Modélisation et Simulation de la Fabrication des Matériaux Composites à Matrices Thermodurcissable ou Thermoplastique en Conditions Sévères de Mise en Œuvre et Mise en Forme

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Evolution of Industrial Applications

Penetration into new markets: Cost reduction is a key!

Importance of performance

Biomedical

Aerospace

~20C

Military

Commercial aircraft

Today

Mass transport

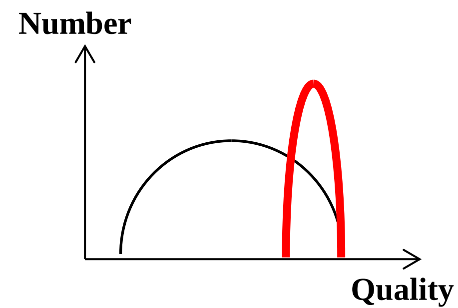
Automotive

Construction

Tomorrow

Importance of cost

Reproducibility & Quality



Final Quality Depends on the Manufacturing !

Talyor-made material?

PROCESS

P, T, v, t

Process control?

Trial & error?

Predictive tool!

Fiber

$E_f \quad G_f \quad \nu_f \quad \sigma_f \quad \alpha_f$

Matrix

$E_m \quad G_m \quad \nu_m \quad \sigma_m \quad \alpha_m$

Curing

Crystallinity

μ-structure

V_f

θ_f

$L_f \,/\, D_f$

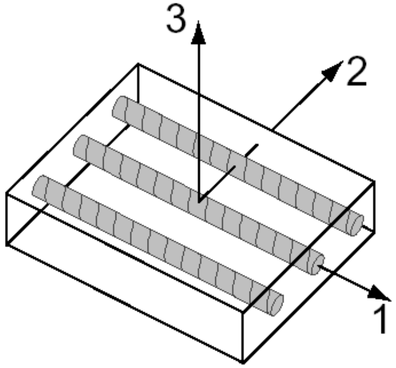
Voids

Interface

Residual stress

Composite

$E_{ij} \quad G_{ij} \quad \nu_{ij} \quad \sigma_{ij} \quad \alpha_{ij}$



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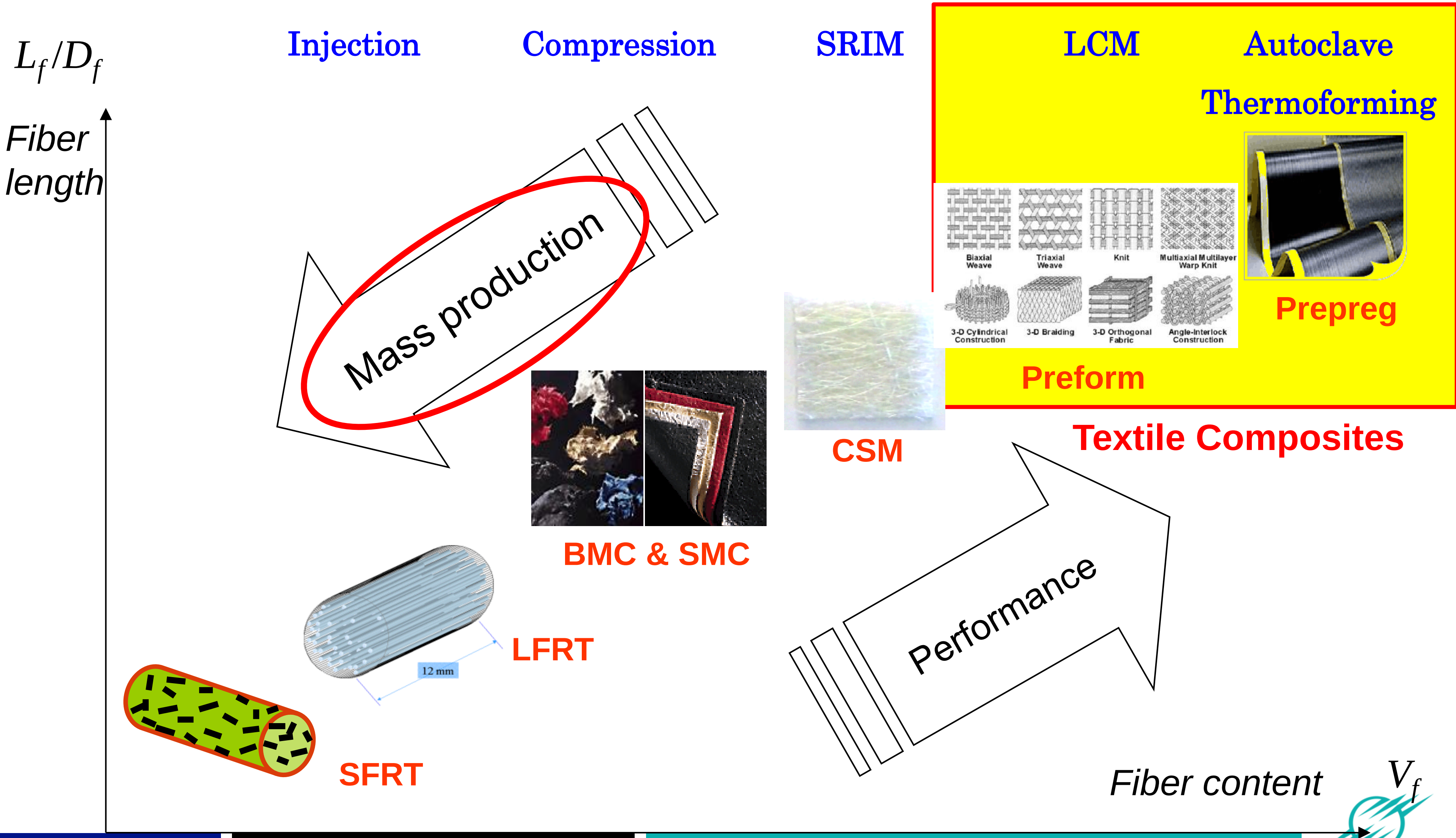
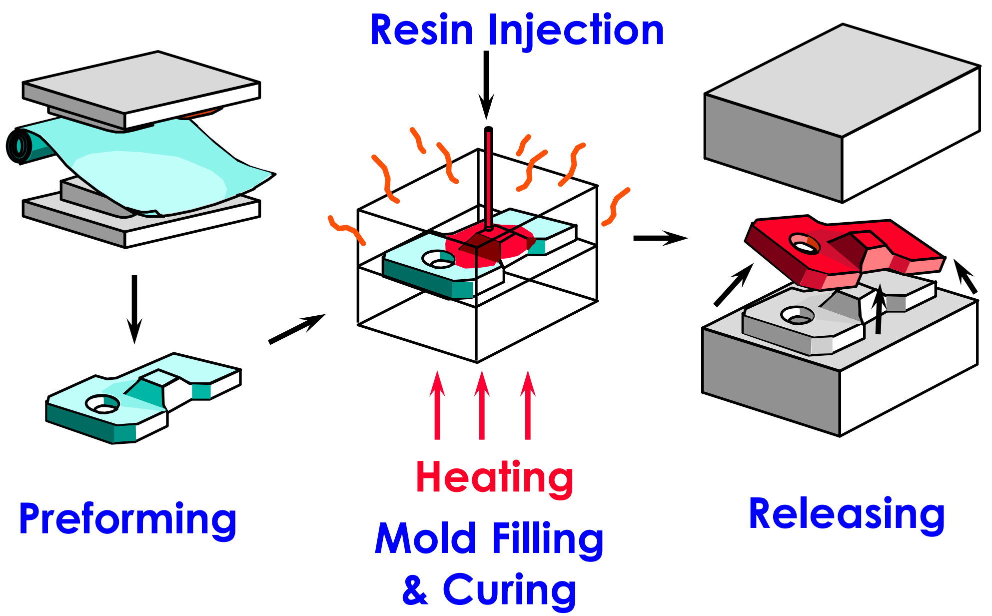
Materials & Processes



