University of BRISTOL
Bristol Composites Institute

Pre-preg and AFP process modelling

SIMPROCS Platform Grant dissemination event 20/04/2023

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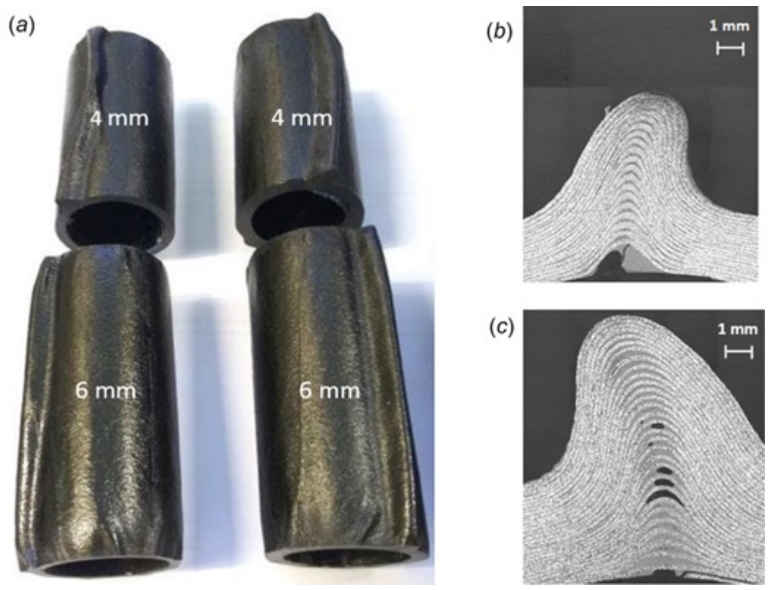
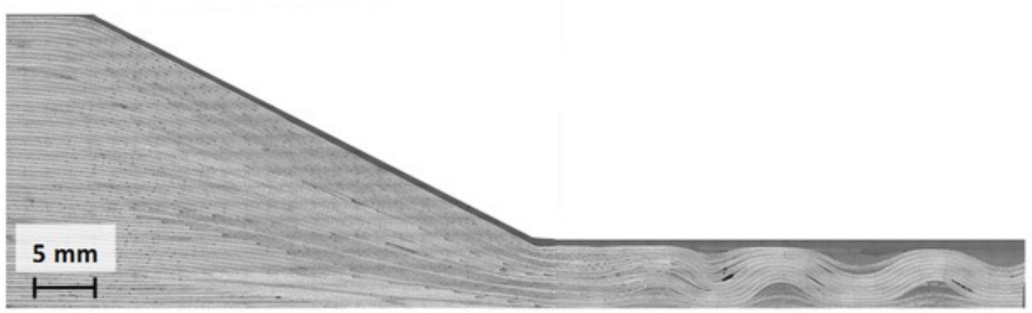
Talk Outline

- The industrial problem and research challenge in 2014
- State-of-the-art at the end of the DefGen project
- SIMPROCS a vehicle for further scientific development and an integrator for societal impact
- Easing-off material characterisation and model parameter extraction
- Scaling-up and speeding up the models
- Automated Fibre Placement simulations
- Lessons learnt and Where next?

The industrial and research challenge in 2014

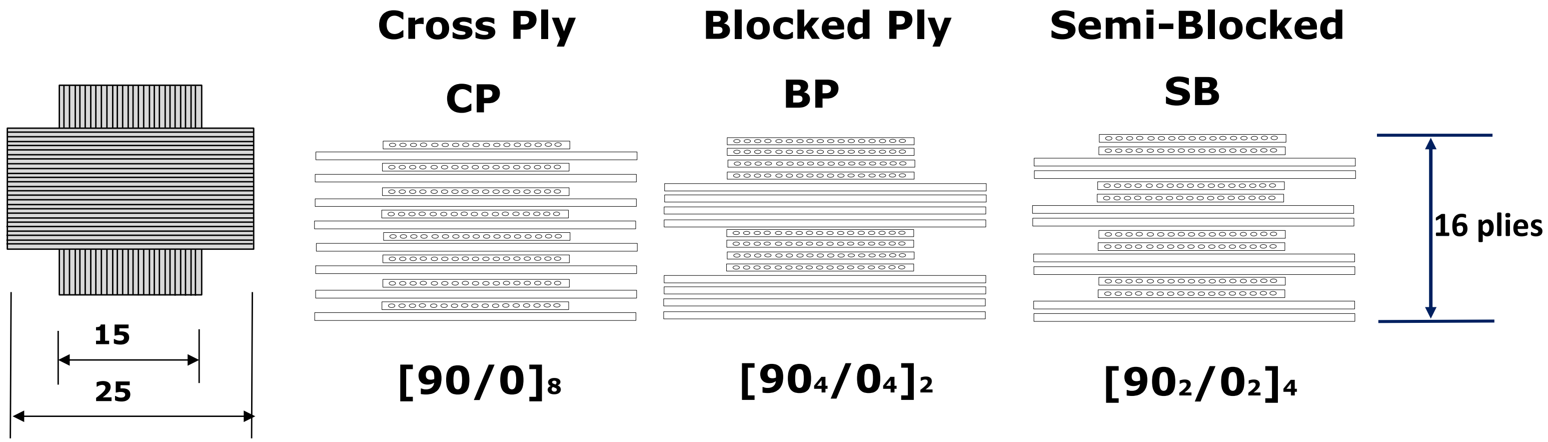
- Severely tapered laminate such as blades are very thick in certain regions and this can be responsible for manufacturing induced defects.
- Variability in the ability of the base material (prepreg) to compact induces process robustness issues.
- Time-consuming, costly and wasteful manufacturing trials needed to optimise the process.
- Lack of understanding of the phenomena leads to low maturity of process simulations.

