DTU

DTU Wind

Danish Composite Award – MSc Project:

Simulation and experimental validation of the infusion process for wind turbine blades

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Supervisors: Rob Pierce
Philipp Haselbach

Outline

- Context and motivation
- Focus & main research questions

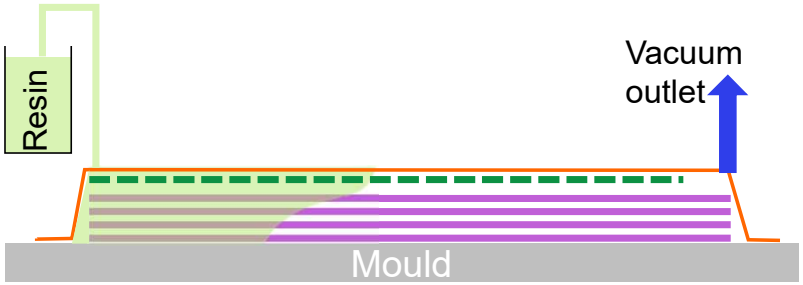
- How to choose the right perforation pattern for the release film
- Numerical considerations: thickness transformation & homogenisation methods
- Link to manufacturing quality

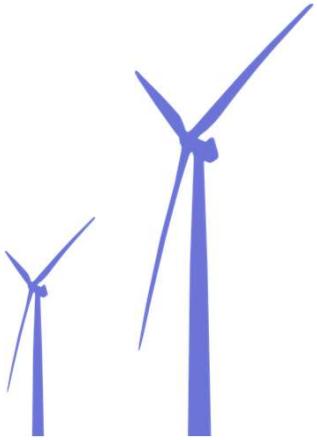
- Conclusions & Perspectives

- Questions

Context

- Fibre-reinforced composites: fitting material choice for large structures with high performance requirements
- Wind turbine blades typically manufactured by impregnating dry fabrics with liquid resin under vacuum (VARI)

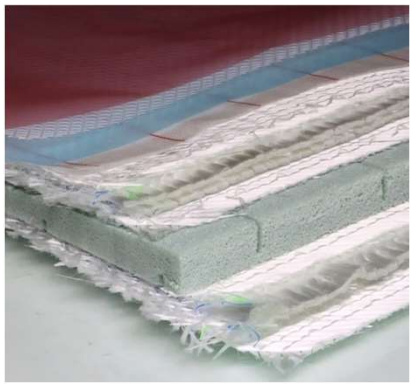




- **Larger** wind turbine blades
- Manufacturing and ensuring **consistent quality** becomes more **complex**
  - Larger blades → more complex lay-up with e.g. pre-cast elements
  - Typical defects: dry spots and voids
- With 100+meter blades, critical manufacturing **defects** are **expensive**

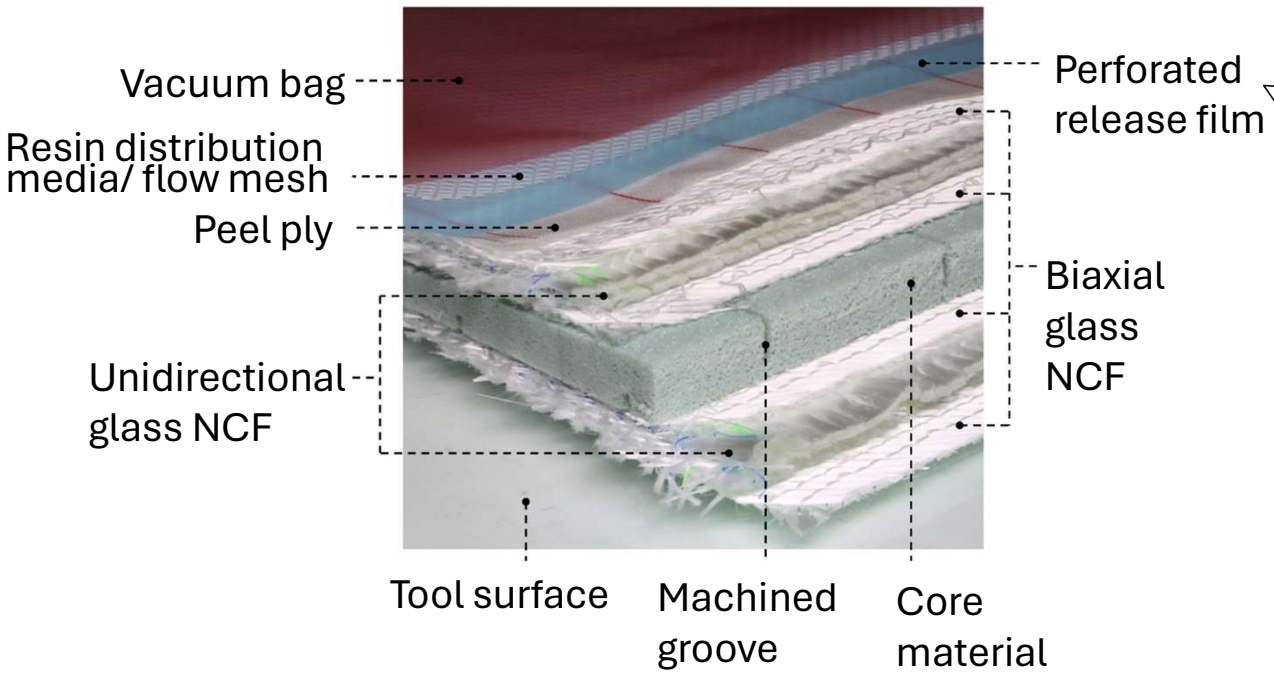
➔ Numerical simulations to optimize the process conditions and avoid defects