Liquid Composite Molding

Impregnation of <u>continuous</u> dry textile reinforcement by liquid resin

- **Resin Transfer Molding process**



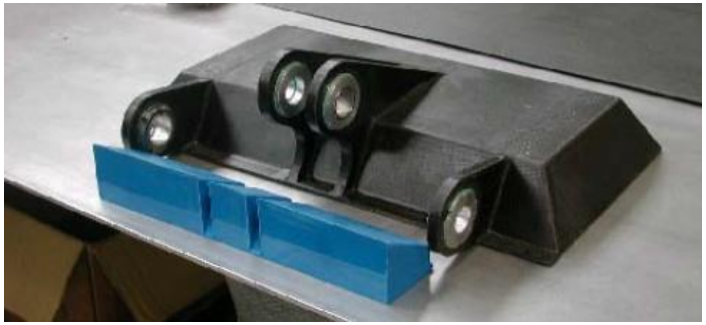
✓**Large and complex structures without assembling**

✓**Reduction of raw material cost and labor**

✓**Free from volatile trouble**

A320/A340 spoiler

Preform



Final product

Low Cost ! Product Quality ?

Titanium?
or
Carbon fiber prepreg?

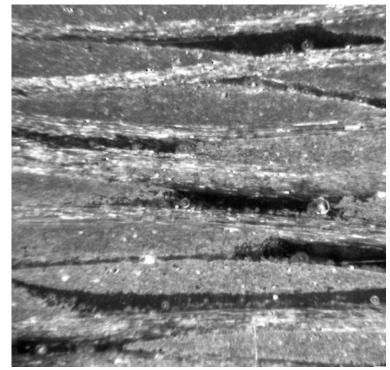
- Impact resistance (bird strike)
- Fatigue (high speed rotation)
- Cost

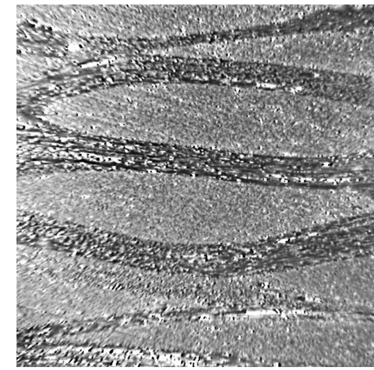
<u>LEAP engine fan blade</u>

3D carbon interlock + Epoxy
(Resin Transfer Molding)

- Low manufacturing cost
- Enhanced impact resistance

Quality?: Defects (porosity, void)

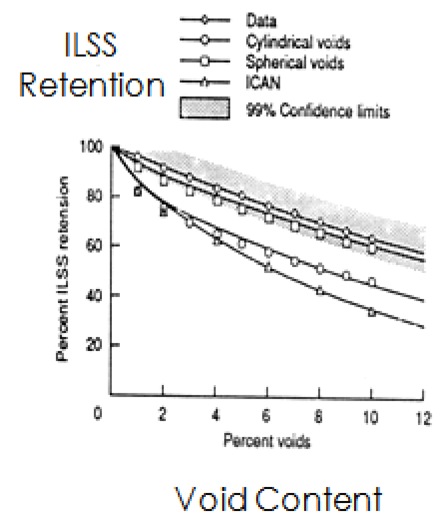




<u>Degeneration of mechanical performances</u>

Aeronautic standard

Void content < 2%



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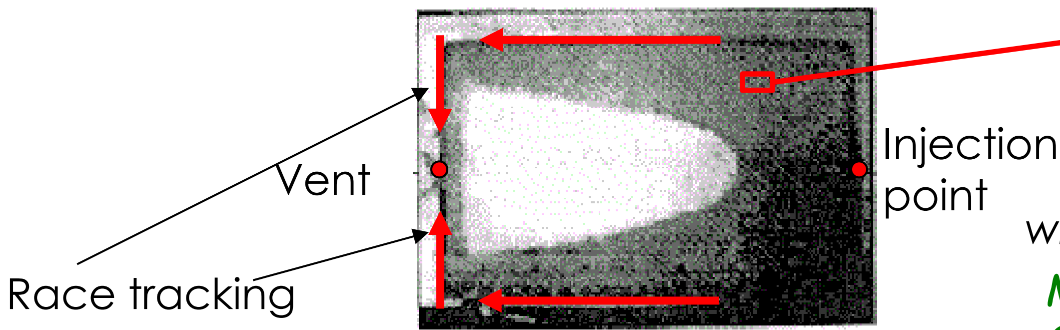
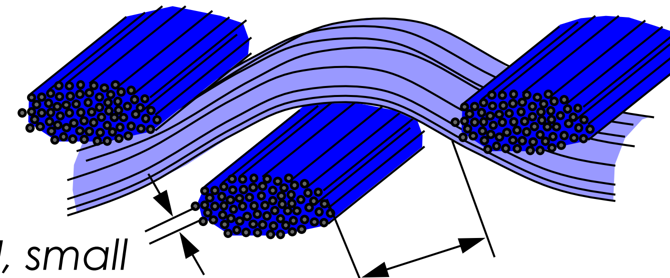
Void Defects in Different Scales

Void, Porosity, Air bubble, Dry zone, etc.

