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Liquid resin infusion simulation

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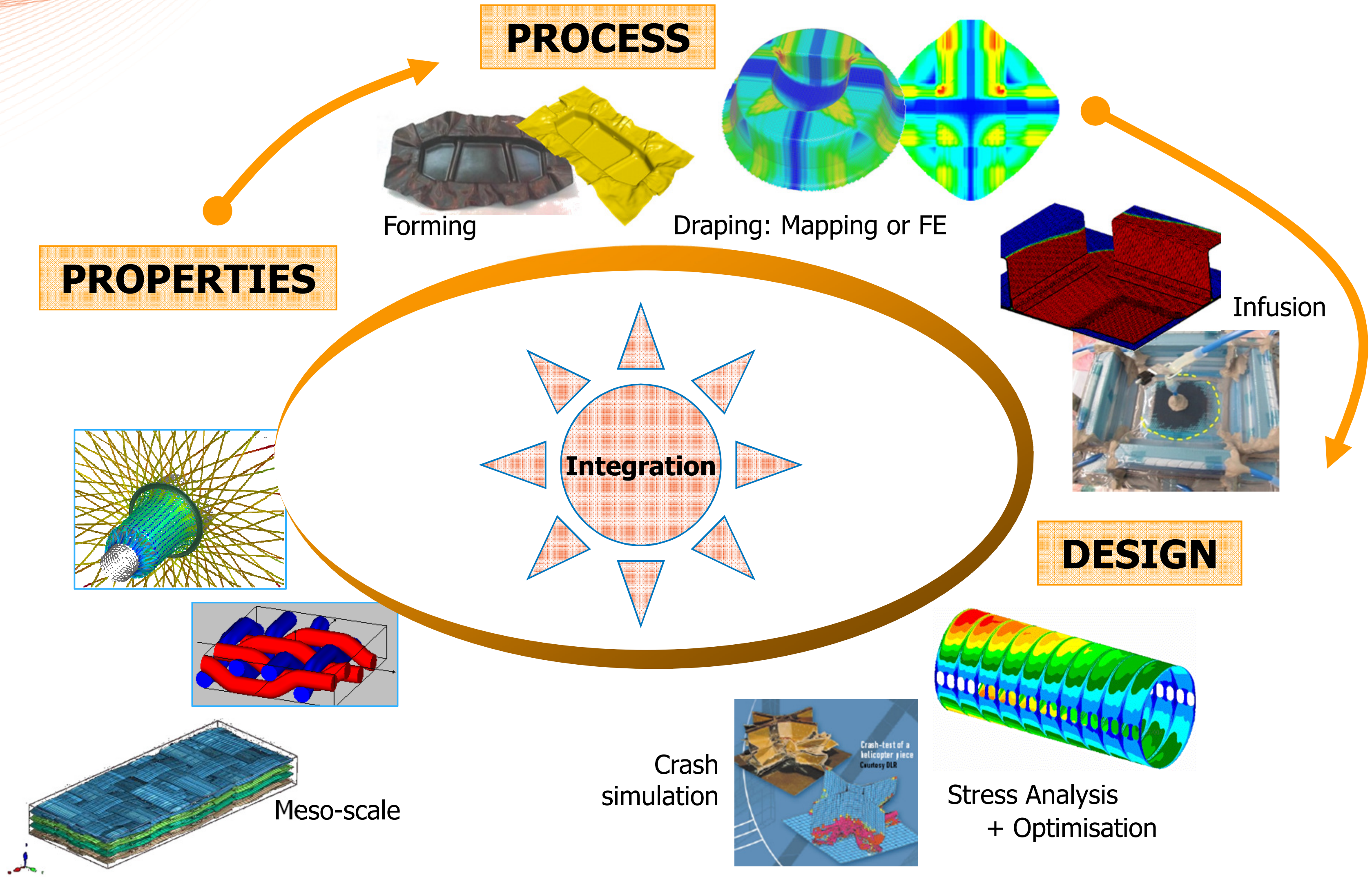
Summary of Presentation

- Liquid Composite Moulding methods
- Resin Transfer Moulding (RTM) versus Liquid Resin Infusion (LRI)
- LRI infusion with one sided tooling and membranes
- Some basic theory and methods for infusion simulation
- Materials testing and calibration (Vf and permeability versus compressibility)
- Example demonstrator test and simulation
- The EU Framework VII project INFUCOMP
- Conclusions

The simulation chain

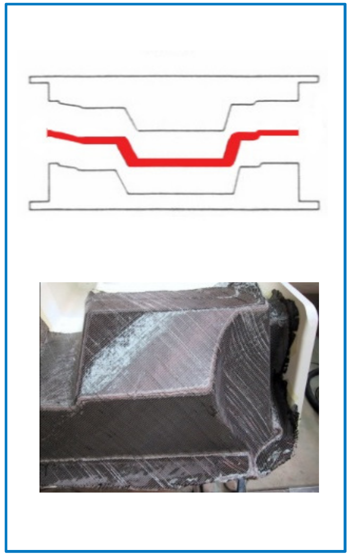


Manufacturing methods: Pre-preg versus Resin Infusion

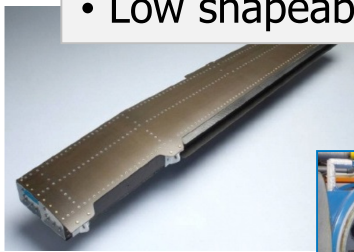
1. **Pre-preg technologies:**
Mixes fibres and resin at the materials stage



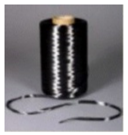
Shaping/
preforming



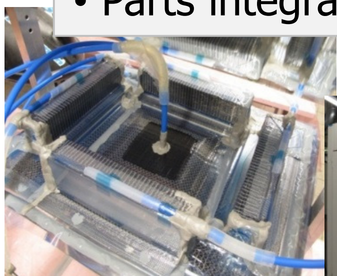
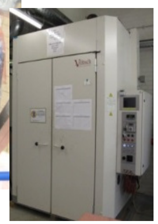
- Toughened resins
- Excellent fibre control
- High V_f ratios
- Low shapeability/integration




2. **Infusion technologies:**
Mixes fibres and resin at the part manufacturing stage

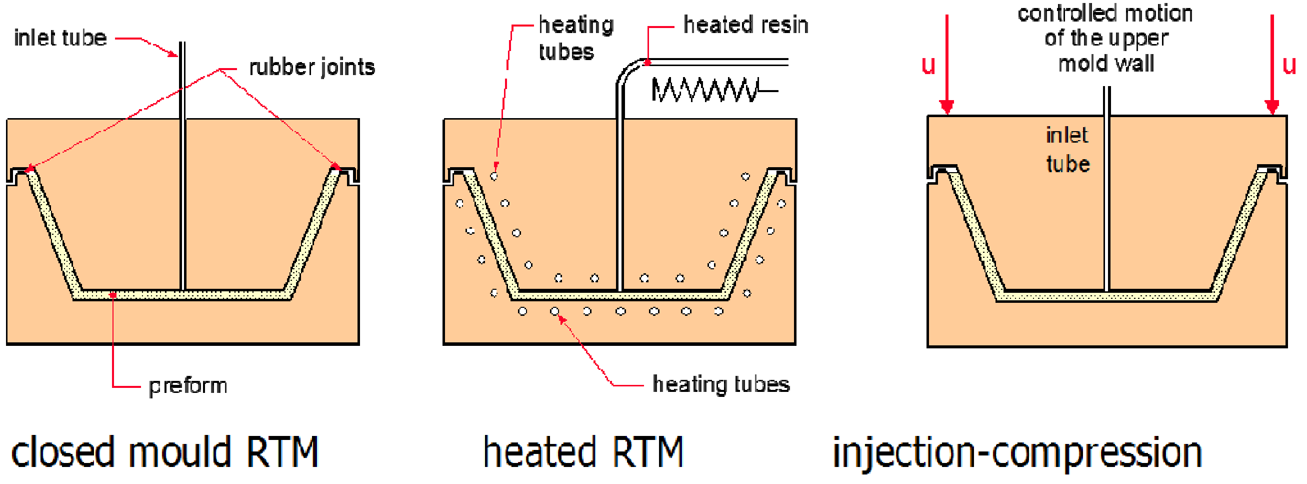


- Low viscosity resins (low ductility/impact properties)
- Less control over fibres and V_f
- Parts integration is possible

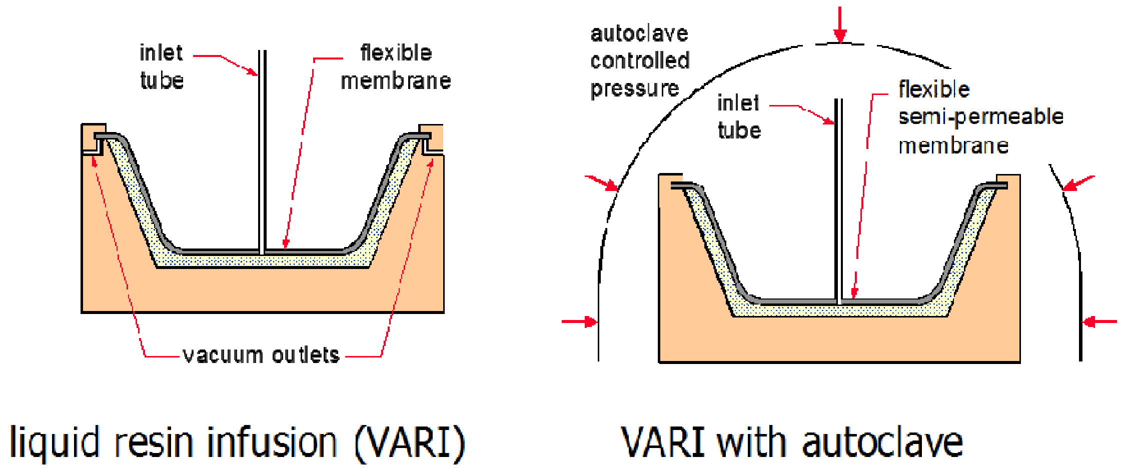
Types of infusion

- For small to medium parts
- High quality
- Relatively fast production

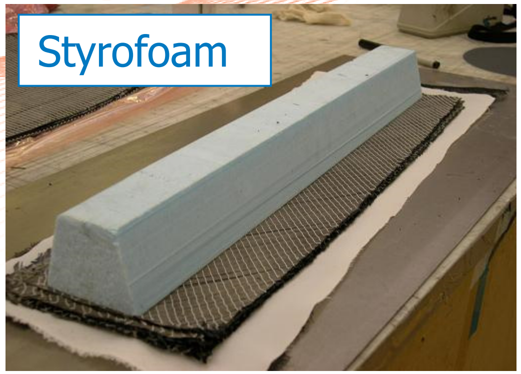


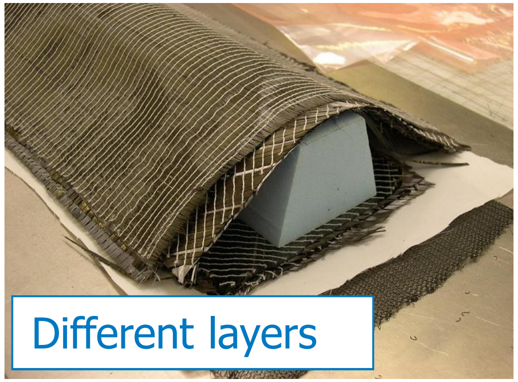
- Large parts
- Fast infusion with flow media