➔ In-depth understanding of the process necessary

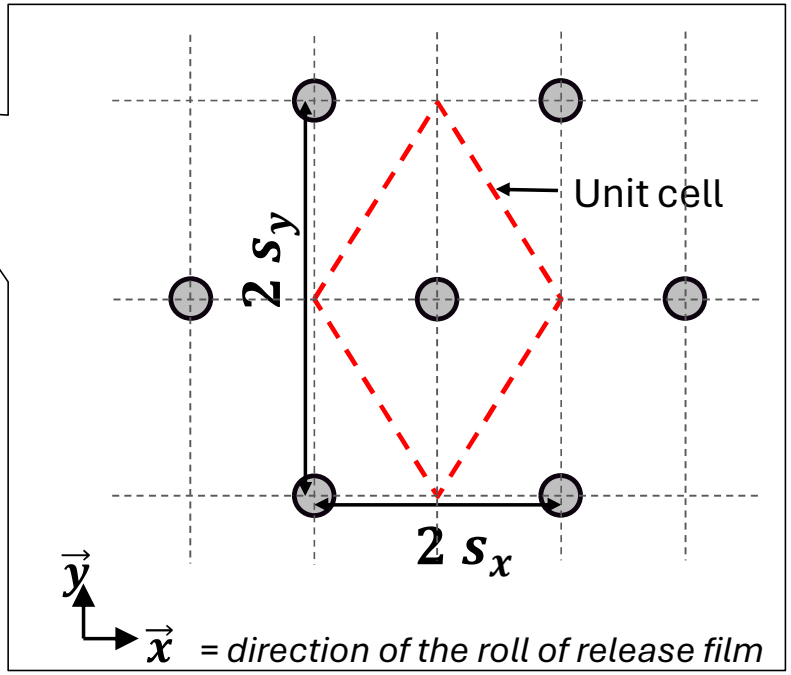


Pierce R. 2023 *IOP Conf. Ser.: Mater. Sci. Eng.* **1293** 012009

Context



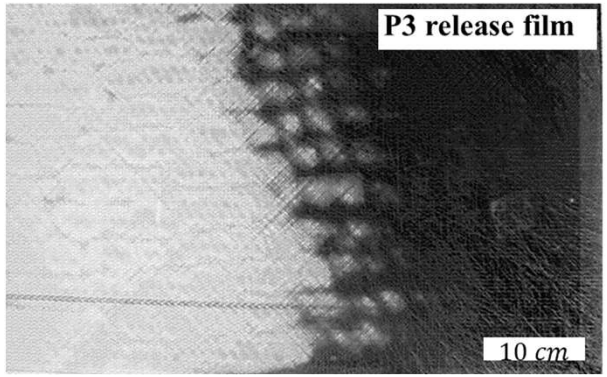
Representative layup of a thin sandwich structure for a wind turbine blade. Pierce R. 2023 *IOP Conf. Ser.: Mater. Sci. Eng.* **1293** 012009.

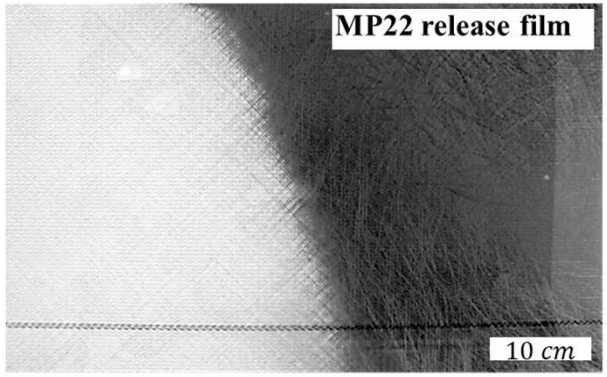


Perforated release films are impermeable membranes with discrete perforations.

Motivation

- Different perforation patterns and different infusion quality.





- Higher risks of introducing defects (voids, dry spots) with converging flow fronts*.

- Challenge for numerical modelling of the resin flow** specifically for the mesh quality (small thickness and perforation diameter compared to other dimensions).

- **How to choose the right perforation pattern?**
- **How to homogenise the release film in numerical simulations of resin flow?**

* Pearce, Guild, and Summerscales. *Compos A Appl Sci Manuf* 1998;29:141-52; ** Pierce R. 2023 *IOP Conf. Ser.: Mater. Sci. Eng.* **1293** 012009.

Resin flow & permeability

- Flow of a viscous and incompressible fluid through a homogeneous porous material described by **Darcy's law**:

$$\mathbf{v} = \phi\mathbf{U} = -\frac{\mathbf{K}}{\eta} \cdot \nabla P$$

- Permeability ~ size of the channels the resin can go through
- Often expressed as a function of the V_f of the fabric
- Ellipsoidal flow front in a fabric with an inlet point, described by 3 principal permeabilities:
  - $K_1$and K_2(in-plane), K_3(through-thickness)
  - Angle β defining the orientation of K_1 vs. roll direction
- Model used to describe the flow of resin through the fabric during infusion*'**
- Darcy-based solver used in most filling simulation softwares (e.g. PAM-RTM ***)

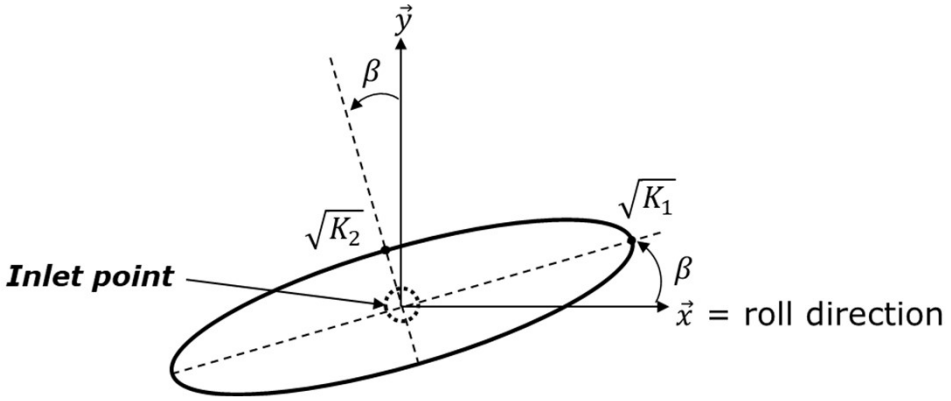
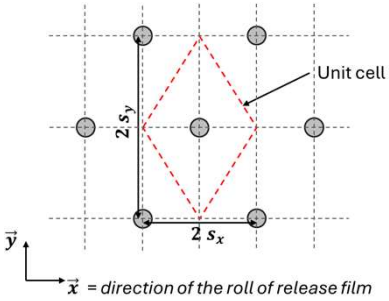