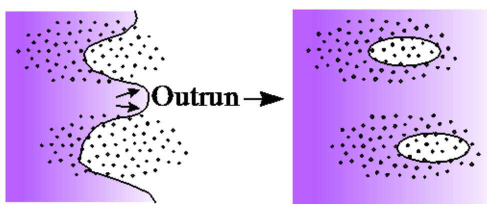
- **Dry zone (short shot)**



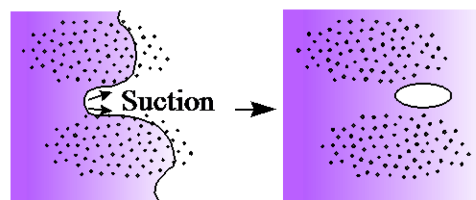


- **Tow void (inside tow)**

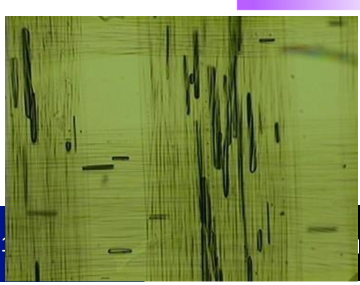
Intra-bundle void



- **Channel void (between tows)**

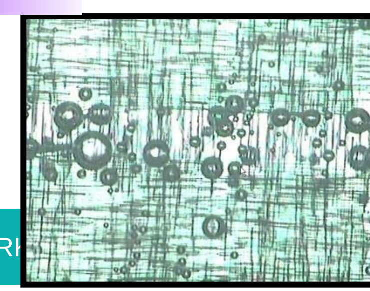


Inter-bundle void



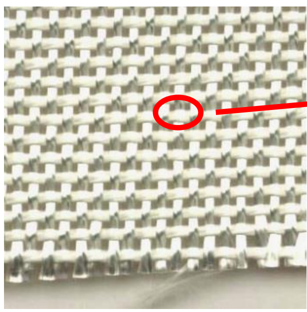
1~10µm

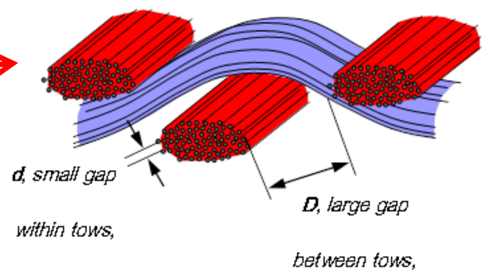
0.1~1mm

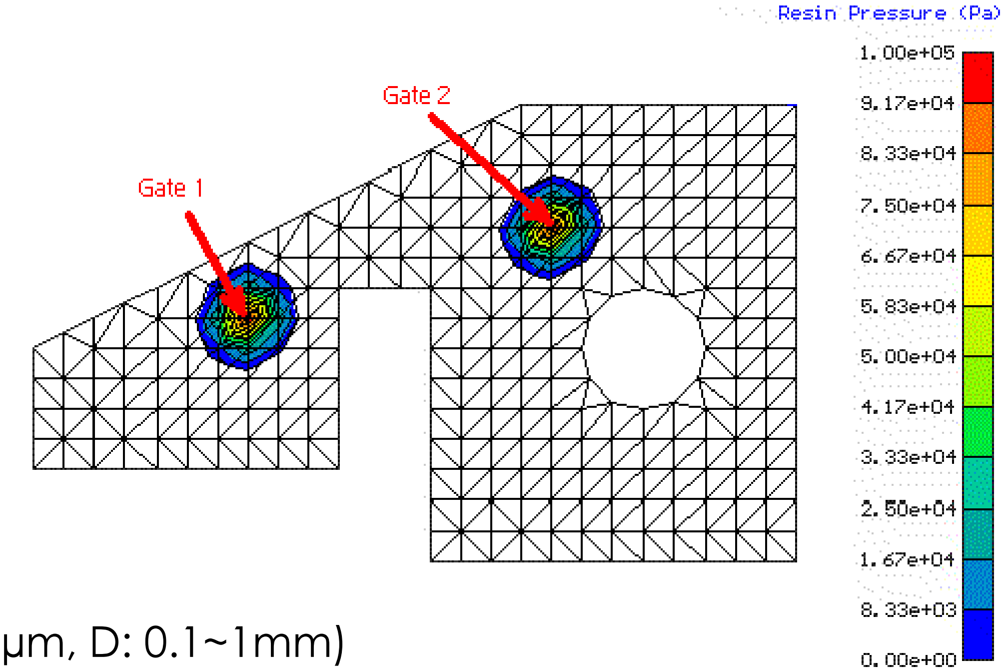


Resin Flow Modeling in Different Scales

- **Macroscopic scale**
  - ✓ Homogeneous porous medium
  - ✓ Darcy's law

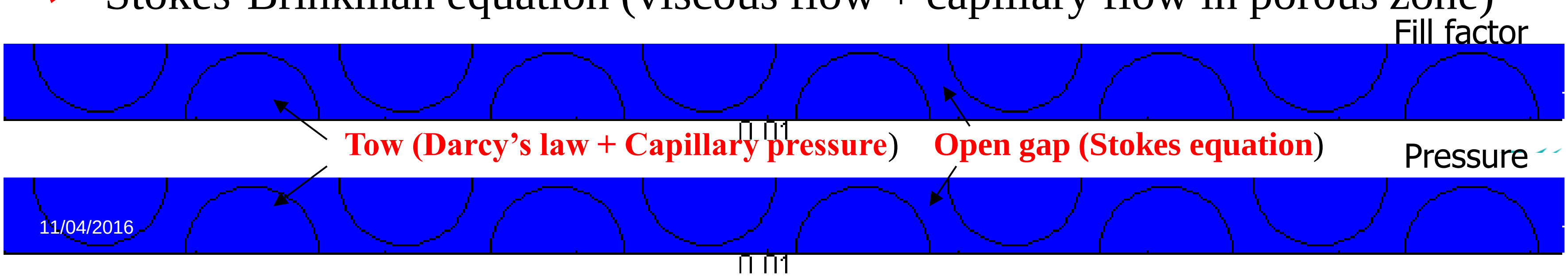






Homogeneous Heterogeneous (d: 1~10 μm, D: 0.1~1mm)

- **Mesoscopic scale**
  - ✓ Heterogeneous medium: open gap and micro porous zone
  - ✓ Stokes-Brinkman equation (viscous flow + capillary flow in porous zone)



Macroscopic Flow Analysis

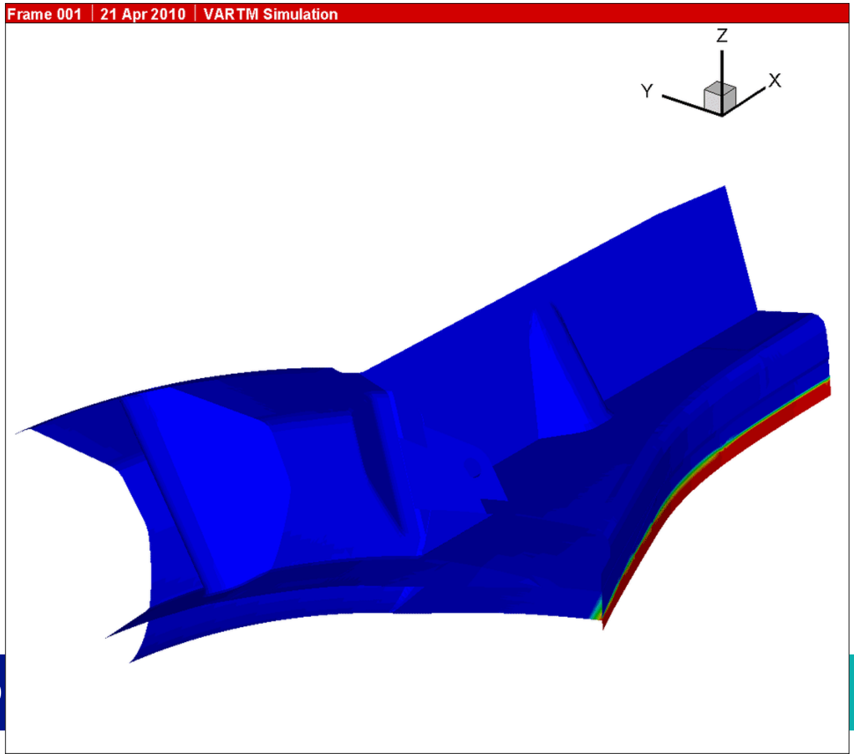
- **Single-phase analysis**
  - ✓ Incompressible liquid

    P=P$_{vent}$ at the flow front

$$\frac{\partial}{\partial x_i}\left(\frac{K_{ij}}{\mu_r}\frac{\partial p}{\partial x_j}\right)=0$$

Automotive front hood (half body)