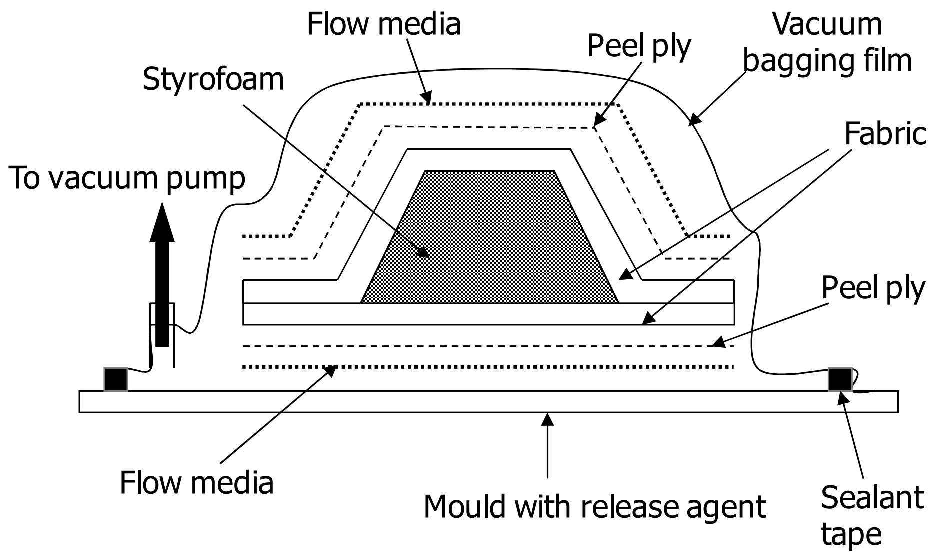
INFUCOMP

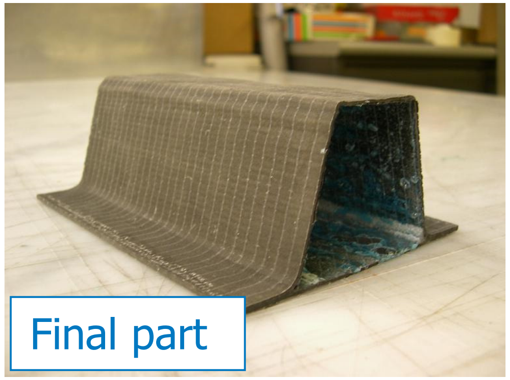


VARI – Experimental setup



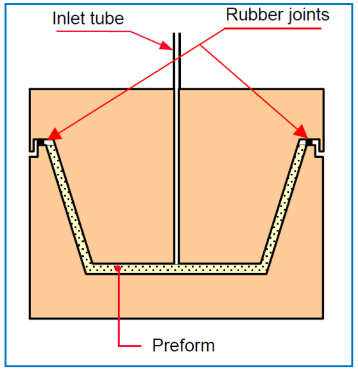




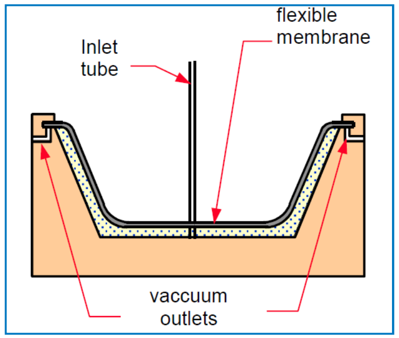


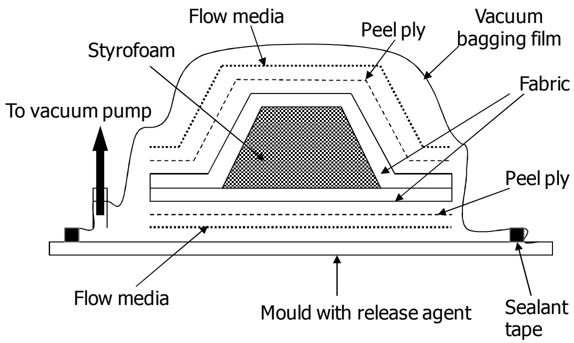
RTM versus LRI infusion

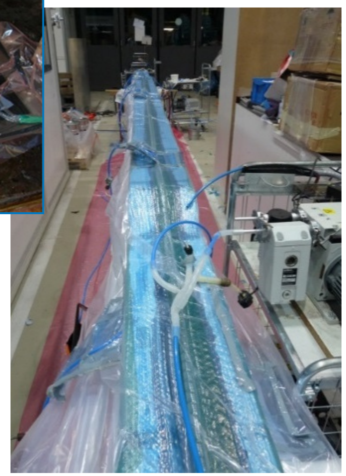
Resin Transfer Moulding (RTM)



Liquid Resin Infusion (LRI)

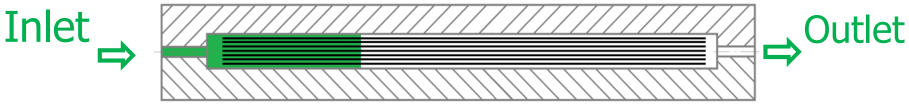






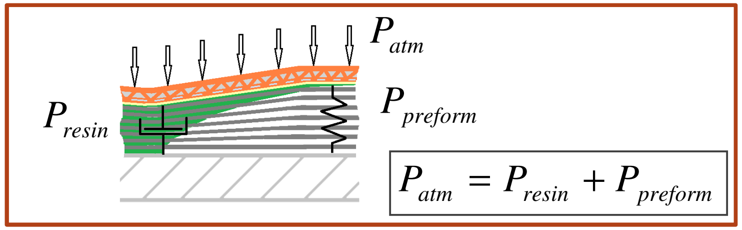
Flow processes in RTM and LRI

1. Resin Transfer Moulding (RTM)

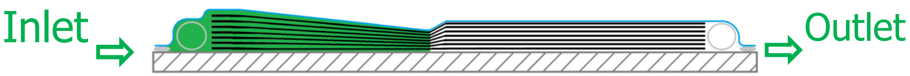


- Tooling constrains fabric
  - Constant permeability
  - Constant Fibre Volume ratio
  - 2D resin flow

2. Liquid Resin Infusion (LRI)

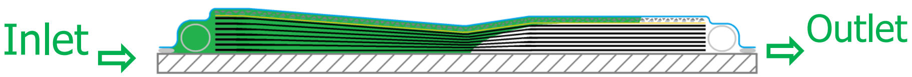


2a. LRI without flow media



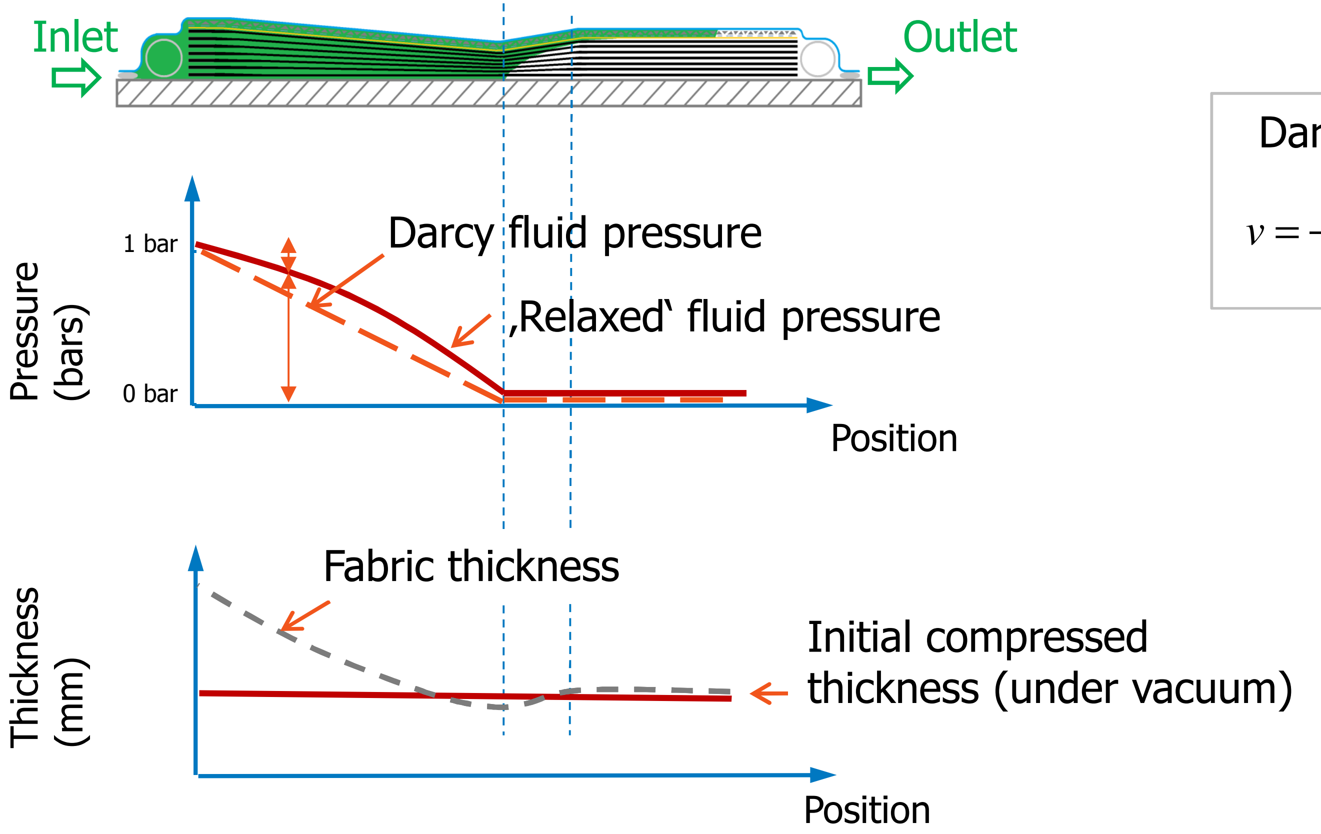
- Variable compaction gives non-uniform permeability and V_f
- 2D resin flow

2b. LRI with flow media



- Flow media gives fast surface flow and infusion through-the-thickness
- 3D resin flow

