TRANSVERSE LIQUID COMPOSITE MOULDING: DEVELOPMENT AND COMPARISON OF PROCESS MODELS

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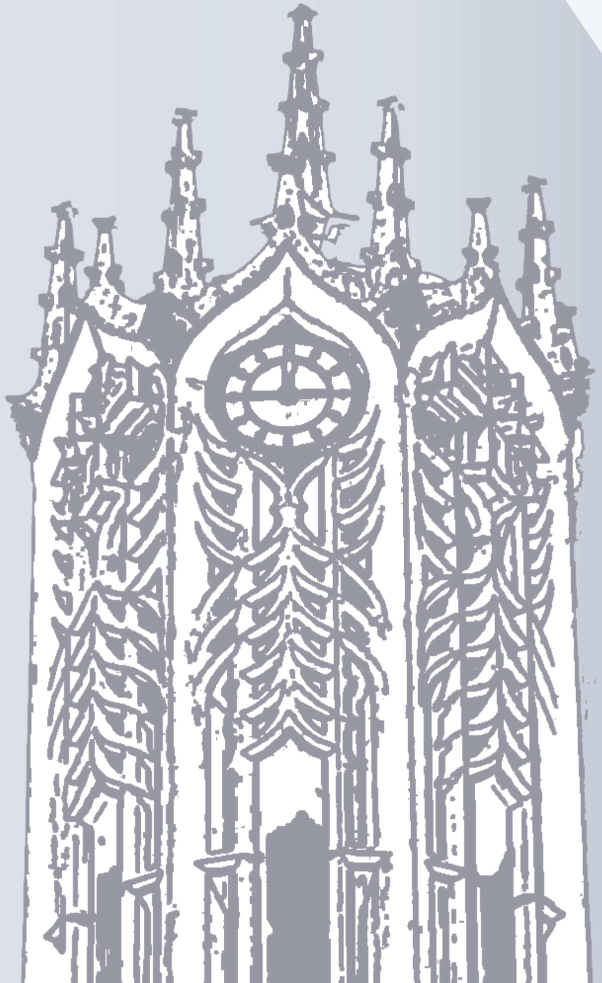

ICCM23

INTERNATIONAL CONFERENCE ON COMPOSITE MATERIALS

BELFAST 2023

UNIVERSITY OF AUCKLAND Waipapa Taumata Rau NEW ZEALAND

CENTRE FOR ADVANCED MATERIALS MANUFACTURING & DESIGN

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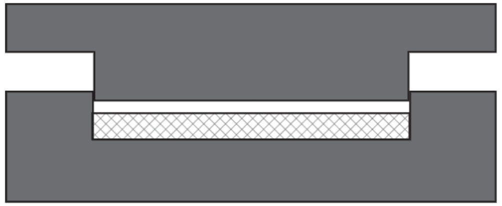
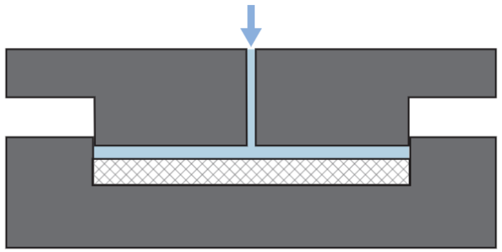
Transverse Liquid Composite Moulding

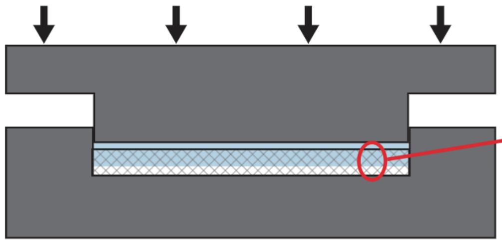
- Liquid Composite Moulding: impregnation of a dry preform with liquid resin in a mould
- Impregnation in the through-thickness (transverse) direction ⇒ reduce the flow length
- **Compression Resin Transfer Moulding (CRTM)**



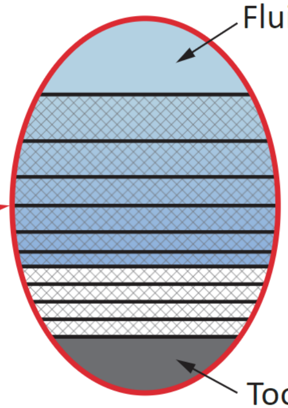
1. Partial mould closure to create cavity above dry preform



2. Resin injection into cavity



3. Mould closure to impregnate and compact preform

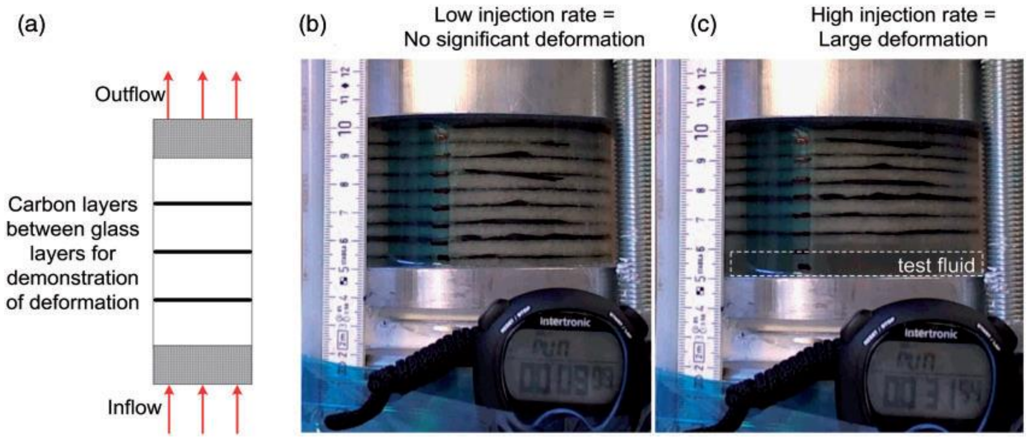


Aircraft wing rib preform for CRTM

Gardiner G. Compression RTM for production of future aerostructures. Composites World 2020. https://www.compositesworld.com/articles/compression-rtm-for-production-of-future-aerostructures

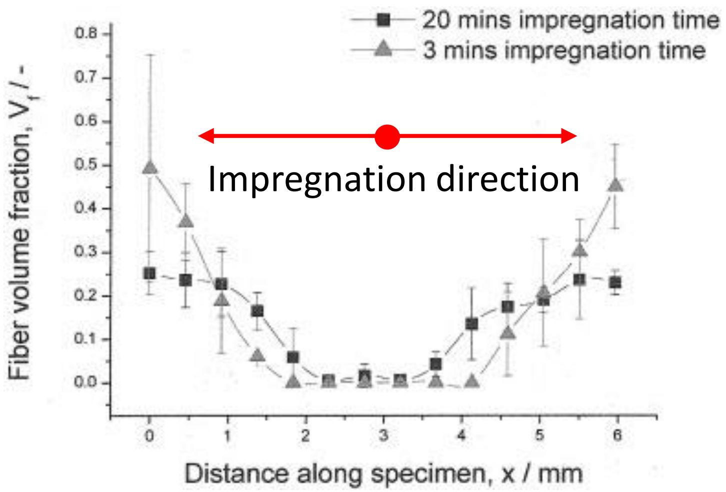
- Examples of non-uniform compaction during through thickness impregnation

  Increasing fibre volume fraction in the impregnation direction



Klunker et al. (2015)

Impregnation direction



Wolfrath et al. (2005)

Impregnation direction

Studer et al. (2019)

Klunker F, Danzi M, Ermanni P. Fiber deformation as a result of fluid injection: Modeling and validation in the case of saturated permeability measurements in through thickness direction. J Comp Mat 2015;49(9):1091–105.
Studer J, Dransfeld C, Jauregui J, Keller A, Wink M, Masania K, Fiedler B. Effect of fabric architecture, compaction and permeability on through thickness thermoplastic melt impregnation. Comp A 2019;122:45–53.
Wolfrath J, Michaud V, Månson J. Graded Glass Mat–Reinforced Polypropylene. Poly Comp 2005;26(3):361-369

Motivation and aims

- **Non-uniform fibre volume fraction** in the final part can lead to inconsistent structural properties
- Simulate the resin flow and preform deformation to predict the **homogenisation time** and **tooling forces** for transverse LCM processes
- Many process models have been developed which make various simplifying assumptions to reduce computational cost and model complexity

Aims

- Compare transverse LCM process models with varying model complexity
- Investigate manufacturing conditions that result in accurate predictions for these process models

Flow through deformable porous media

- Conservation of mass (fluid and solid)
- Darcy's law for flow through porous media
- Terzaghi's law: total applied stress = effective stress + fluid pressure, $\frac{\partial p}{\partial x} + \frac{\partial \sigma_{eff}}{\partial x} = 0$
- Constitutive relation for permeability $K(\phi_s)$
- Constitutive relation for compaction stress $\sigma_{eff}^{wet}(\phi_s), \sigma_{eff}^{dry}(\phi_s)$

Effective stress

Permeability

Fibre volume fraction

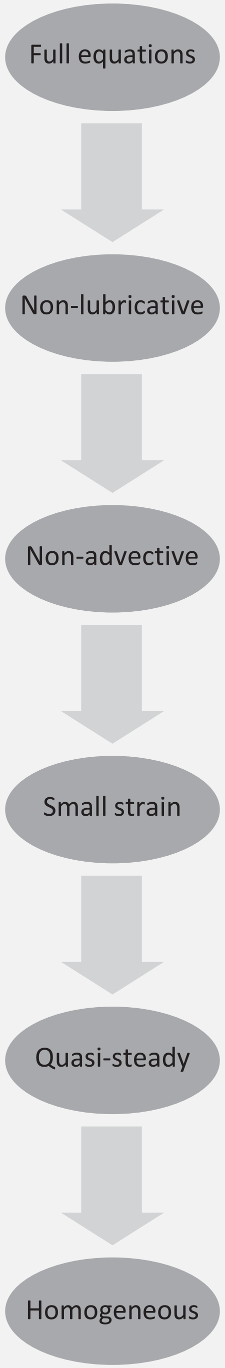
$$\frac{\partial}{\partial x}\left(\frac{K(\phi_s)}{\mu}\frac{\partial \sigma_{eff}}{\partial x}\right) = \frac{1}{\phi_s}\left(\frac{\partial \phi_s}{\partial t} + v_s\frac{\partial \phi_s}{\partial x}\right)$$

Fluid viscosity

Solid velocity

Simplified process models

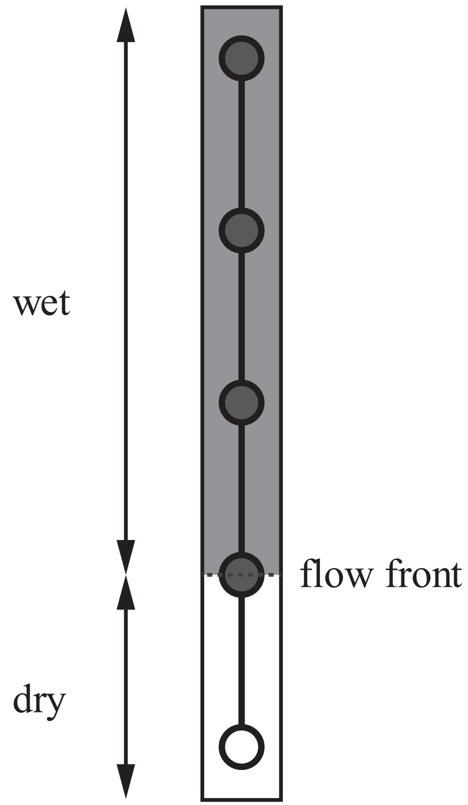
Simplifications to the governing equation