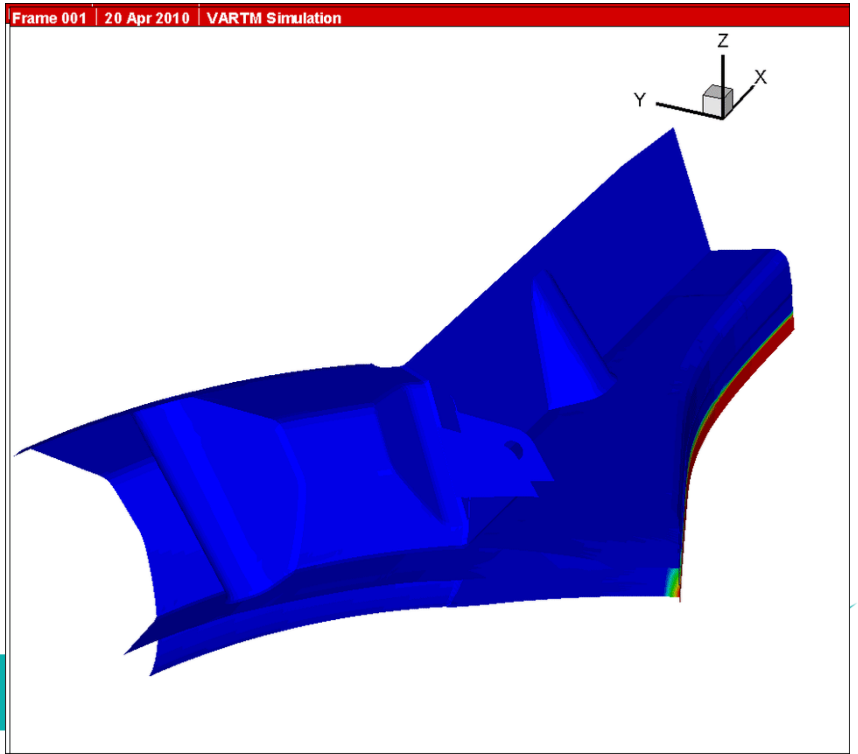
SAFRAN / Nacelle



- **Two-phase analysis**
  - ✓ Incompressible liquid + Compressible air

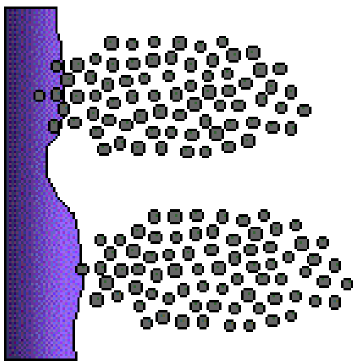
    P=P$_{vent}$ at the vent

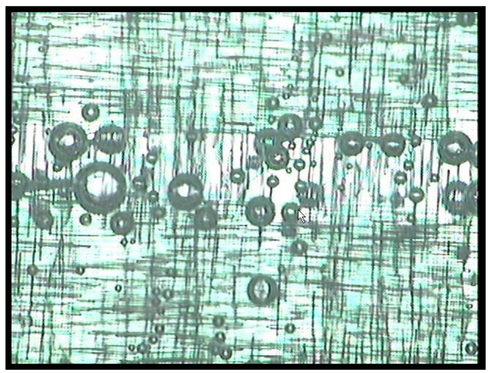
$$\frac{\partial}{\partial x_i}\left(\frac{K_{ij}}{\mu_r}\frac{\partial p}{\partial x_j}\right)=0 \qquad \frac{1-V_f}{p_a}\frac{\partial p_a}{\partial t}=\frac{\partial}{\partial x_i}\left(\frac{K_{ij}}{\mu_a}\frac{\partial p_a}{\partial x_j}\right)$$

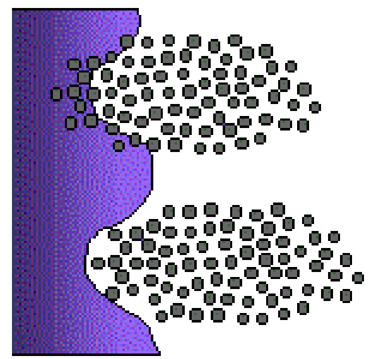


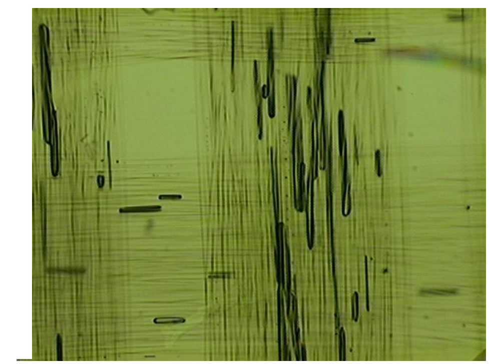
Microvoid Formation Mechanism

- **Mechanical air entrapment at the flow front**
- **Competition between the viscous flow between fiber tows and the capillary wicking inside the fiber tow**



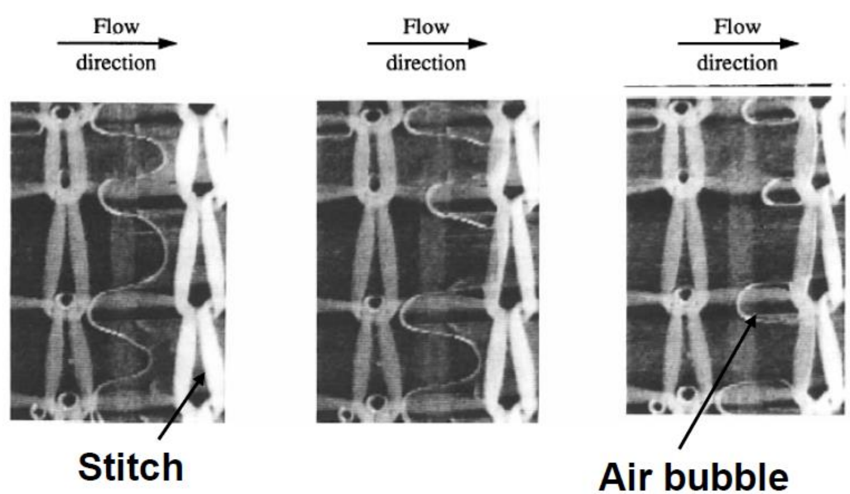






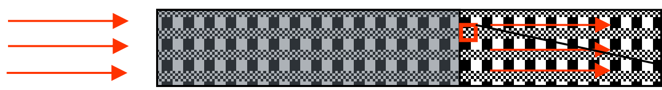
Low resin velocity: Channel void

High resin velocity: Tow void



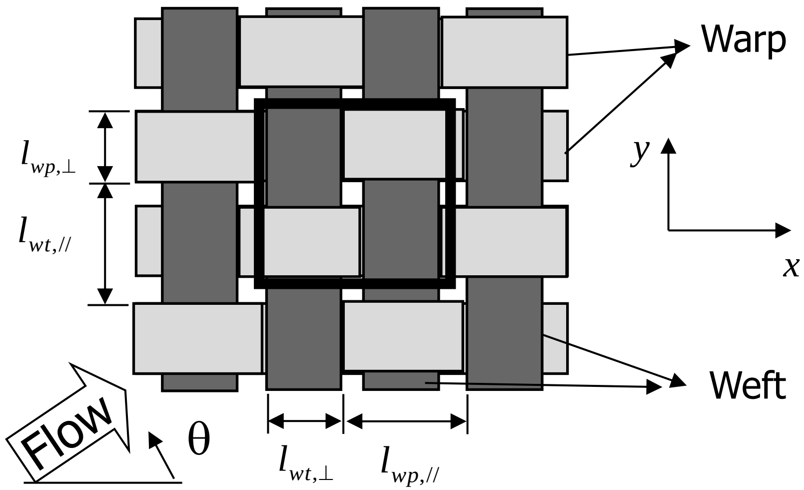
Mutli-scale Flow Model: Microvoid Formation

