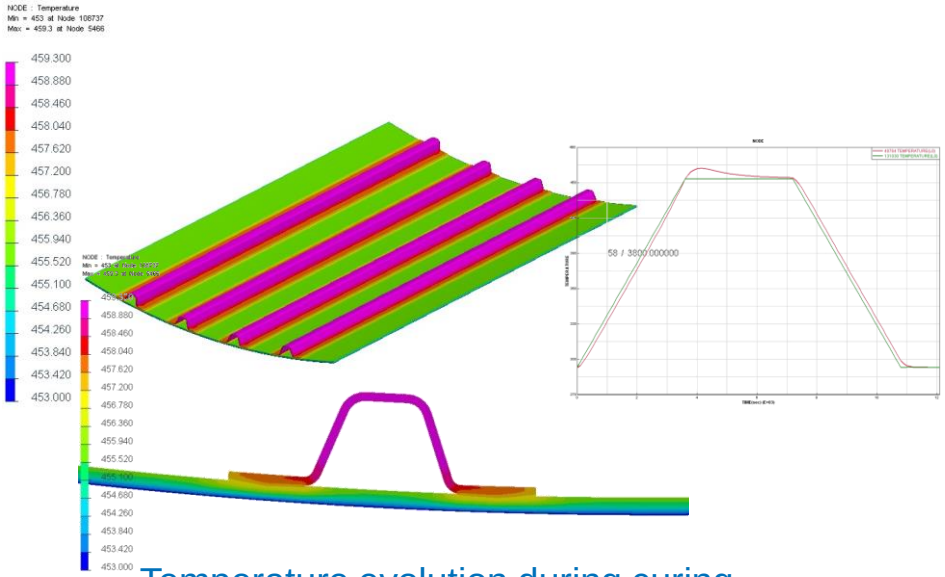
- Green curve is the temperature evolution
- Red curve is the degree of cure evolution
- Blue curve is the glass transition temperature evolution