Fig: Elliptical flow front in the fabric plane with a central inlet point

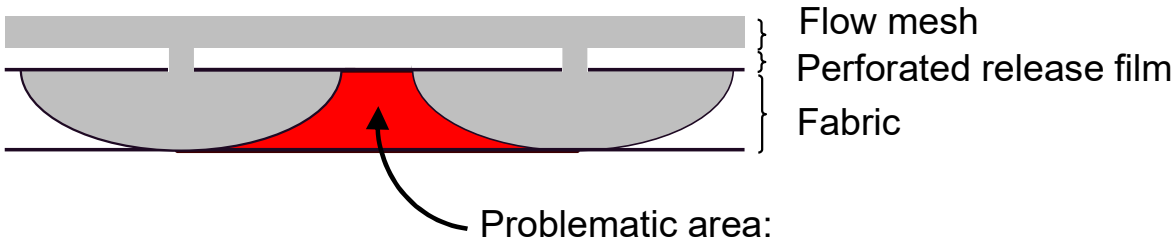
*Arbter R., et al. *Compos A Appl Sci Manuf* 2011;49.2:1157-1168; **Vernet N. et al. *Compos A Appl Sci Manuf* 2014;61:172-184; ***ESI Group. "PAM-RTM 2022 - User's Guide". (2022).

Spacing criteria



Analytical development:

- Interactions between unit cells neglected.
- Perforation diameter neglected due to the dimensions considered*
- Flow front shape emerging from one perforation assimilated to an ellipsoid described by the fabric permeability K_1, K_2, K_3 and the fabric stack thickness h.



- Objective: minimizing the problematic area
- New criteria derrived: $s_i < 0.43\ h \sqrt{\frac{K_i}{K_3}}$

*Mekic, S., Akhatov, I., & Ulven, C. *Polym Compos*, 2009 *30*(7):907-17.

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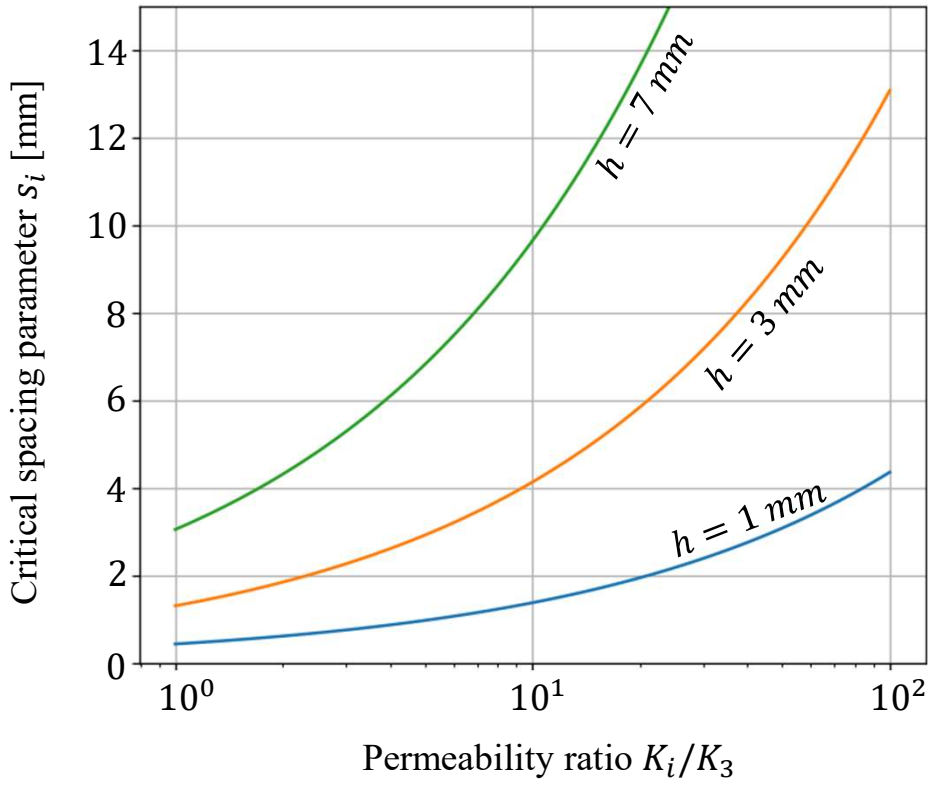

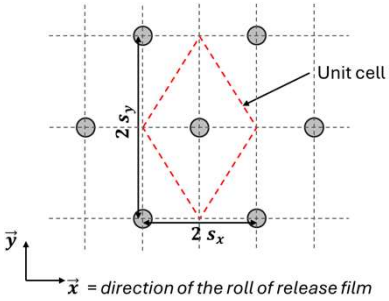

For a fabric with know permeability and a given stack thickness, the spacing criteria indicate which perforation pattern lower the risk of introducing defects.

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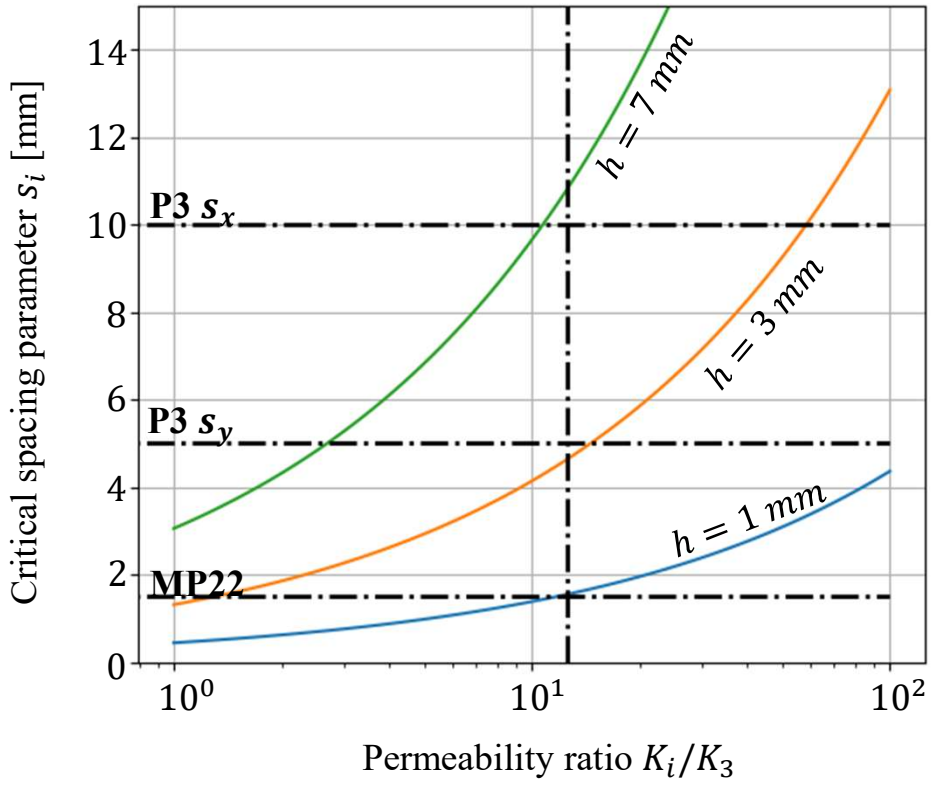