- **Homogeneous medium at the macro-scale**

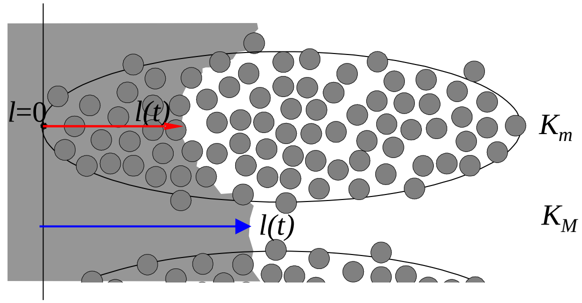


$$\nabla \cdot \left(\frac{K}{\mu} \nabla P \right) = 0$$

- **Microstructure of fabric**



- **Double-scale flow**



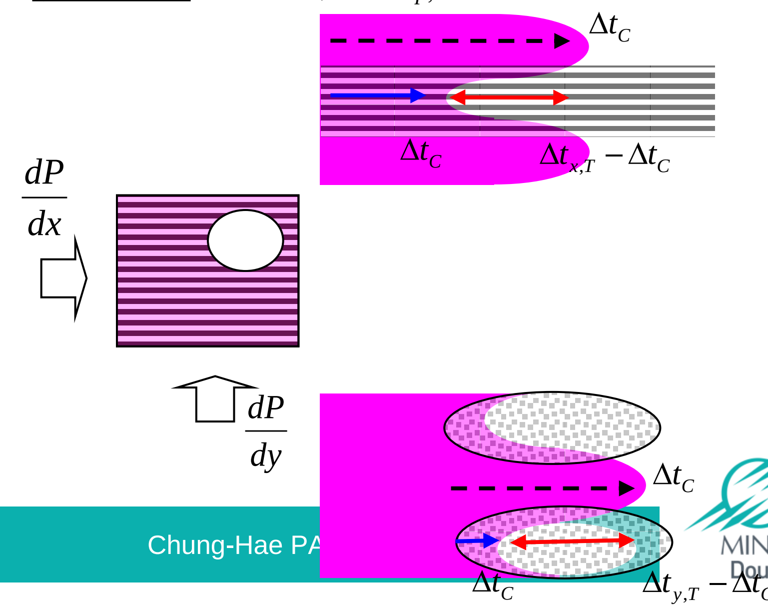
Macropore $\quad < \vec{v} > = - \frac{\mathbf{K}_M}{\mu} \nabla P$

Micropore $\quad < \vec{v} > = - \frac{\mathbf{K}_m}{\mu} \nabla \left(P - P_{cap} \right)$

$$P_{cap} = \left(\frac{F}{D_f} \right) \frac{1-\phi}{\phi} \gamma \cos\theta$$

γ: Surface tension

θ: Contact angle



Microvoid Formation Modeling

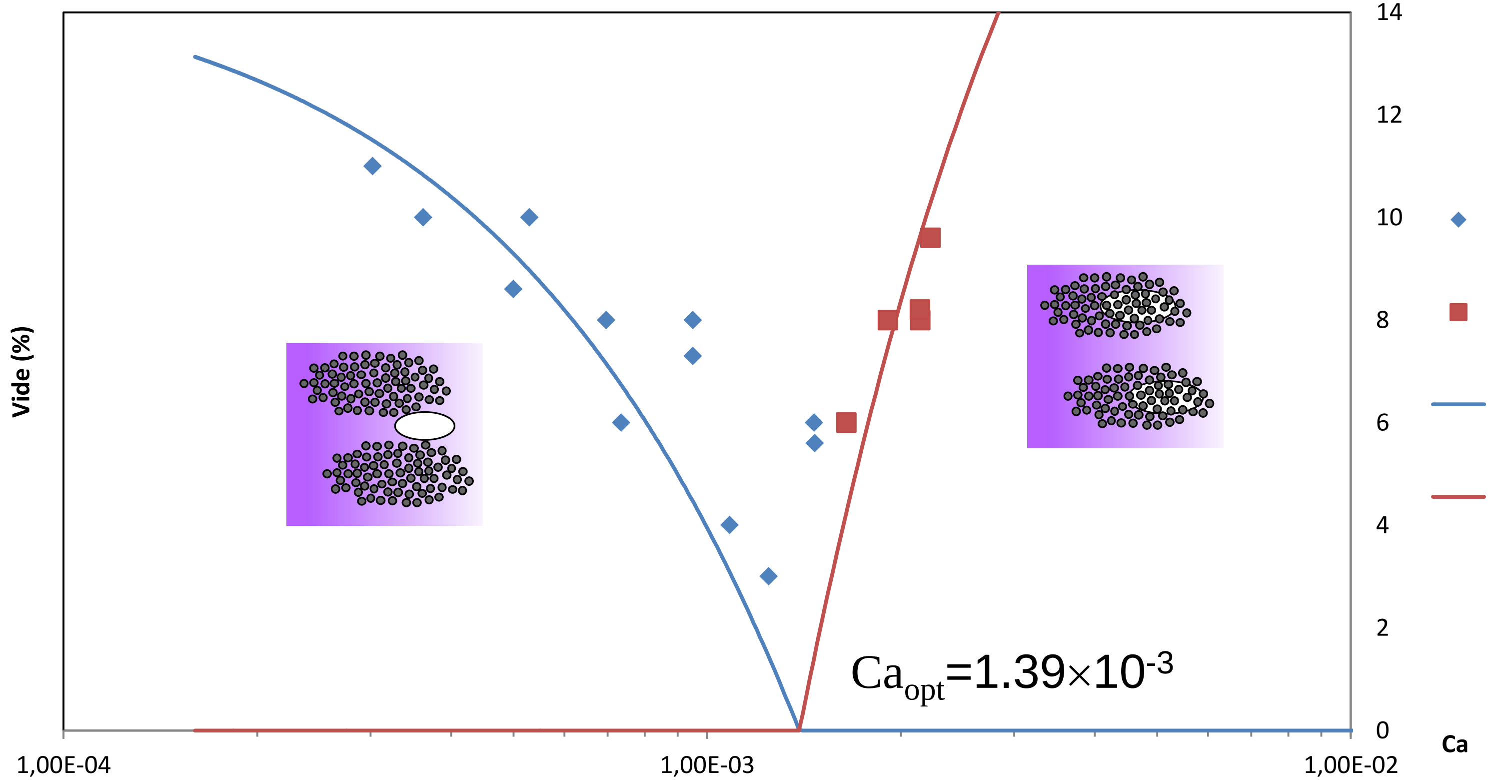
- **Unidirectional fabric / constant flow rate injection / in-situ measurement**
- **Analytical solution for void content against *Ca***

$$fn\left(K_M, K_T, V_{f,T}, D_f, l_T, \ln(Ca^*)\right)$$

Fabric micro-architecture

$$Ca^* = \frac{\mu \bar{u}}{\gamma \cos\theta}$$

$\bar{u}$: resin velocity



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Microvoid Formation in Woven Composites