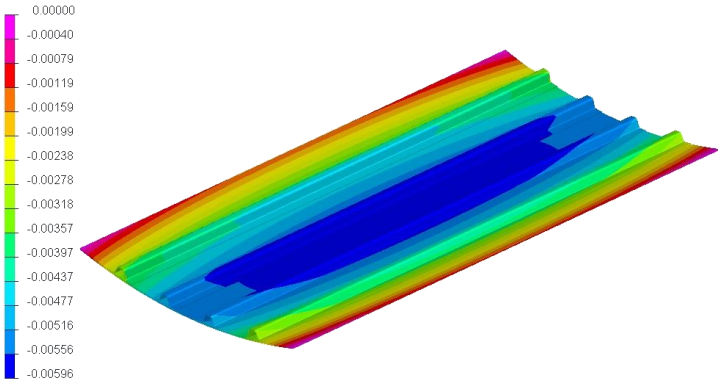
PAM-DISTORTION simulation

Fuselage Panel

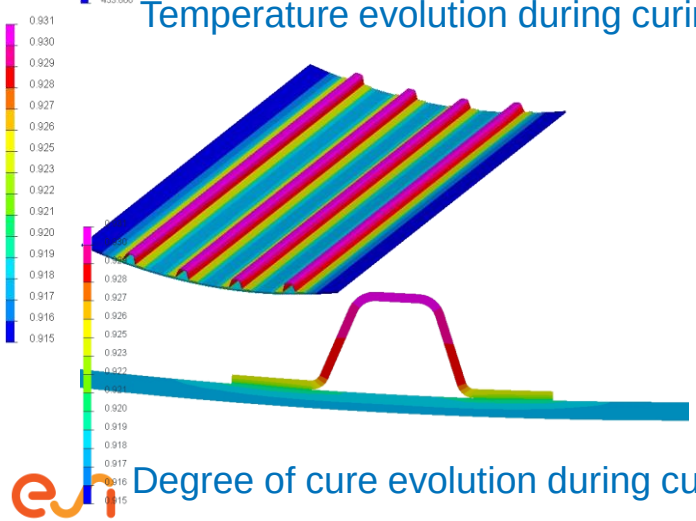




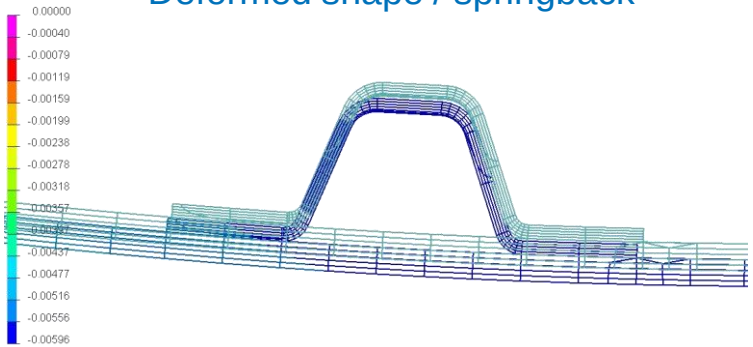
Temperature evolution during curing



Deformed shape / springback



Degree of cure evolution during curing



Initial and deformed geometries

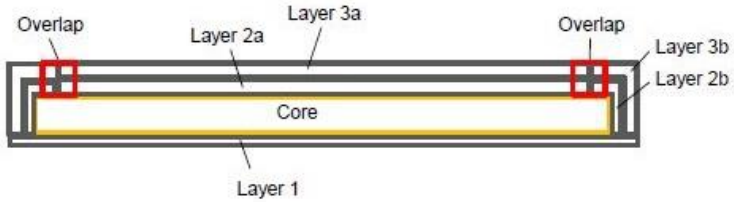
KTM Race Car Application

Front Splitter

KTM TECHNOLOGIES

Front Splitter

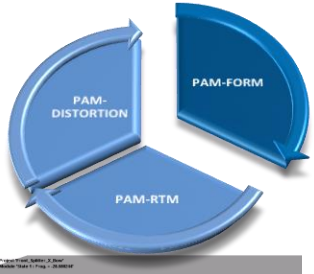