Pressure and thickness variations in LRI

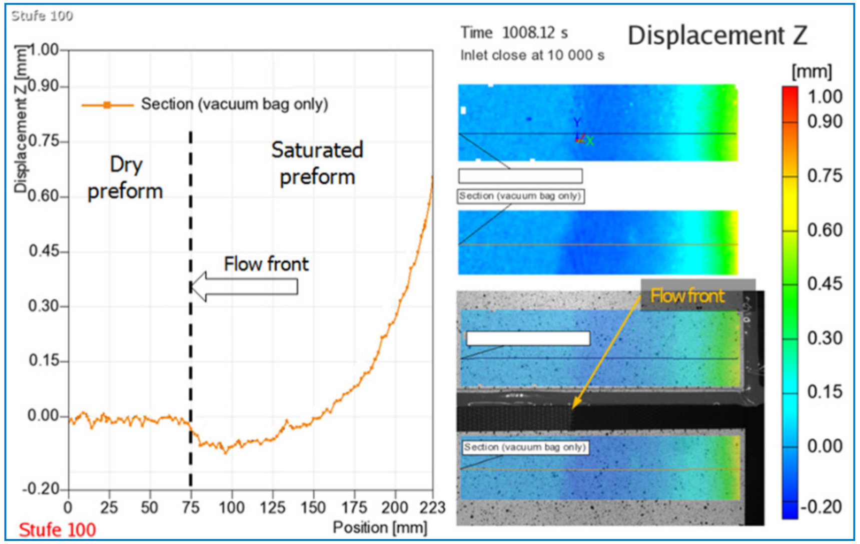


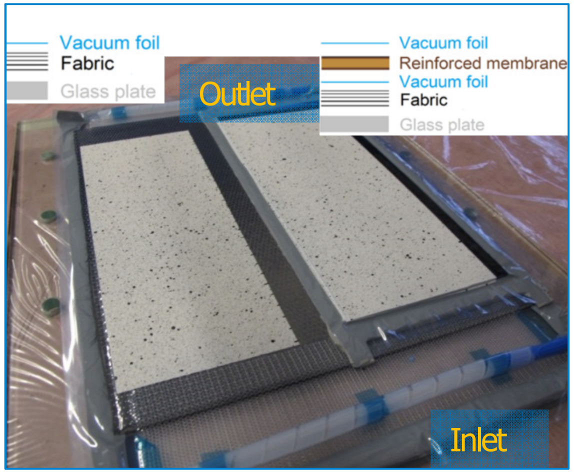
Darcy law

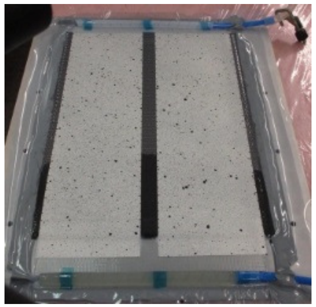
$$v = -\frac{K}{\mu} \cdot \frac{\partial P}{\partial x}$$

Preform thickness changes during resin infusion

GOM Aramis system with two cameras





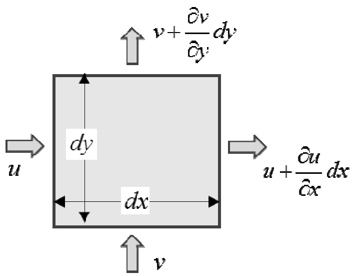


RTM and LRI basic theory for analysis

Resin Transfer Moulding (RTM)

Darcy law: $v = -\frac{K}{\mu} \cdot \frac{\partial P}{\partial x}$

Mass conservation (Continuity) equation:

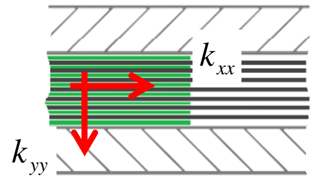


$\nabla \cdot (\mathbf{v}) = 0$

For transient steady state (no mass effect)

$$\boxed{\frac{\partial \cdot}{\partial x}\left(\frac{K}{\mu} \cdot \frac{\partial P}{\partial x}\right) = 0}$$

$$\boxed{[C]\{P\} = \{b\}}$$

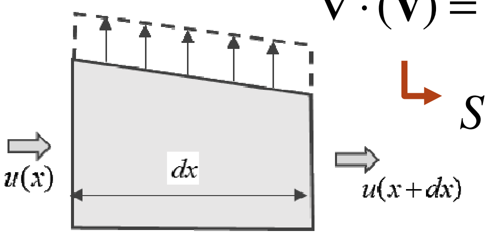


For 1D $K = k_{xx}$

For 2D $K = \begin{bmatrix} k_{xx} & 0 \\ 0 & k_{yy} \end{bmatrix}$

Liquid Resin Infusion (LRI)

Mass conservation:

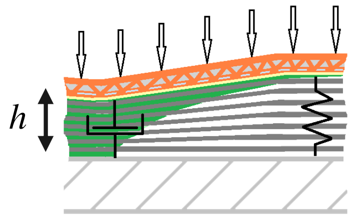


$\nabla \cdot (\mathbf{v}) = S$

$S = \frac{dh}{dt}$

$$\frac{\partial \cdot}{\partial x}\left(\frac{K}{\mu} \cdot \frac{\partial P}{\partial x}\right) = S$$

$$\boxed{[C]\{P\} = \{b\} + \{s\}}$$



For 1D $K = k_{xx}(V_f)$

For 2D $K = \begin{bmatrix} k_{xx}(V_f) & 0 \\ 0 & k_{yy}(V_f) \end{bmatrix}$

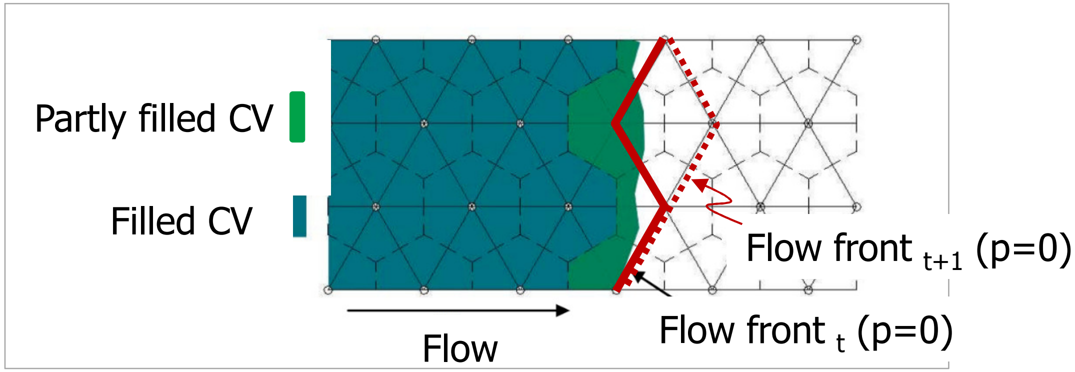
where $V_f = f$(Pressure)

We need:
- V_f versus Pressure
- k_{xx}, k_{yy} versus Pressure

Finite Element solutions (Control Volumes)

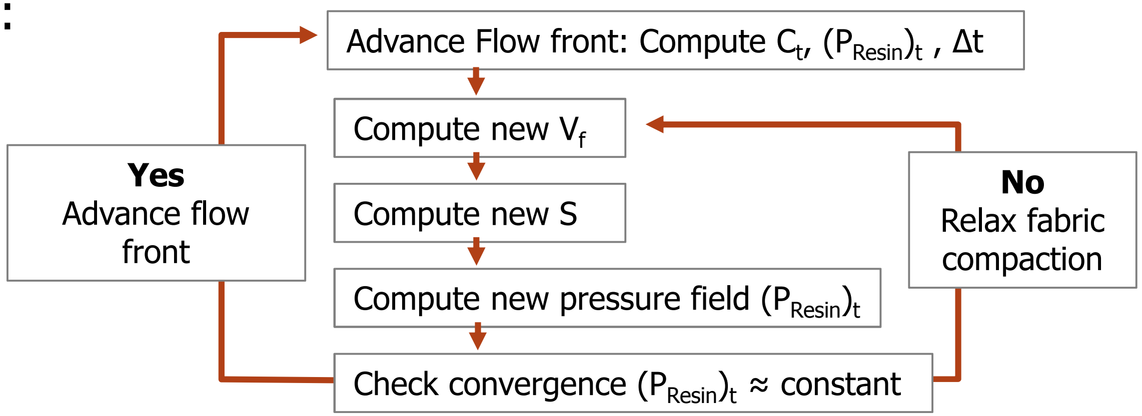
RTM and LRI solutions:

- The FE mesh
- Control Volumes (CV)
- Implicit time stepping solution to progressively fill CV 's



And specific to LRI problems:

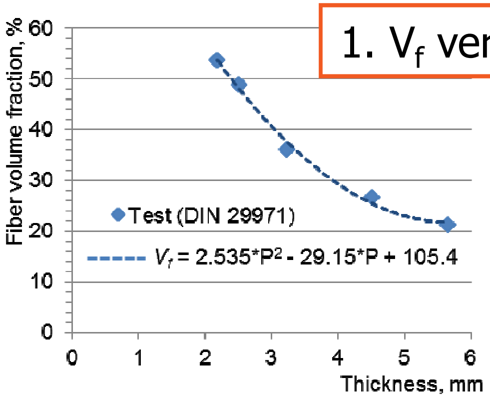
- At each timestep the fabric relaxes; K and P_{Resin} are not known
- An iterative solution to converge P_{Resin} (or fabric thickness) is required

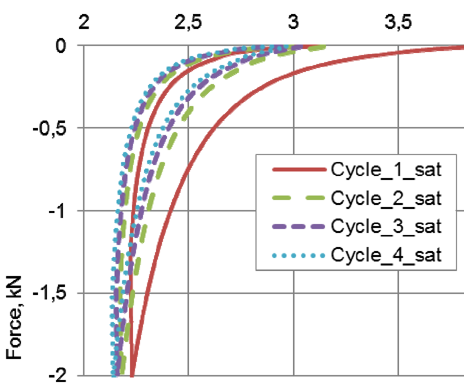


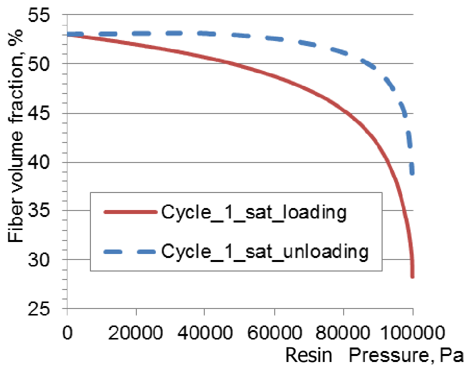
Materials properties needed for LRI analysis

