The University of Nottingham
UNITED KINGDOM · CHINA · MALAYSIA

Gap Formation and Resin Flow in Bent Preforms for Resin Transfer Moulding

A. Endruweit, M. Matveev

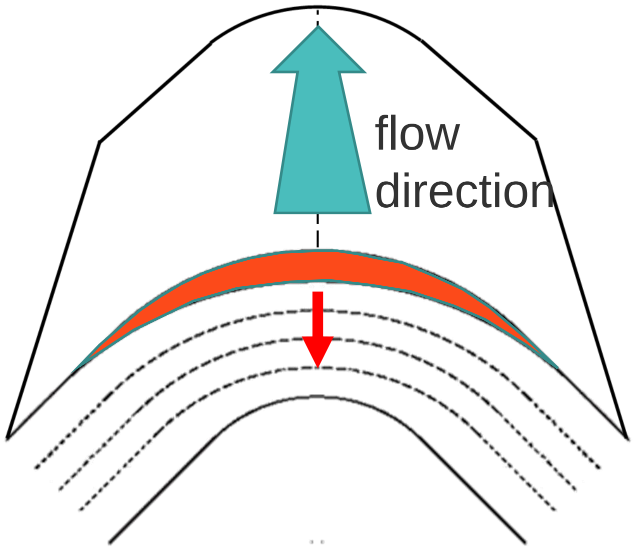
Composites Research Group, Faculty of Engineering
University of Nottingham, UK

Motivation

Manufacture of composite components employing Resin Transfer Moulding

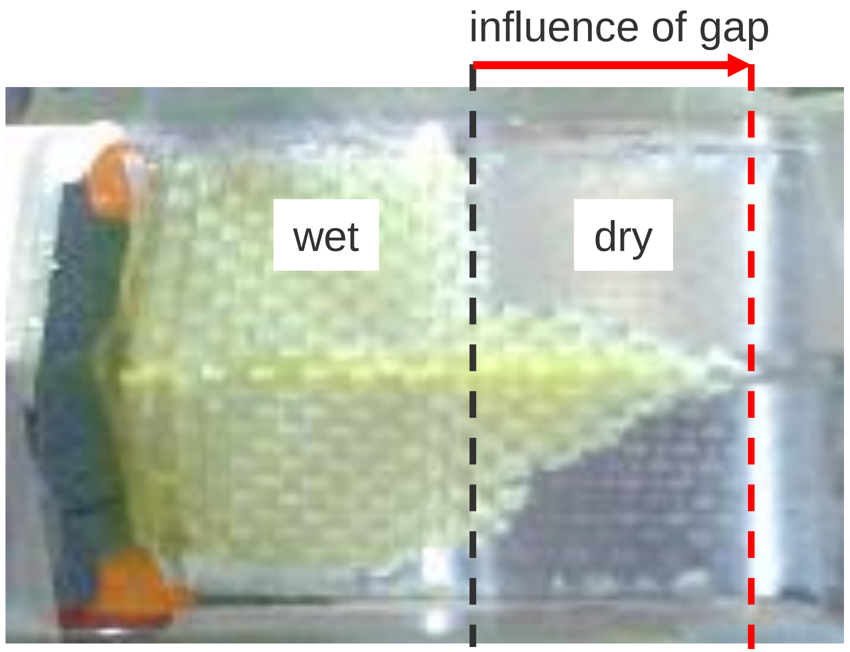
Localised reinforcement compression at bends in component

➡ formation of gaps between reinforcement and tool surface



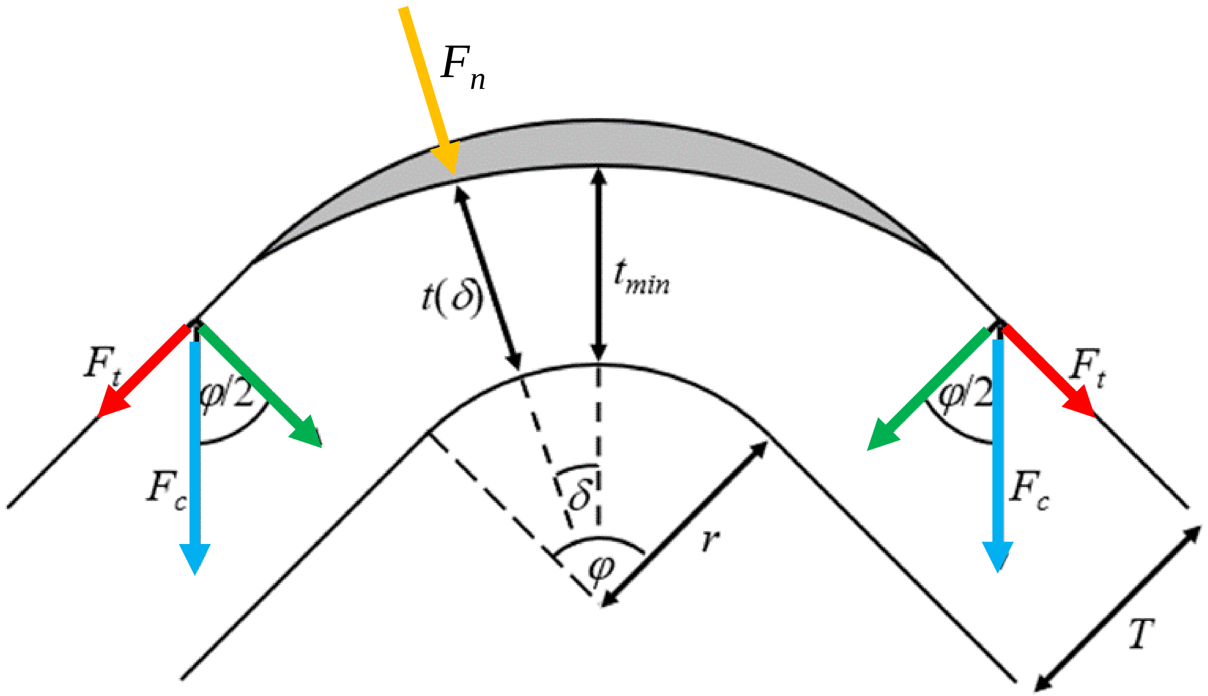
Experiment: Perspex tool, 90° bend

Observation:
Local effect on flow front propagation; racetracking makes process hard to control



Koutsonas, Spiridon (2015) Race-track modelling and variability in RTM for advanced composites structures. PhD thesis, University of Nottingham.