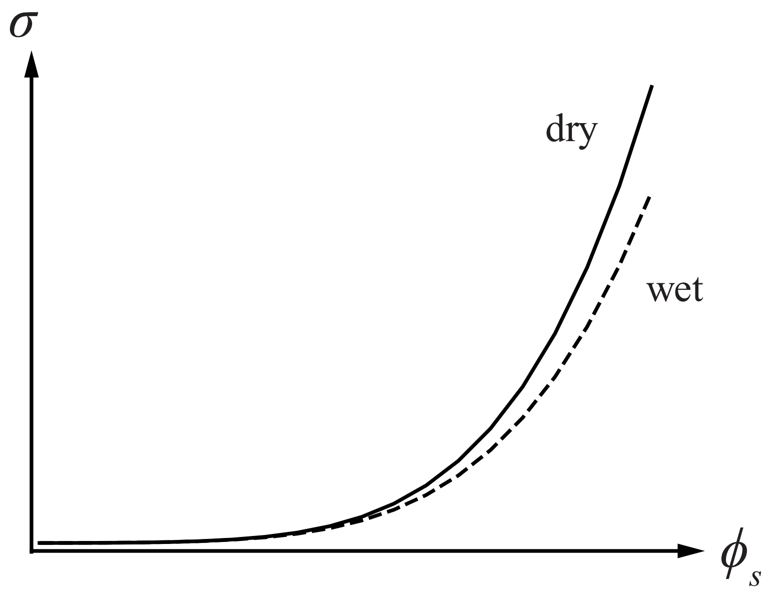


Decreasing model complexity

- Previous studies have made assumptions to simplify the full governing equation to reduce computational cost and model complexity
- Many simplified models are based on the assumption of relatively slow flow and small deformations

Non-lubricative assumption





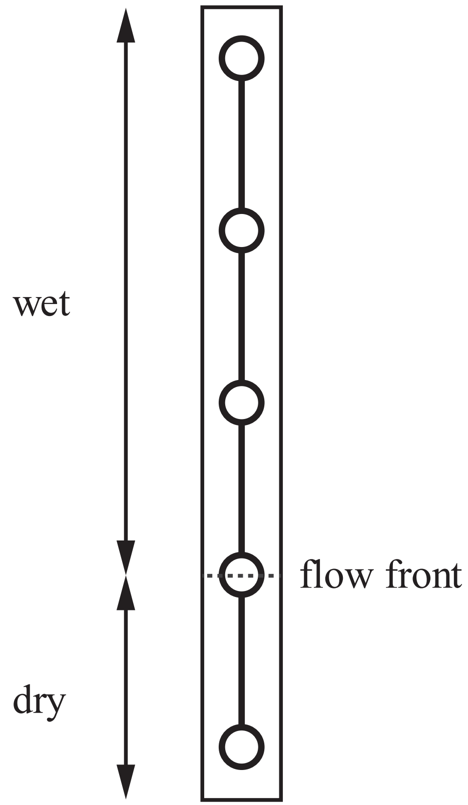
Full equations

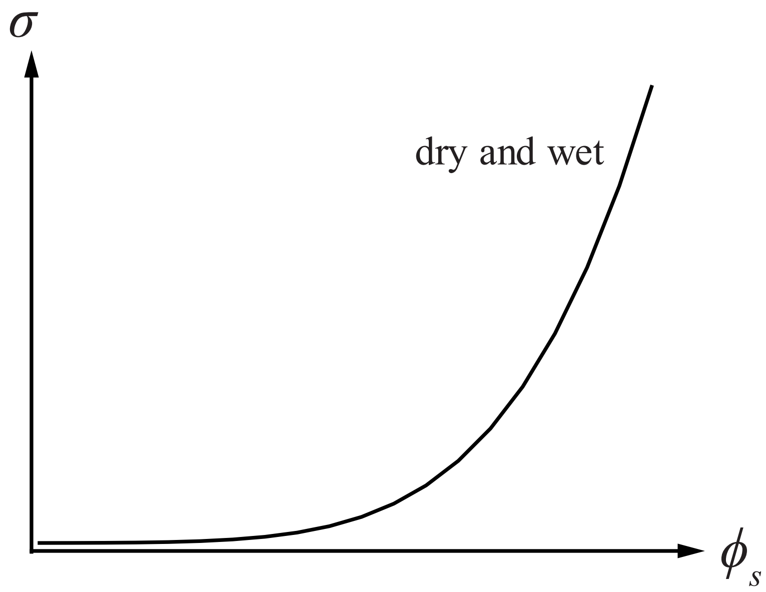
Identical wet & dry compaction behaviour

Non-lubricative

Non-lubricative assumption

- Assume negligible lubrication effects





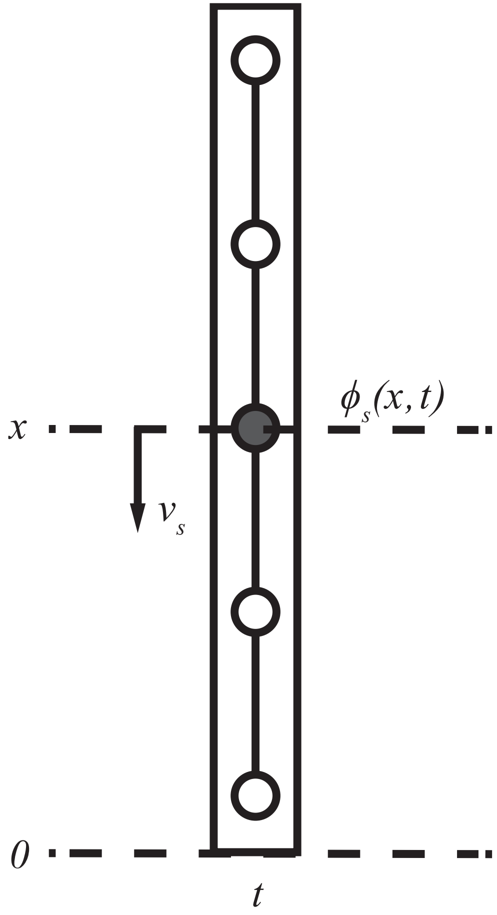
Full equ ations

Identical wet & dry compaction beh aviour

Non-lubri cative

Non-advective assumption

- The time derivative of ϕ_s must include the change in ϕ_s due to the **movement of the solid**, as well as the change in ϕ_s at x.
- At time t:



Full equations

Identical wet & dry compaction behaviour

Non-lubricative

Non-advective assumption

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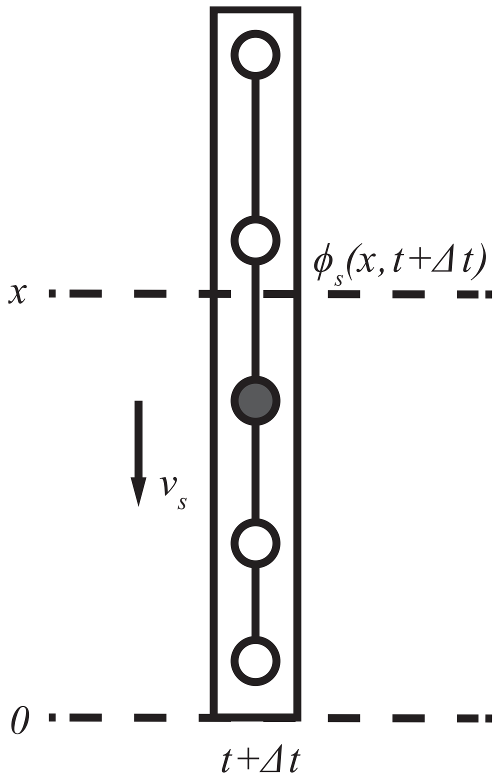
- At time $t + \Delta t$:



Full equations

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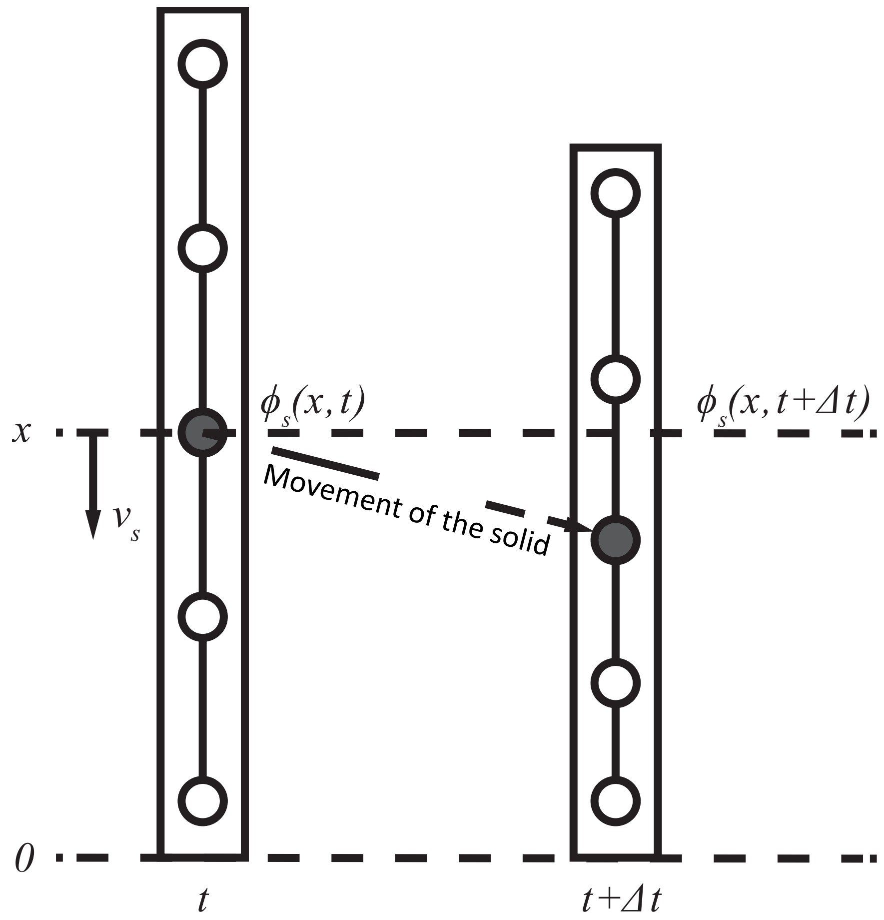
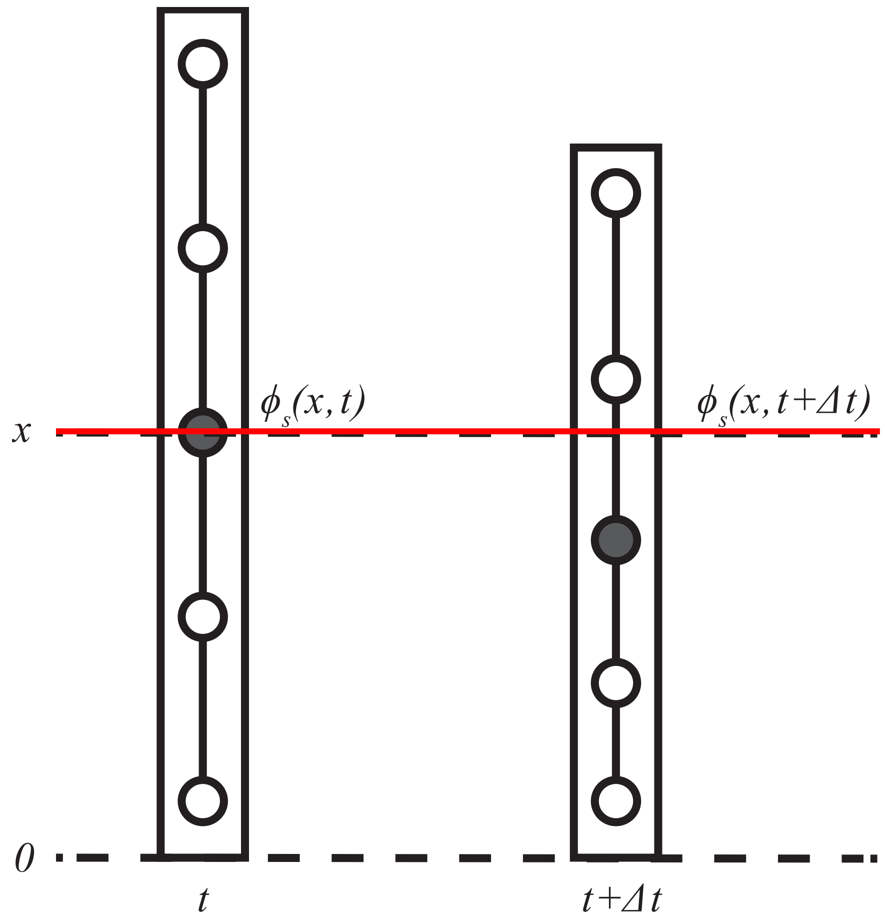


