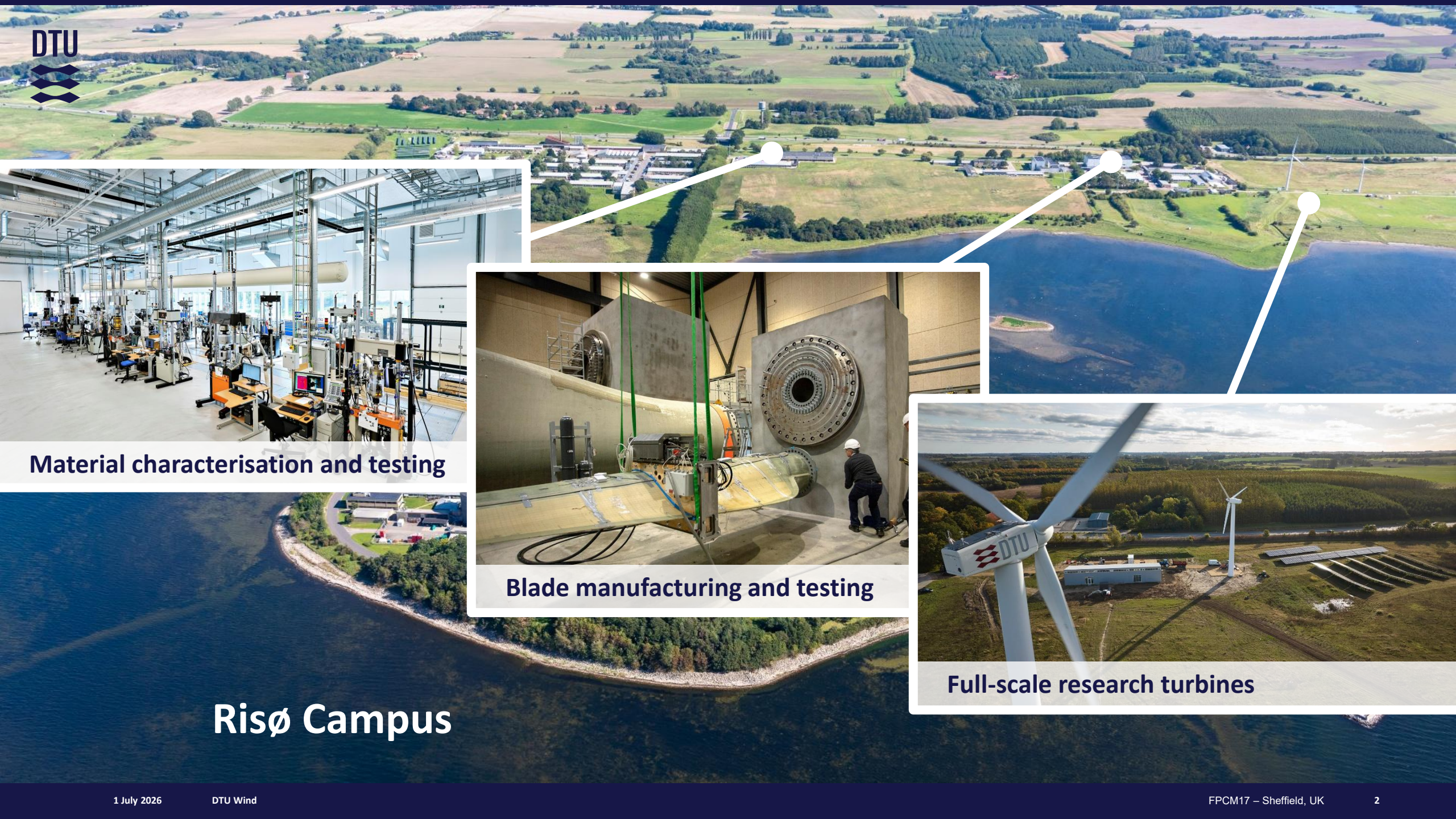


Characterisation and Modelling of Supporting Materials for the Vacuum Assisted Resin Infusion of Wind Turbine Blades

Robert S. Pierce, Lucie M. Laborderie, Maksim Larionov, Philipp Haselbach, and Anthony Fraise

DTU Wind and Energy Systems, Denmark



Material characterisation and testing



Blade manufacturing and testing



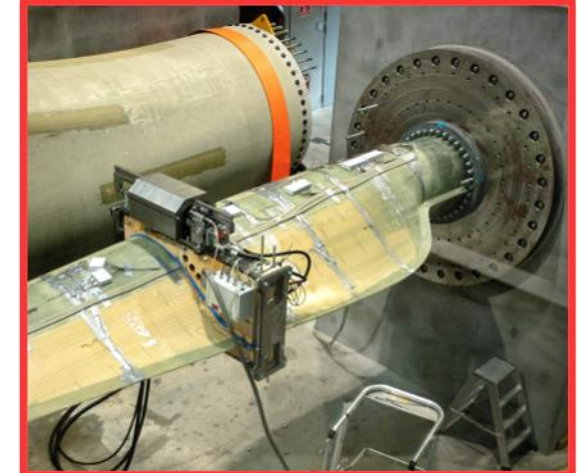
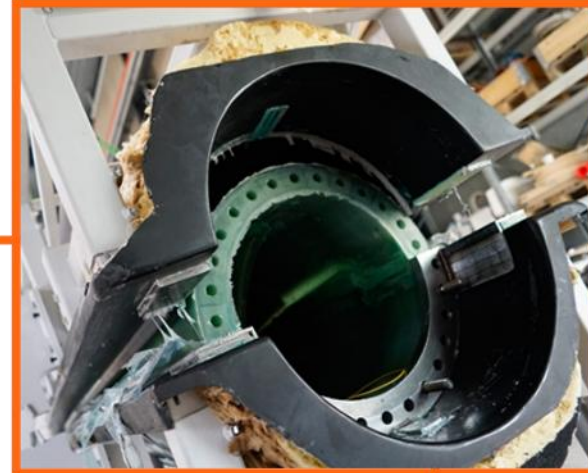
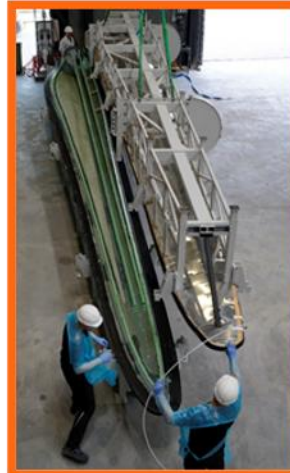
Full-scale research turbines

Risø Campus

Manufacturing wind turbine blades

- Vacuum Assisted Resin Infusion / Vacuum Infusion
- Wide range of materials inside the bag...