Gap formation



tool closing force: $F_c = \dfrac{F_0(T,a,b)}{\cos(\varphi/2)}$

tensile force: $F_t = \mu F_c \cos(\varphi/2)$

normal force: $F_n(\delta)$ **model?**

local pressure: $p = \dfrac{dF_n}{dA}$

reinforcement compressibility: $t(\delta) = a\left(\dfrac{p(\delta)}{10^5\ \text{Pa}}\right)^{-b}$

geometry parameters: φ, r, T (and L)

material parameters: μ, a, b

tool closing force: $2F_c$

Describe gap in terms of

- Minimum reinforcement thickness (at $\delta = 0$), t_{min}
- Opening half angle (at $t = T$), δ_T

Gap formation (experiments)

Three points on reinforcement surface are known:

$$\delta = \pm\delta_T \ , \ t = T \qquad \text{and} \qquad \delta = 0 \ , \ t = t_{min}$$

Describe surface as circle,

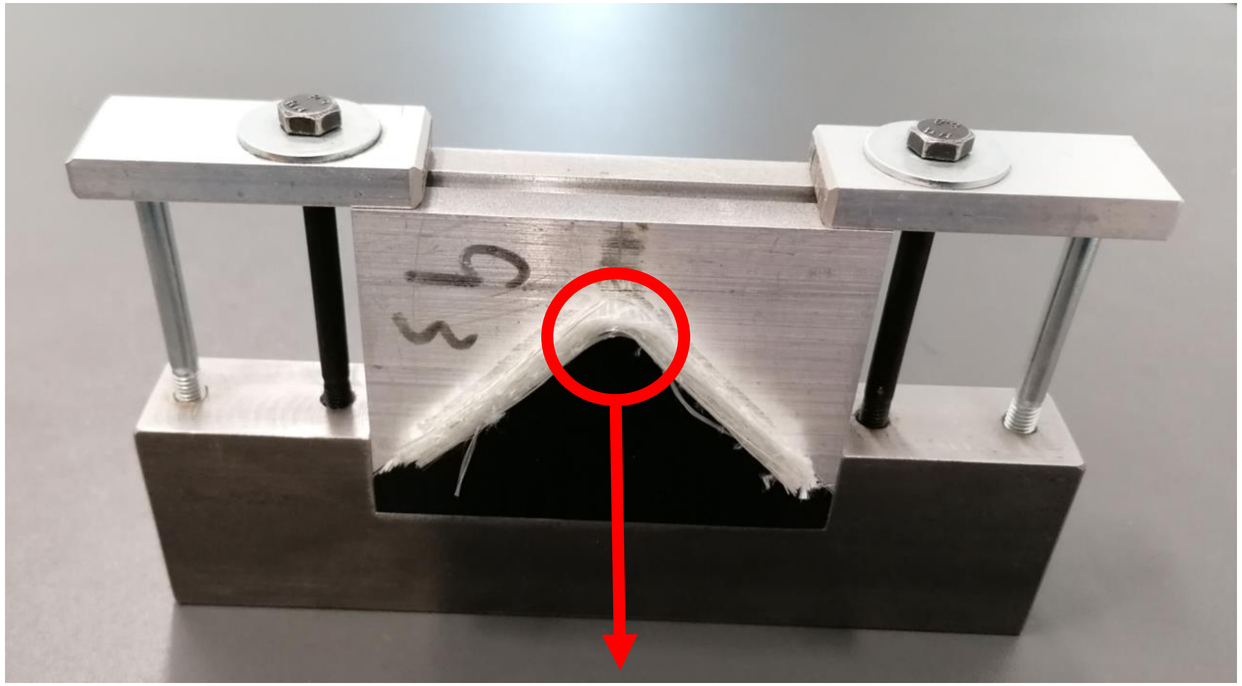
- with radius

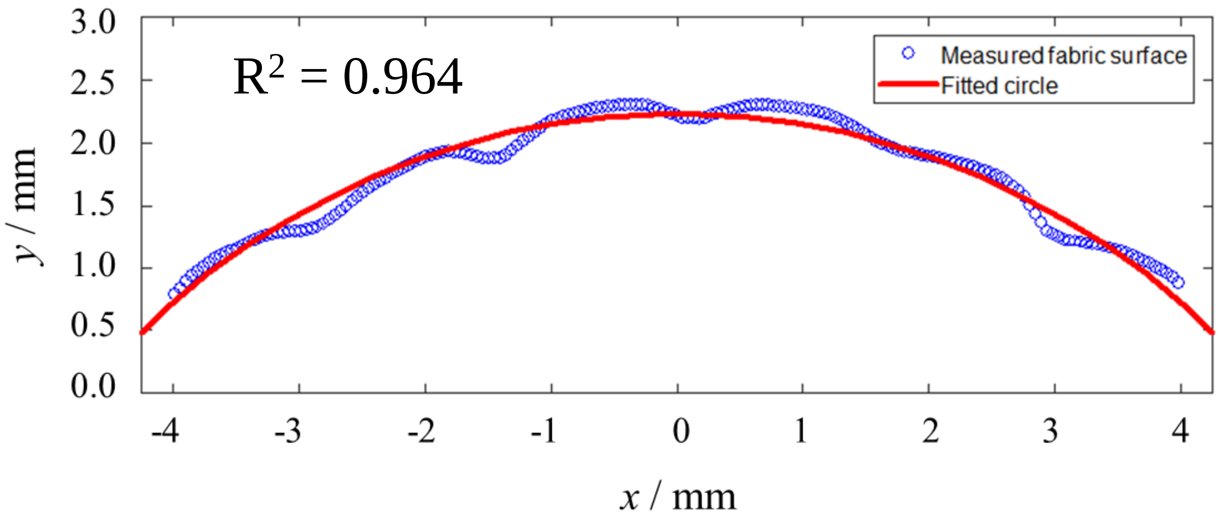
$$R = \frac{2(r+T)(r+t_{min})\cos\delta_T - (r+T)^2 - (r+t_{min})^2}{2((r+T)\cos\delta_T - (r+t_{min}))}$$

- and offset (of centre point)

$$x_c = \frac{(r+T)^2 - (r+t_{min})^2}{2((r+T)\cos\delta_T - (r+t_{min}))}$$

Experimental data suggest that this is a reasonable description





Effective permeability (analytical)

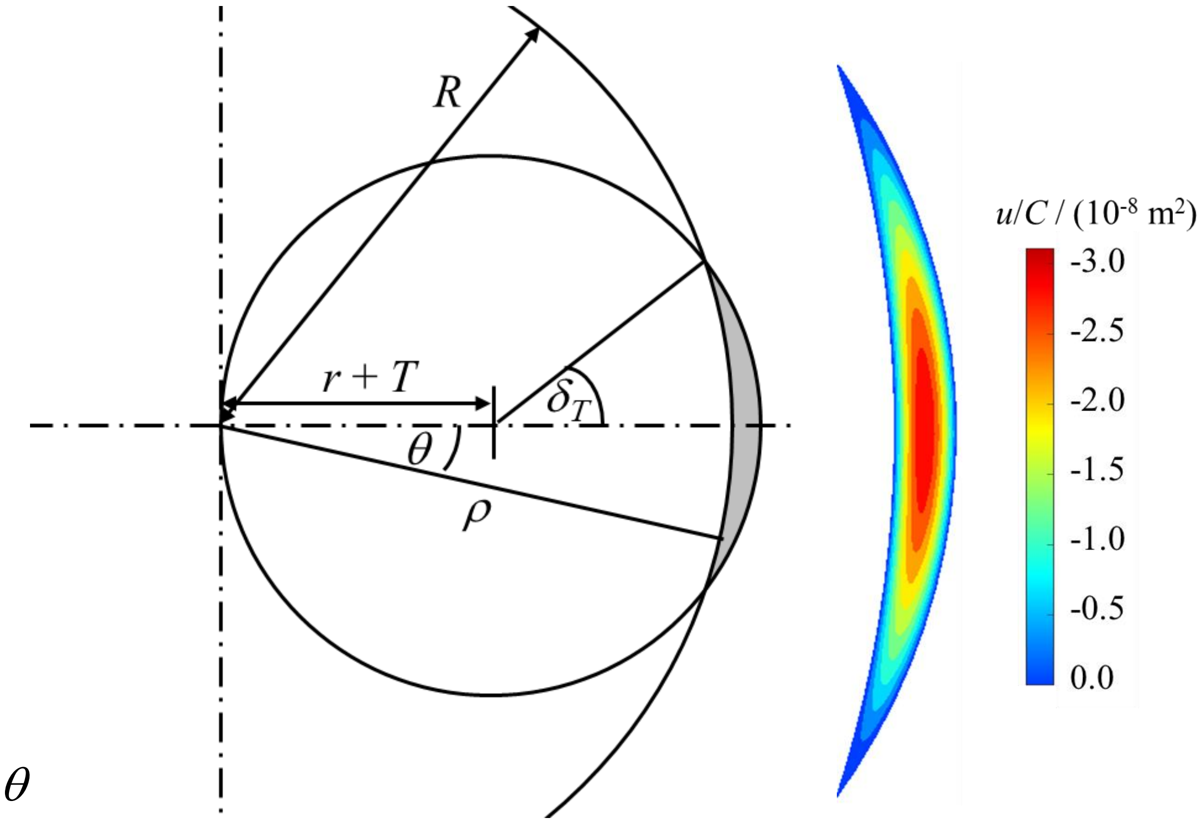
For axial flow in gap, solve Poisson equation