material time derivative
= local + advective

Non-advective assumption

- Assume negligible advection (assume that the movement of the solid v_s is negligible)

material time derivative
= local + ~~advective~~



$$\frac{\partial}{\partial x}\left(\frac{K(\phi_s)}{\mu}\frac{\partial p}{\partial x}\right) = -\frac{1}{\phi_s}\frac{\partial \phi_s}{\partial t}$$

Small strain approximation

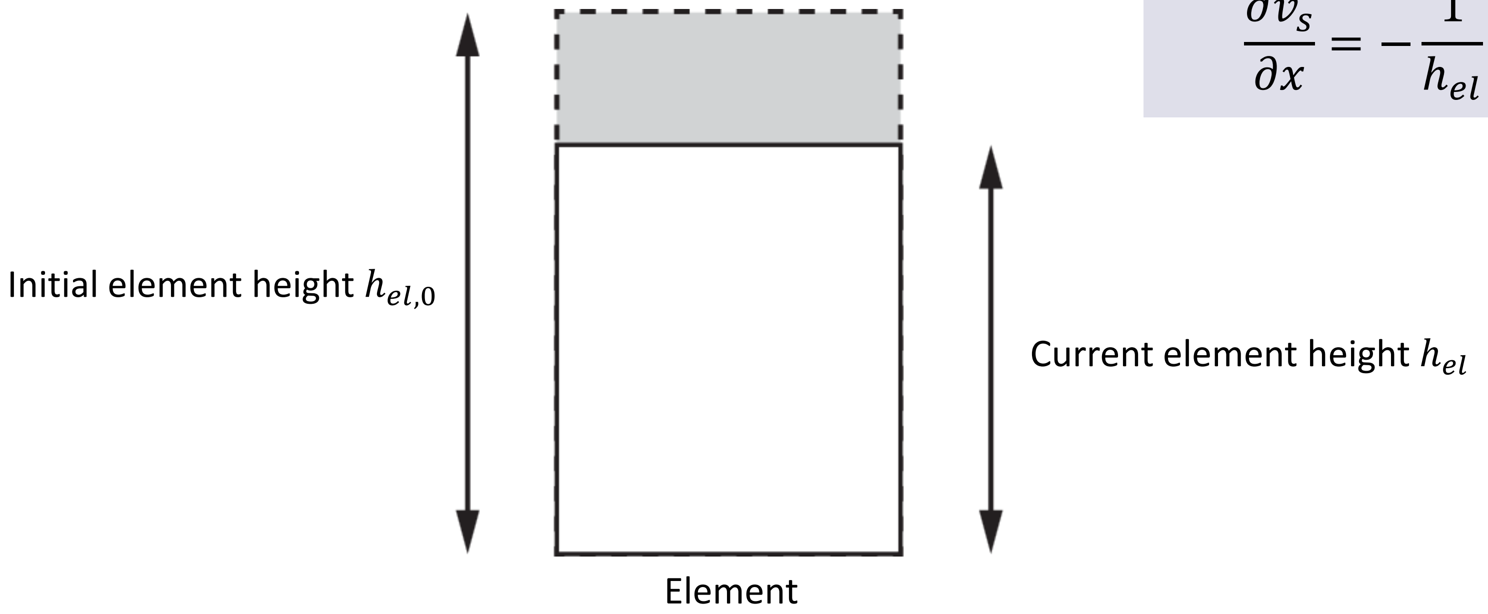
- Large deformations

$$\nabla . v_s = -\frac{1}{dV}\frac{d(dV)}{dt}$$

dV: current elementary volume

In 1D:

$$\frac{\partial v_s}{\partial x} = -\frac{1}{h_{el}}\frac{dh_{el}}{dt}$$



Full equations

Identical wet & dry compaction behaviour

Non-lubricative

Neglect change in ϕ_s in time due to movement of the fabric

Non-advective

Small strain approximation

Small strain

Small strain approximation

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- Assume small deformations

$$\nabla . v_s = -\frac{1}{dV_0}\frac{d(\Delta V)}{dt}$$

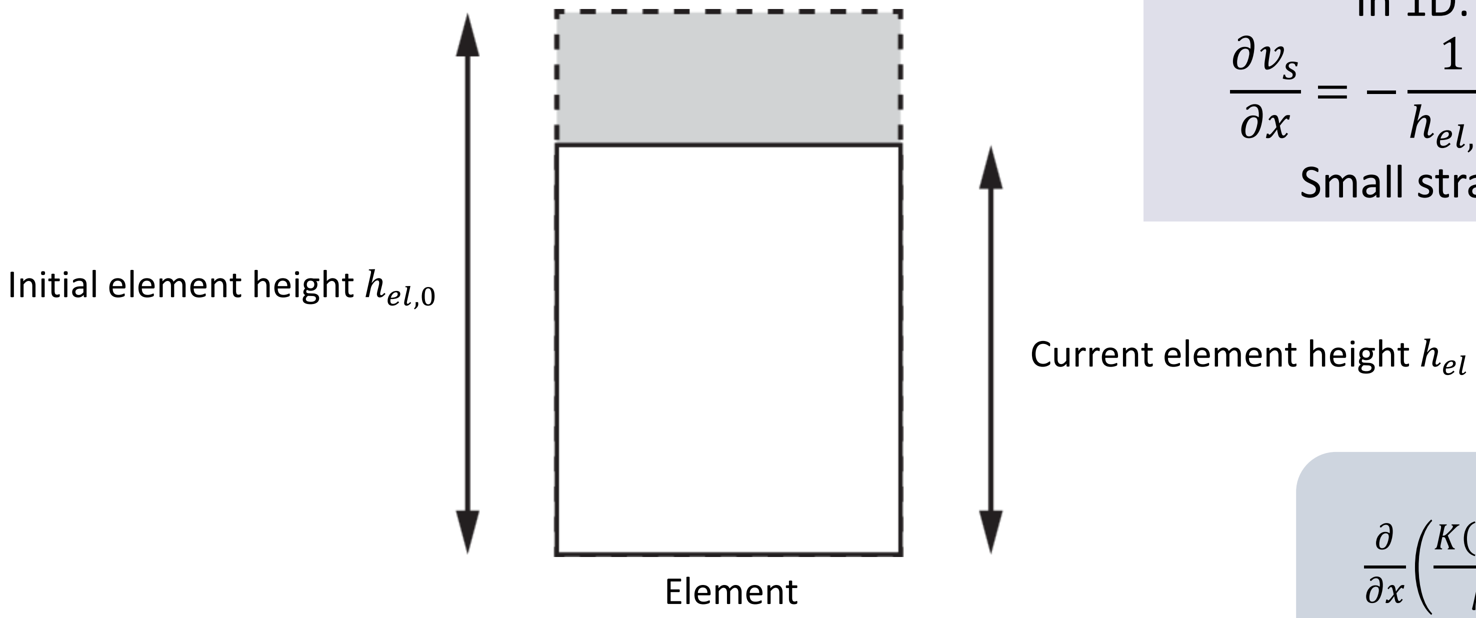
dV_0: initial elementary volume

$\Delta V = dV_0 - dV$: change in elementary volume

In 1D:

$$\frac{\partial v_s}{\partial x} = -\frac{1}{h_{el,0}}\frac{dh_{el}}{dt}$$

Small strain



$$\frac{\partial}{\partial x}\left(\frac{K(\phi_s)}{\mu}\frac{\partial p}{\partial x}\right) = -\frac{\phi_0}{\phi_s^2}\frac{\partial \phi_s}{\partial t}$$

Quasi-steady assumption

Full equations

Identical wet & dry compaction behaviour

Non-lubricative

Neglect change in ϕ_s in time due to movement of the fabric

Non-advective

Small strain approximation

Small strain

Neglect transient term

Quasi-steady

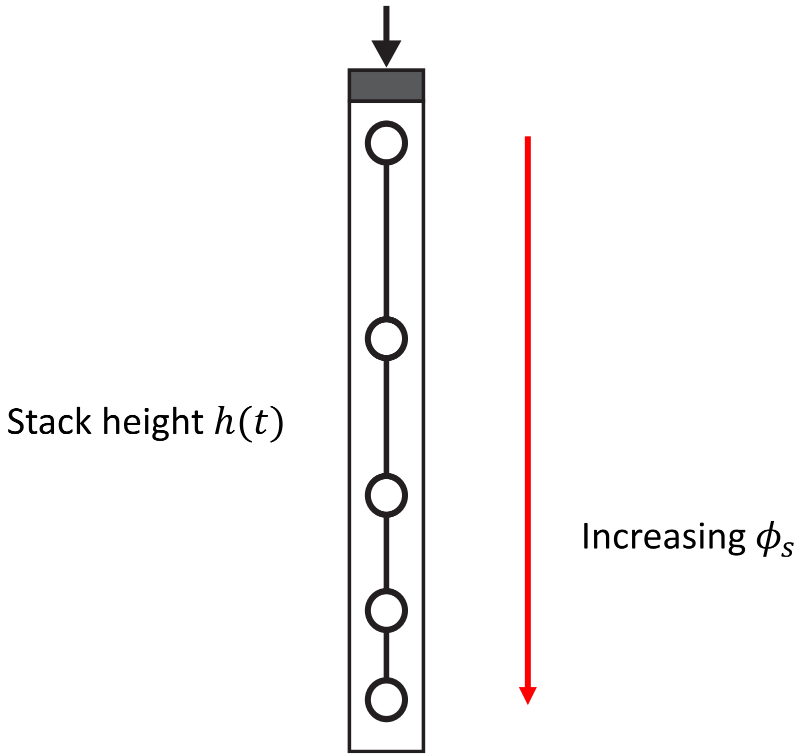
- Assume that flow and deformation are sufficiently slow and solve to steady state at each time step by neglecting the transient term, $\frac{\partial \phi_s}{\partial t} \to 0$