Laminate definition

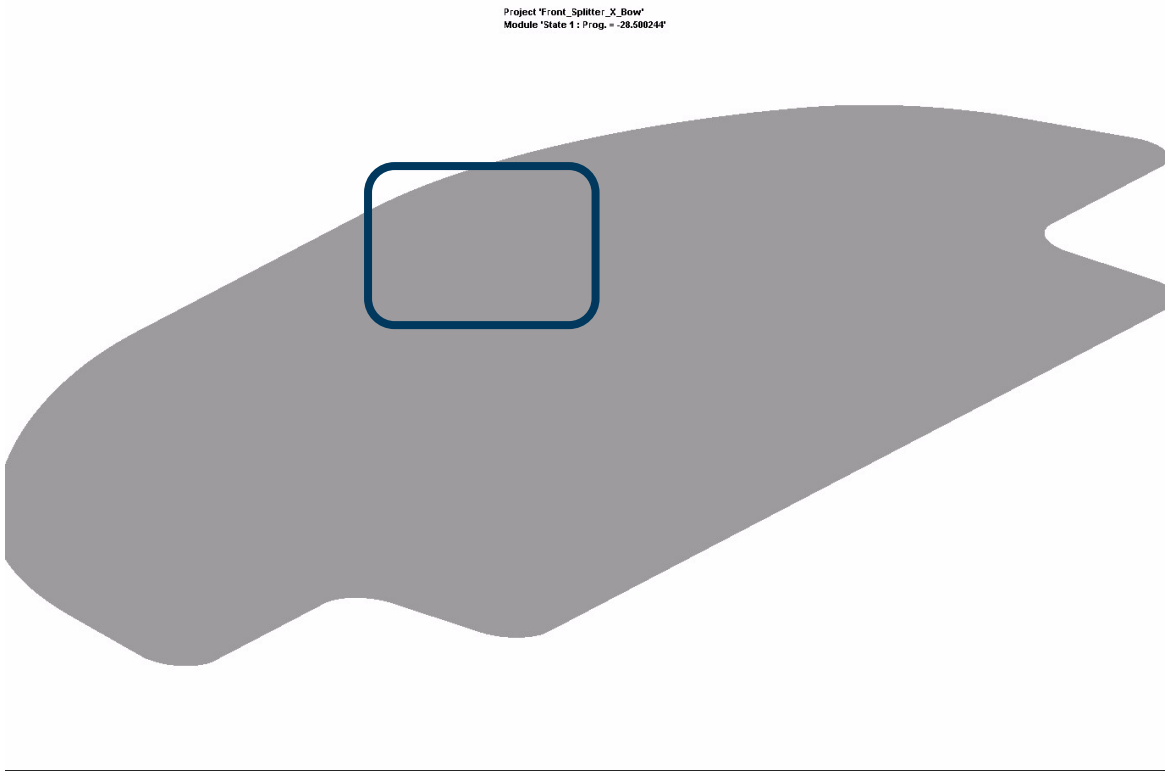


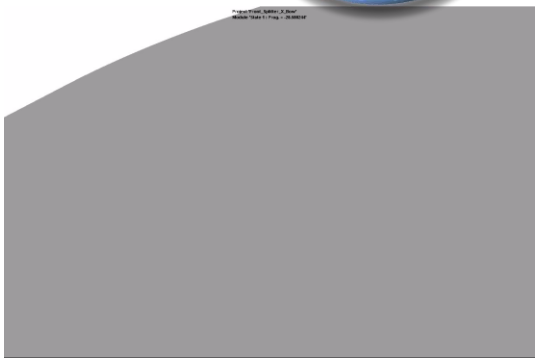
Zoom-in on structure

Fiber: Tenax–J STS 40 F13 24 K 1800 tex; Binding type: plain
Resin+ Hardener: EpikoteResin04695/1 and EpikureCuringAgent 05357
Core: Büfadur67 –15, PUR Foam

Preforming of upper plies
With PAM-FORM



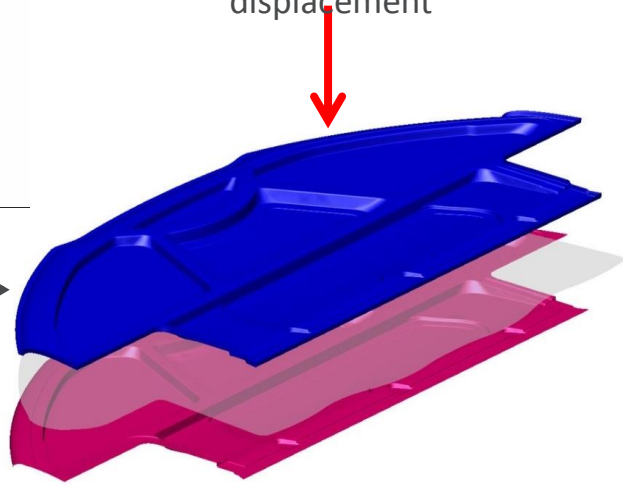




Upper tool's displacement

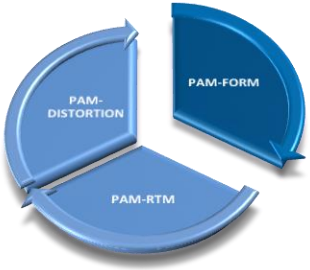
Upper tool

Lower tool (lock)