$$C = \frac{1}{\rho}\frac{\partial}{\partial \rho}\left(\rho \frac{\partial u}{\partial \rho}\right) + \frac{1}{\rho^2}\frac{\partial^2 u}{\partial \theta^2} \qquad C = \frac{1}{\eta}\frac{\Delta p}{L}$$

Special case: "moon shaped" duct

$$x_c = -(r+T) \qquad \text{and} \qquad R = 2r + T + t_{min}$$

$$\delta_T = \operatorname{acos}\frac{(r+t_{min})^2 - (r+T)^2 + 2(r+T)(r+t_{min})}{2(r+T)^2}$$



$r+T = 5.0$ mm , $R = 9.5$ mm

Analogy to torsion of bars (Timoshenko)

$$u(\rho,\theta) = C\,\frac{1}{4}\rho^2 - C\,\frac{r+T}{2}\rho\cos\theta + C\,\frac{(r+T)R^2}{2}\frac{1}{\rho}\cos\theta - C\,\frac{R^2}{4}$$

Calculate

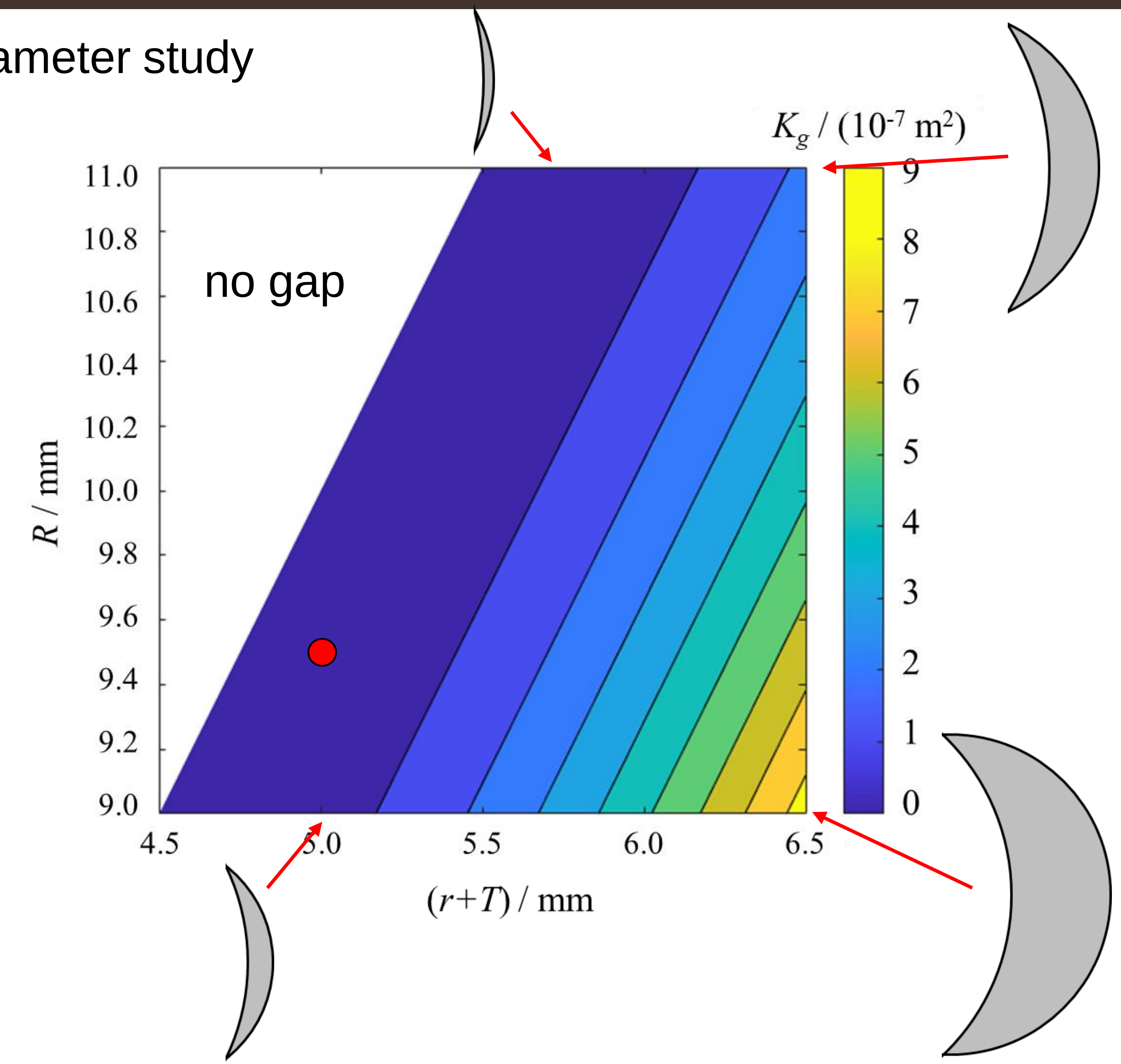
$$Q = \int_{-\theta_T}^{\theta_T}\int_{R}^{2(r+T)\cos\theta} u\,\rho\,d\rho\,d\theta \qquad \text{and} \qquad A = \int_{-\theta_T}^{\theta_T}\int_{R}^{2(r+T)\cos\theta} \rho\,d\rho\,d\theta$$

➡ $$K_g = -\frac{Q}{C\,A}$$

Gap only: $K_g = 1.41\times10^{-8}$ m^2

Effective permeability (analytical)