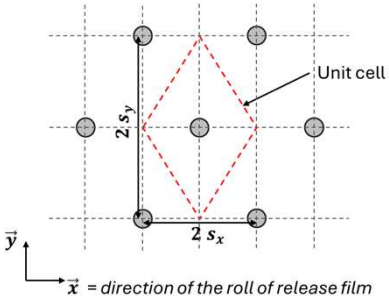

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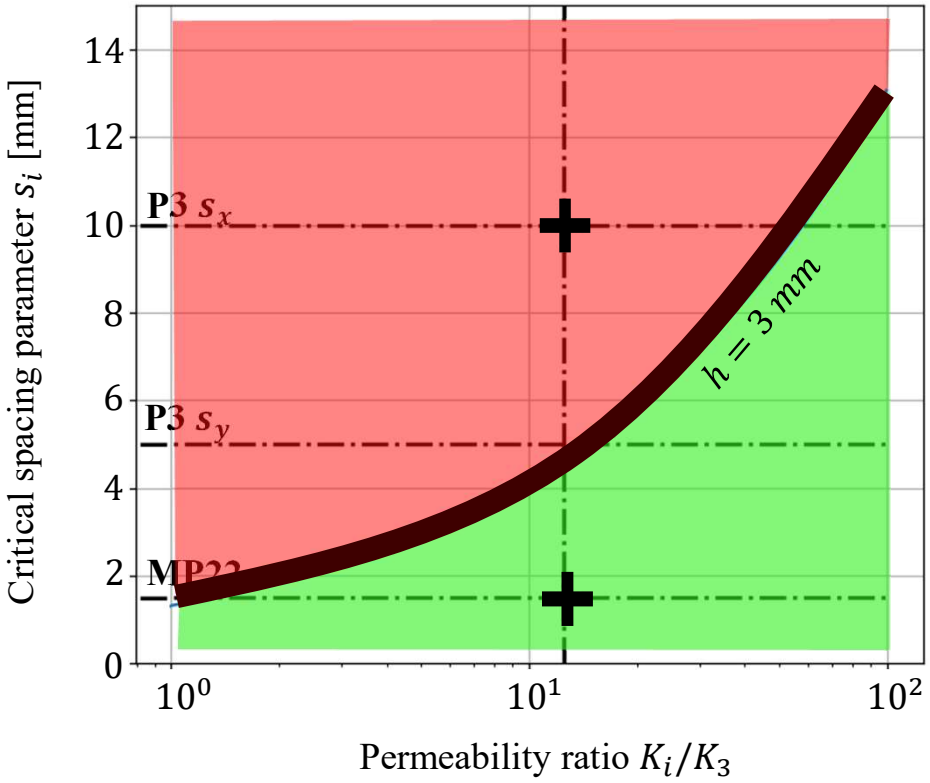

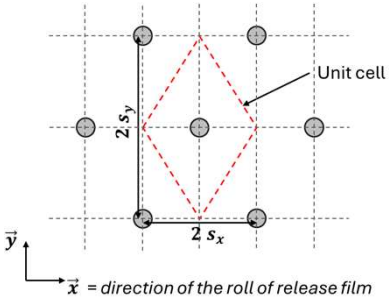

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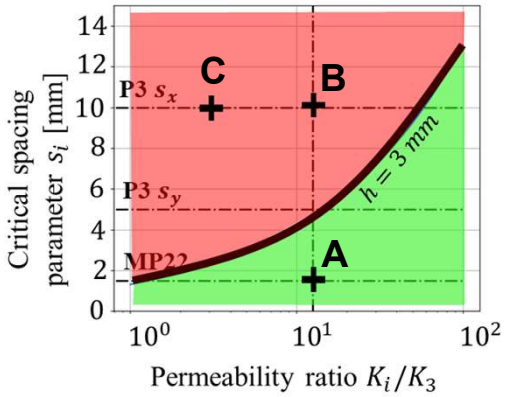
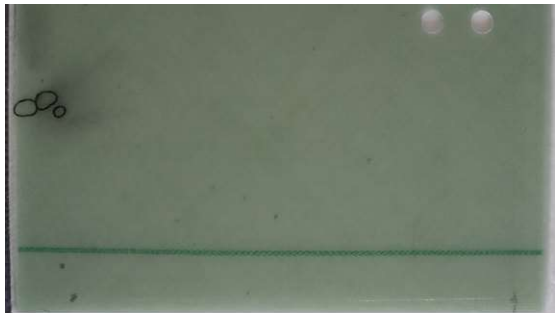
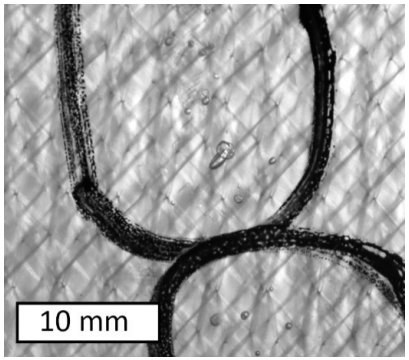
Experimental validation

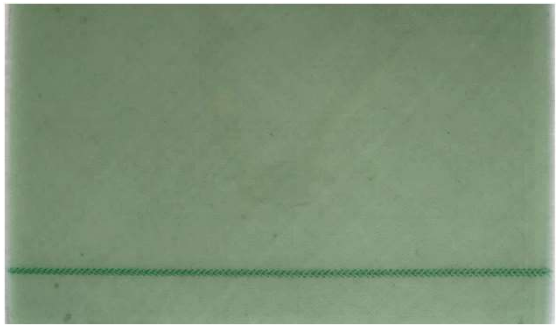


B)