Images courtesy of DTU Wind Bladelab



Layup

Infusion

Curing

Finishing

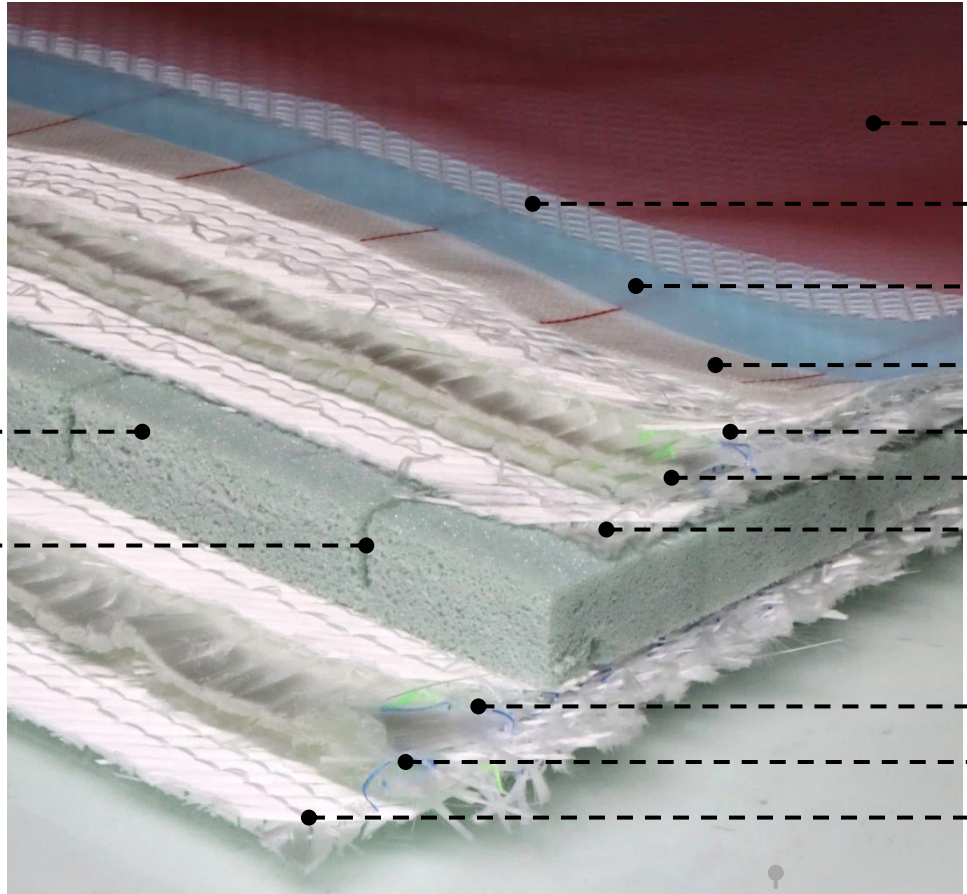
Testing

Common layup of blade materials

Core material

Lightweight foam / balsa

Machined grooves / features



Consumables

Vacuum bag

Distribution media

Perforated release film

Peel ply

Glass fabric reinforcement materials

Tool surface

¹ R.S. Pierce, *IOP Conf. Ser.: Mater. Sci. Eng.*, vol. 1293, 012009, 2023
DOI: 10.1088/1757-899X/1293/1/012009

Permeability of **consumable materials**

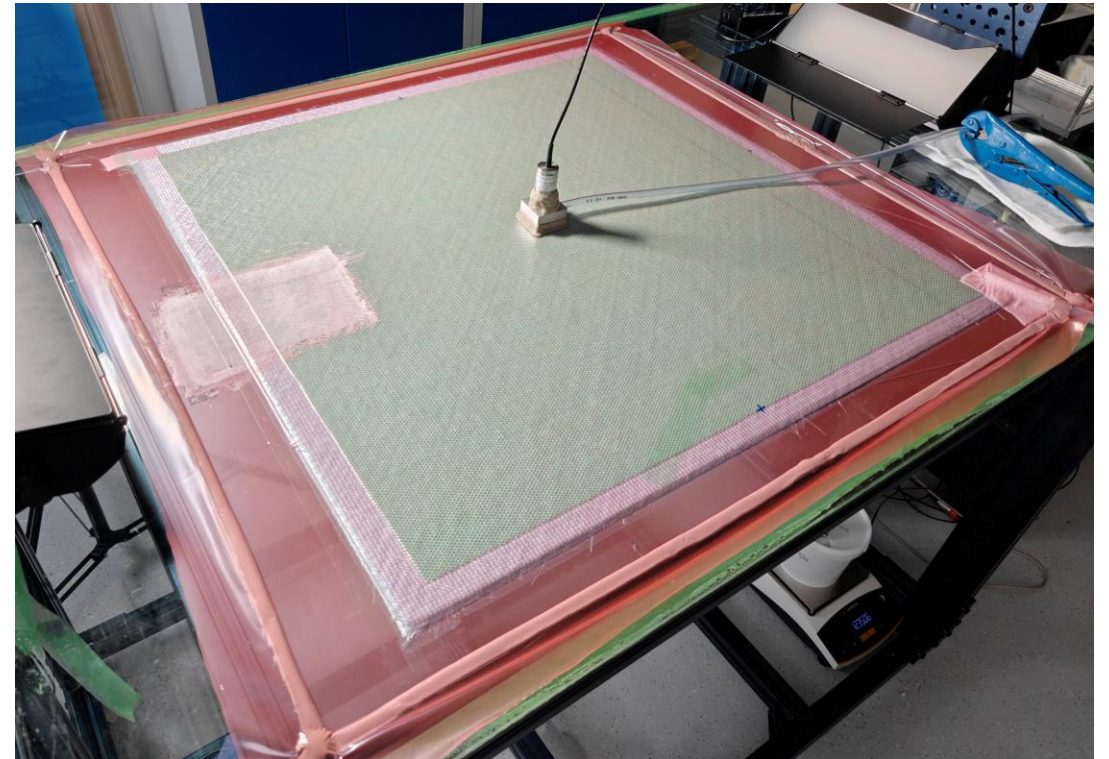
Distribution media: Experimental permeability testing

Problem:

- High permeability, used as a single layer, direct contact with the vacuum bag
- Properties often assumed or inversely estimated

New characterisation method:

- Extends on principles from ISO4410:2023
- Accounts for fabric imprint and bag deformation
- Specifically for distribution media (flow only in the distribution media)
- Simultaneous permeability and porosity determination

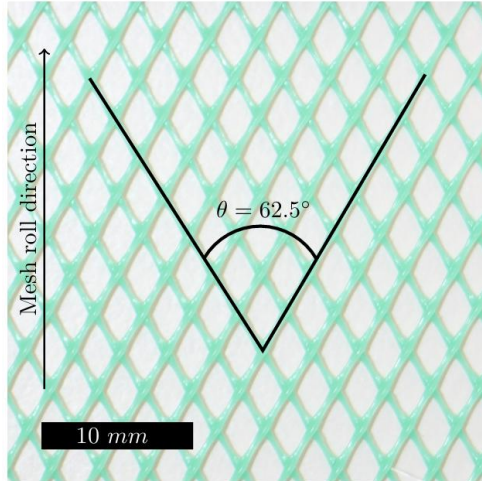


² L. M. Laborderie et al., *IOP Conf. Ser.: Mater. Sci. Eng.*, vol. 1338, 012040, 2025
DOI: 10.1088/1757-899X/1338/1/012040

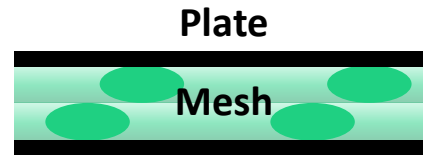
Student work:
Konstantina Gkournelou, Adrien Winther, and Lucie Laborderie