Parameter study



From Darcy-Weisbach

$$K_g = \frac{2\,D_h^2}{c}$$

Hydraulic diameter

$$D_h = \frac{4\,A_g}{P_g}$$

A_g: gap cross-sectional area

P_g: perimeter

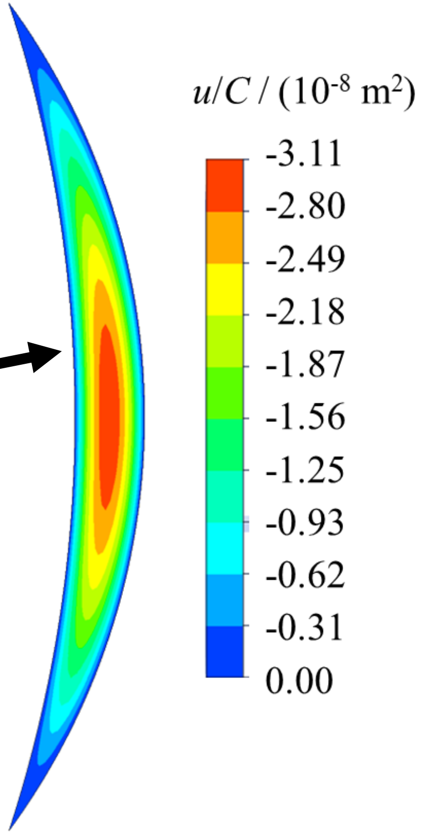
Shape factor, c

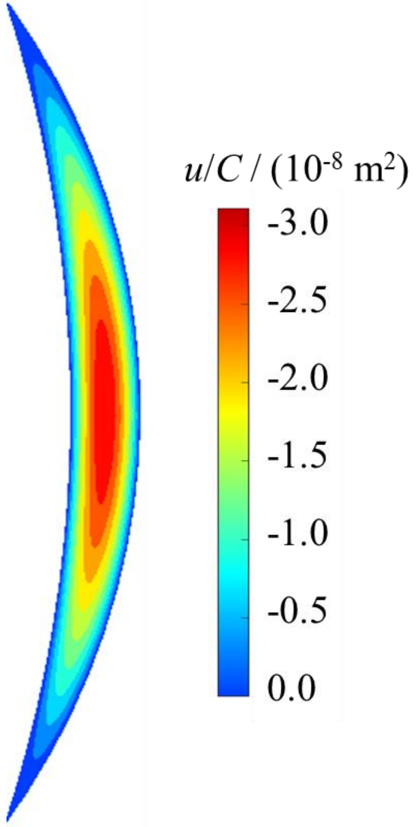
- is a measure for the effect of viscous friction on flux;
- is related to the length of boundaries between fluid layers moving at different velocity in laminar flow.

Effective permeability (numerical)

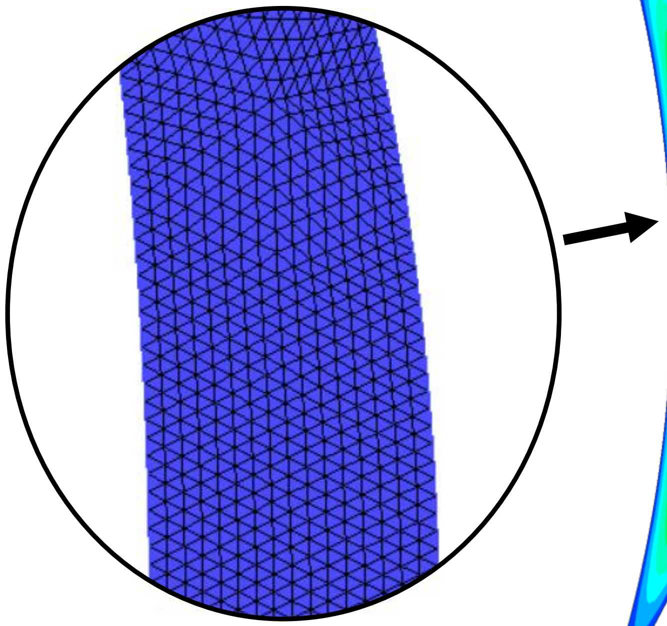
Validation of steady-state CFD simulation (axial flow in moon shaped gap)

	Numerical (Ansys CFX)	Analytical
Flow velocity distribution		





Fine discretisation required



Effective permeability

Numerical (Ansys CFX): $K_g = 1.44 \times 10^{-8}\ m^2$

Analytical: $K_g = 1.41 \times 10^{-8}\ m^2$

Effective permeability (simulation)

The University of Nottingham
UNITED KINGDOM · CHINA · MALAYSIA

Analyse axial and transverse flow through bend using CFD

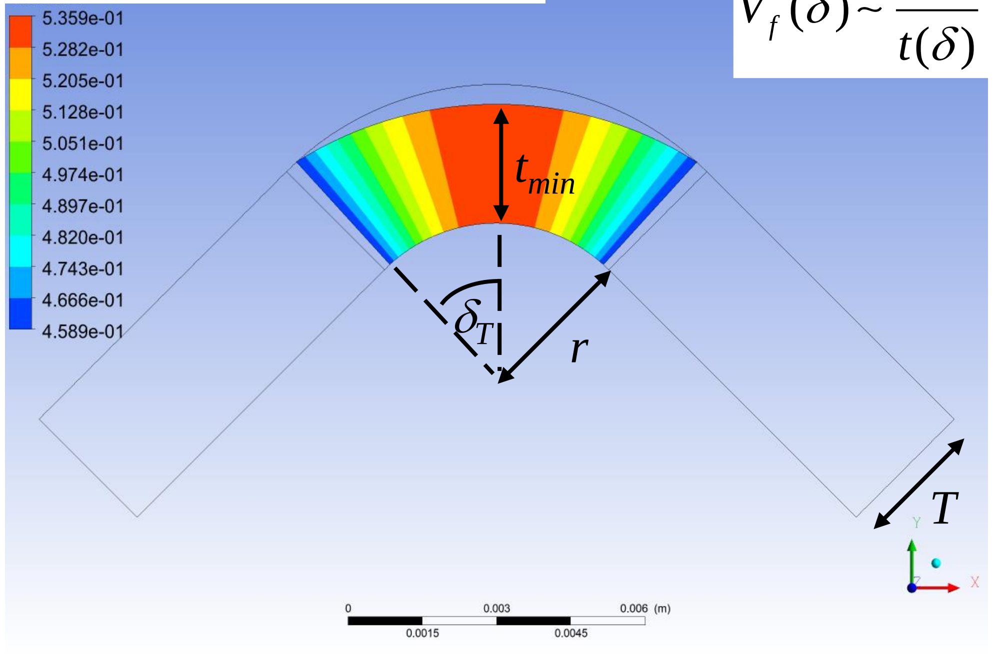
Reinforcement on both sides of bend: porous medium with uniform properties (thickness T)

Compressed reinforcement ($-\delta_T < \delta < \delta_T$): porous medium with varying properties (thickness $t(\delta)$)