A)



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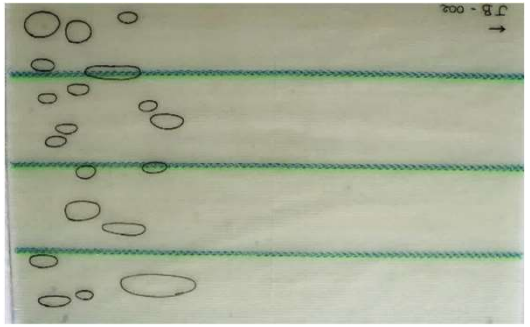
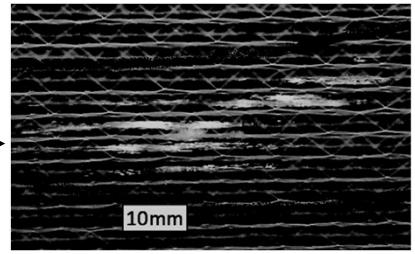
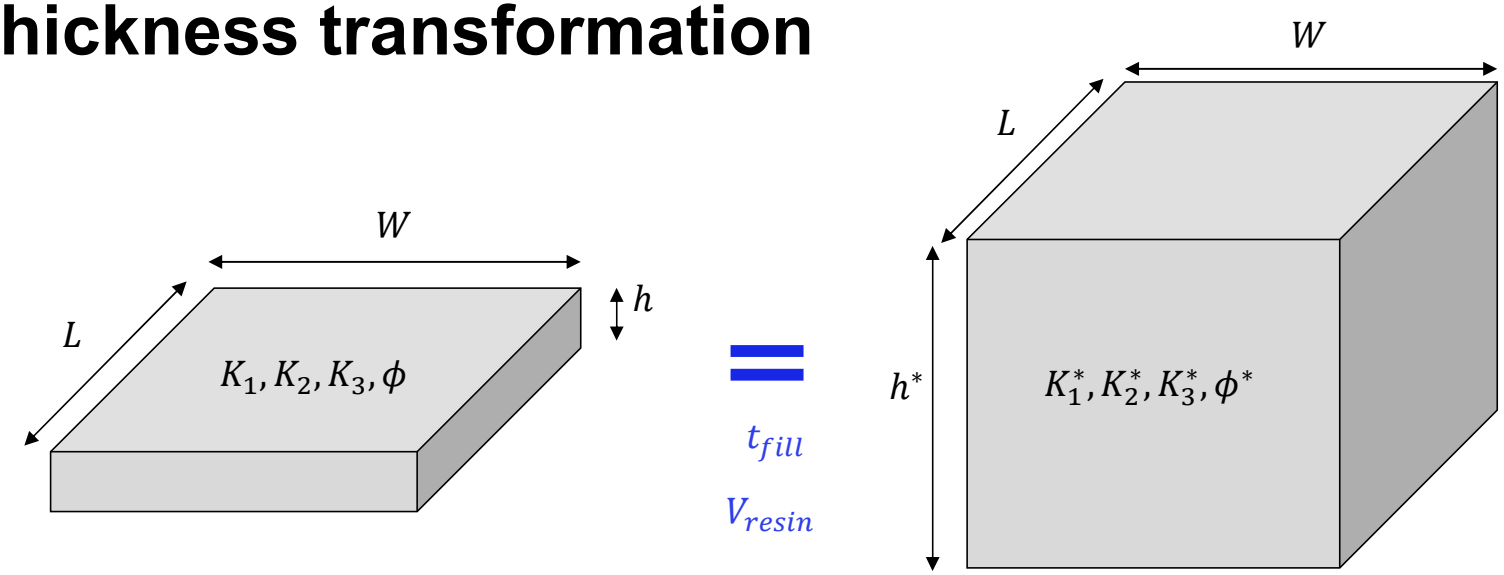




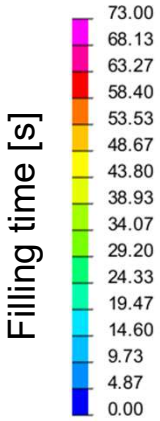
Thickness transformation

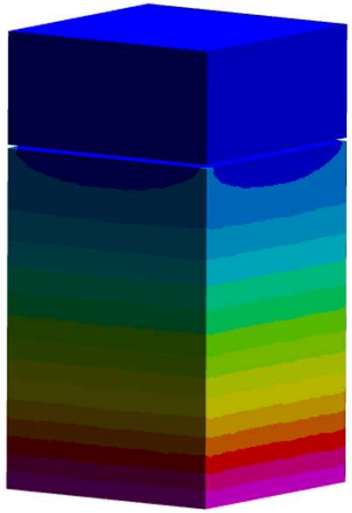


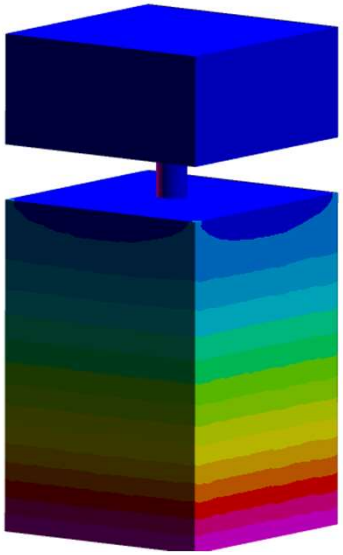
- Conservation of volume → $\phi h = \phi^* h^*$ ➔ $\phi^* = \phi \frac{h}{h^*}$
- Same filling times → Darcy's law for linear unsaturated flow with constant inlet pressure, should be verified on each direction

$$t_{fill} = \frac{h^2 \phi \, \eta}{2 \, K \, \Delta P} \rightarrow \frac{h^*}{K_3^*} = \frac{h}{K_3} \text{ and } \frac{\phi^*}{K_{1,2}^*} = \frac{\phi}{K_{1,2}}$$