We need:
- V_f versus Pressure
- k_{xx}, k_{yy} versus Pressure

1. V_f versus pressure

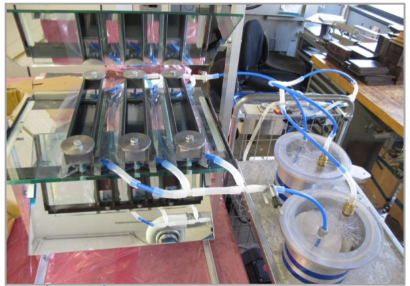


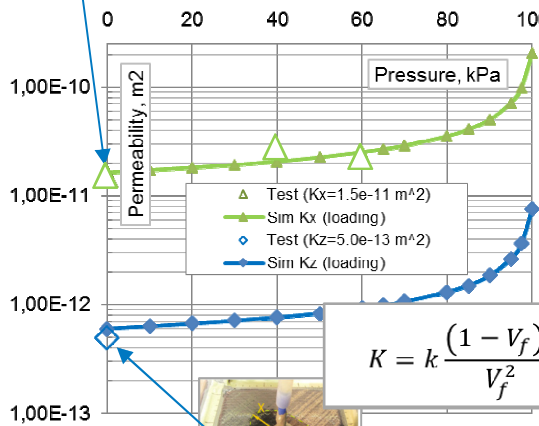




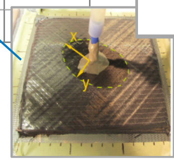
2. Viscosity: Assumed manufacturers data

3. Permeability versus pressure



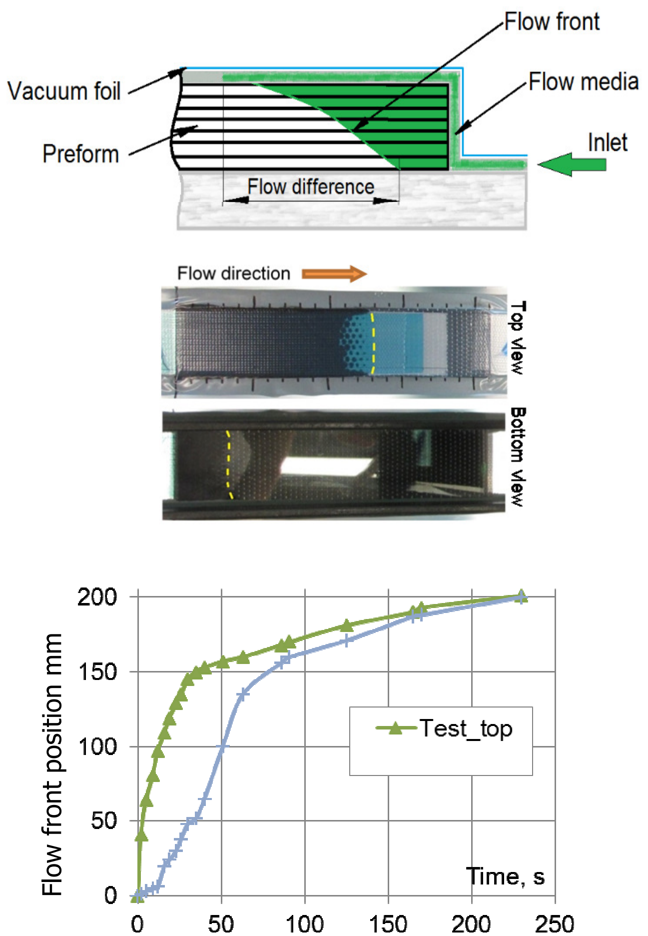


$$K = k\,\frac{(1 - V_f)^3}{V_f^2}$$

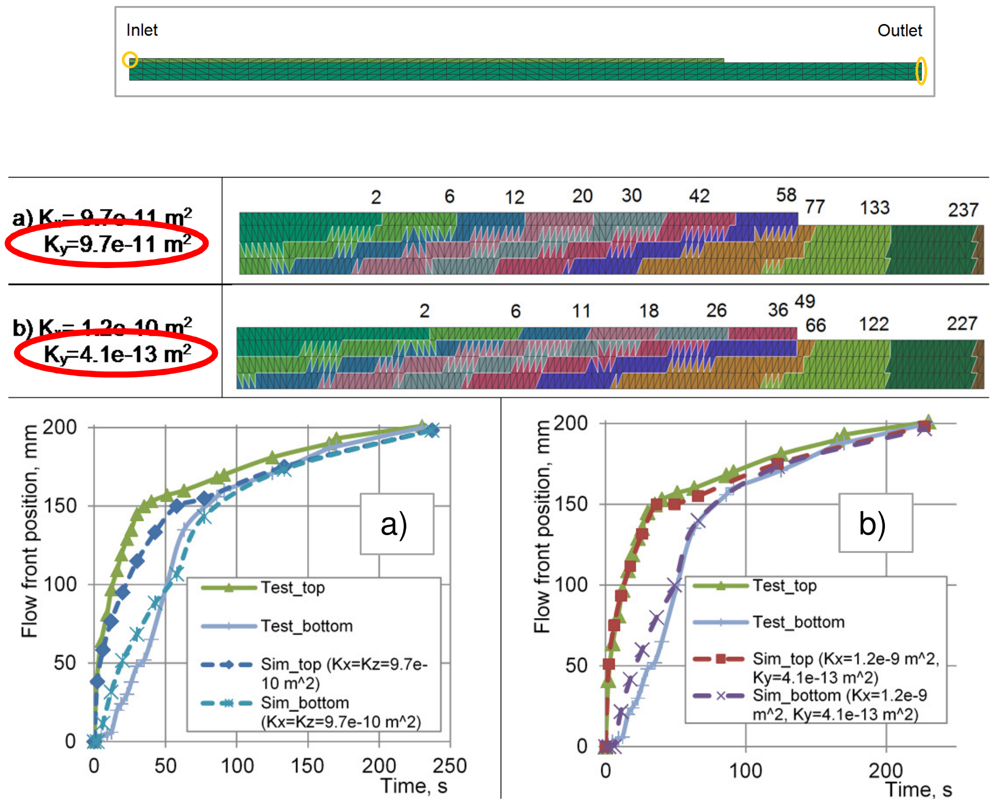


Kozeny-Carman

Orthotropic flow media and separation plies



Test measurements

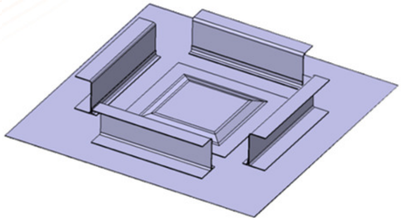


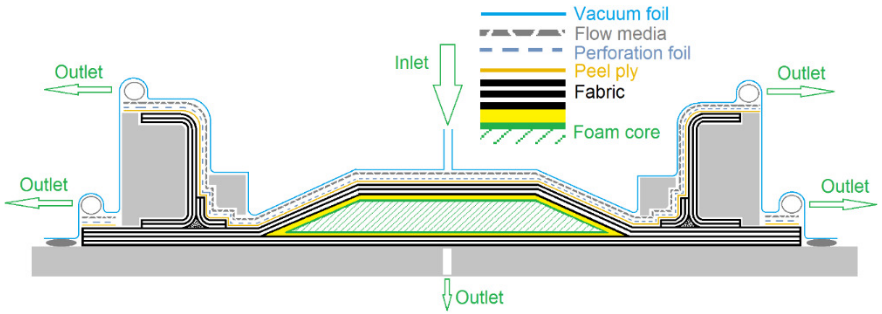
Comparison test and simulation

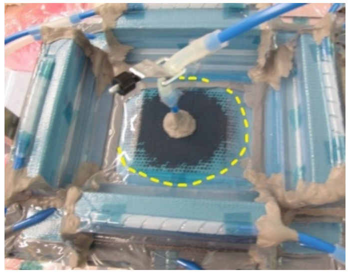
Test details and example infusion

Demonstration module:

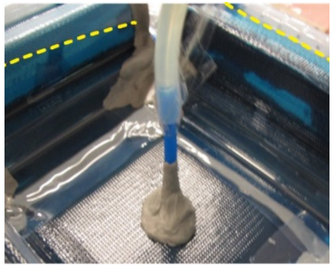
- Consists of four C-Spars molded to an outer skin
- Central panel portion has a sandwich (foam) construction



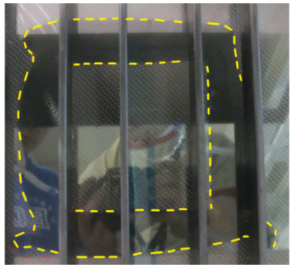




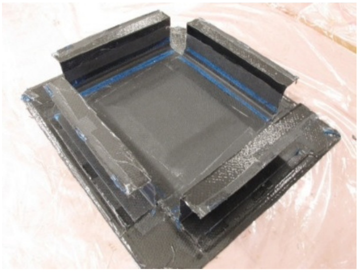
17 sec



224 sec



311 sec



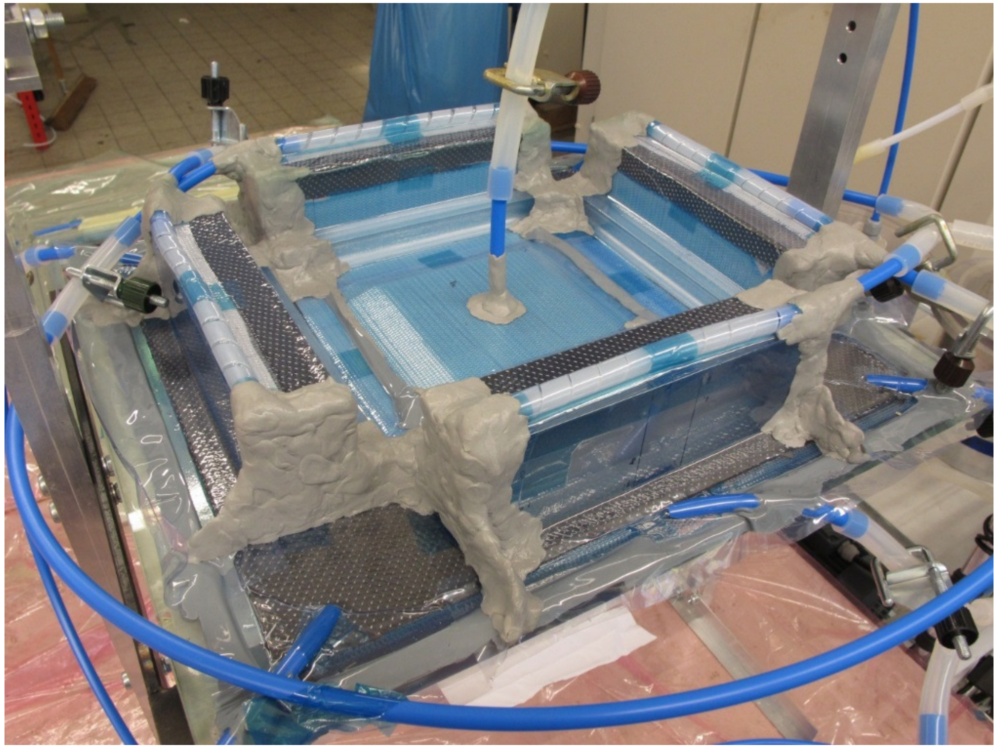
Final

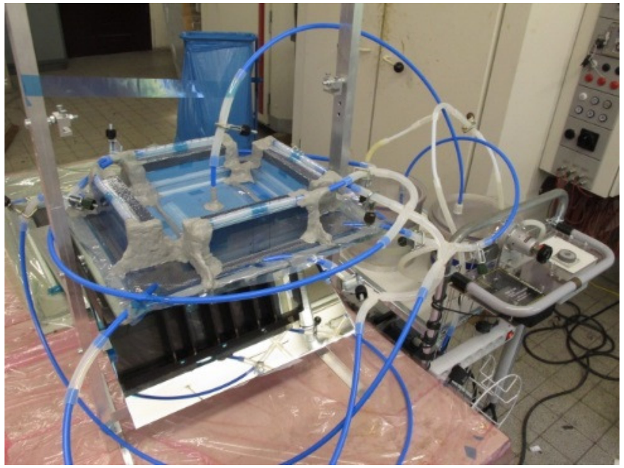
Courtesy Piagio Aerospace and IFB

Test details and example infusion

Demonstration module :