In gap: fluid only

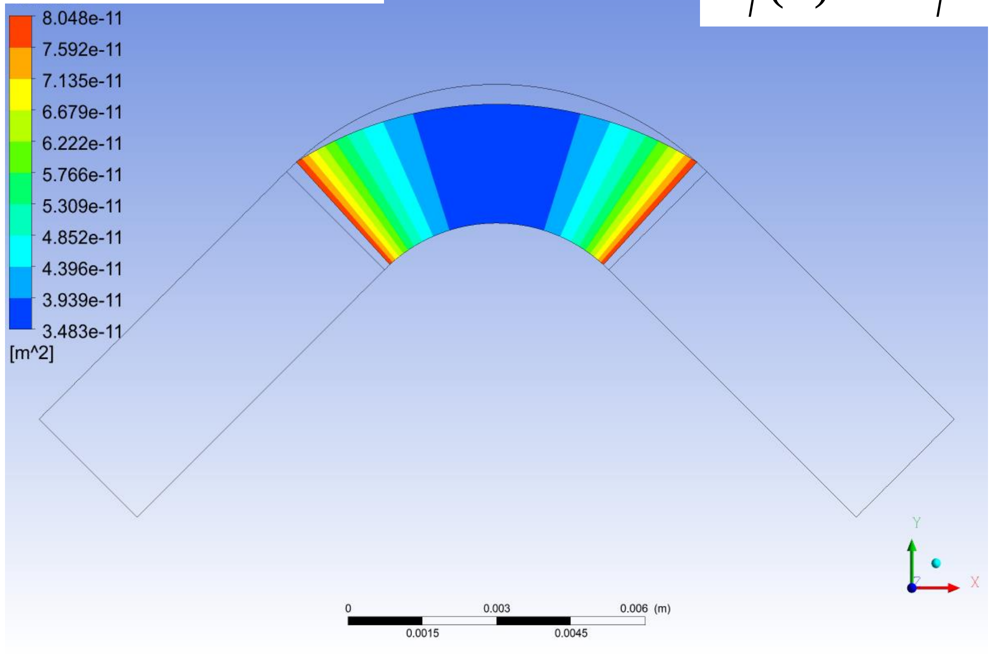
Local fibre volume fraction

$$V_f(\delta) \sim \frac{1}{t(\delta)}$$



Local permeability

$$K_f(\delta) = A V_f^{-B}$$



Effective permeability (simulation)

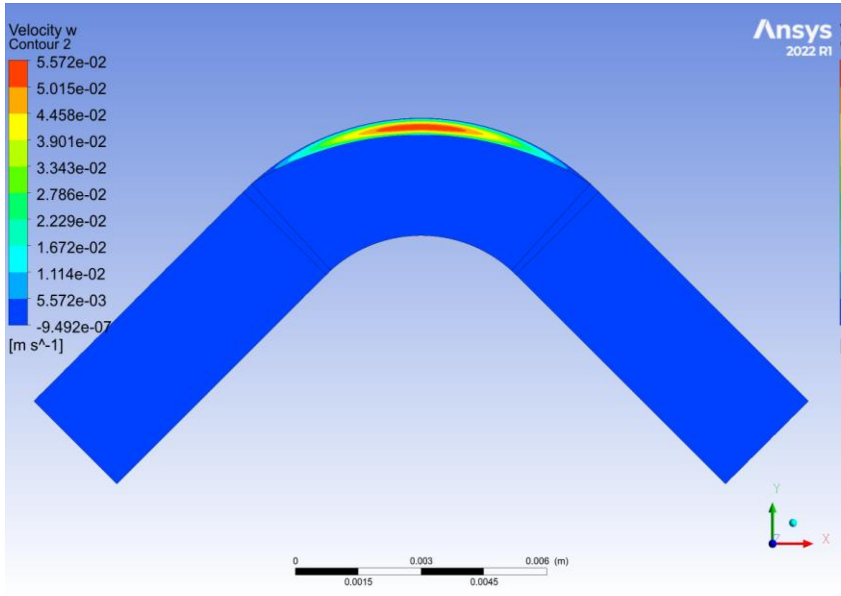
Steady-state flow simulation (saturated flow)

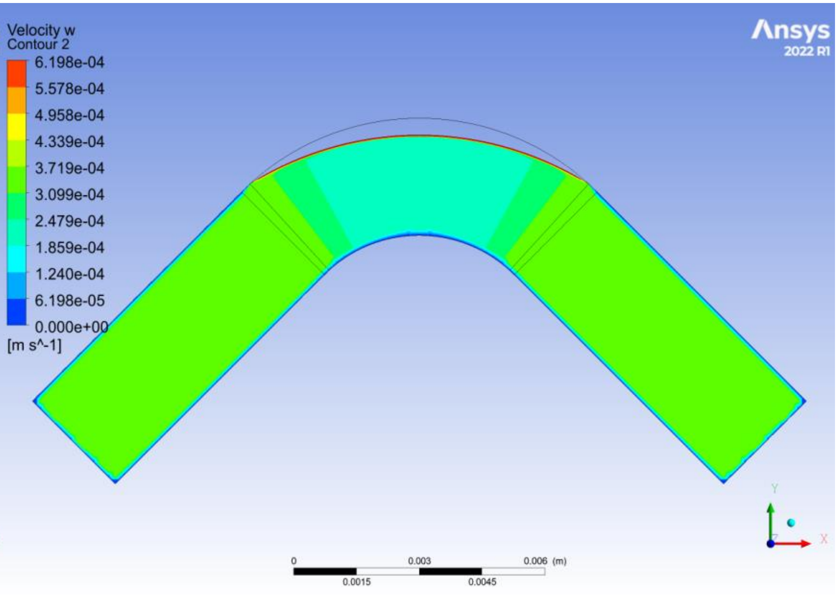
φ	r / mm	T / mm	t_{min} / mm	δ_T	R / mm	x_c / mm
90°	3.20	2.80	2.40	42°	7.60	-2.00