As the flow and deformation become very slow (time derivatives approach zero), solutions should converge

$$\frac{\partial}{\partial x}\left(\frac{K(\phi_s)}{\mu}\frac{\partial p}{\partial x}\right) = 0$$

Homogeneous deformation assumption

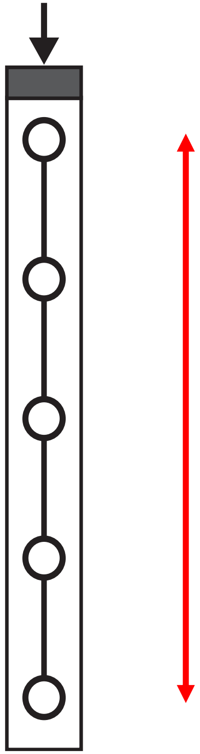
- Due to hydrodynamic compaction, the nodes are non-uniformly distributed through the thickness for saturated fabric



Homogeneous deformation

- Assume the distribution of fibre volume fraction is homogeneous through the thickness

Stack height $h(t)$

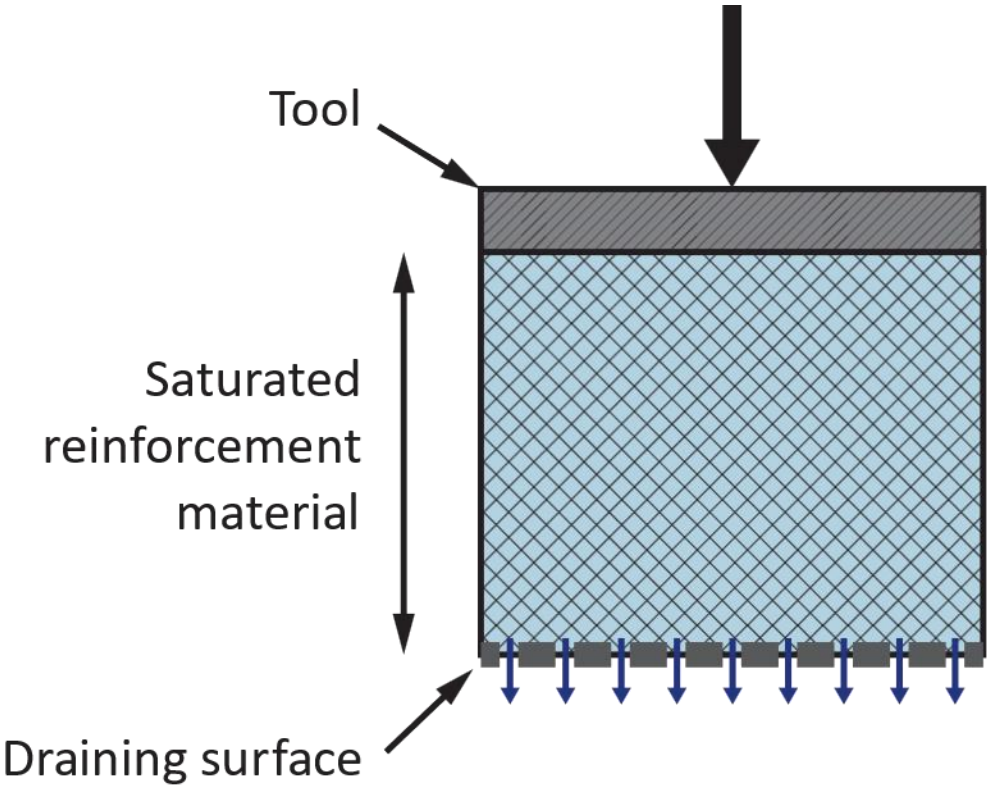


Uniform $\phi_s = \frac{\phi_0 h_0}{h(t)}$

$$\frac{K(\phi_s)}{\mu}\frac{\partial^2 p}{\partial x^2} = -\frac{1}{h}\frac{\partial h}{\partial t}$$

Comparison of simulation results from different process models

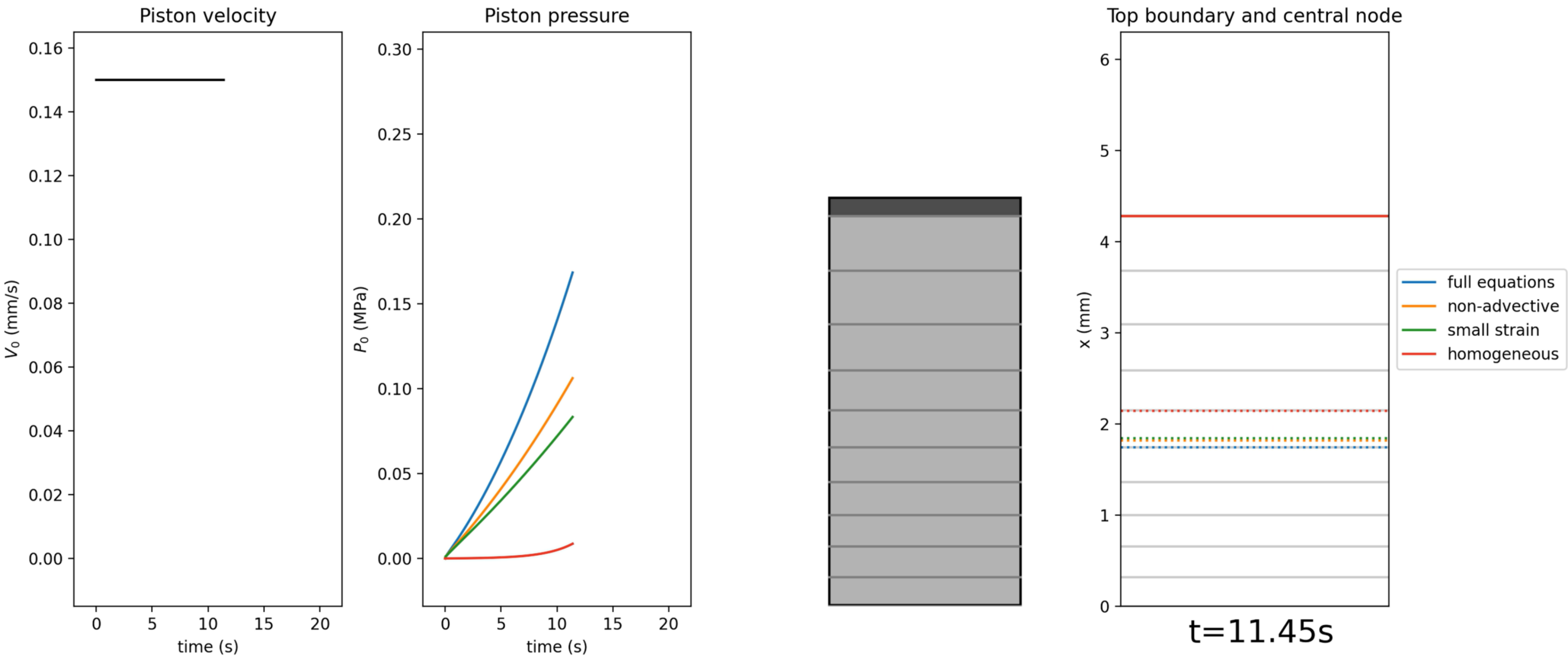
- Simplest scenario involving transverse flow and compaction
- Occurs during consolidation of prepreg plies, last stage of most transverse LCM processes when the preform is held at constant thickness/pressure



Compression of a saturated stack

Constant compaction velocity

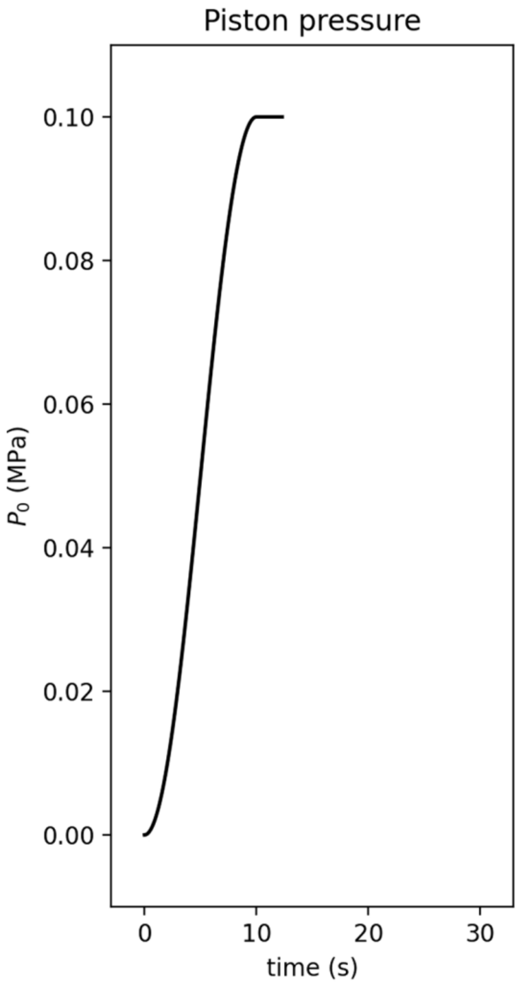
Grey lines represent elements in the full model