Distribution media: Example study

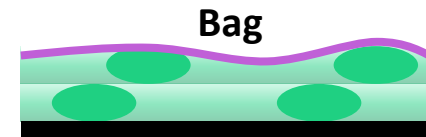
- Investigation of permeability and porosity sensitivity to boundary conditions:



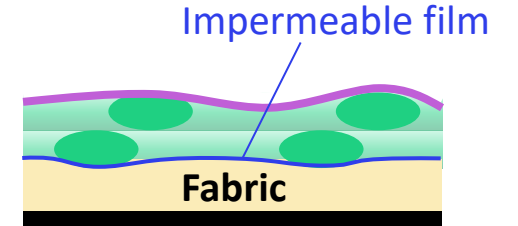
Cell angle $\theta = 62.5^\circ$
 Polymer density $\rho = 910 \text{ kg/m}^3$
 Mesh areal mass $m_A = 0.099 \text{ kg/m}^2$



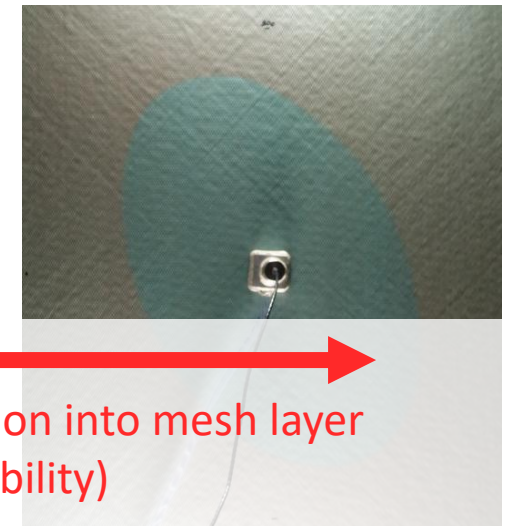
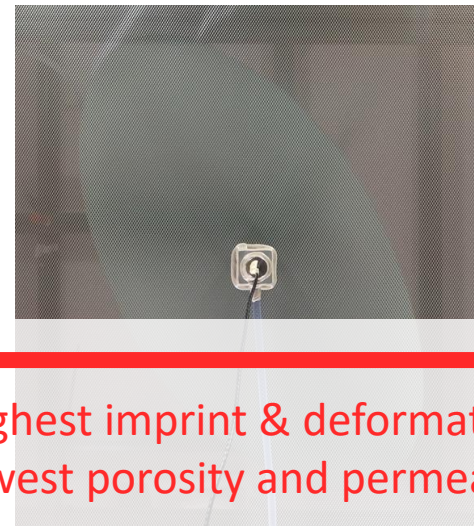
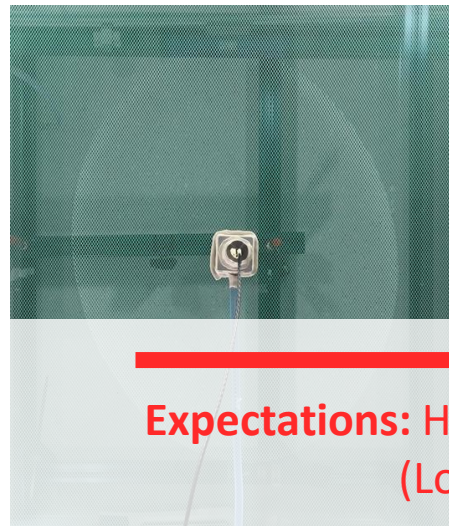
Most similar to ISO4410



Isolates effect of bag deformation



"Realistic" infusion case



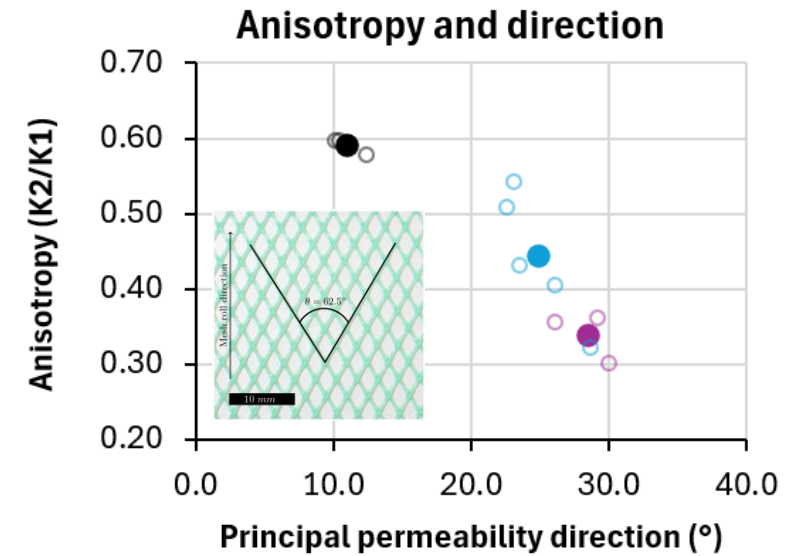
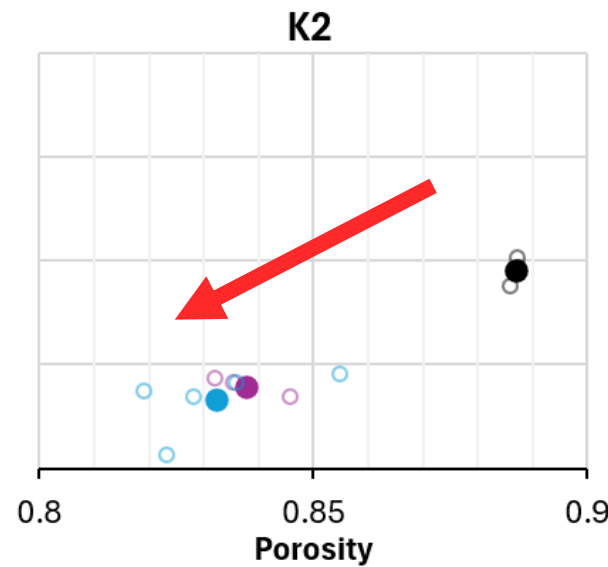
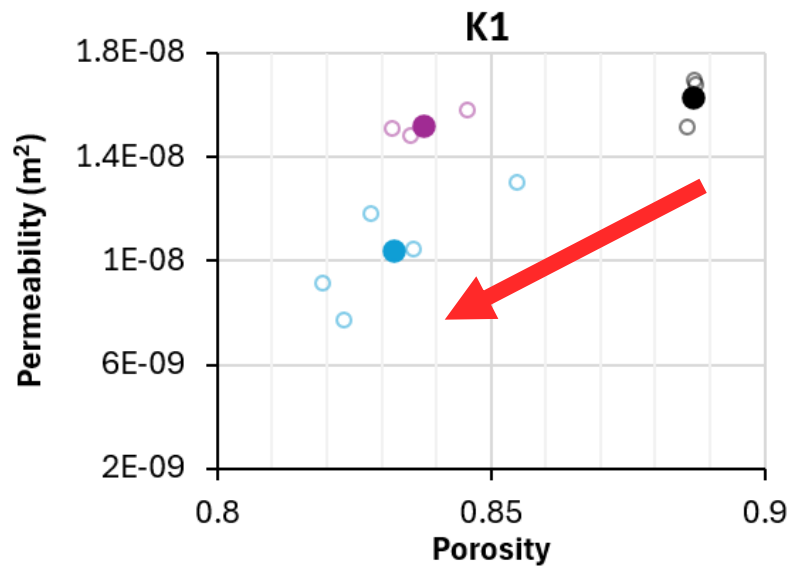
Expectations: Highest imprint & deformation into mesh layer
 (Lowest porosity and permeability)