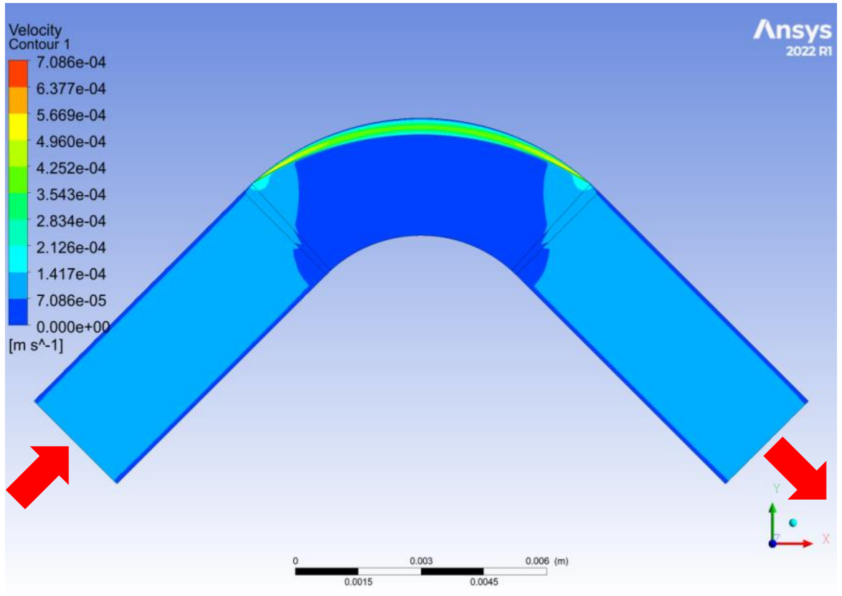
Determine permeability from mass flow

axial $K_a = 5.03\times10^{-10}$ m^2

transverse $K_t = 9.37\times10^{-11}$ m^2





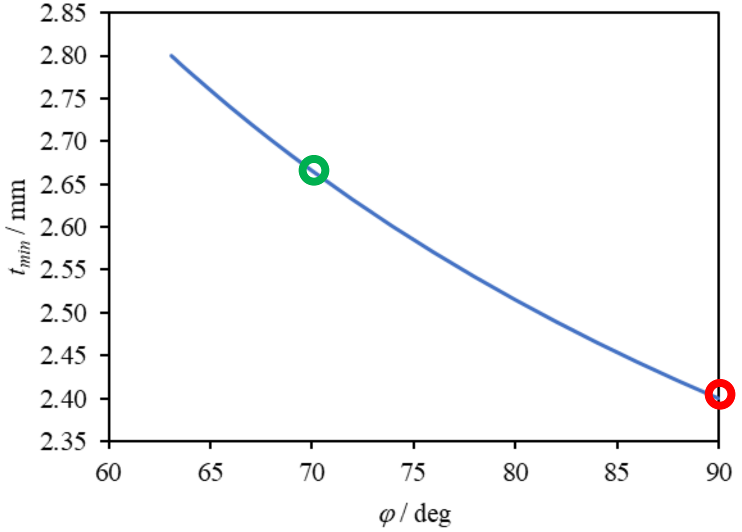


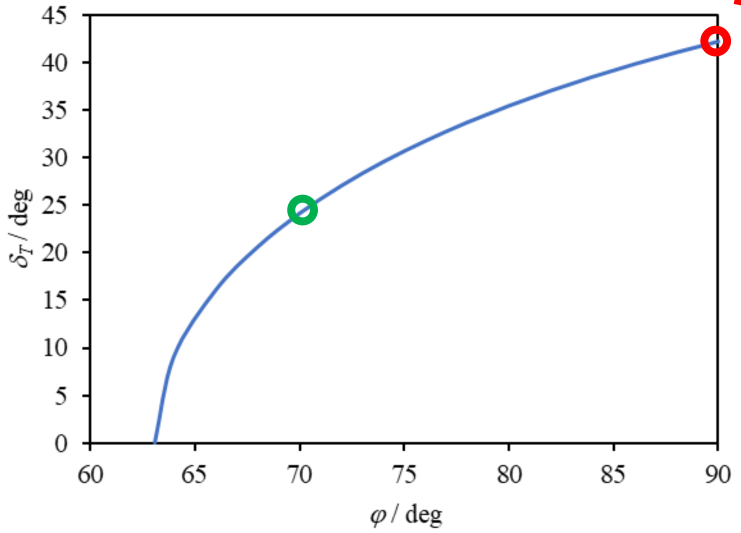
Permeability of flat reinforcement at thickness T is 8.01×10^{-11} m^2

Effective permeability (simulation)