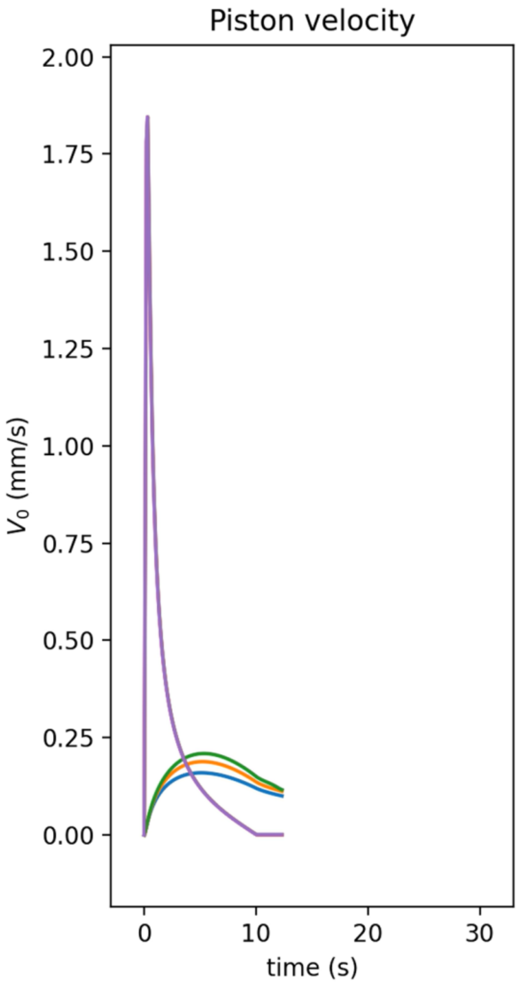


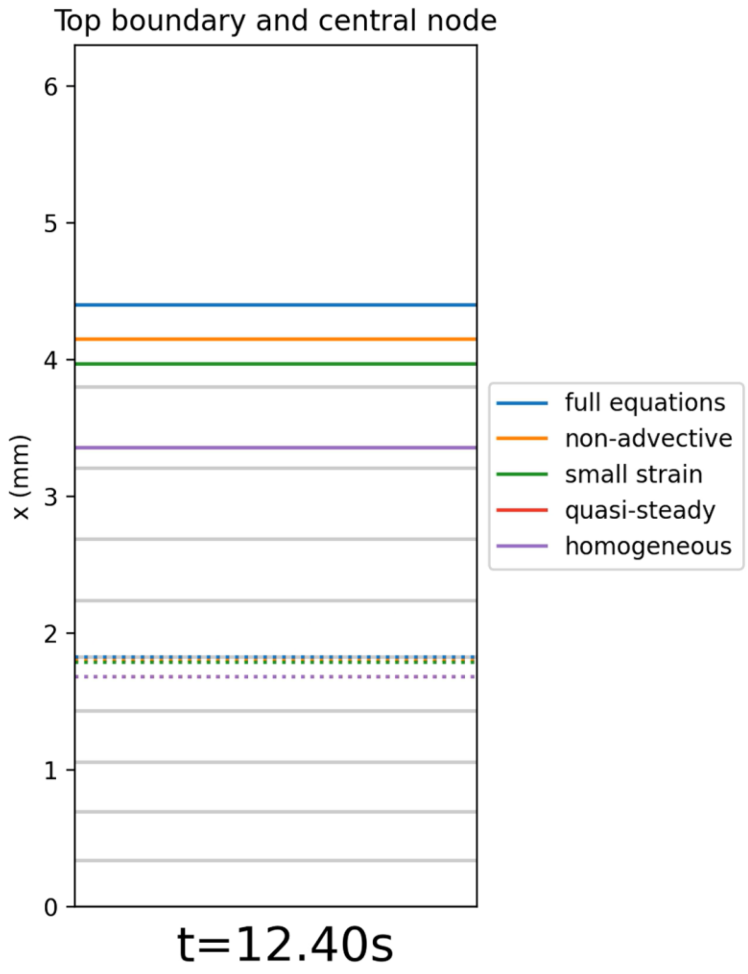
Compression of a saturated stack

Ramp-up to constant compaction pressure

Grey lines represent elements in the full model







Compression of a saturated stack

Node positions

Resulting tool velocity/pressure

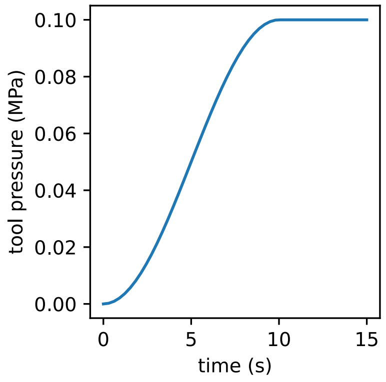
Simulation inputs:

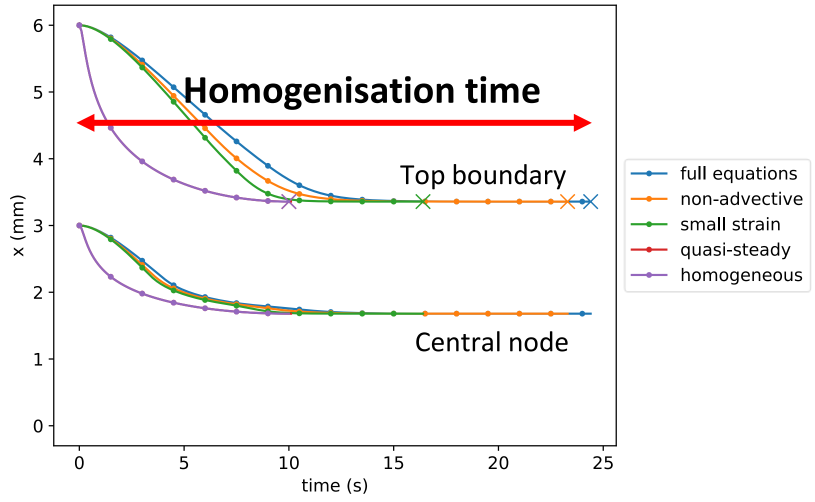
6mm stack of NCF

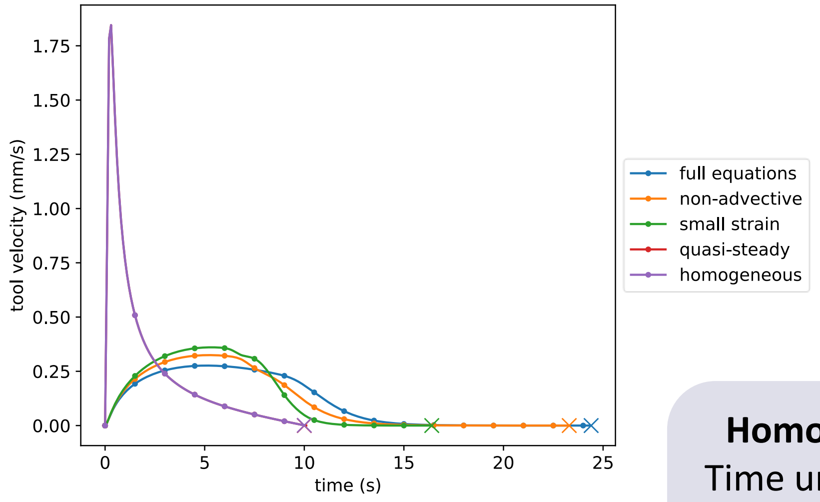
Viscosity 0.1 Pa.s

100 elements

Tool pressure

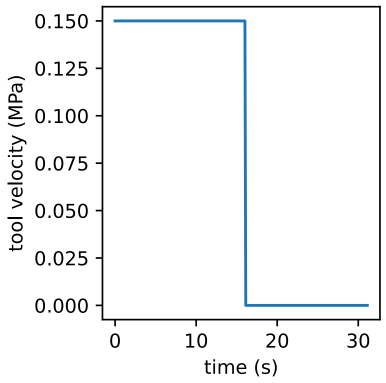


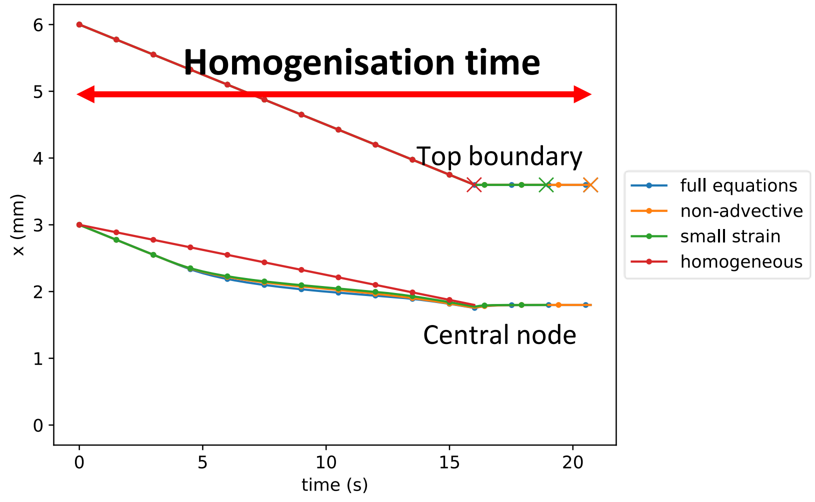


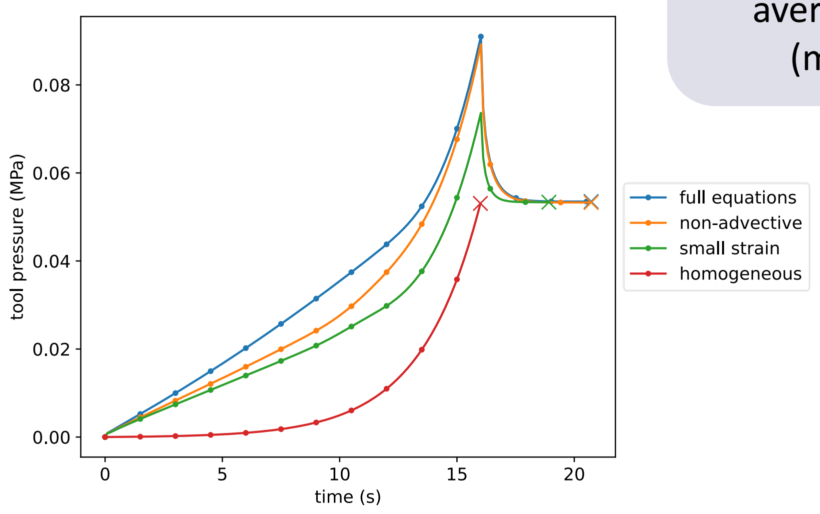


Homogenisation time: Time until ϕ_s of all nodes are within 10^{-6} from the average value of ϕ_s (marked as 'X')

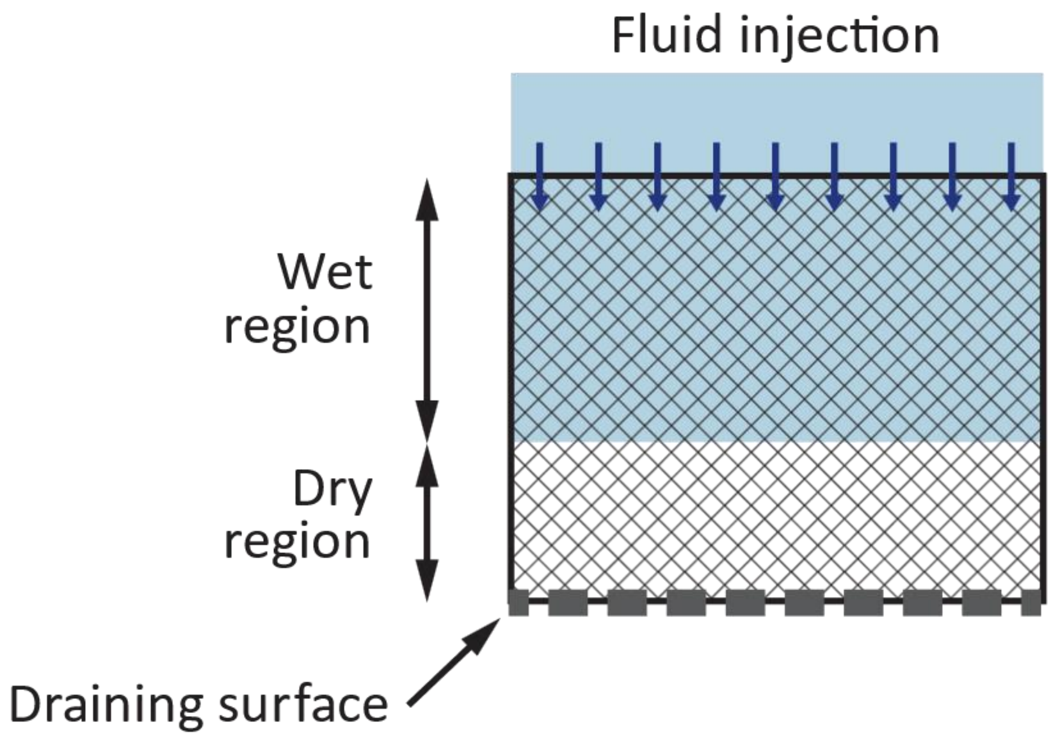
Tool velocity





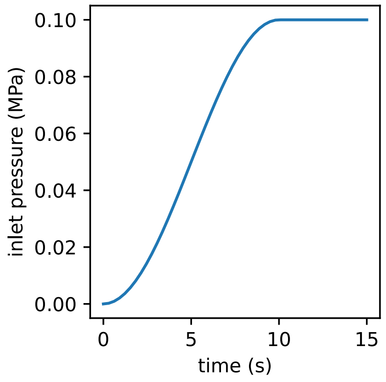


- Injection of fluid at a given flow rate or pressure into a dry preform
- e.g., the first stage of CRTM