² L. M. Laborderie et al., *IOP Conf. Ser.: Mater. Sci. Eng.*, vol. 1338, 012040, 2025
 DOI: 10.1088/1757-899X/1338/1/012040

Student work:
Konstantina Gkournelou, Adrien Winther, and Lucie Laborderie

Distribution media: Example results

- Results intuitively match expectations:
 - Greater bag deformation / fabric imprint reduces porosity and permeability
- But anisotropy and principal direction are also significantly affected

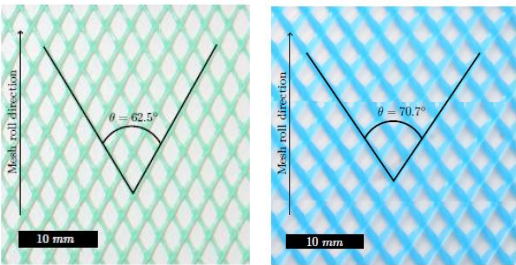


Student work:

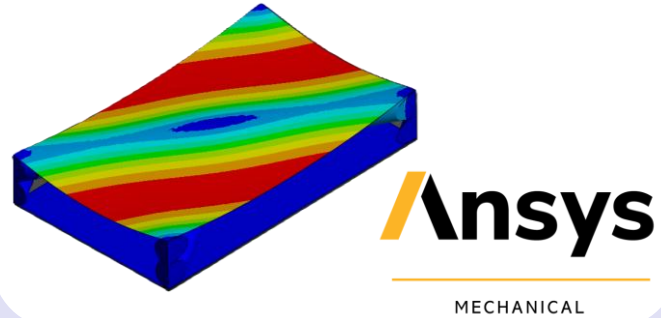
Konstantina Gkournelou, Adrien Winther, and Lucie Laborderie

Distribution media: Predictive permeability simulation

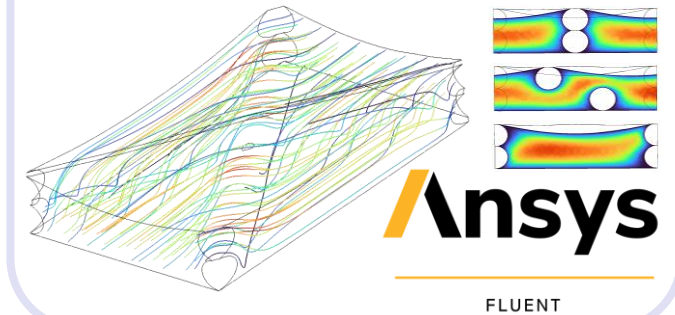
1. Physical measurements



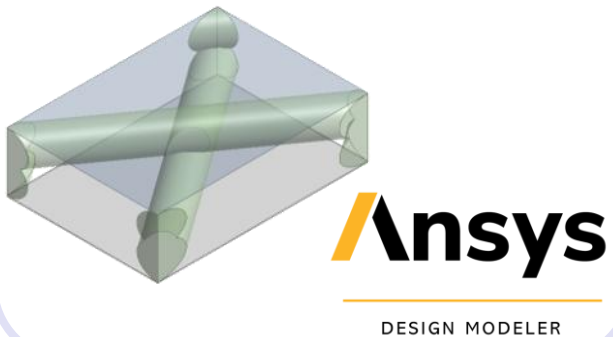
3. Compaction simulation (FEA)



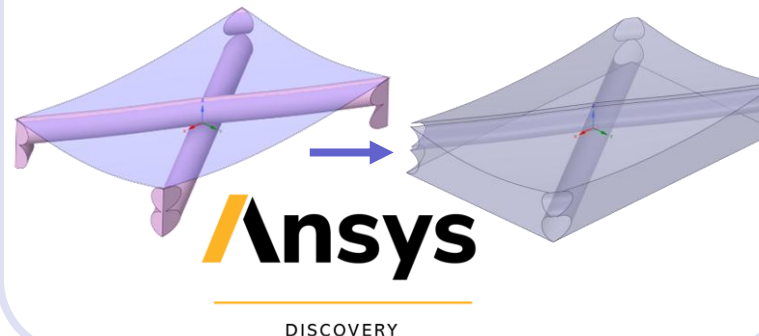
5. Flow simulation (CFD)