Thickness transformation – numerical validation







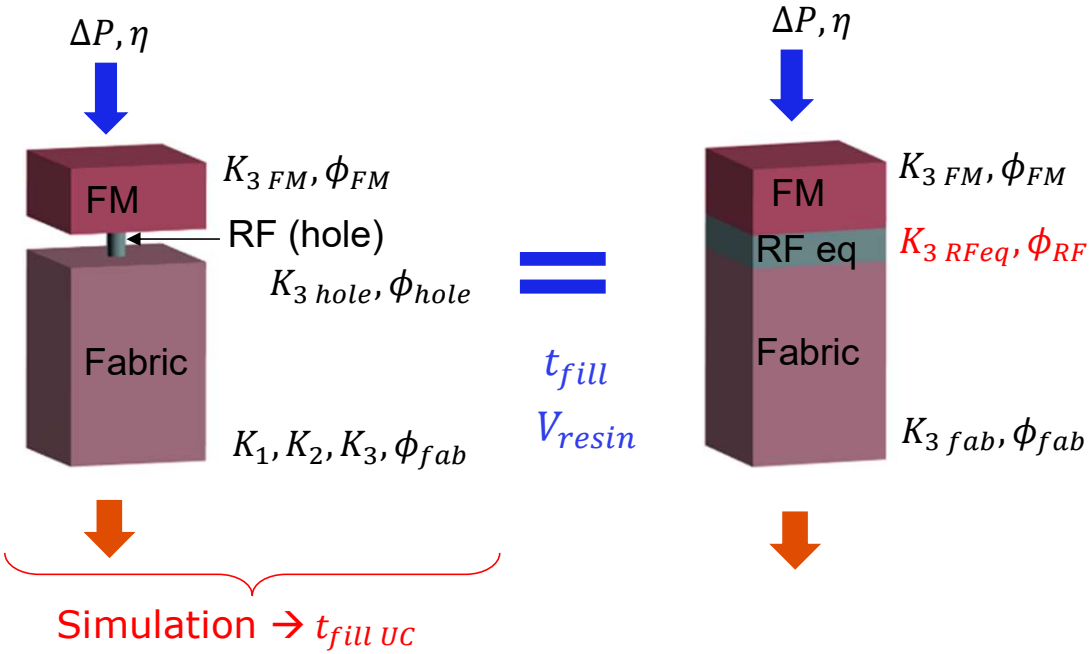
Ref. UC
(thin release film)

$\epsilon = 0.07\%$

Ref. UC
With artificial increase
of RF thickness

Release film homogenisation

Coupled analytical-numerical method:

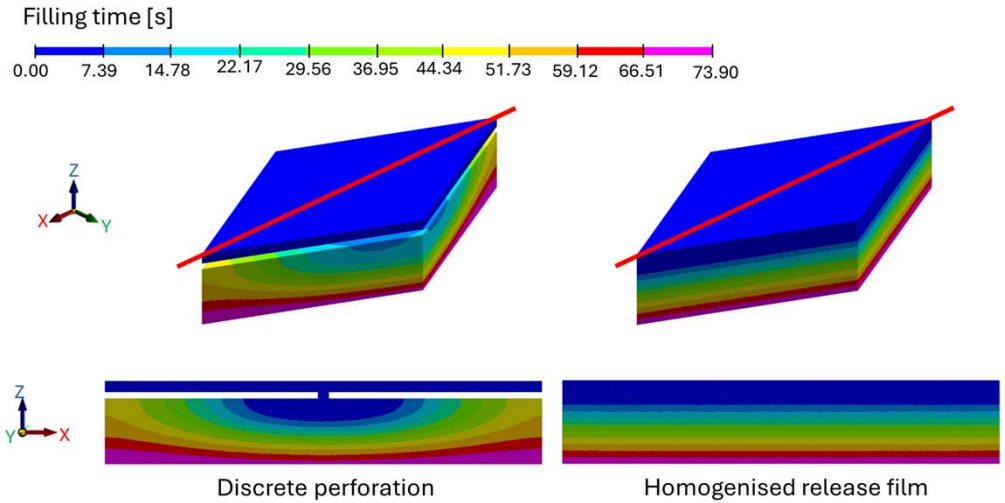


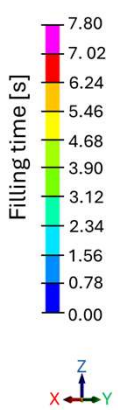
- $\phi_{RF} = \frac{\pi\,(d/2)^2}{2\,s_x\,s_y}$

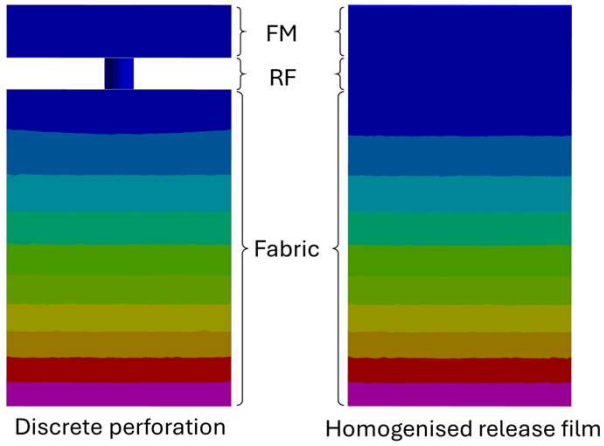
- Darcy's law in 1D: $\mathbf{v} = \phi\mathbf{U} = -\frac{\mathbf{K}}{\eta} \cdot \nabla P$

➔ $t_{Fill} = \frac{\eta}{2\,\Delta P} \sum_{i=\{FM,RF,fab\}} \left(\frac{\Phi_i}{K_i} l_i^2 + 2 l_i \Phi_i \sum_{j<i} \frac{l_j}{K_j} \right)$

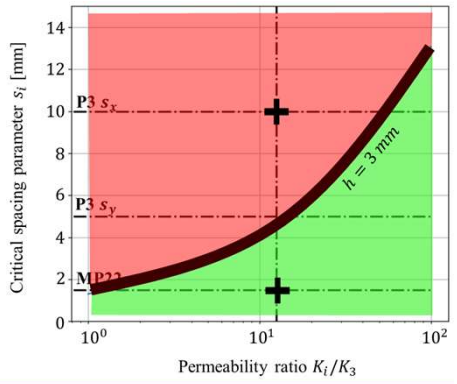
Release film homogenisation







- Filling times ($\epsilon < 1\%$) ✓
- Flow front shapes ✗



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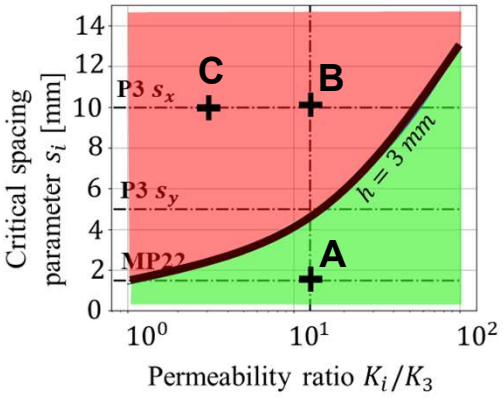