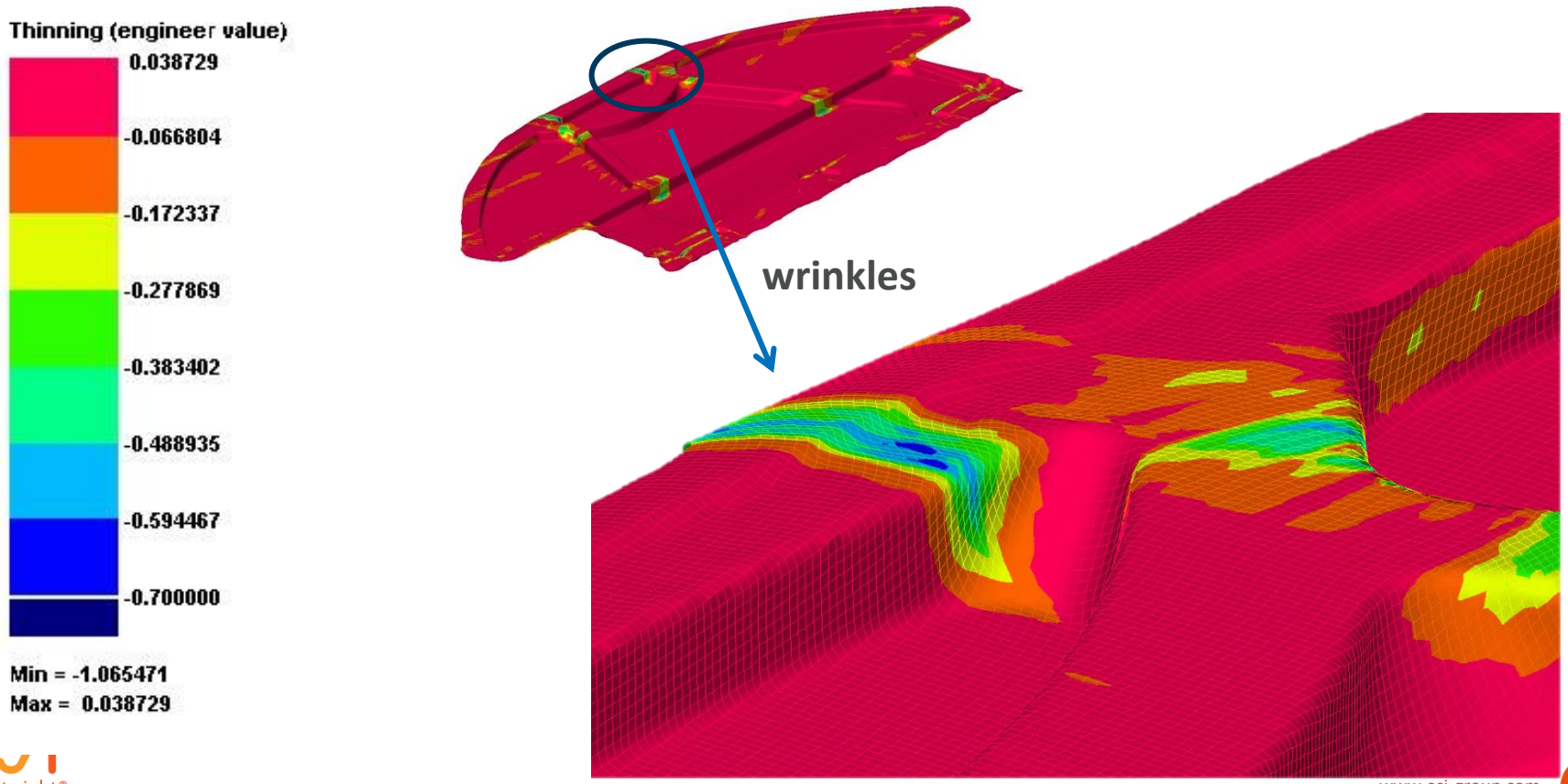


Preforming Simulation

To predict and optimize Thickness distribution

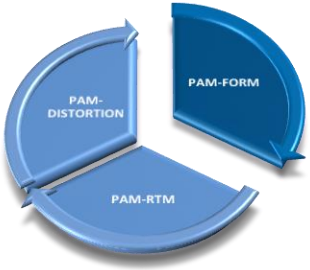


Thinning contour

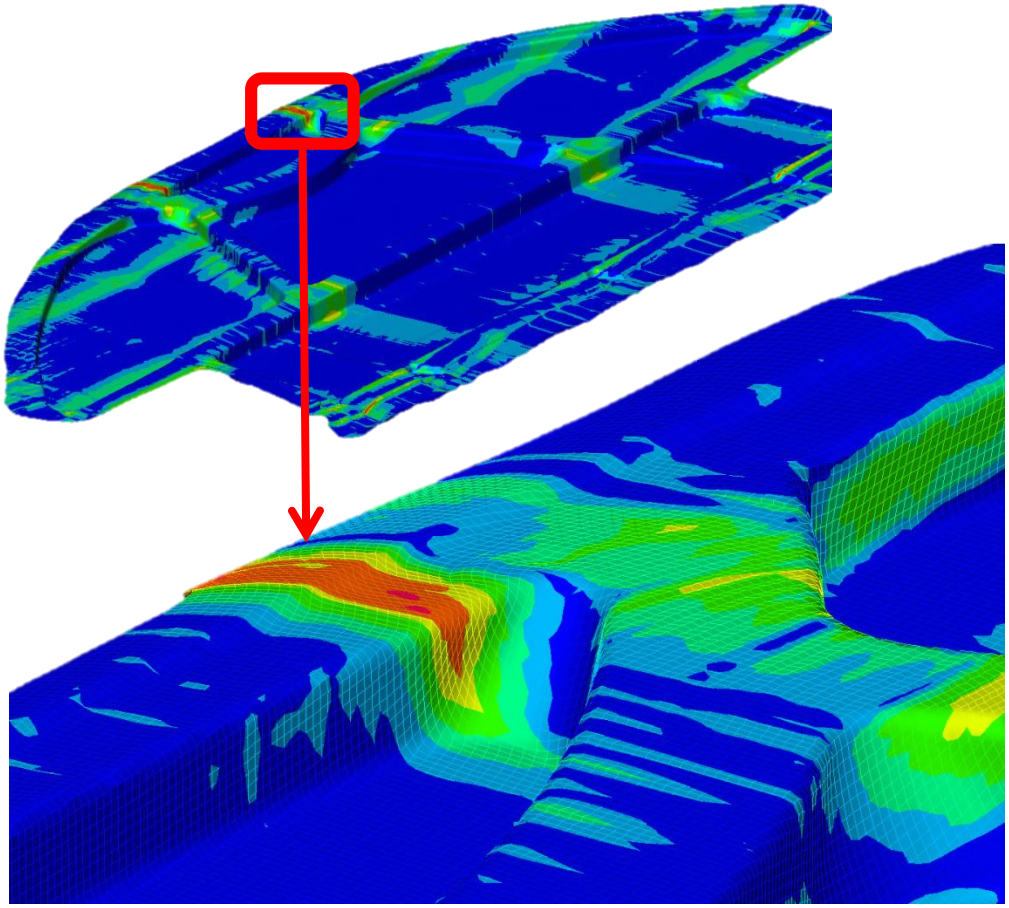


Preforming Simulation

To predict and optimize Shearing