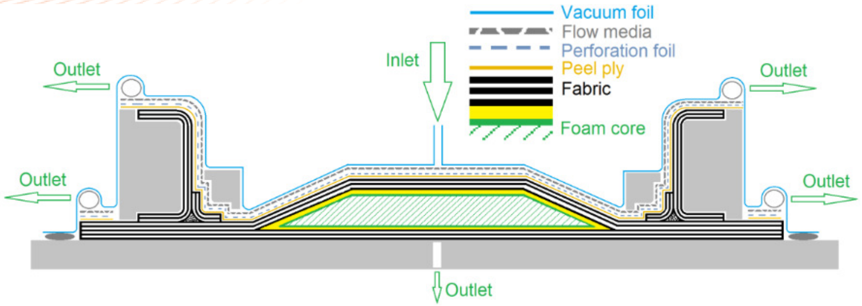
- Consists of four C-Spars molded to an outer skin
- Central panel portion has a sandwich (foam) construction

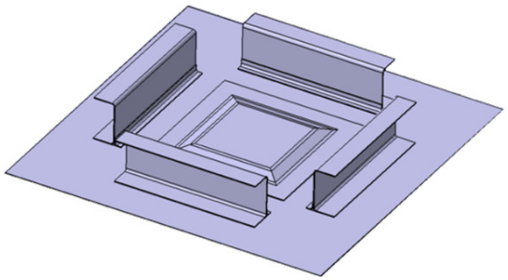


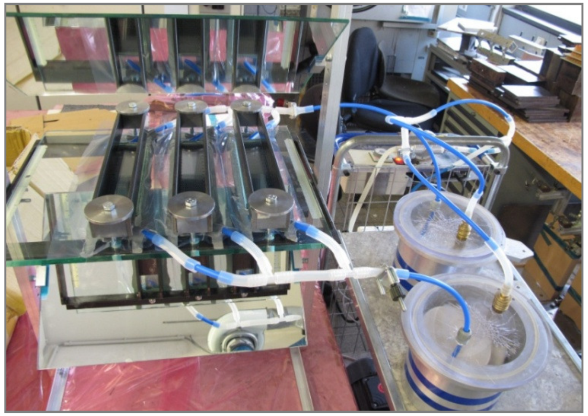


Courtesy Piagio Aerospace and IFB

Other testing work for the demonstrator



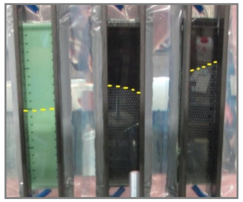


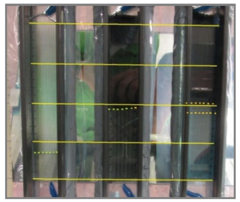


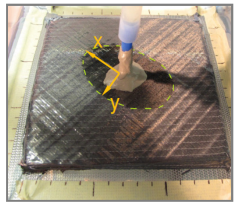
Other permeability measurements:

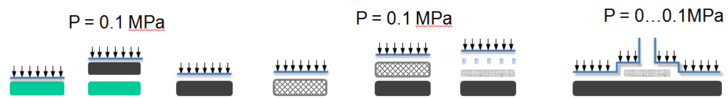
- Sandwich core interface
- Flow media permeability
- Through thickness permeability

Foam-fabric interface			Flow media			Fabric through-thickness



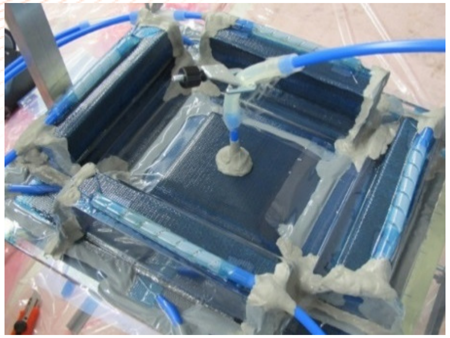






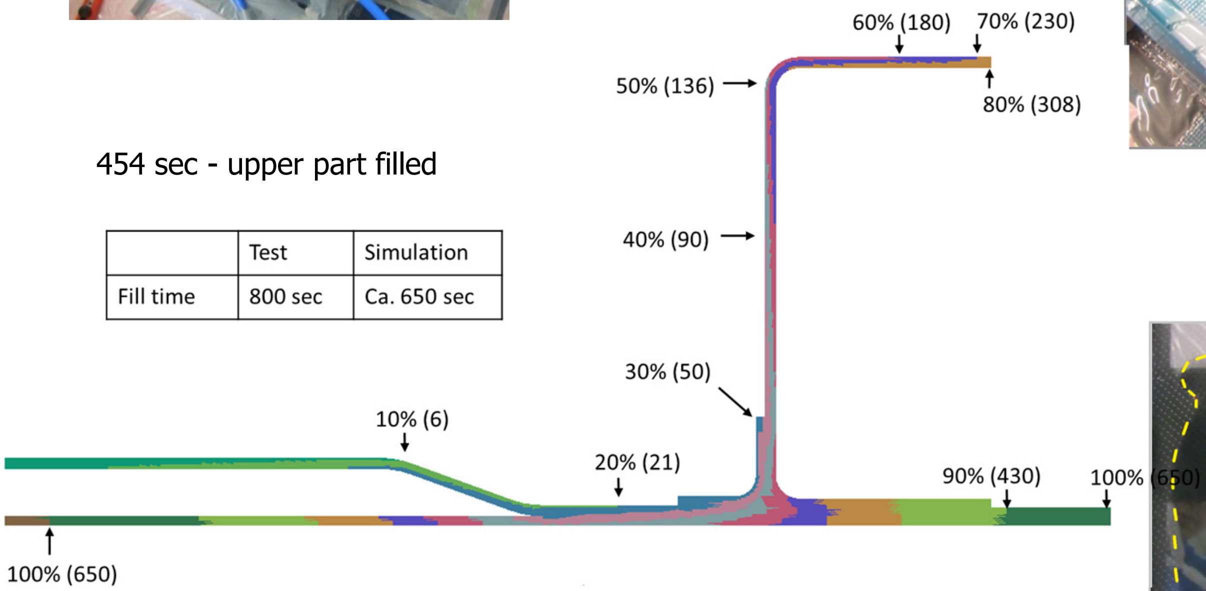
7.1E-11	**3.7E-11**	2.3E-11	8.0E-10	3.5E-10	**4.1E-10**	**K_z=5.0E-13**
Estimated permeability, m^2						
In-plane						Through-thickness

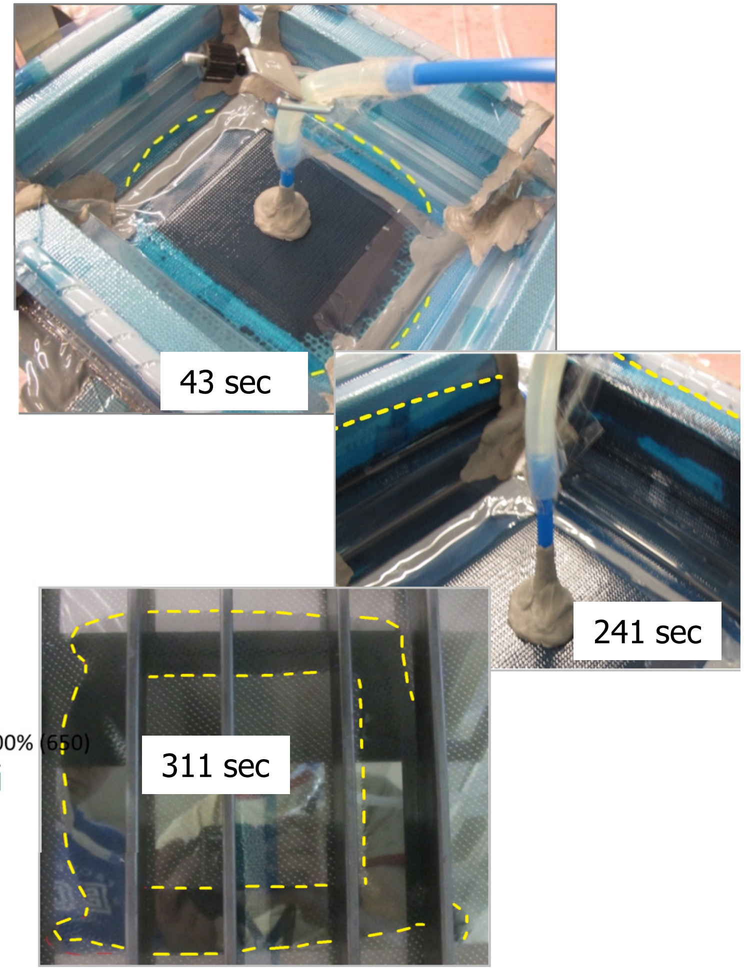
2D analysis with ‚full‛ flow media covering



454 sec - upper part filled

	Test	Simulation
Fill time	800 sec	Ca. 650 sec





INFUCOMP project: Acknowledgement and partners

Title: Simulation based solutions for industrial manufacture of large infusion composite parts