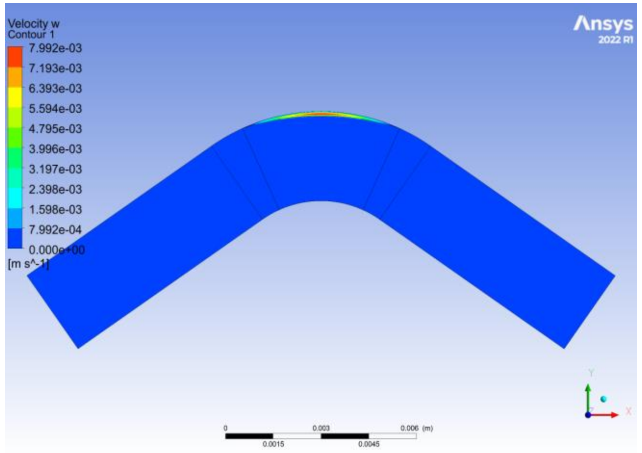
Effect of bend angle

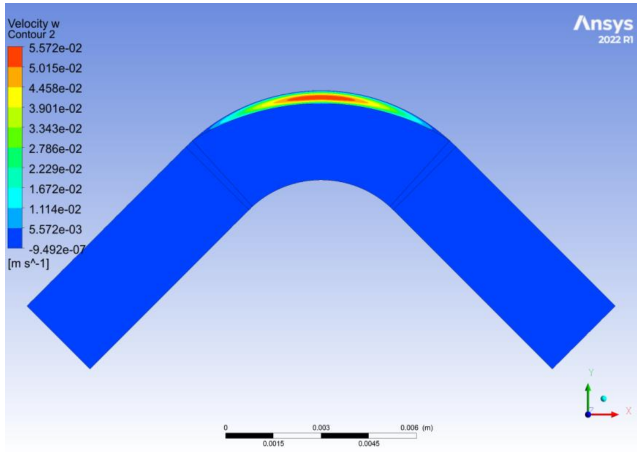
(preliminary) estimate for gap shape



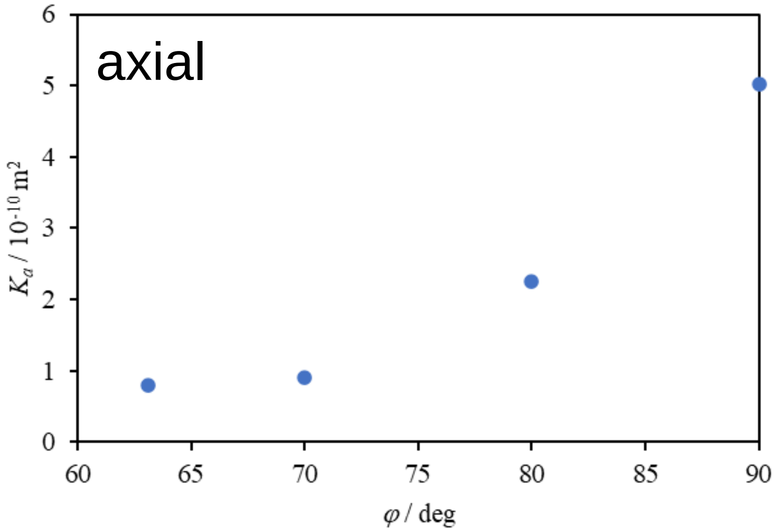


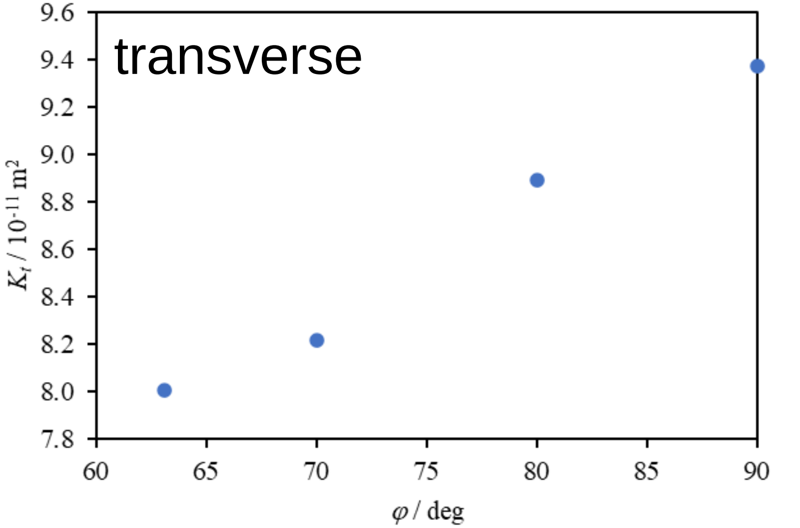
simulation models





effective permeability



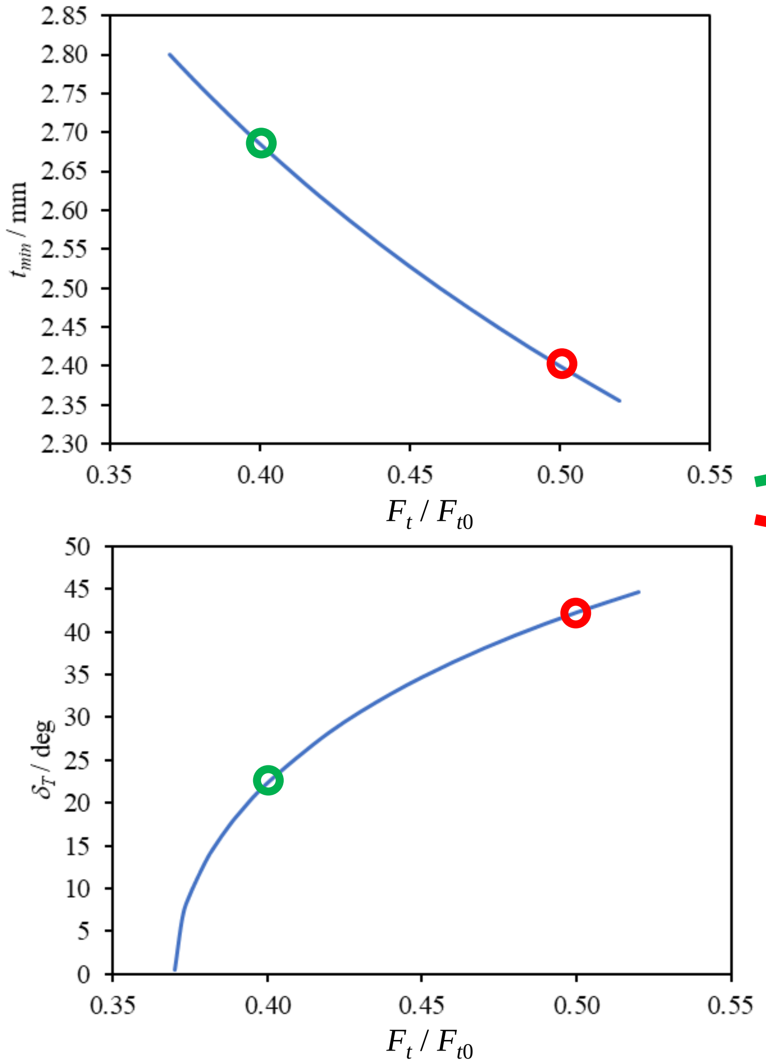


Effective permeability (simulation)

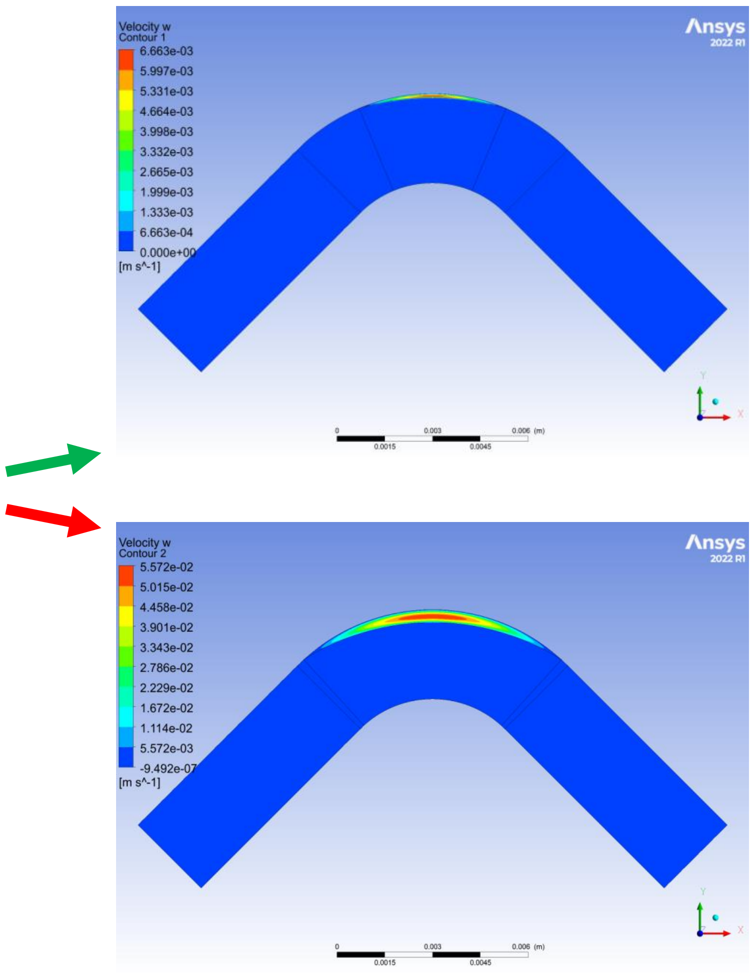
The University of Nottingham
UNITED KINGDOM · CHINA · MALAYSIA