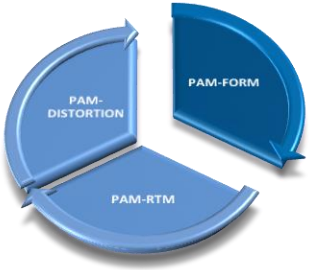


Shear angle



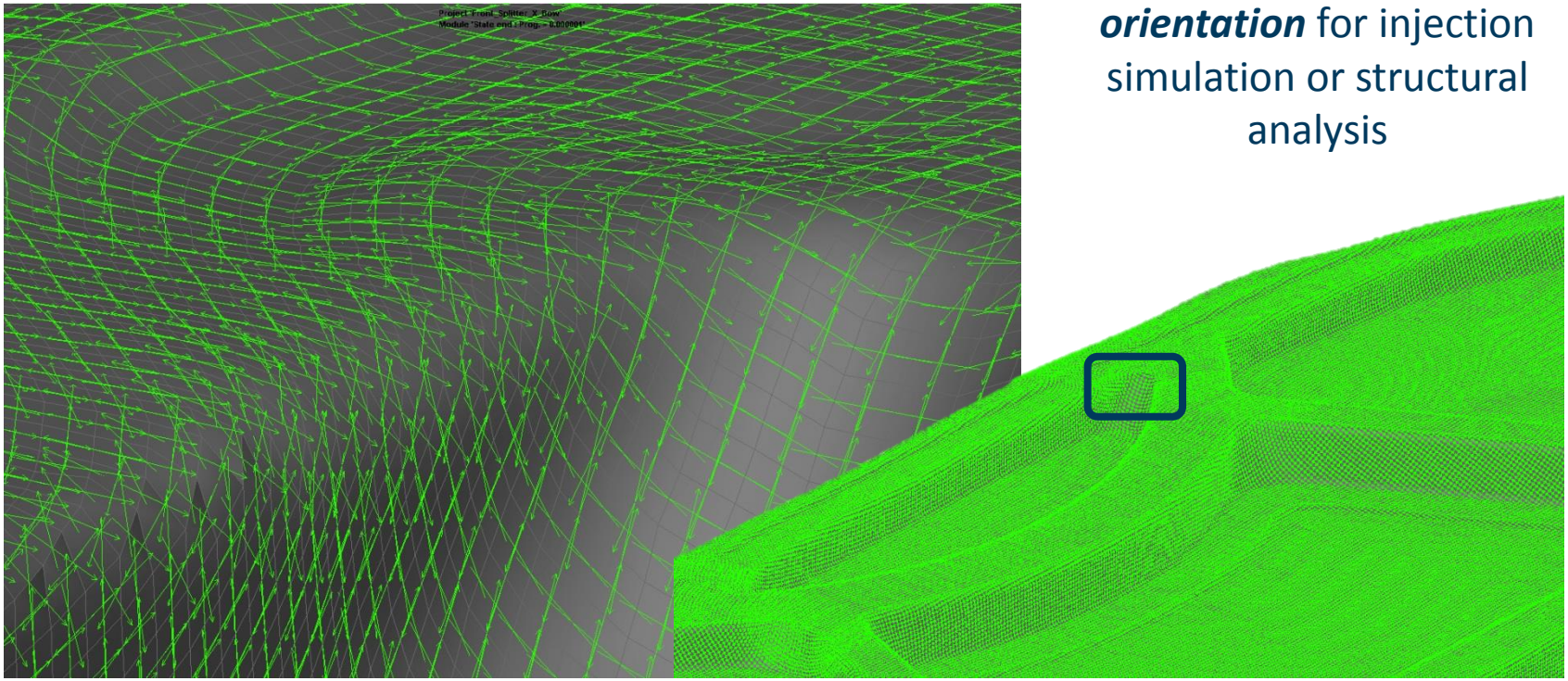
Preforming Simulation

To predict and optimize
Fiber orientations



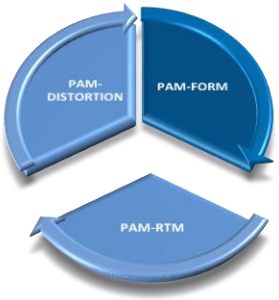
Fiber orientations

Export your ***fiber orientation*** for injection simulation or structural analysis