Four years: 2009–2013

http://www.esi-group.com/corporate/alliances/projects/infucomp/infucomp

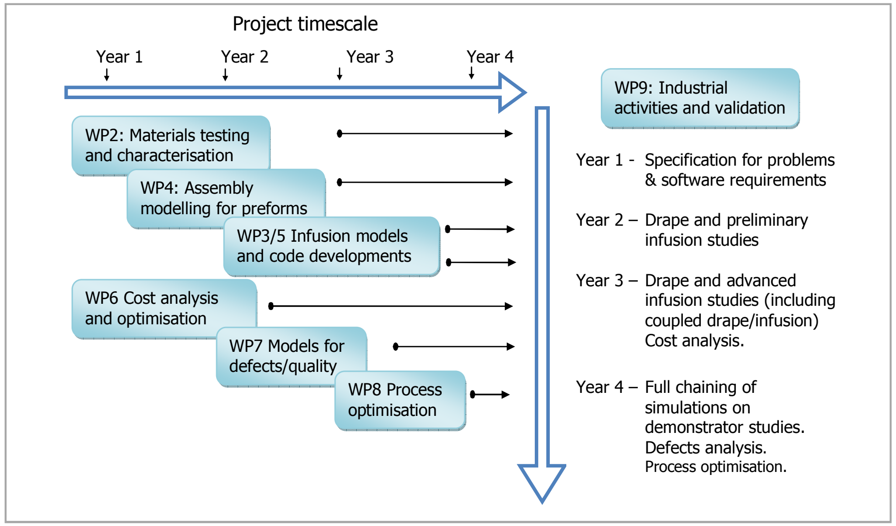
	Name	Activity
1 co-ord.	ESI GmbH	Coordination and software development
2	ARMINES	Resin infusion modelling
3	University Cranfield	Resin viscosity modelling / optimisation
4	DAHER Aerospace	Industrial demonstrator studies
5	ESI Group	Software development
6	Hexcel	Materials supplier (infusion characterisation)
7	Katholieke Universiteit Leuven	Fabrics testing and characterisation
8	University Patras	Cost analysis of infusion processes
9	Swerea SICOMP AB	Fabric testing and characterisation / residual stresses
10	Bombardier Aerospace	Industrial demonstrator studies
11	Israel Aerospace Industries Ltd	Industrial demonstrator studies
12	INASCO	Infusion sensor and monitoring
13	Institute for Aircraft Design	Preforming modelling and links to infusion
14	Piaggio Aero Industries S.p.A.	Industrial demonstrator studies

INFUCOMP: Some main activities

Testing: Fabrics and resins	• Shear and compaction for 5 identified fabrics • Resin viscosity for 2 resins • New (air) test for permeability
Constitutive models	• New fabric models (shear, bending, thickness…) • New resin (viscosity) model • Numerical model for permeability
Infusion code (PAM-RTM)	• Single processor to multi-processor architecture • Specific tools for ‚fast' meshing
Cost modelling	• For various industrial demonstrator parts • Optimisation of costs with respect to manufacturing
Residual stresses	• Prediction models for selected project composites • Surface finish
Optimisation	• Of process conditions on part time and quality
Demonstrators	• Stringer and skin assemblies • Belly fairing structures • Main spars } Preforming and infusion

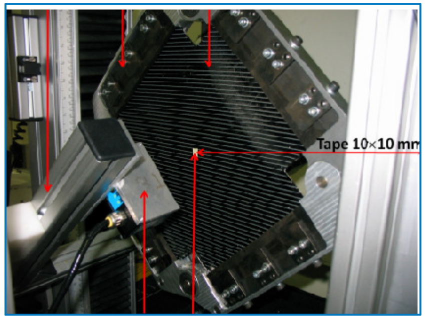
Some main activities in INFUCOMP

- Materials Chracterisation: Fabrics, Resin viscosity, Permeability, Flow media
- Software: DMP version, Coupled Stokes-Darcy, Meshing tools
- Cost analysis
- Optimisation: Cost, quality, defects…
- Residual stresses
- Industrial demonstrators



Some material tests

Frame Grips Sample



Laser sensor Laser spot

In-situ thickness laser measurements on picture frame (KU Leuven)

Instron load cell

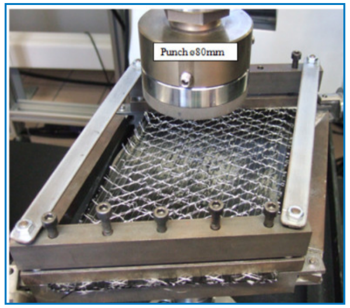
Upper loaded glass plate

Lower glass plate

DIC camara

- Yarn compressibility testing (KU Leuven)

- IFB Fabric compaction
- Hexcel compaction with shear



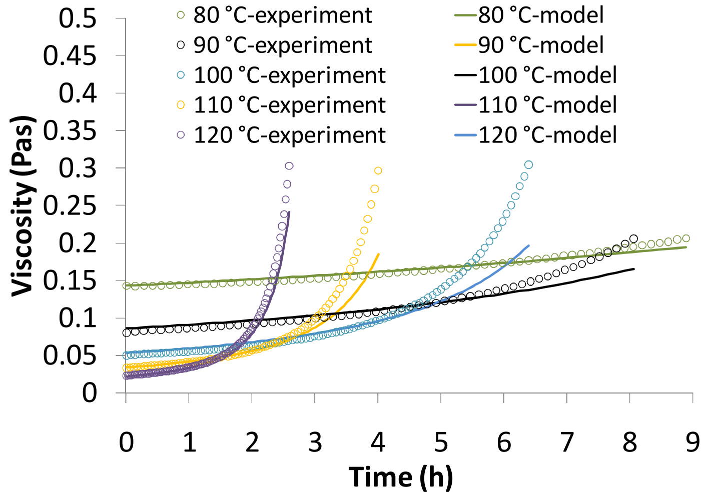
Courtesy IFB, Hexcel and KU Leuven (INFUCOMP)

Viscosity modelling: New tests and analytical model

Previous viscosity models (used temperature and degree of cure)

$$\mu(T,\alpha) = A \cdot \exp\left(\frac{B}{T} + \kappa \cdot \alpha\right)$$

- Up to 14 parameters for model fitting
- Good for long duration description (e.g autoclaving)
- Poor for short term description (e.g. infusion)



The new model viscosity model:

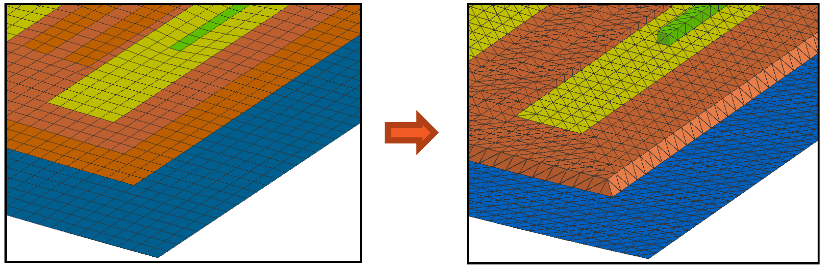
$$\frac{d \ln \eta_o}{dt} = A e^{-E/RT} \left(\ln \frac{\eta_o}{\gamma} \right)^m \qquad \eta = \eta_o e^{D\left(\frac{1}{T} - \frac{1}{T_o}\right)}$$

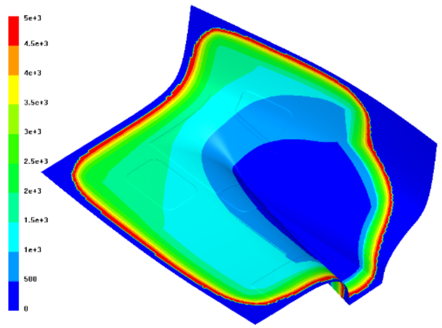
- Single state variable (ref viscosity) and 5 parameters
- Simplified test program
- Accurate for short term viscosity changes (infusion)
- Validated for two resin and general temperature cycles

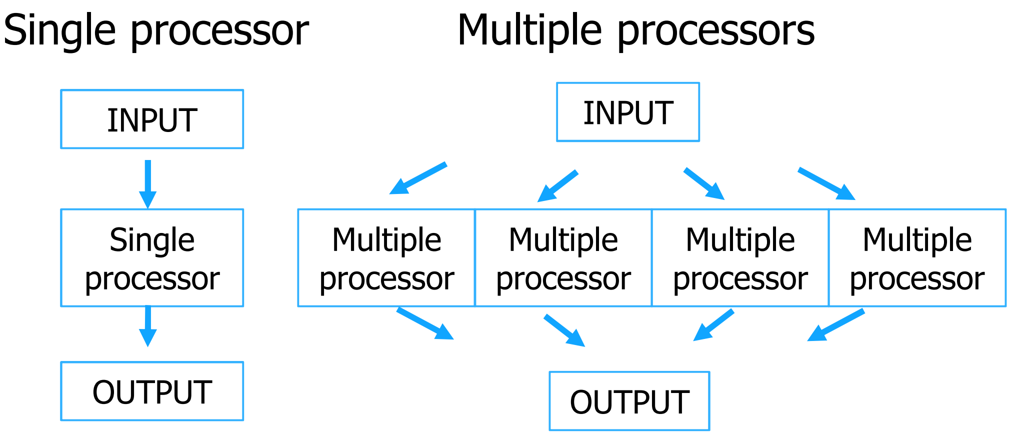
Courtesy Cranfield University (INFUCOMP)

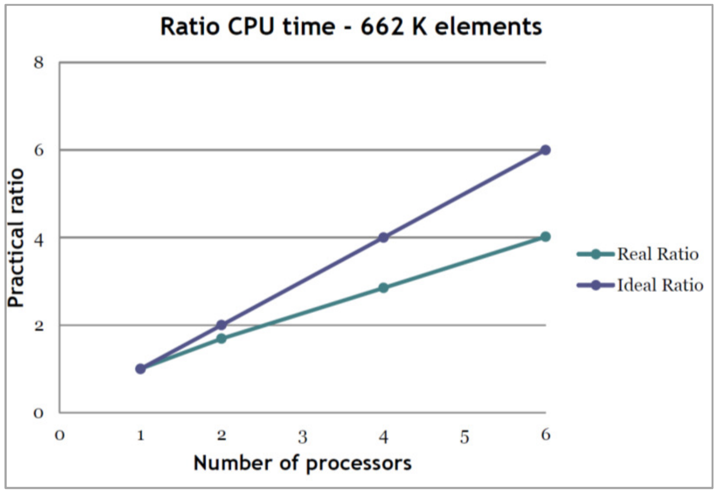
Single processor versus DMP code architecture

Moving from 2D shell to 3D solids requiring 10^6+ elements:



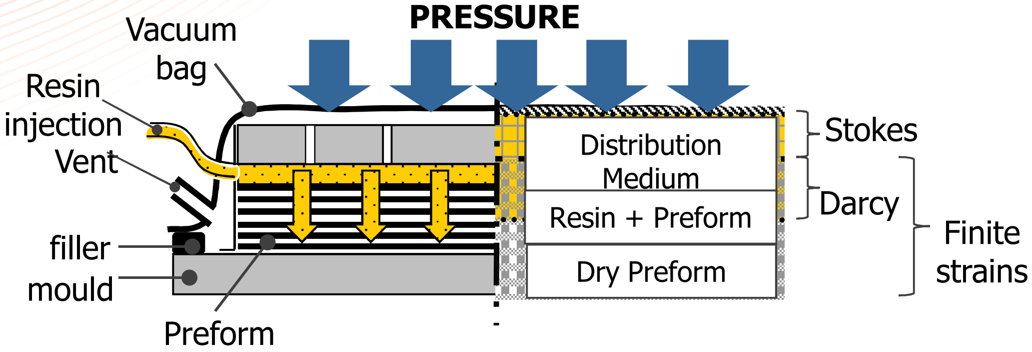


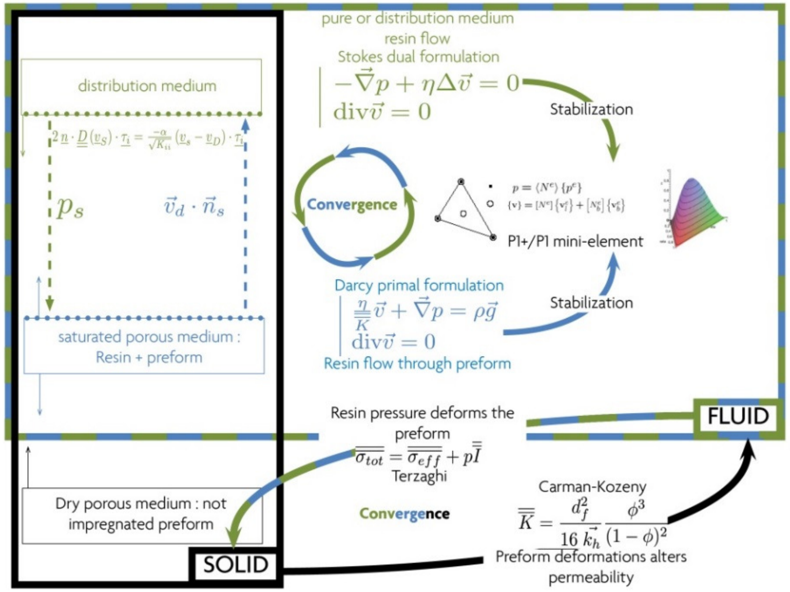




Courtesy ESI (INFUCOMP)

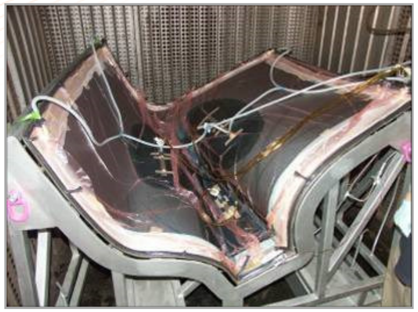
Coupled Stokes-Darcy flow





Courtesy ESI Group and ARMINES (INFUCOMP)

Some industrial parts in INFUCOMP

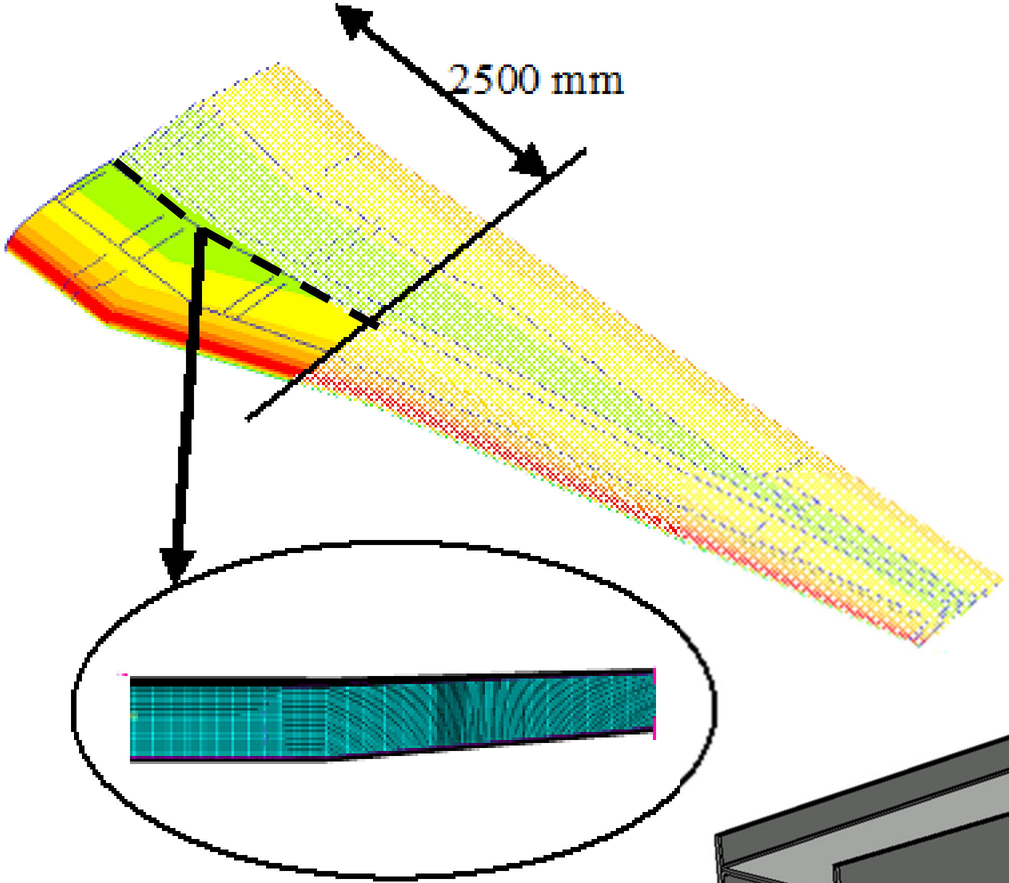


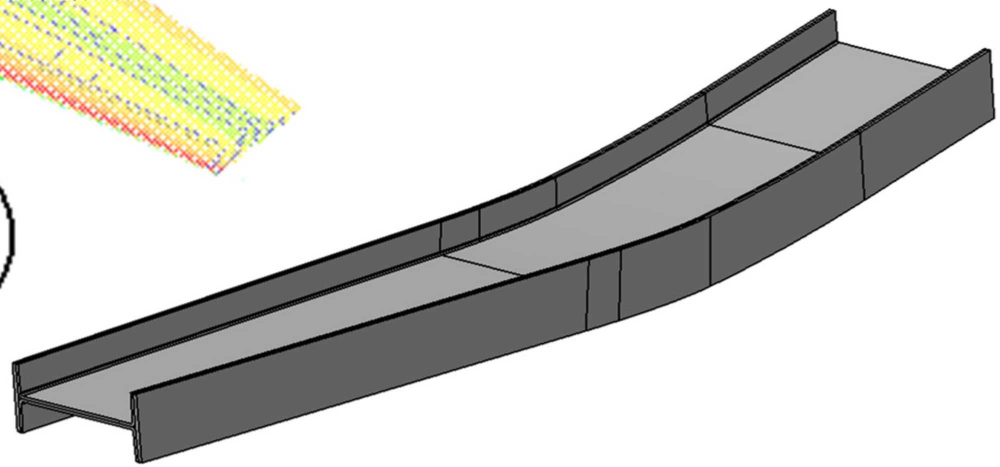
1. IAI - G250 Aft Wing/Fuselage Fairing-Monolithic NCF
2. Bombardier integrated stringer/skin and
3. Daher main spars

Courtesy IAI and Bombardier Aerospace (INFUCOMP)

Large scale demonstrator

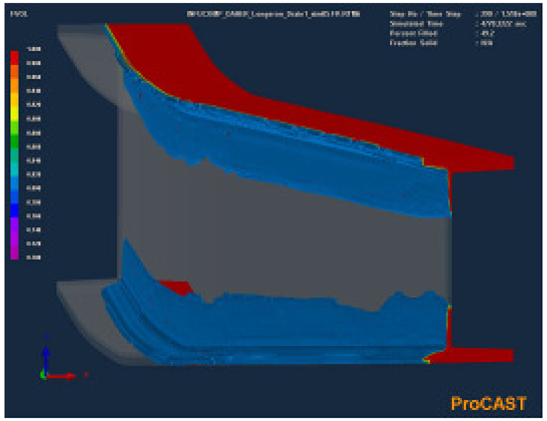
- Demonstrator of wing box main spar's business jet (landing gear box area)
- Proprietary DAHER-SOCATA wing box spar design

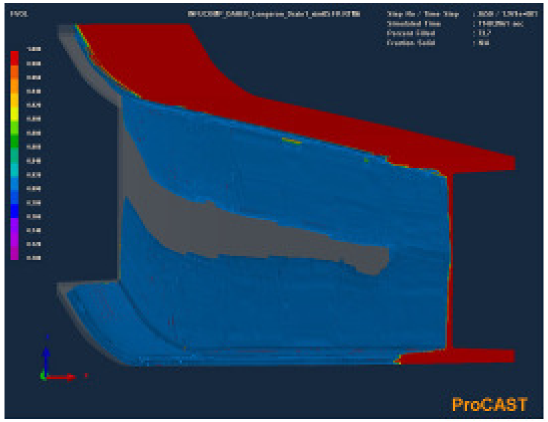


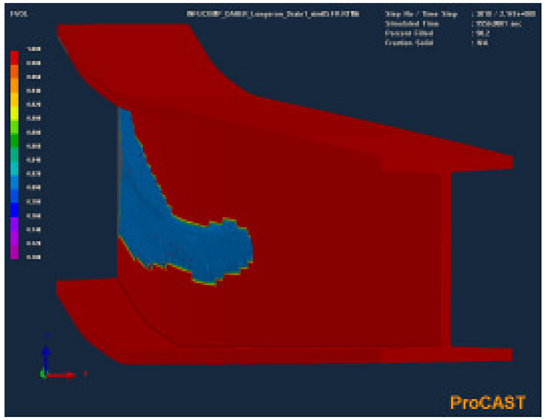


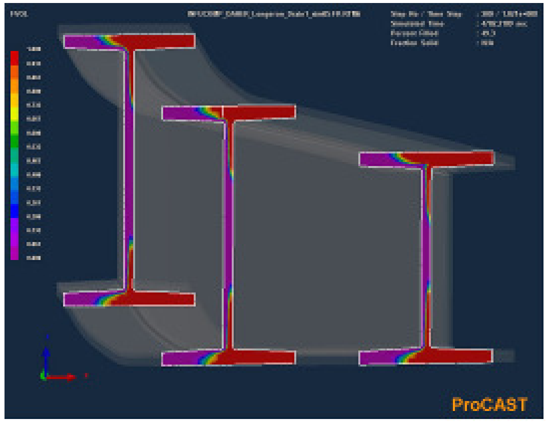
Main Spar simulation results

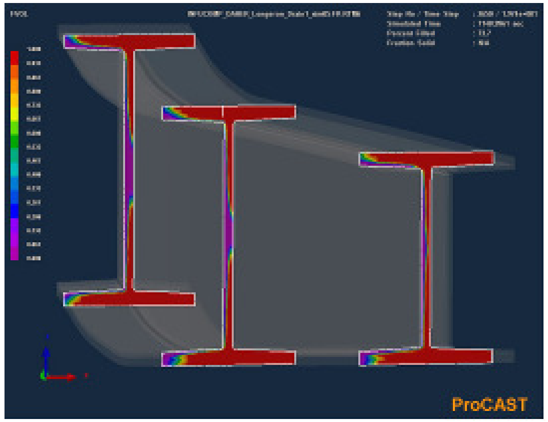
Typical simulation results:

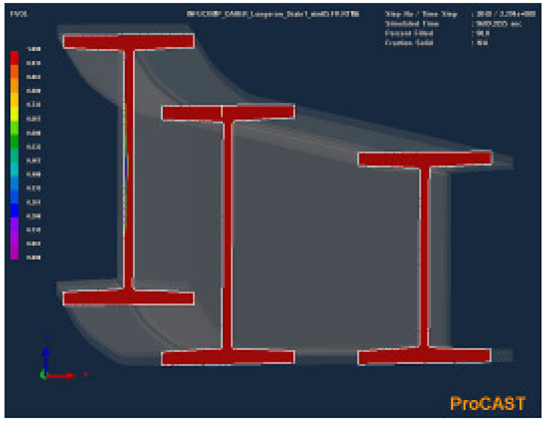




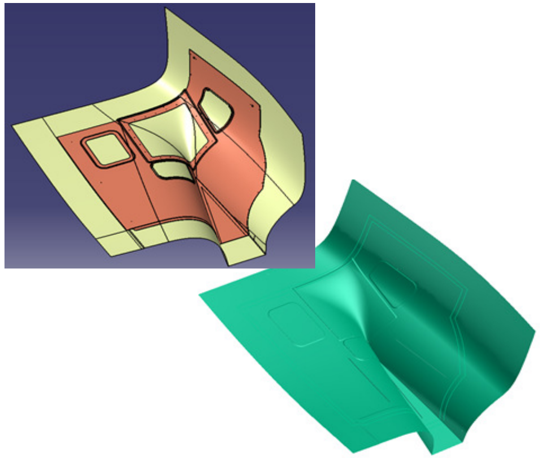


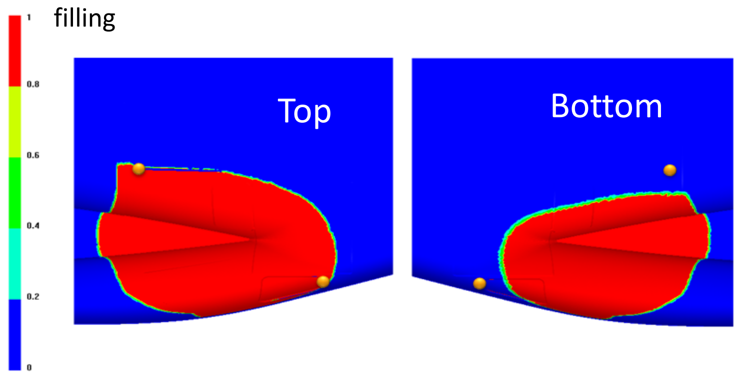


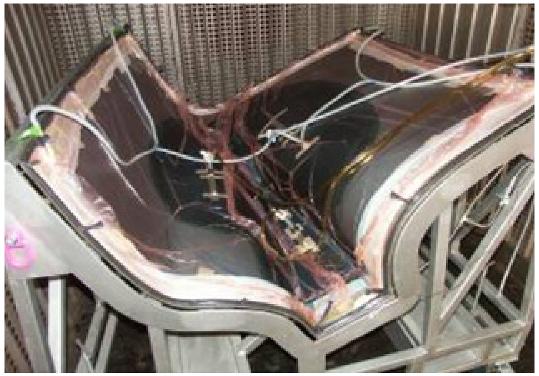


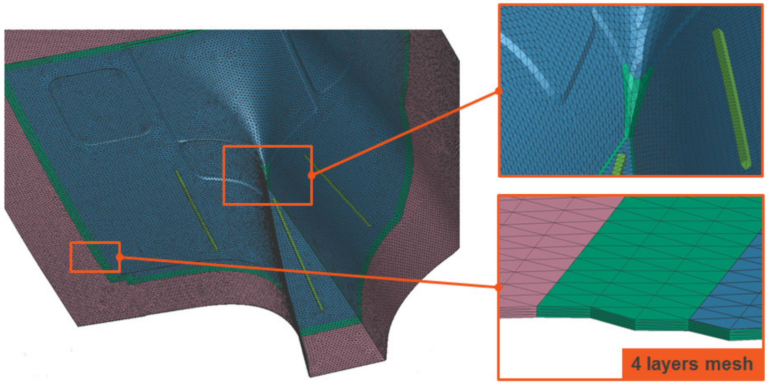


An example study (fuselage fairing)





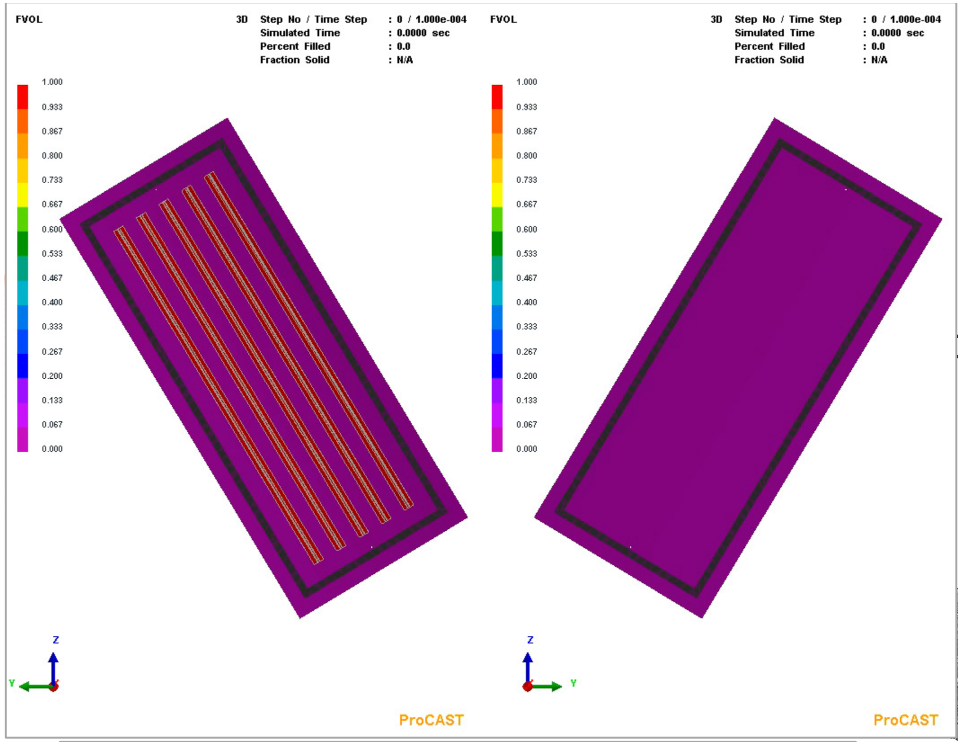




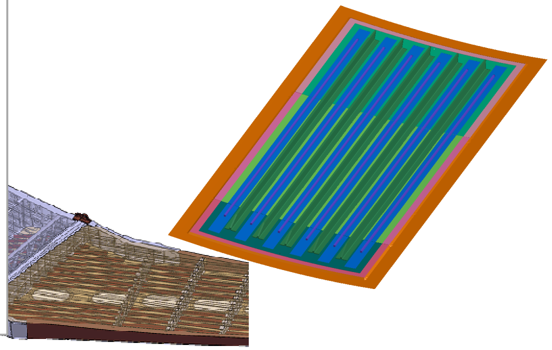
Parameter	
Number of elements	856,203
Filling time	48.5 min
Filling time – Trims extension	62.2 min
Number of CPU	8
CPU time	26 hrs

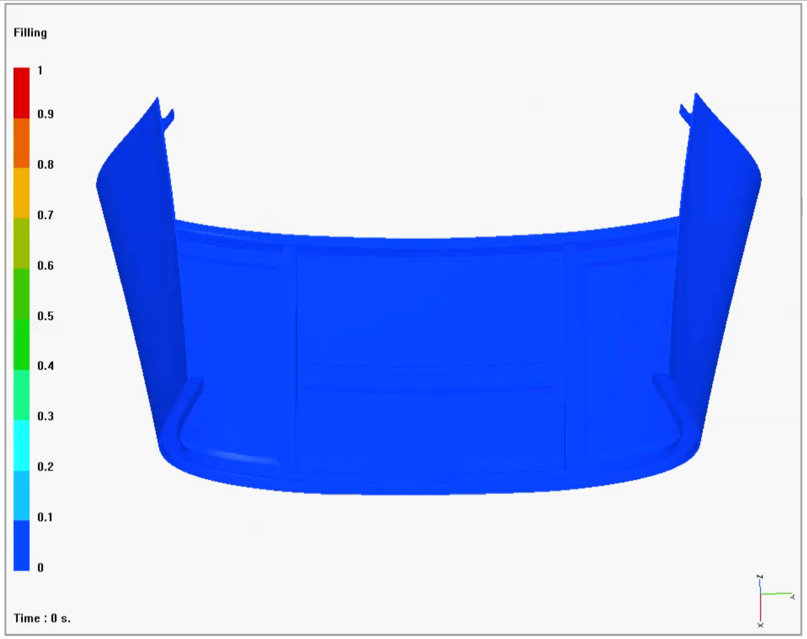
Courtesy IAI and ESI GmbH

Two example parts

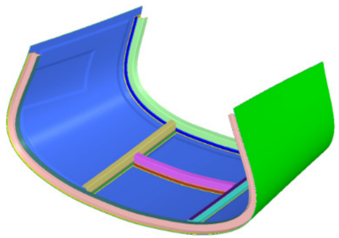


ts (G250 aircraft)





rt (P180 Aventi II aircraft)



Courtesy IAI and Piaggio Aerospace

Conclusions

- Analysis of LRI processes is possible, but accuracy depends on good material tests and chracterisation:
    1. Orthotropic permeability (no standard tests today)
        - For fabrics
        - For flow media and separation plies
    2. Fabric compressibility for Vf versus Pressure (no standard tests today)
    3. Viscosity dependent on temperature and time
- Detailed 3D meshing and analysis (high CPU and modelling effort)
- Knowledge and correct modelling of phenomina such as race tracking, piping systems, interfaces, temperature….

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Thank you

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