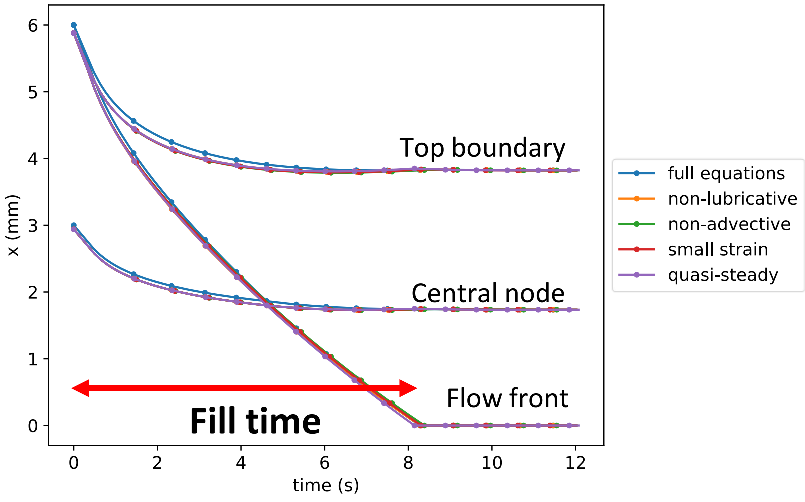


Resin impregnation into a dry stack

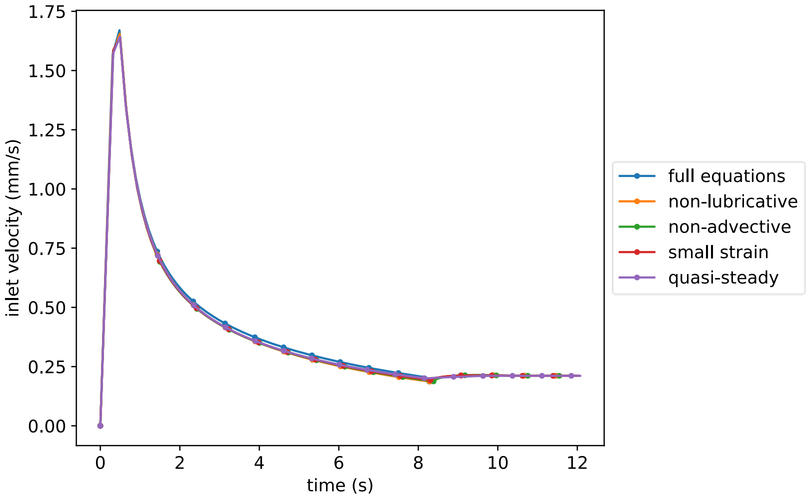
Inlet pressure



Node positions



Resulting inlet velocity/pressure



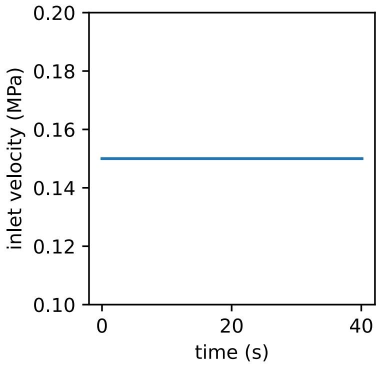
Simulation inputs:

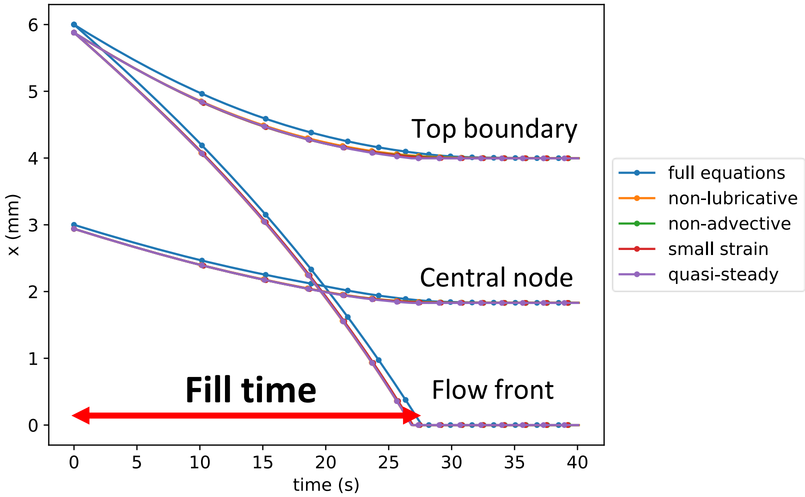
6mm stack of NCF

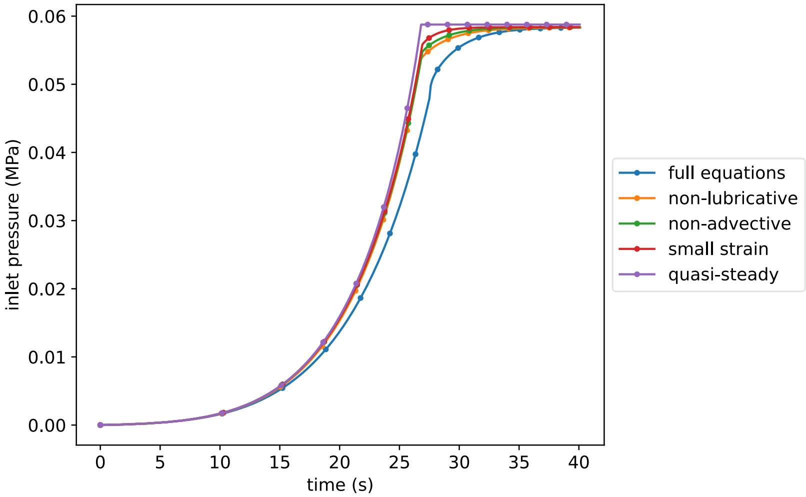
Viscosity 0.1 Pa.s

100 elements

Inlet velocity

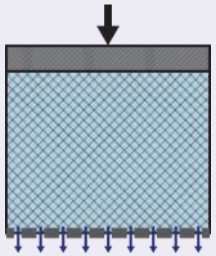




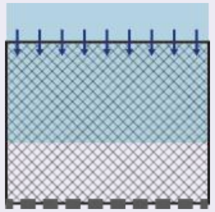


Parametric study

Parametric study: Fluid viscosity



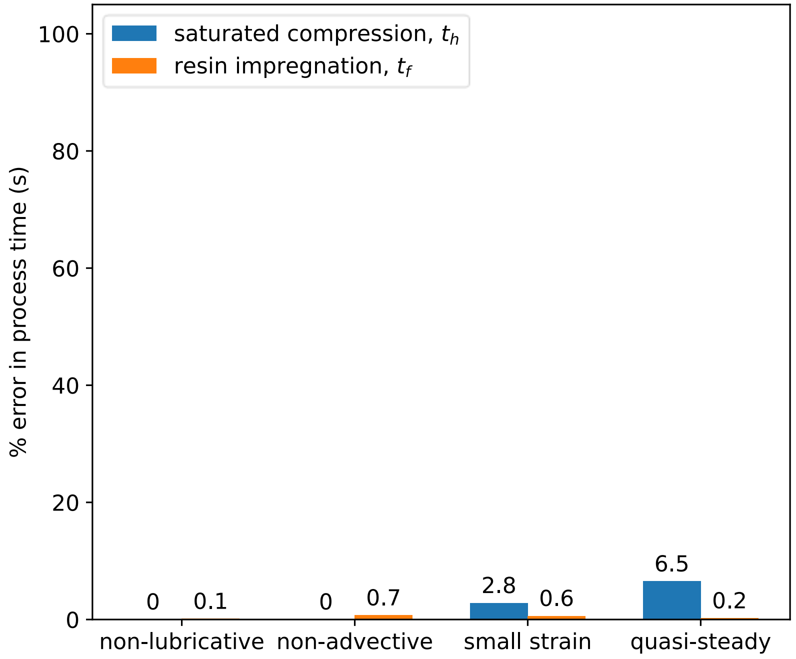
Saturated compression
t_h: homogenisation time