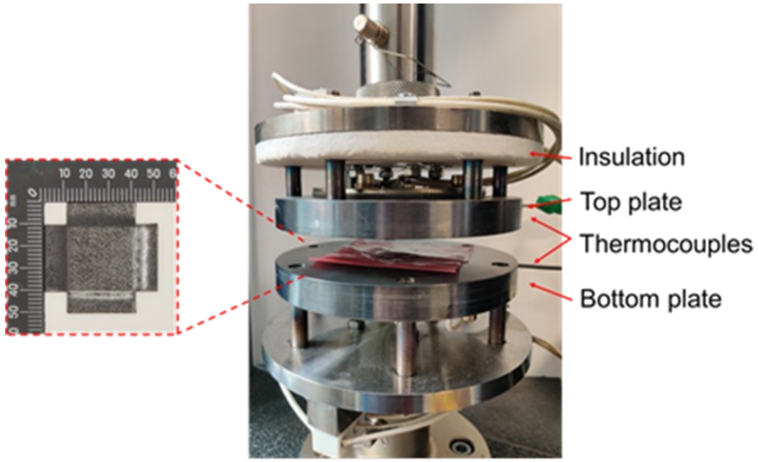


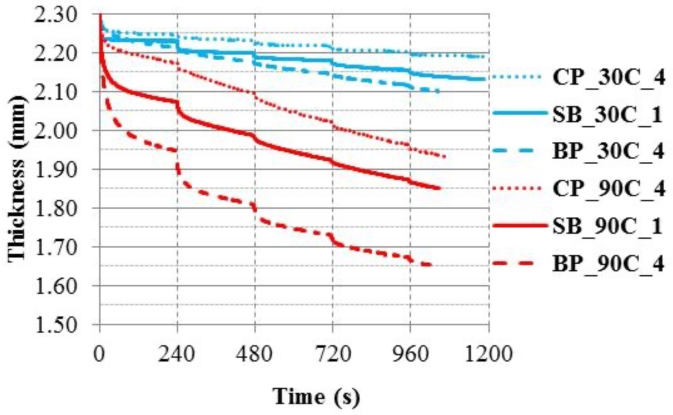


Lab scale testing: understanding the material

- Strong scale effects: different behaviour of thin-thick, wide-narrow tapes.
- Percolation - Squeezing flow transition
- Convergence to a compaction limit at high P/T
- Identifiable properties
- Covering a wide range of P/T/Rates