- **Modeling the formation and compression of microvoids**

P_{inj}=const
Plain weave

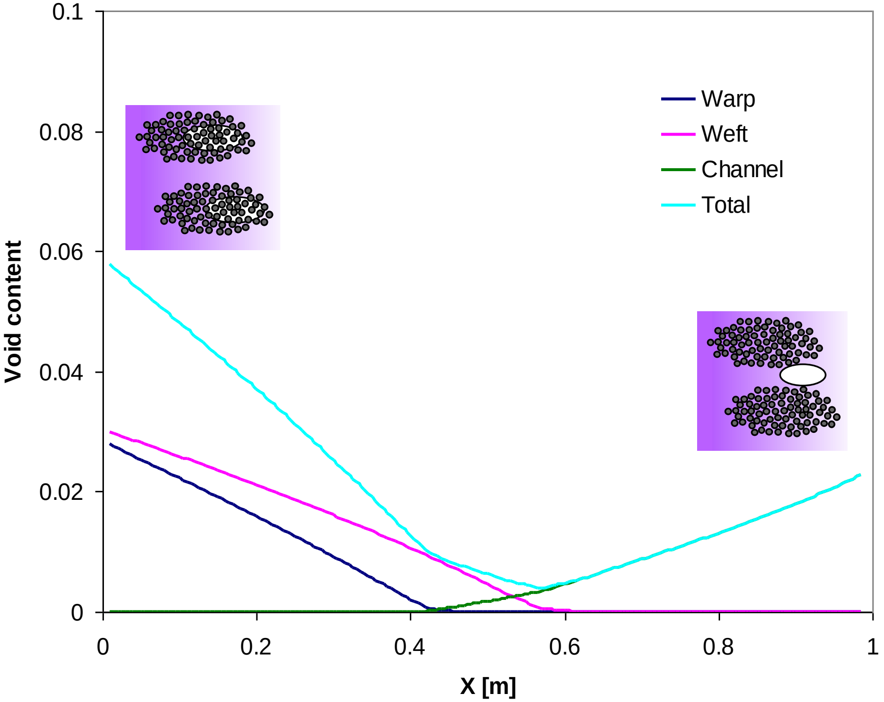
Influence of tow orientation!

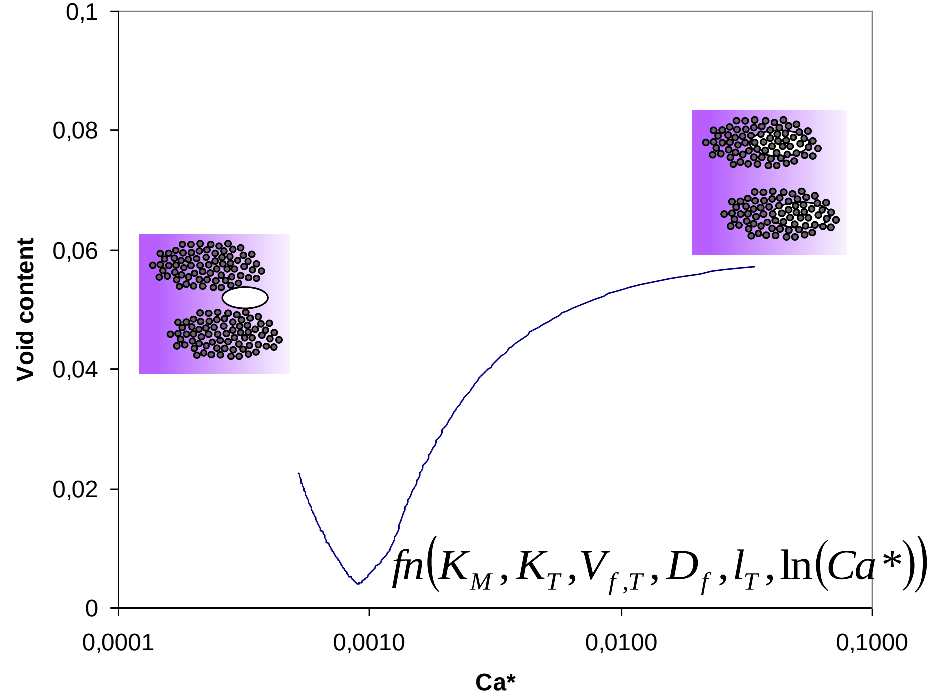
✓ Void content vs. position

✓ Void content vs. *Ca**

$$Ca^* = \frac{\mu\bar{u}}{\gamma\cos\theta}$$

$\bar{u}$: resin velocity



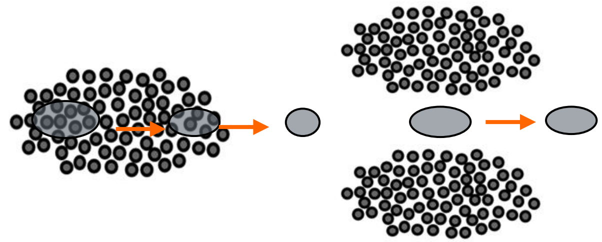


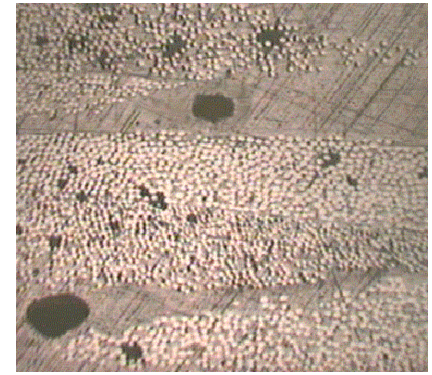
Microvoid Migration Modeling

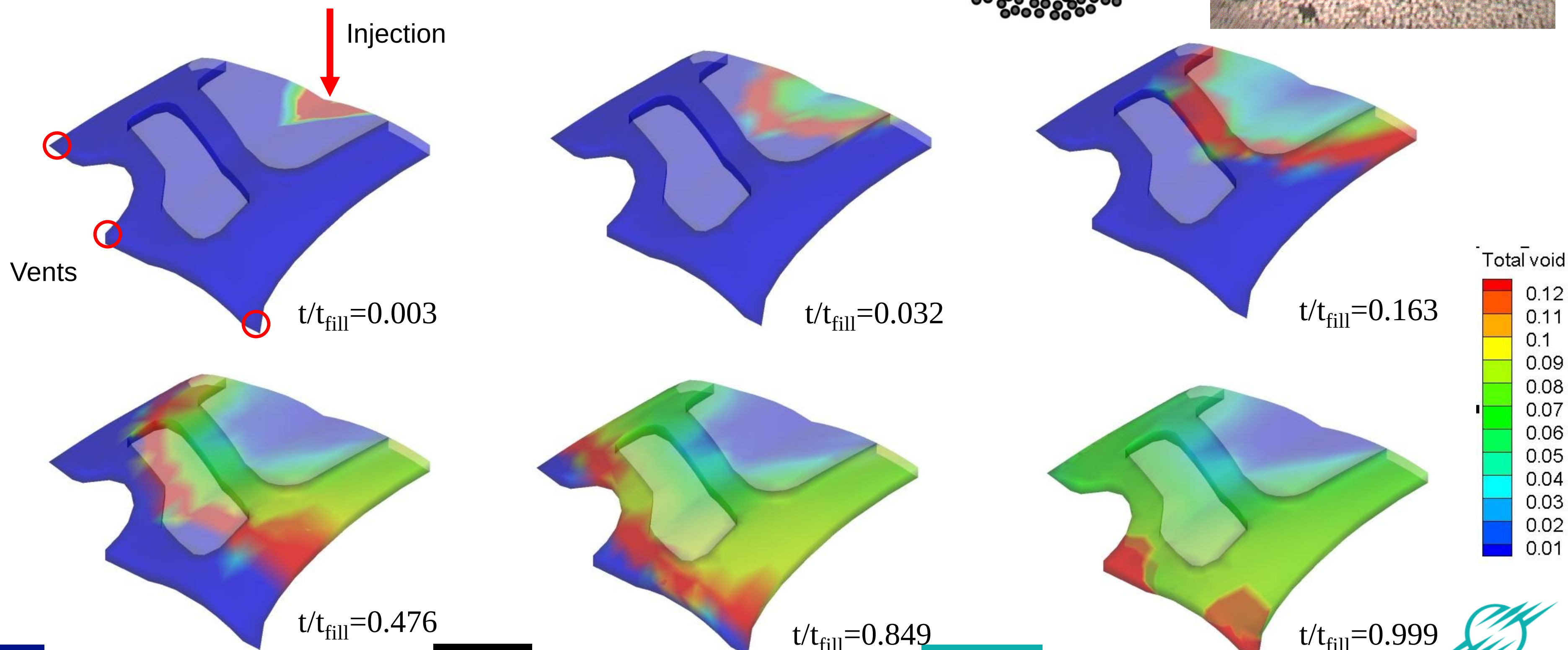
$$\frac{\partial V_{air,C}}{\partial t} + \nabla \cdot \left(V_{air,C} \cdot \vec{u}_{air} \right) = \dot{S}$$