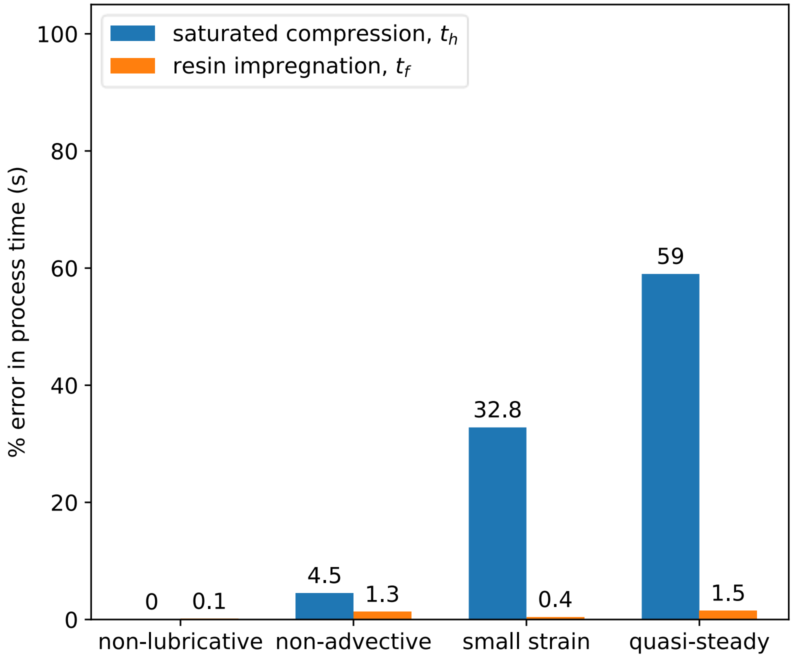
Resin impregnation
t_f: fill time

Converges with lower viscosity

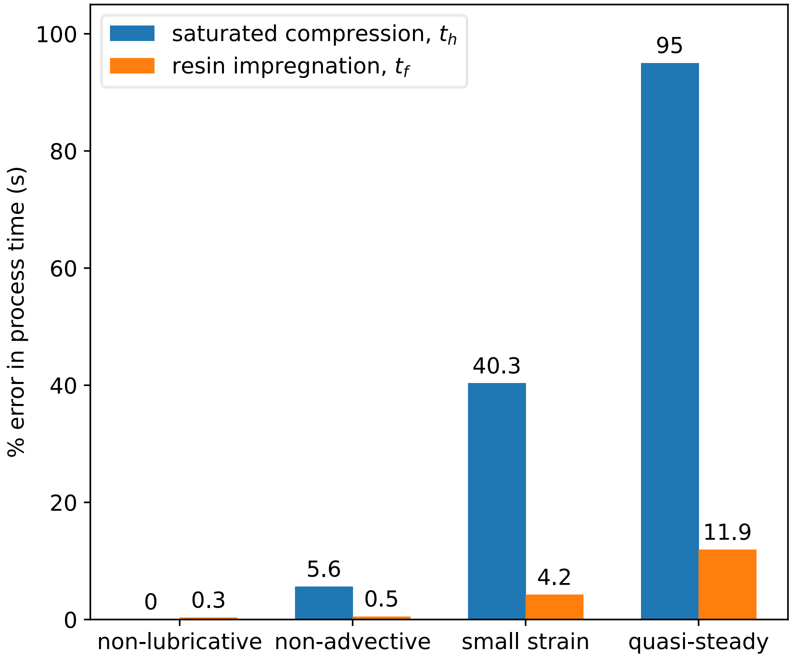
μ = 0.01 Pa.s



μ = 0.1 Pa.s

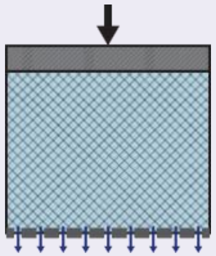


μ = 1 Pa.s

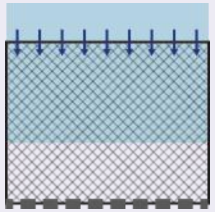


Converges with increasing model complexity

Parametric study: Applied pressure ramp-up



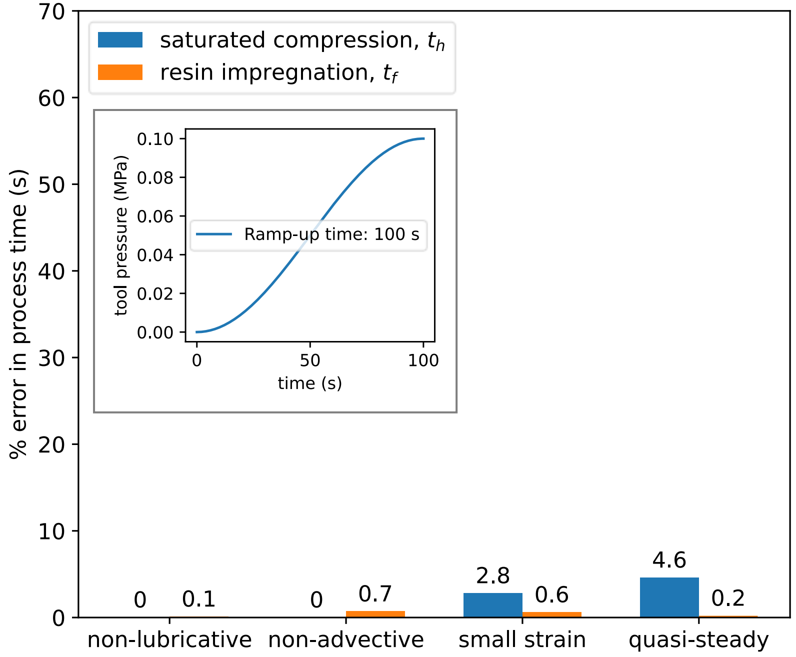
Saturated compression
t_h: homogenisation time



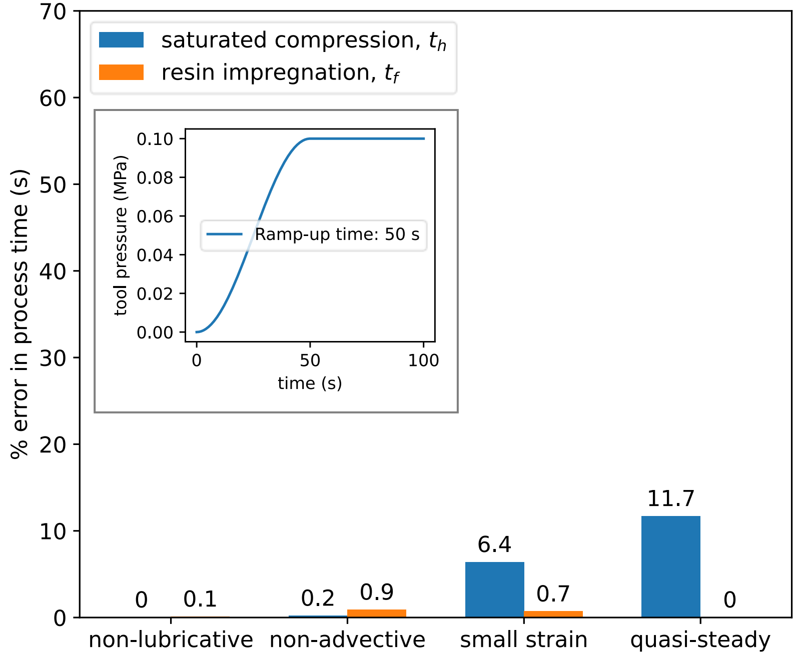
Resin impregnation
t_f: fill time

Converges with slower flow/deformation

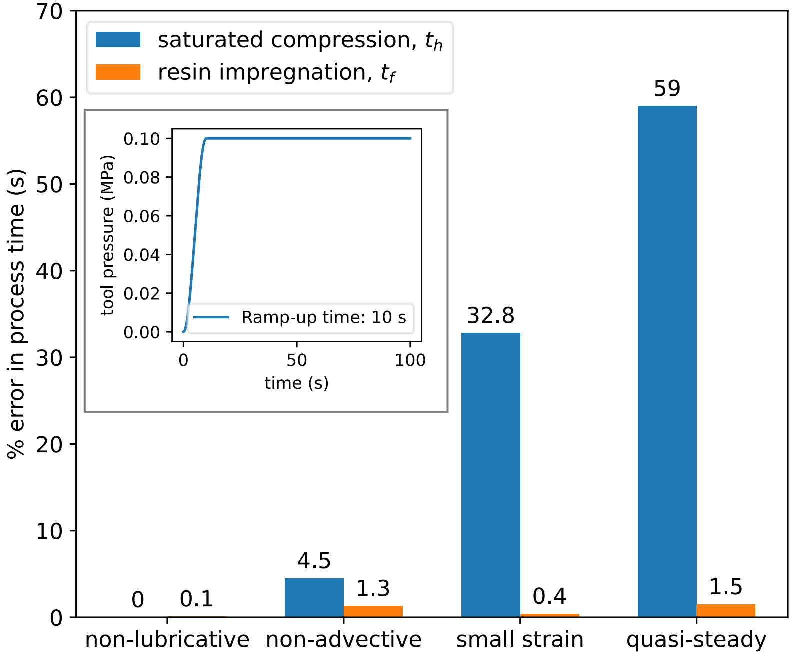
Ramp-up time = 100 s



Ramp-up time = 50 s



Ramp-up time = 10 s



Converges with increasing model complexity

Parametric study

Full equations

Identical wet & dry compaction behaviour

Non-lubricative

Neglect change in ϕ_s in time due to movement of the fabric

Non-advective

Small strain approximation

Small strain

Neglect transient term

Quasi-steady

Uniform through-thickness ϕ_s

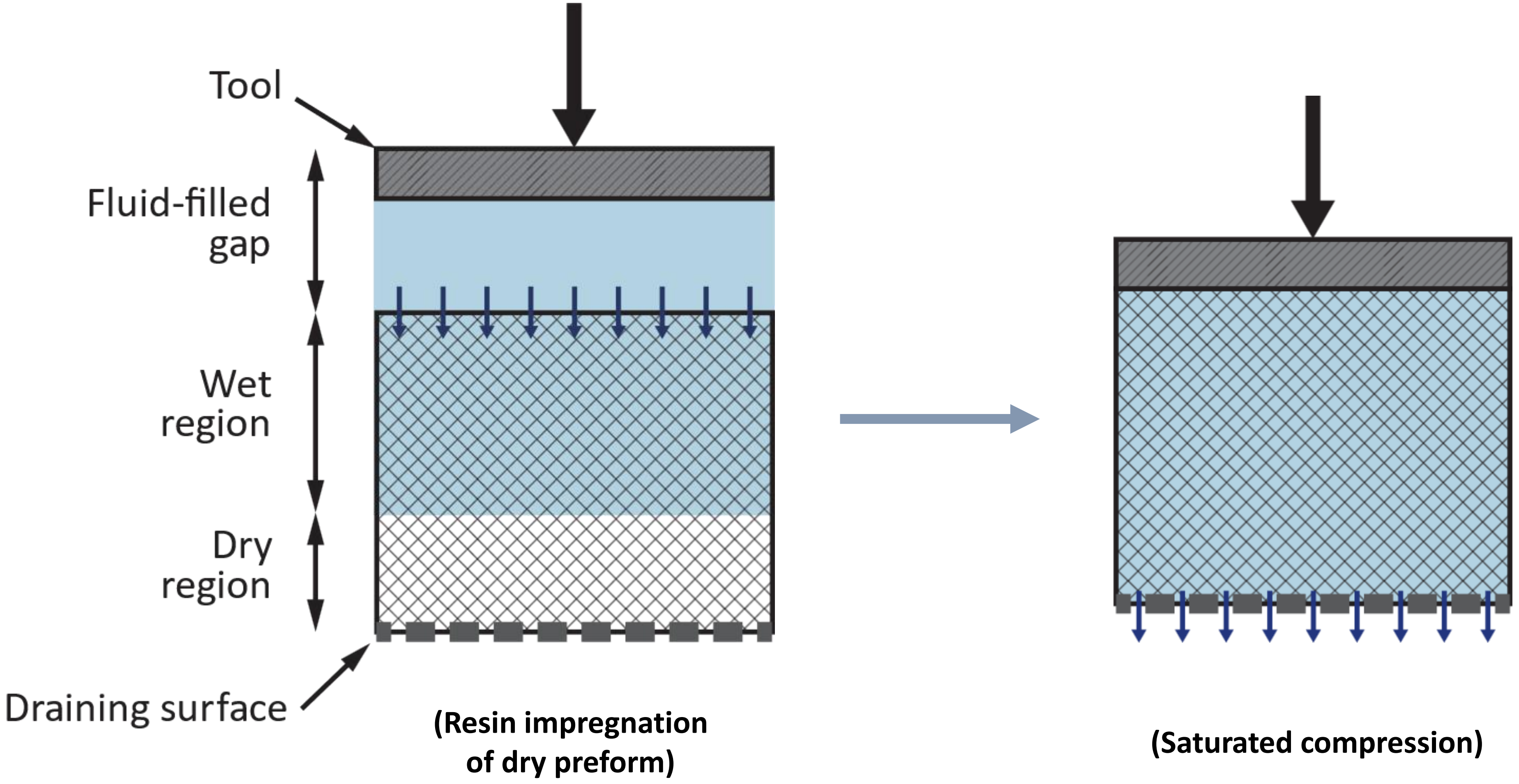
Homogeneous

Increasing error with decreasing model complexity

- Large errors when **tool is in direct contact** with preform, with decreasing error with model complexity
- Smaller errors when top surface is a **free surface** – flow and deformation are slow, sufficient to assume quasi-steady
- Amount of **hydrodynamic compaction** increases with:
  - Fluid viscosity
  - Tool velocity
  - Stack thickness