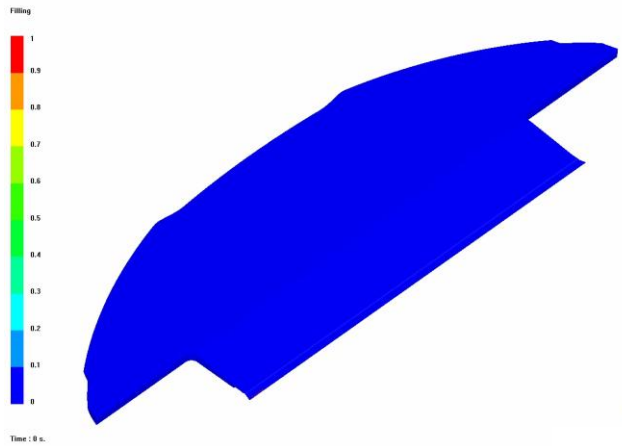
Injection Simulation

To predict and optimize
Dry spots & Porosities

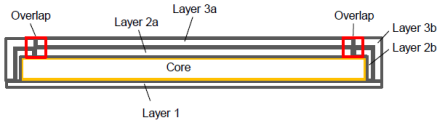


3D Injection with PAM-RTM

- Takes into account fiber orientations (impact on permeability) from preforming simulation