2. Simple CAD model



4. Conversion to fluid domain

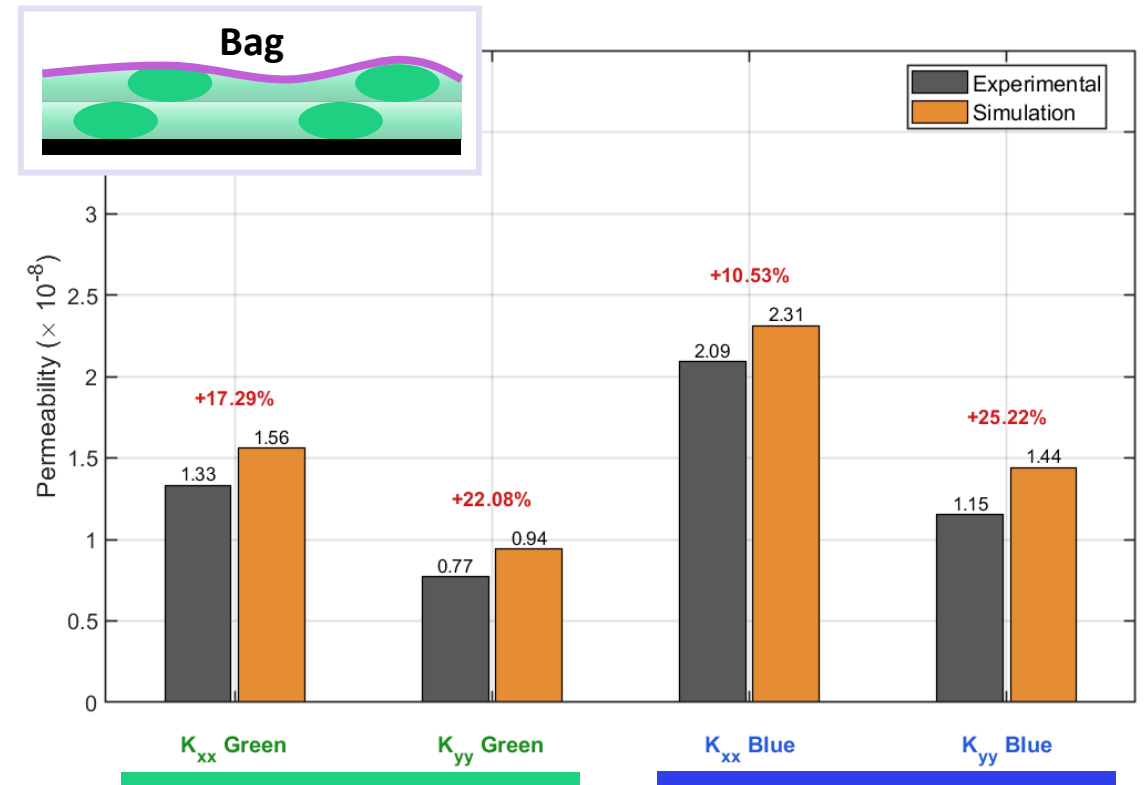
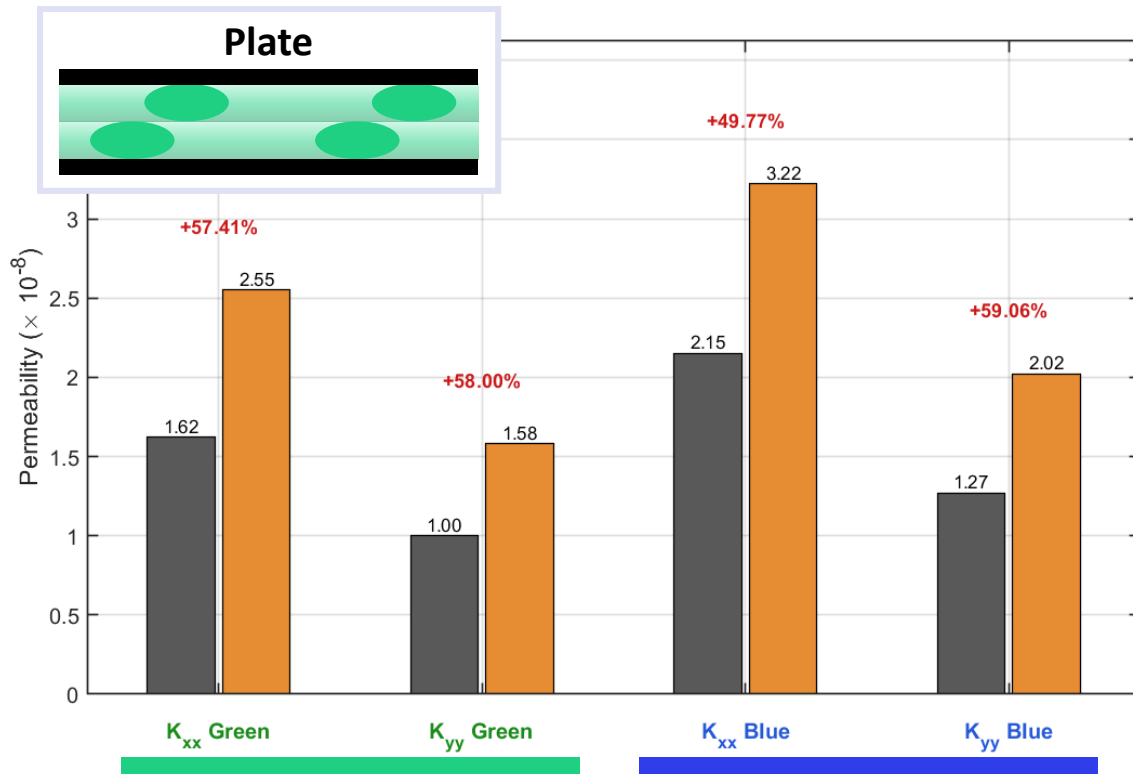


6. Permeability calculation

Student work:
Pietro Perego

Distribution media: Predicted results

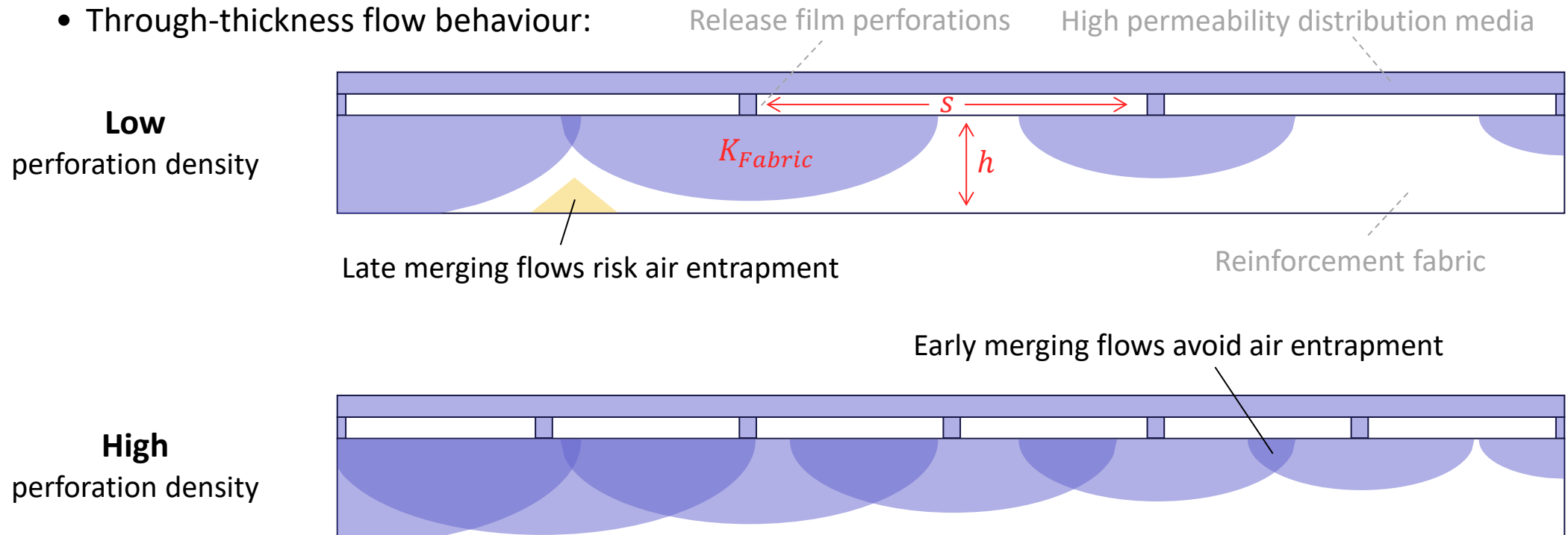
- Trends are very well captured for two different mesh designs, despite highly-simplified models



Student work:
Pietro Perego

Perforated release films: Problem

- Perforation pattern significantly affects infusion behaviour and quality
- Through-thickness flow behaviour:



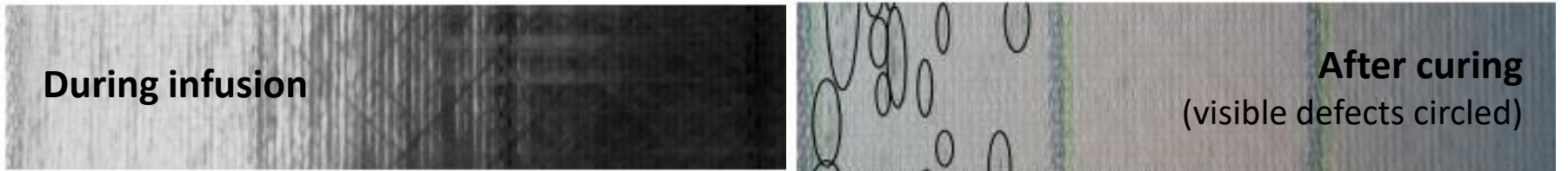
Perforated release films: Problem

- Perforation pattern significantly affects infusion behaviour and quality
- Three similar infusions with different perforation densities:

Low
perforation density



Medium
perforation density



High
perforation density



³ L. M. Laborderie et al., *Composites Part A*, vol. 201, 109431, 2026
DOI: 10.1016/j.compositesa.2025.109431

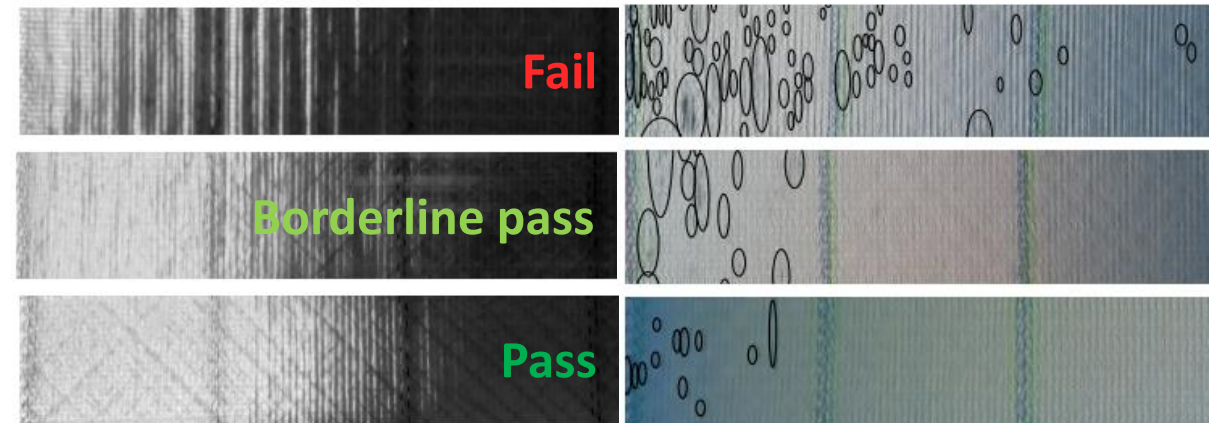
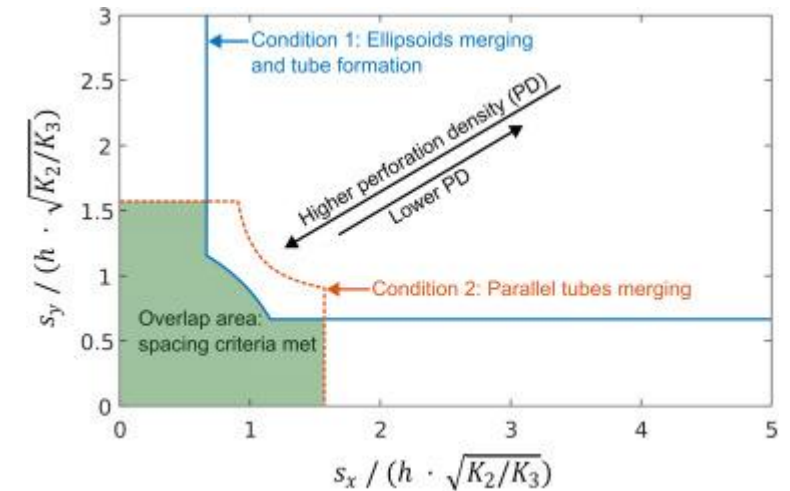
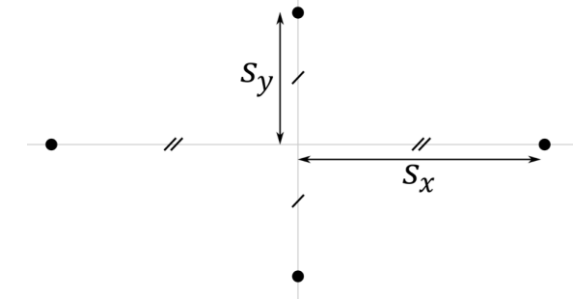
Perforated release films: Solution

- Established an analytical spacing criteria
 - Dependent on fabric permeability and thickness
 - Predictor of homogenised flow and good infusion quality

$$4s_x^2 \leq \frac{16 K_2}{9 K_3} h^2, \quad \text{or} \quad 4s_y^2 \leq \frac{16 K_2}{9 K_3} h^2, \quad \text{or} \quad s_x^2 + s_y^2 \leq \frac{16 K_2}{9 K_3} h^2$$

$$\left\{ \begin{array}{l} s_x \leq \frac{\pi}{2} \cdot \sqrt{\frac{K_2}{K_3}} \cdot h, \quad \text{if } s_y \leq \frac{1}{\sqrt{3}} s_x \\ \frac{2s_x s_y}{\sqrt{s_x^2 + s_y^2}} \leq \frac{\pi}{2} \cdot \sqrt{\frac{K_2}{K_3}} \cdot h, \quad \text{if } \frac{1}{\sqrt{3}} s_x \leq s_y \leq \sqrt{3} s_x \\ s_y \leq \frac{\pi}{2} \cdot \sqrt{\frac{K_2}{K_3}} \cdot h, \quad \text{if } \sqrt{3} s_x \leq s_y \end{array} \right.$$

³ L. M. Laborderie et al., *Composites Part A*, vol. 201, 109431, 2026
DOI: 10.1016/j.compositesa.2025.109431

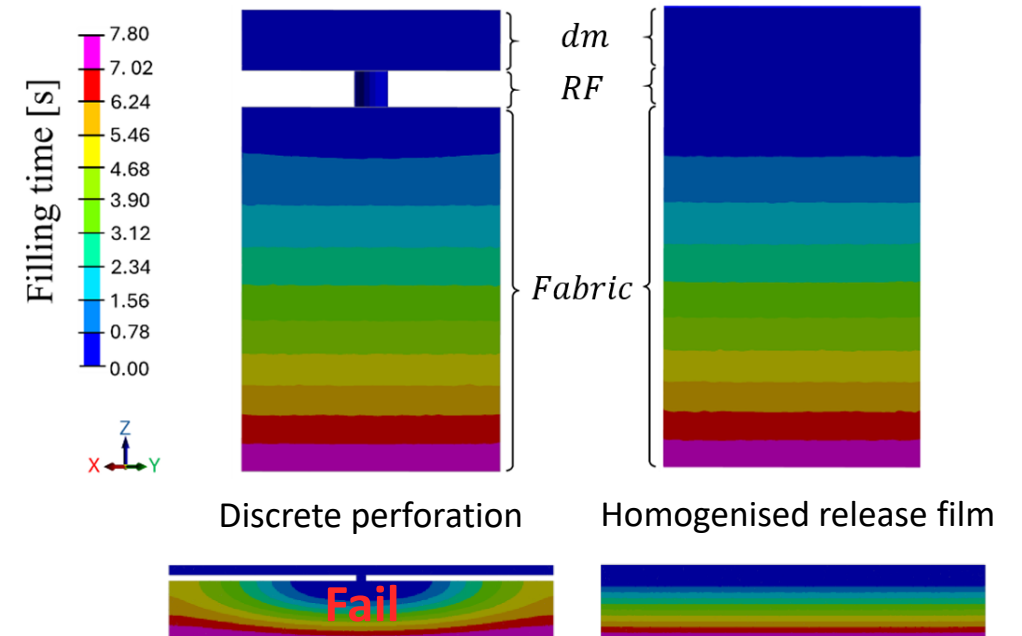


Perforated release films: For modelling

- Inverse (analytical/numerical) method for defining a homogenised release film permeability:
 - Simulate 3D flow through a representative unit cell to obtain filling time, t_{fill}
 - Inversely calculate an equivalent homogenised release film permeability, K_{RF}