- **Microvoid distribution**
  - ✓ **Void migration inside the tow and in the channel**
  - ✓ **Highly bubbly zone (with a constant width) behind the flow front**

Bleeding !







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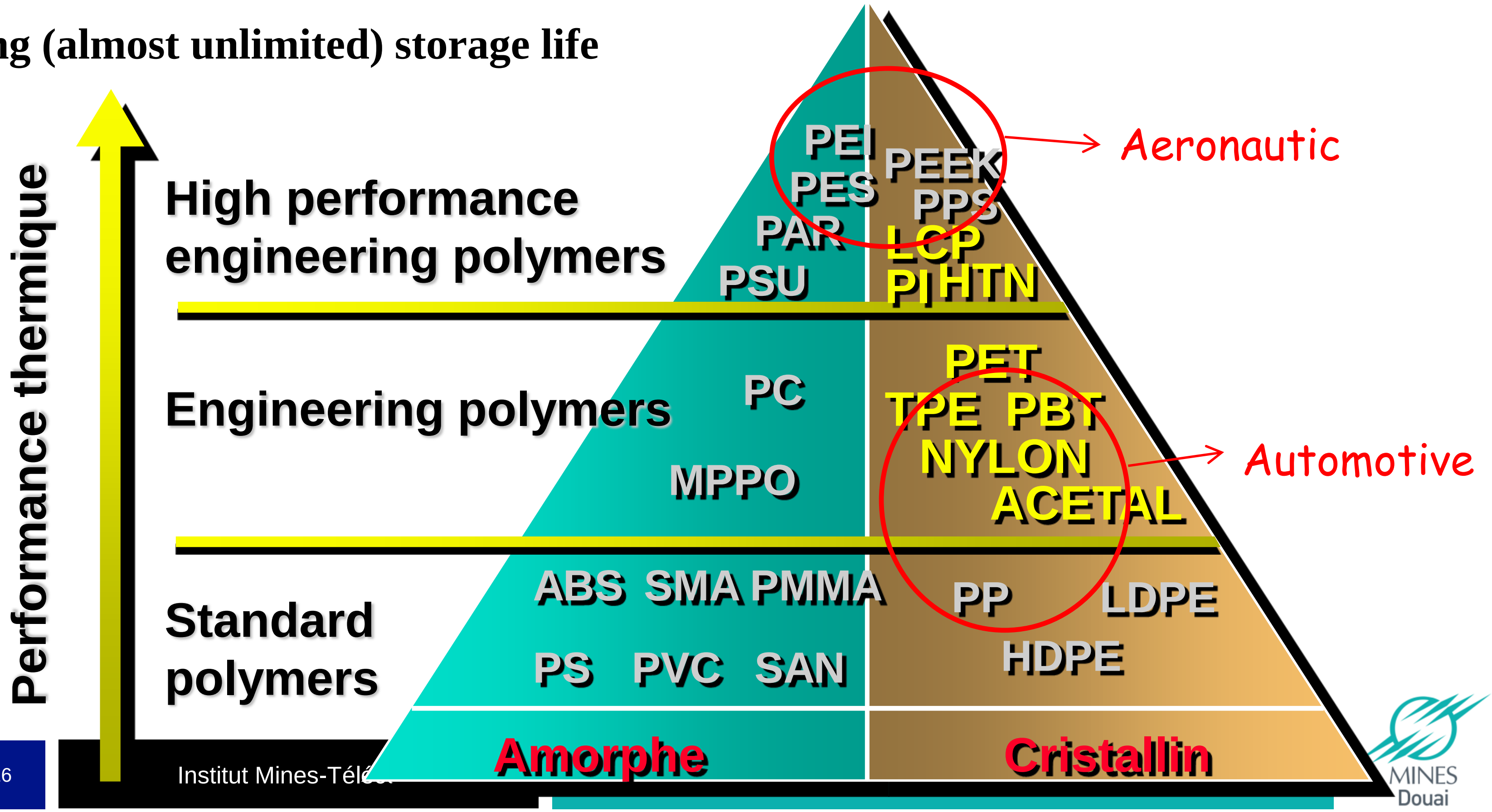
Themoplastic Matrices

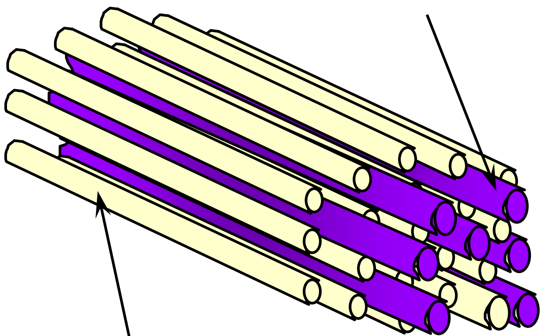
- **Advantages (over thermoset resins)**
  - ✓ High impact resistance
  - ✓ Possibility of patch repair
  - ✓ Long (almost unlimited) storage life
- **Disadvantage**
  - ✓ High viscosity (difficult impregnation)

    0.1-1 Pa s (TS) vs. $10^2 – 10^5$ Pa s (TP)

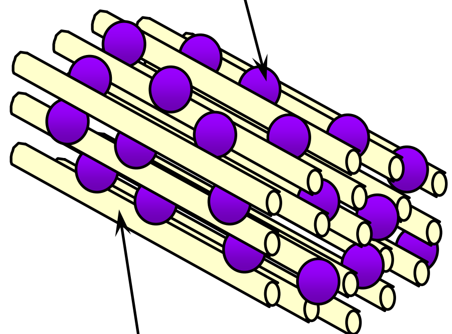


Semi-Products: Polymer-Fiber Pre-Mixture

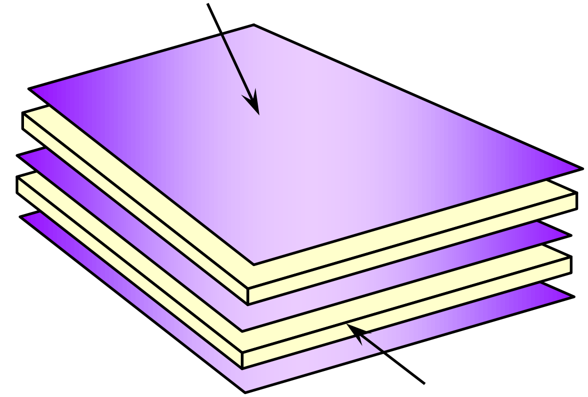
- **Solid polymer + Reinforcing fiber : Reduce the resin flow path**