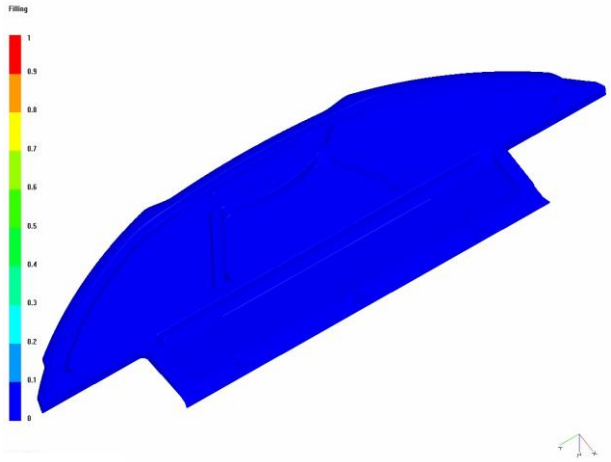


Bottom view



Lay-up

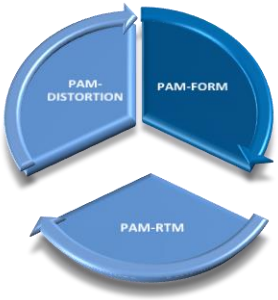
Layer Number	Material	Angle
Layer 1	Tenax – J STS 40 F13	0°/90°
Layer 2a	Tenax – J STS 40 F14	0°/90°
Layer 2b	Tenax – J STS 40 F15	0°/90°
Layer 3a	Tenax – J STS 40 F16	0°/90°
Layer 3b	Tenax – J STS 40 F17	0°/90°



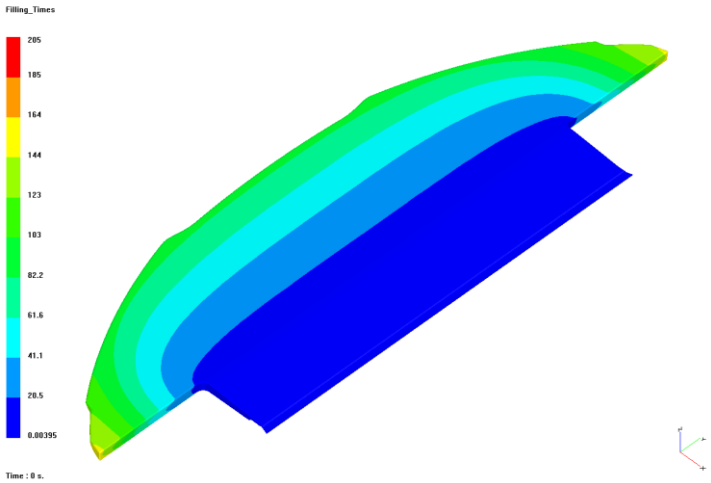
Top view

Injection Simulation

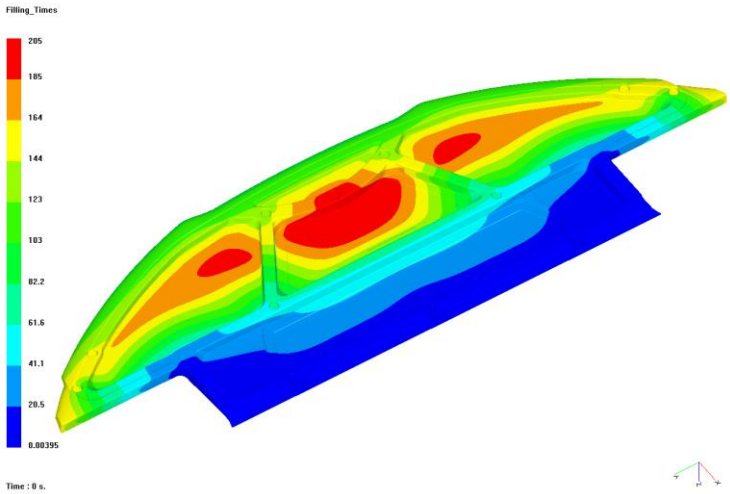
To predict and optimize
Filling time



Filling time



Bottom view



Top view

Selected Industrial References

THANK YOU

composites@esi-group.com