$$K_{RF} = \frac{h_{RF} \cdot (\phi_{RF} h_{RF} + 2\phi_f h_f)}{2 \frac{t_{fill} \Delta P}{\mu} - \phi_f h_f \frac{h_f}{K_f} - \frac{h_{dm}}{K_{dm}} (\phi_{dm} h_{dm} + 2\phi_{RF} h_{RF} + 2\phi_f h_f)}$$

- Only valid when the spacing criteria is met!



⁴ L. M. Laborderie et al., *ECCM21*, vol. 5, 2024
DOI: 10.60691/yj56-np80

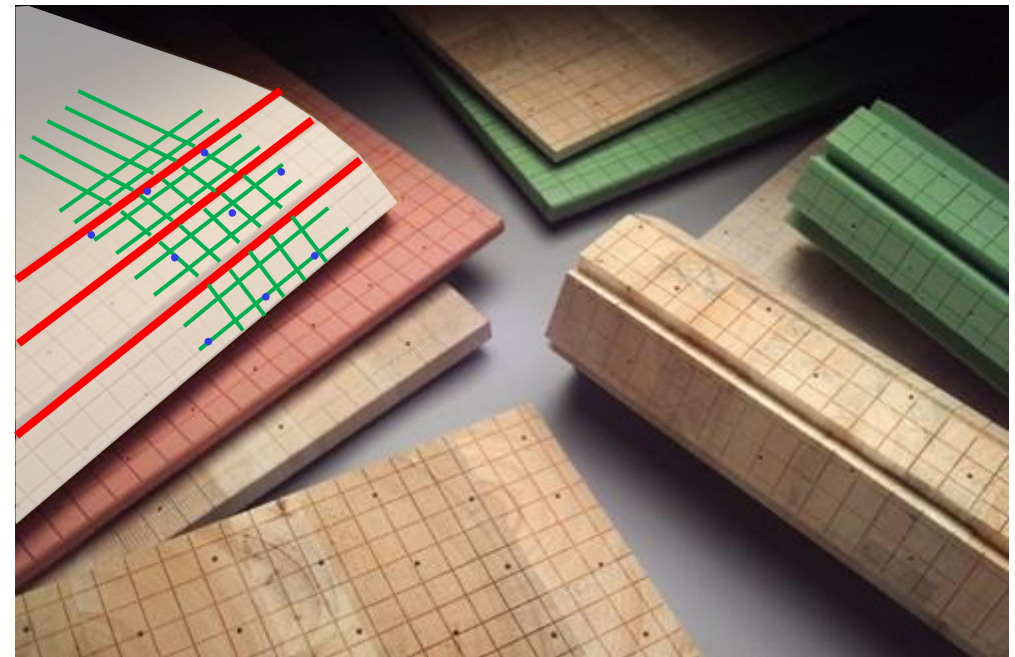
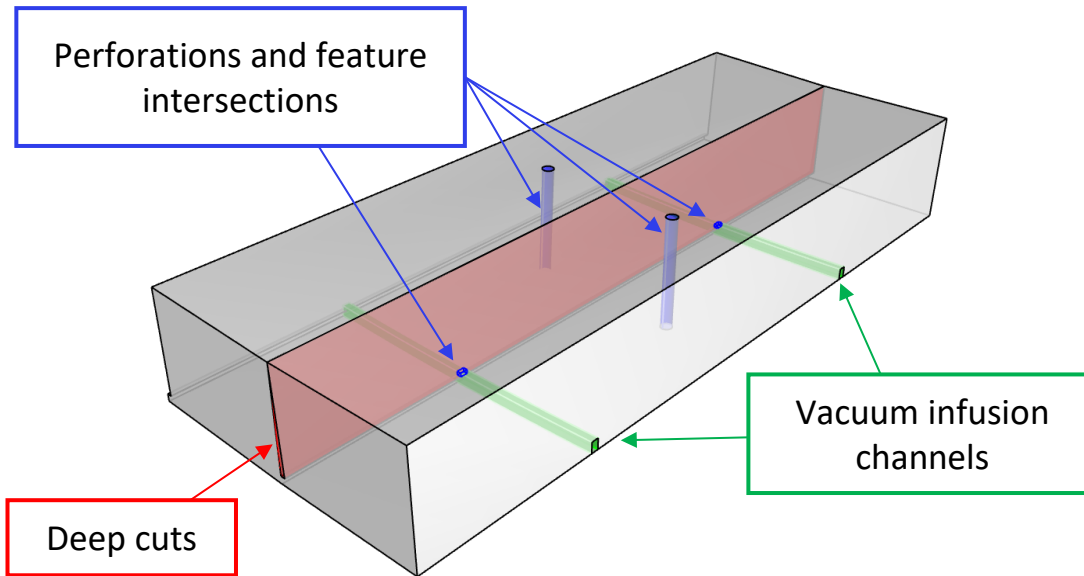
Permeability of core materials

Core material features

Core materials are “kitted” with **different features** according to their location in the blade:

- Need to fit large and complex curvatures
- Resin distribution and flow can be difficult next to core
- Resin needs to travel across the core to fill both sides

- ➔ • Deep cuts
- ➔ • Vacuum infusion channels
- ➔ • Perforations or intersections



Fabric and core channel interaction

- Exhibits stable behaviour over time:



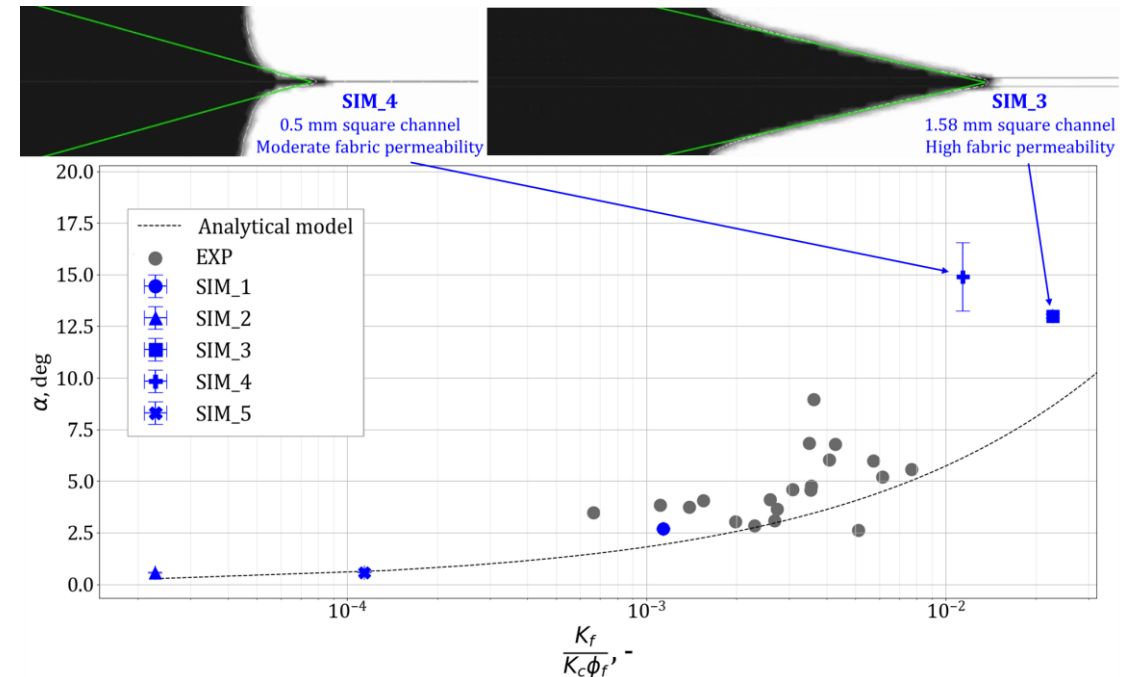
- Simple analytical model for flow shape (angle):

Transverse fabric permeability K_f and Fabric porosity ϕ_f are indicated by blue arrows pointing to the terms in the equation.

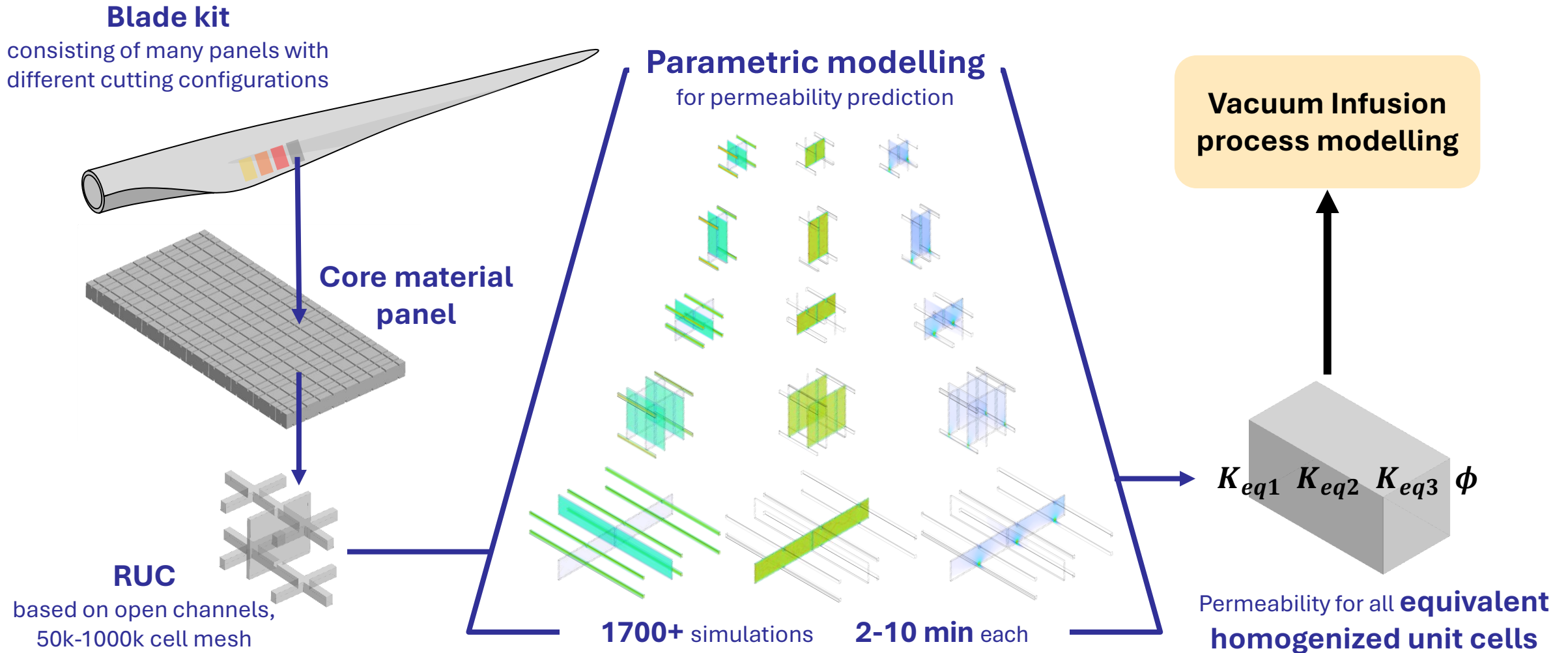
$$\alpha = \tan^{-1} \left(\sqrt{\frac{K_f}{K_c \phi_f}} \right) \times \frac{180}{\pi}$$

Equivalent channel permeability:
$$K_c = \frac{H^2}{12} \left[1 - \frac{192 H}{\pi^5 W} \sum_{i=1,3,5,\dots}^{\infty} \frac{\tanh\left(\frac{i \pi W}{2 H}\right)}{i^5} \right]$$

⁵ M. Larionov et al., *IOP Conf. Ser.: Mater. Sci. Eng.*, vol. 1338, 012041, 2025
DOI: 10.1088/1757-899X/1338/1/012041



Parametric modelling of core material



Summary

Summary

Distribution media:

- Experimental method accounting for bag deformation and fabric imprint
- Framework for predictive permeability modelling

Perforated release films:

- Analytical spacing criteria
- Method for homogenous permeability definition

Core materials:

- Simple analytical model for channel / fabric flow interaction
- Parametric permeability modelling for different kitting features

Questions ?



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References

- ¹ R.S. Pierce, Challenges in permeability characterisation for modelling the manufacture of wind turbine blades, *IOP Conf. Ser.: Mater. Sci. Eng.*, vol. 1293, 012009, 2023
 DOI: 10.1088/1757-899X/1293/1/012009
- ² L.M. Laborderie et al., Investigation and development of experimental methods for the characterisation of flow mesh permeability, *IOP Conf. Ser.: Mater. Sci. Eng.*, vol. 1338, 012040, 2025
 DOI: 10.1088/1757-899X/1338/1/012040
- ³ L.M. Laborderie et al., A spacing criterion for perforated release films in vacuum-assisted resin infusion processes, *ECCM21 Proceedings*, vol. 5, 2024
 DOI: 10.60691/yj56-np80
- ⁴ L.M. Laborderie et al., Avoiding air entrapment in multi-inlet through-thickness flow: Analytical development of spacing criteria and experimental application to vacuum infusion and release film design, *Composites Part A*, vol. 201, 109431, 2026
 DOI: 10.1016/j.compositesa.2025.109431
- ⁵ M. Larionov et al., Analysis of shape of resin flow in vacuum infusion of composite sandwich structures with core channels, *IOP Conf. Ser.: Mater. Sci. Eng.*, vol. 1338, 012041, 2025
 DOI: 10.1088/1757-899X/1338/1/012041

DTU