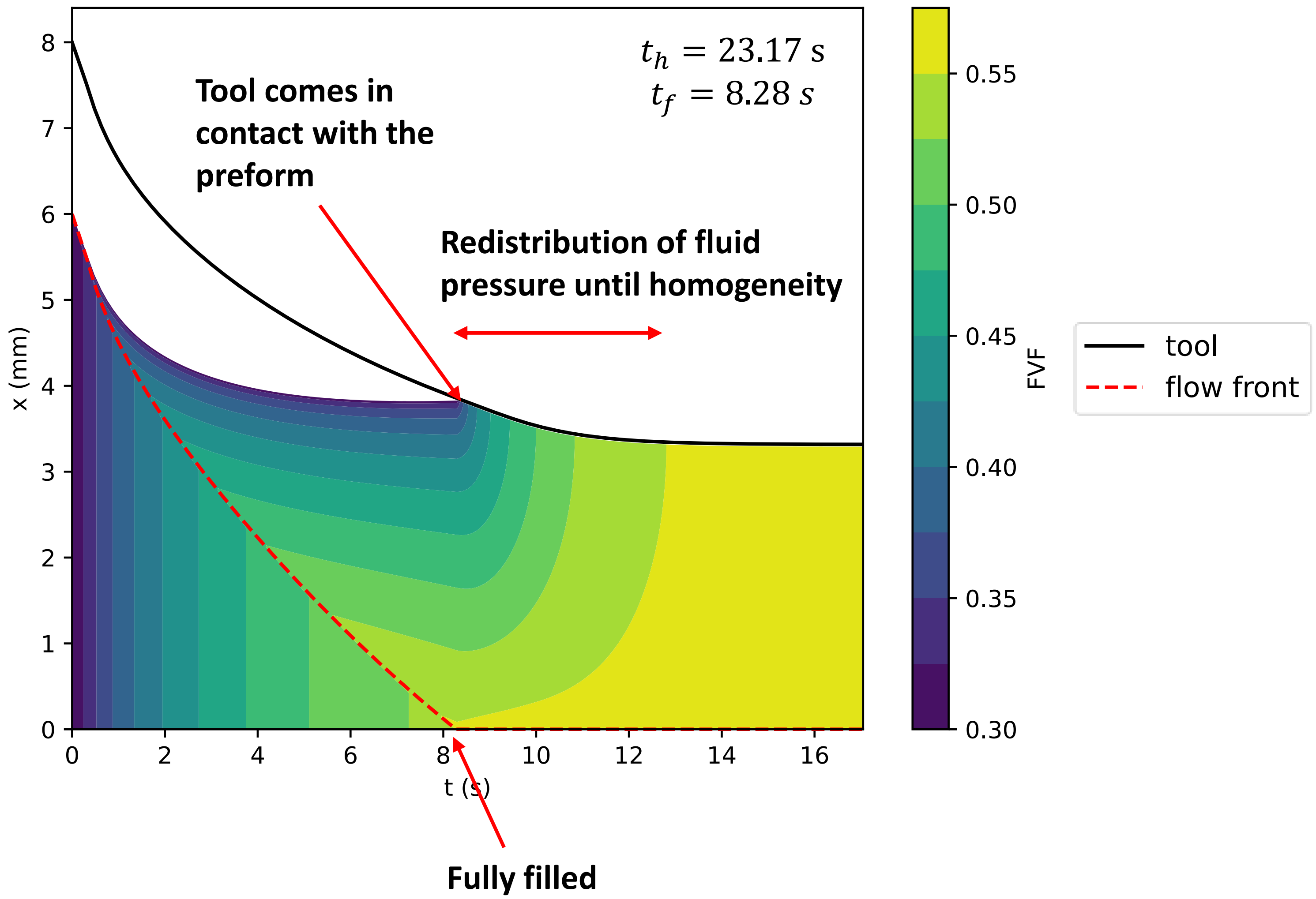
When hydrodynamic compaction effects become significant (increased non-uniformity), the flow and deformation become more non-linear and transient

Compression Resin Transfer Moulding (CRTM)



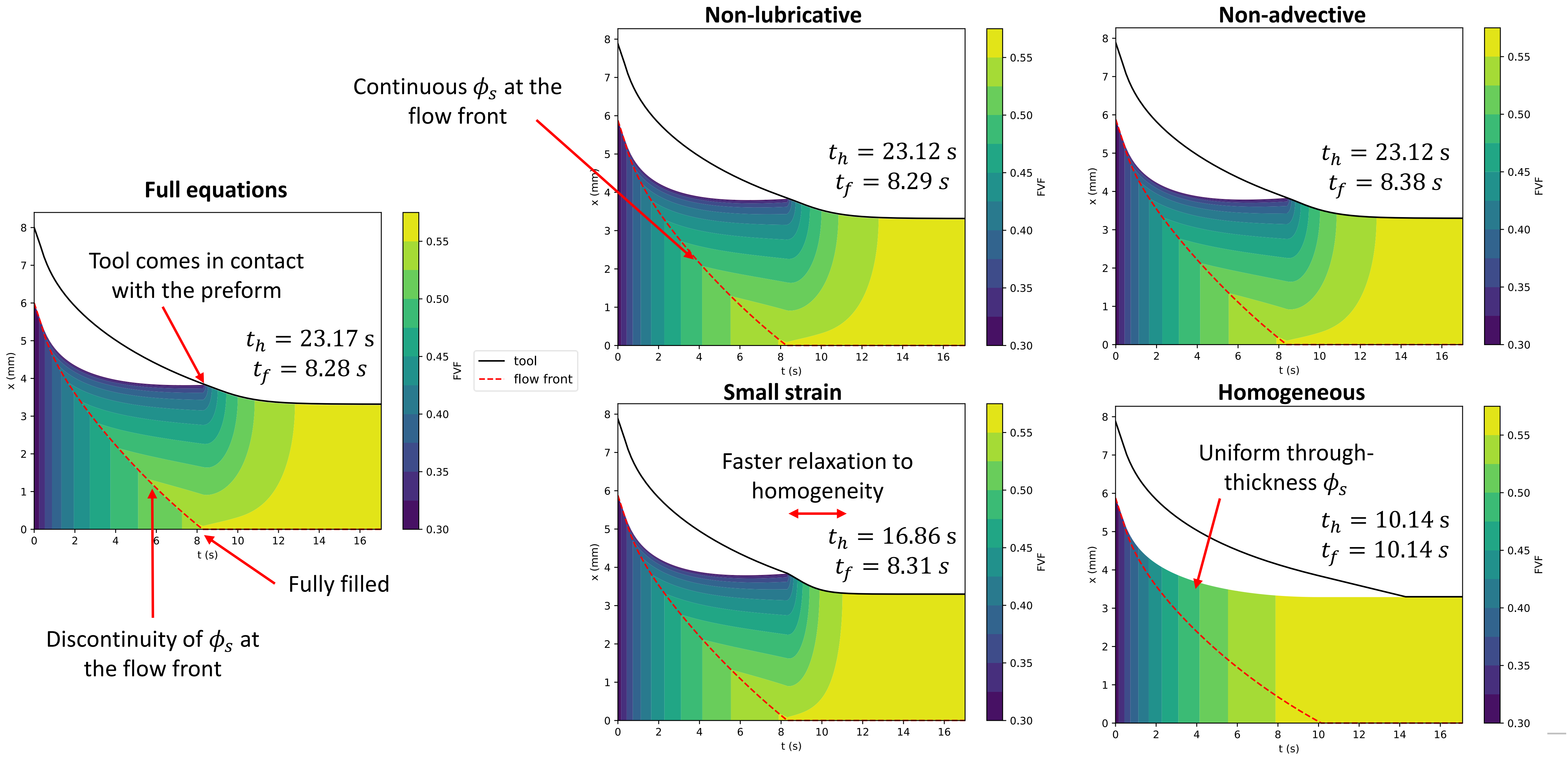
Compression Resin Transfer Moulding (CRTM)

Fibre volume fraction contours



Compression Resin Transfer Moulding (CRTM)

Comparison of fibre volume fraction contours



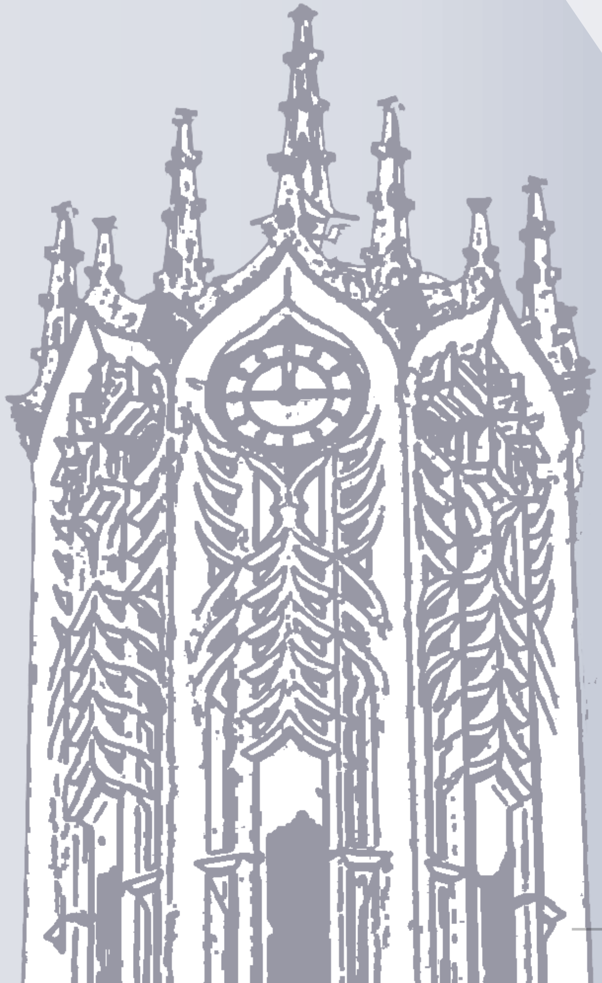
Conclusions

- **Fully coupled, transient** governing equations are required when simulating processes with **direct piston contact** for accurate predictions
- The transient term is negligible during filling - simple **resin injection** can be modelled with a **quasi-steady** model
- Errors in process time increase with amount of hydrodynamic compaction for the simplified models

Based on content recently published in Composites: Part A

Lee J, Duhovic M, Allen T, Kelly P. Computational modelling and analysis of transverse Liquid Composite Moulding processes. Comp A 2023;167:107433

Thank you



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