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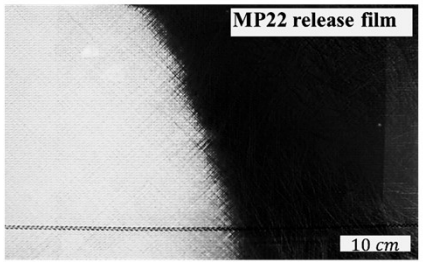

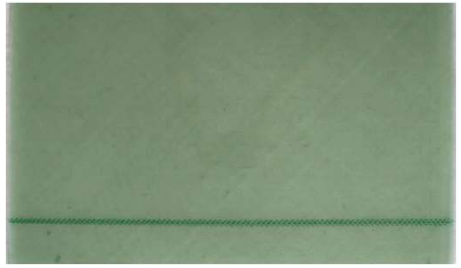

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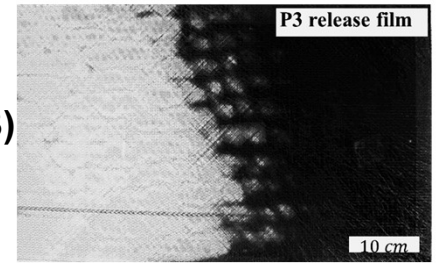

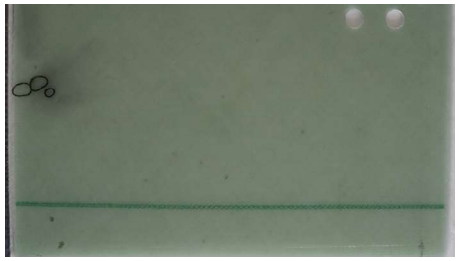

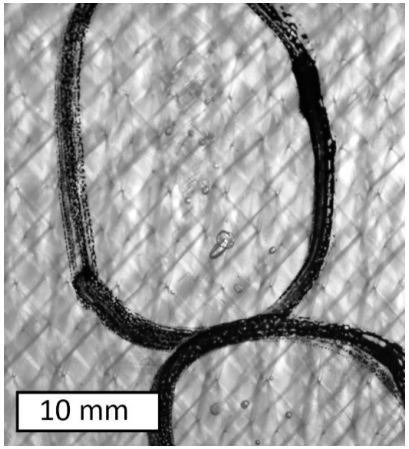

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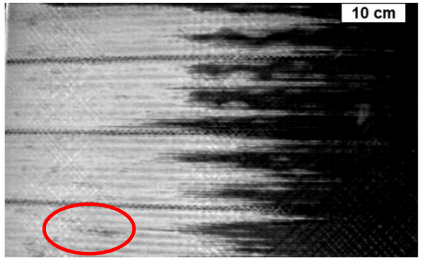
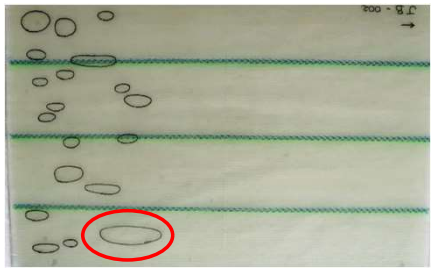
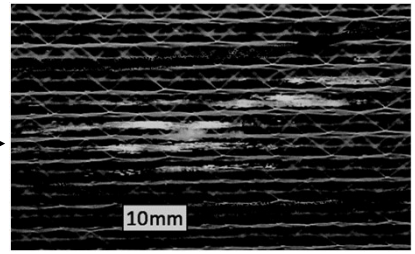






Conclusions and perspectives

Manufacturing considerations:

- Spacing criteria: guidelines for a fabric with known permeability and a given stack thickness
  - uniform flow front during infusion
  - reduced risk of introducing defects

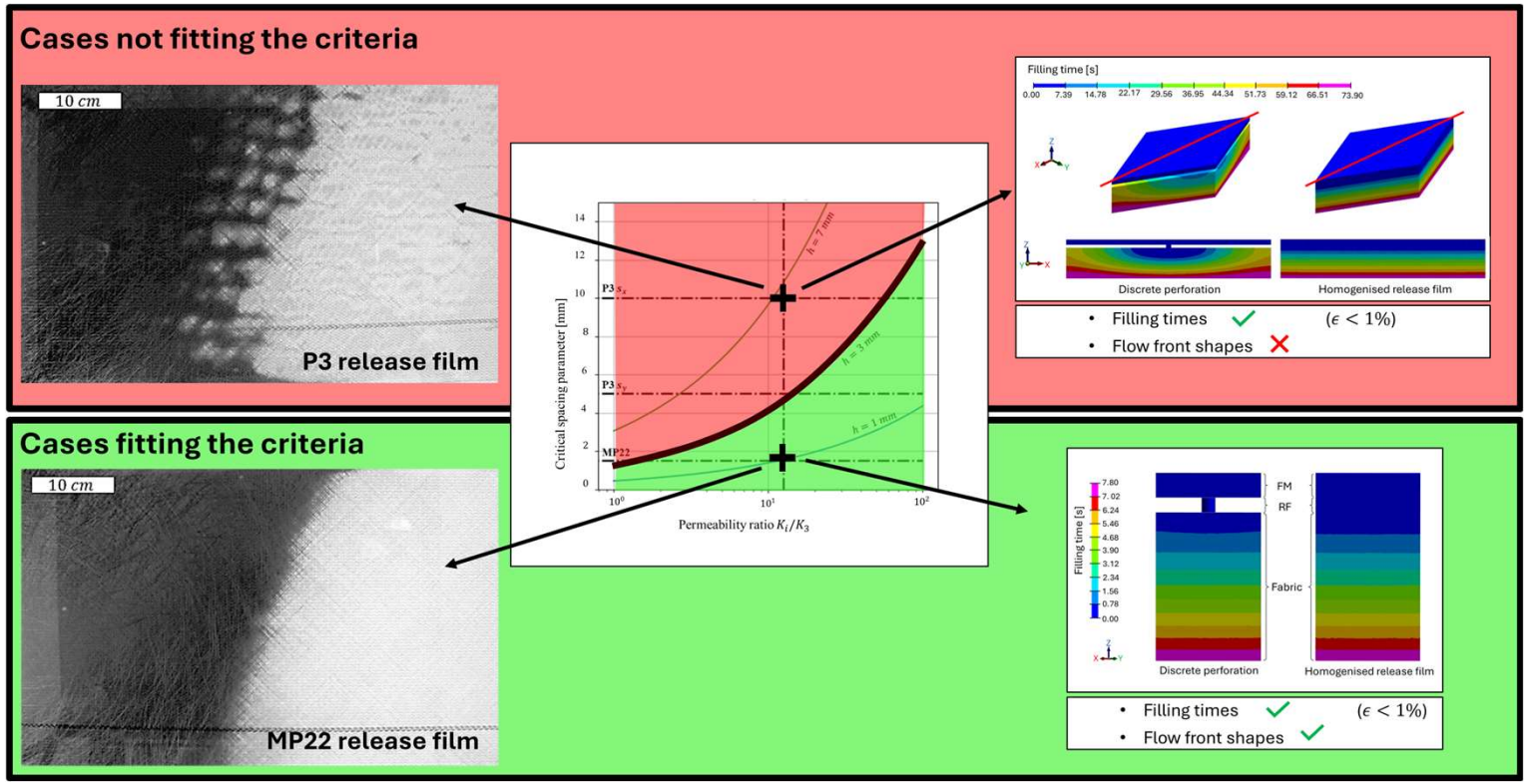
Numerical considerations:

- Thickness transformation method → validated numerically.
- Homogenisation scheme
  - ➢ Accurate in terms of filling times (numerical validation)
  - ➢ Good approximation of the flow front shape only when the spacing criterion is met (numerically & experimentally)
  - ➔ Recommendation to only homogenise the perforated release film when the spacing criterion is met

Perspectives:

- Development of a tri-dimensional version of the spacing criteria accounting for the interactions between the neighbouring unit cells (less conservative) + experimental validation
- Investigate the extension of the criteria to perforated cores

Summary



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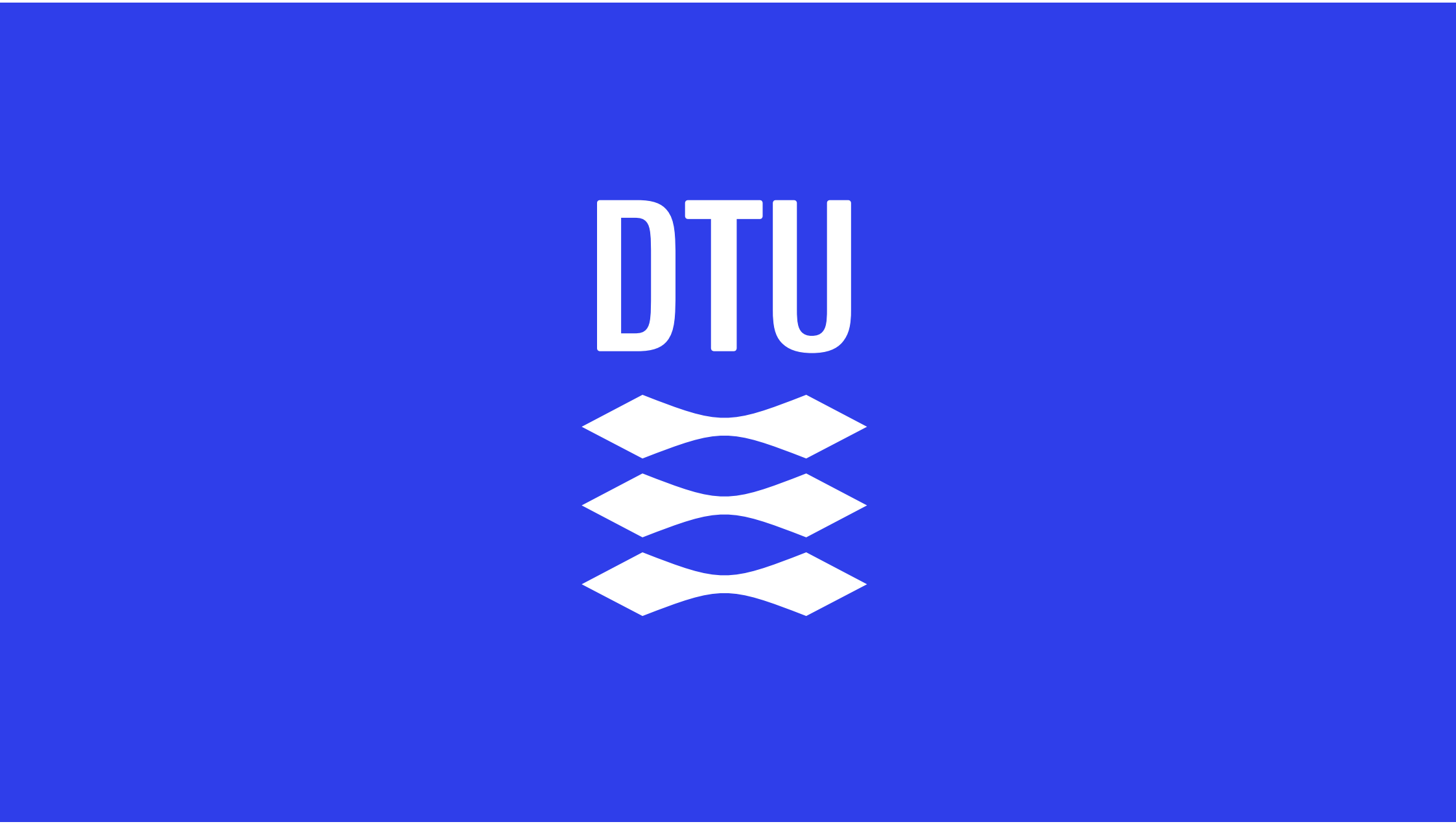
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