Effect of (normalised) tensile force

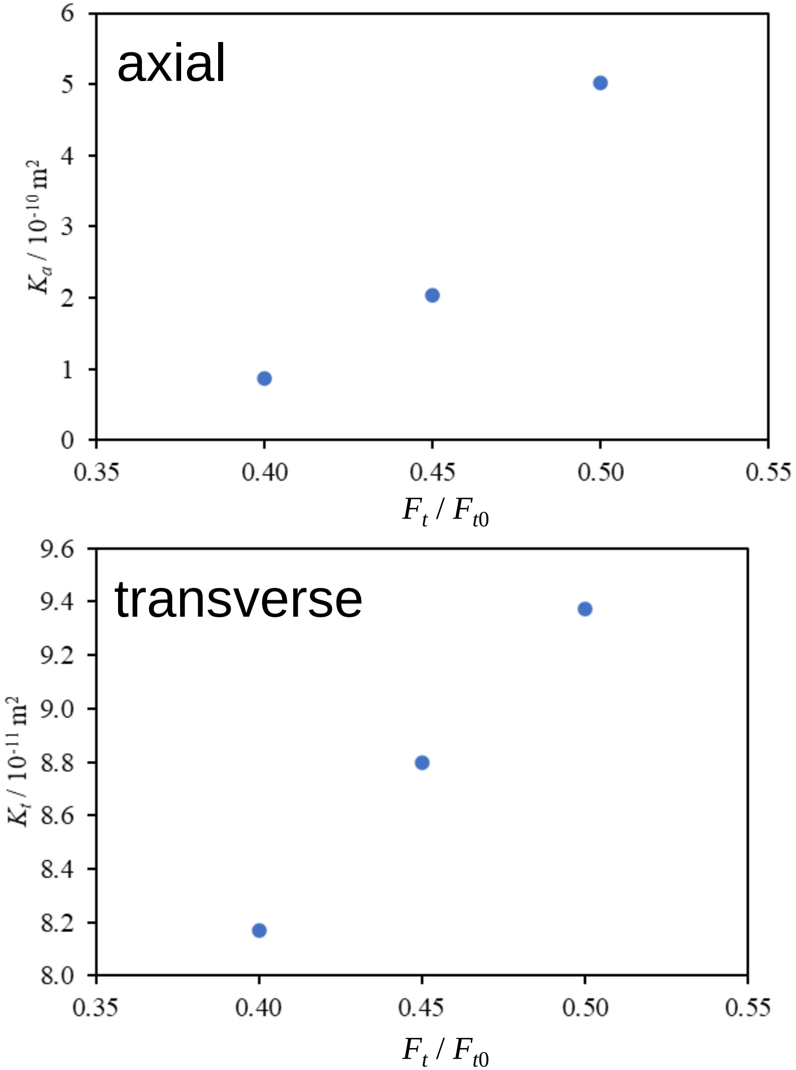
(preliminary) estimate for gap shape



simulation models



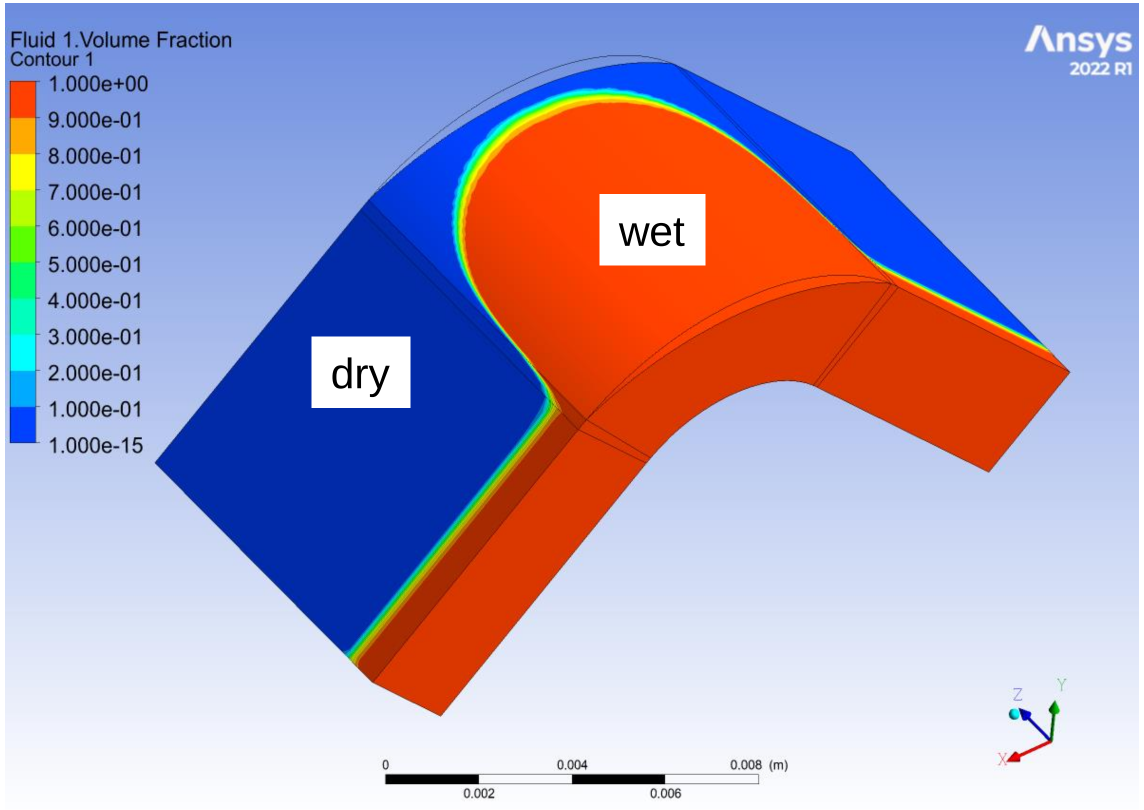
effective permeability



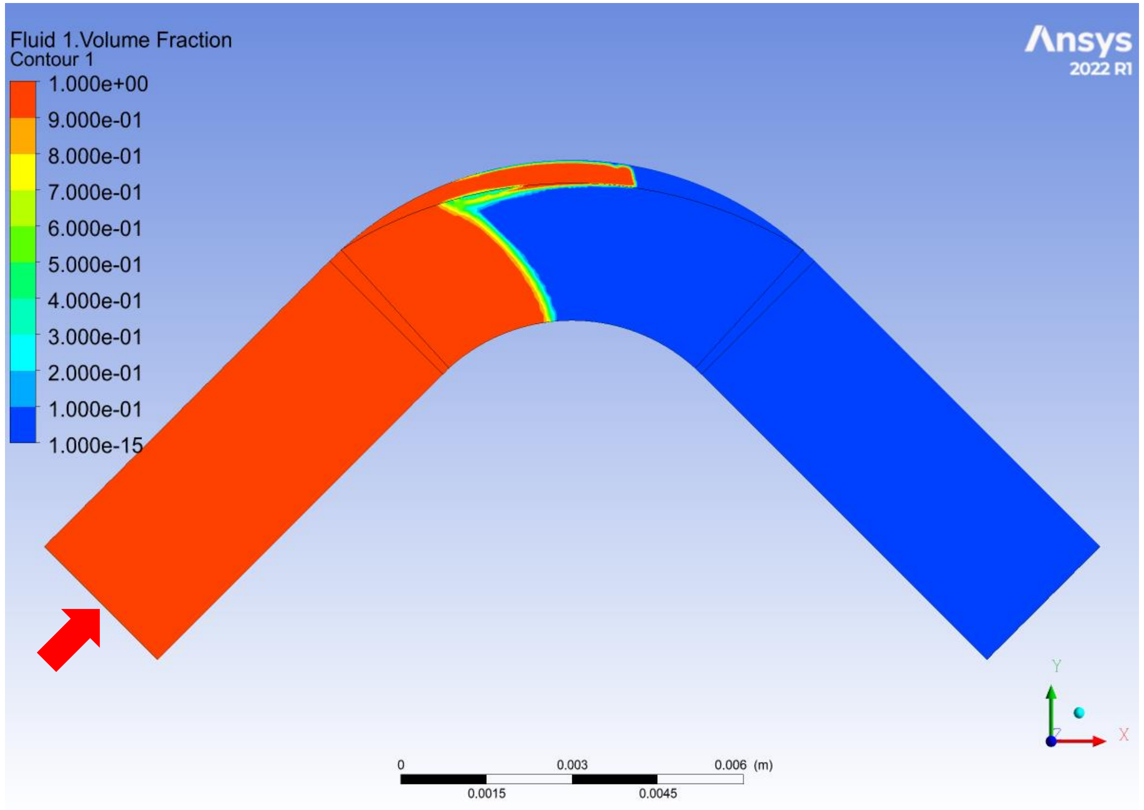
Flow front shapes

Transient flow simulation (unsaturated flow)

axial



transverse



Inside of bend: lagging of flow front (locally reduced reinforcement permeability)

Outside of bend: racetracking in gap

Conclusion

- A model for formation of gap between reinforcement and upper tool surface (and the shape of the gap) still needs to be formulated.

- Descriptors for the gap size were defined, i.e. gap height and opening angle.

- An analytical solution for the effective gap permeability was derived for a special case.

- The effect of different parameters on the gap size was estimated.

- CFD simulations were run to find effective permeabilities of the bend (gap and compressed reinforcement).

- Typical flow patterns at the bend were predicted.

Acknowledgement

The University of Nottingham
UNITED KINGDOM · CHINA · MALAYSIA

This work was supported by the Engineering and Physical Sciences Research Council, UK, through the EPSRC Future Composites Manufacturing Research Hub [EP/P006701/1].