Commingled yarn



Powder-mixed bundle

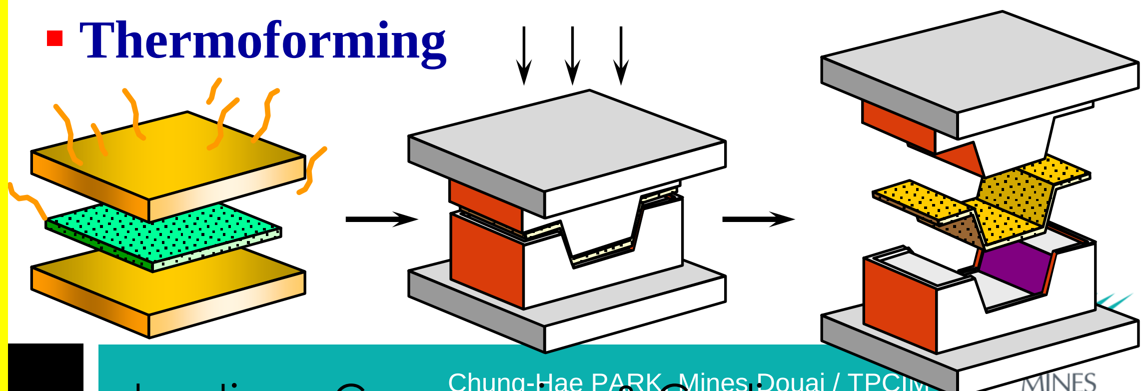


Film stacking

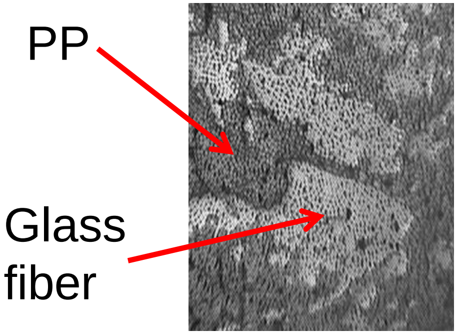
One-shot manufacturing of 3D structure without prepreg

FP7 / MAPICC 3D

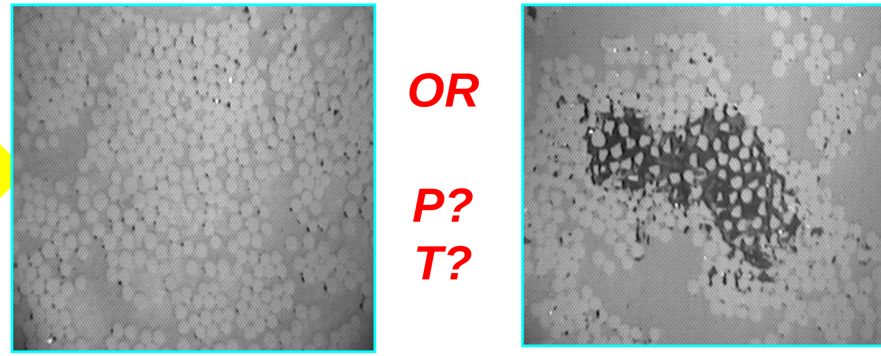
- **Thermoforming**

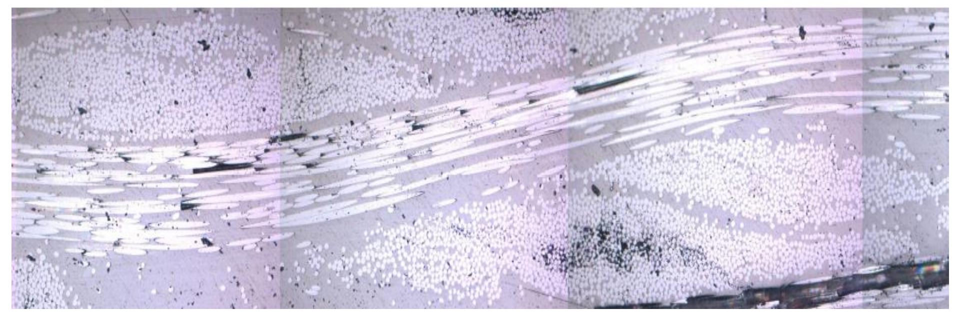


Resin & Air Flow in Micro-Scale

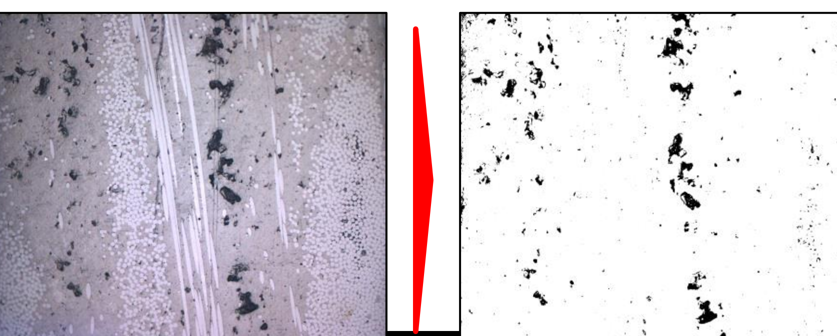


Commingled yarn

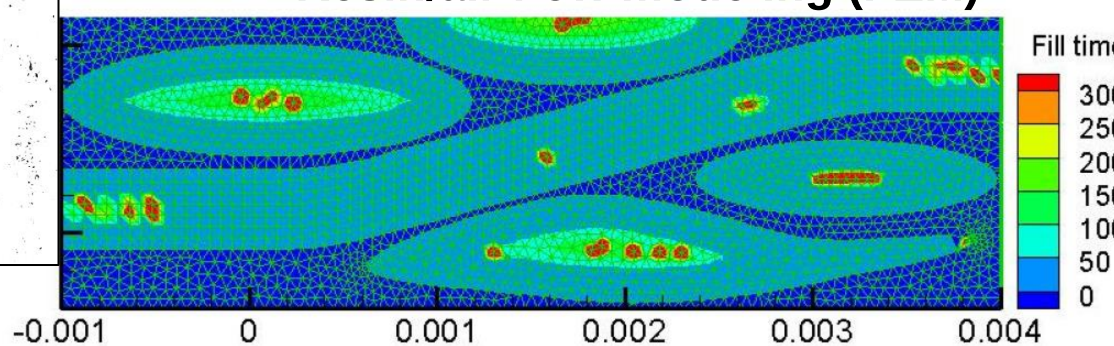




- **Micrographic observation**
- **Image processing (B/W image)**
- **Void content calculation**



- **Real textile architecture**
- **Resin/air flow modeling (FEM)**



Conclusions

- **Low cost manufacturing techniques for structural composites are widely employed for aeronautic and automotive applications.**
- **The final product quality depends on the manufacturing technology.**
- **The simulation tools to predict process-induced defects are indispensable.**
- **The influence from the manufacturing process on the mechanical properties of final products should be considered in the structural design.**
- **Multi-scale and multi-physics approaches should be adopted in the composites manufacturing process modeling.**