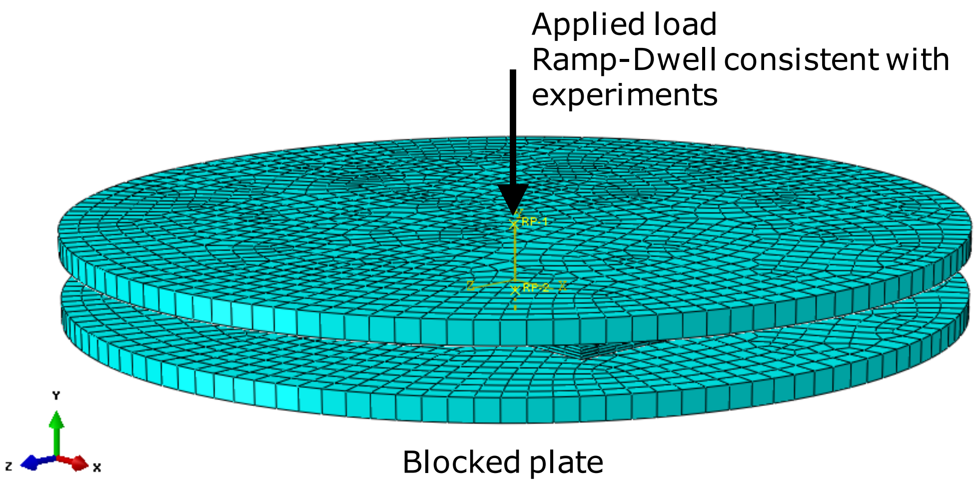




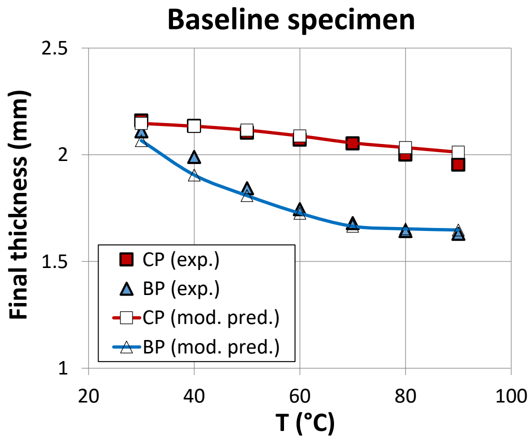
Ramp Dwell Compaction for IM7/8552

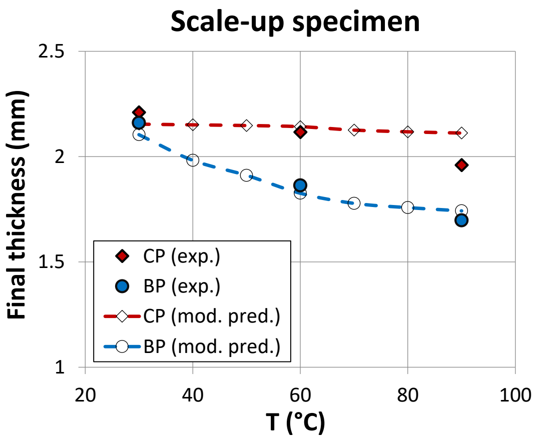
Model implementation

- Implementation of the model into a 3D commercial FE package.
- Adaptation of a hyper-viscoelastic model originally formulated for the modelling of soft connective tissues.
- In practice, fibre direction and volume change are handled through an elastic constituent whilst change in thickness is controlled by the viscous model.

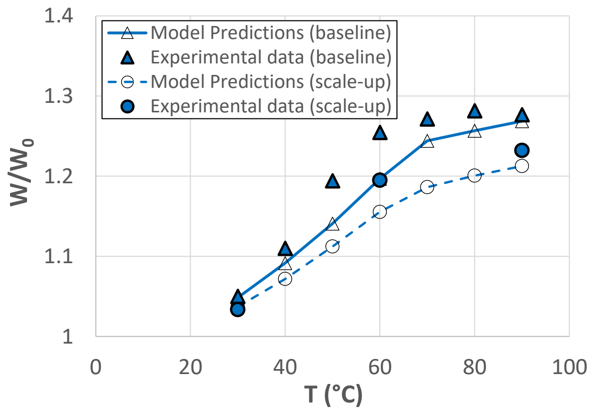


Final thickness evolution vs Temperature



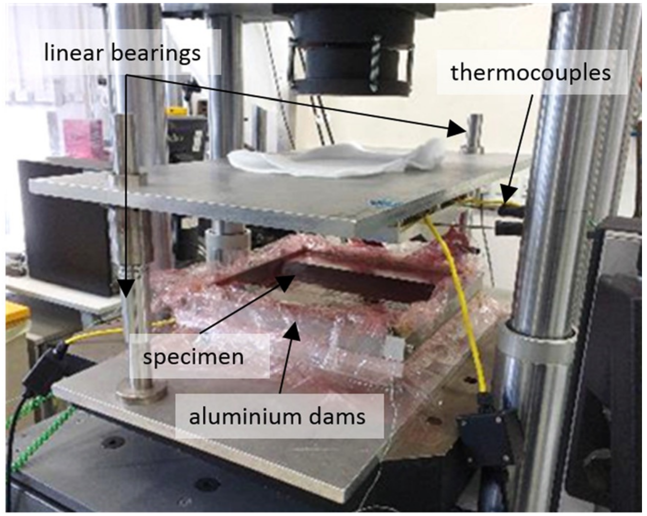


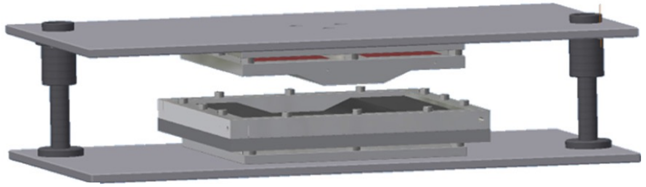
Final width vs Temperature

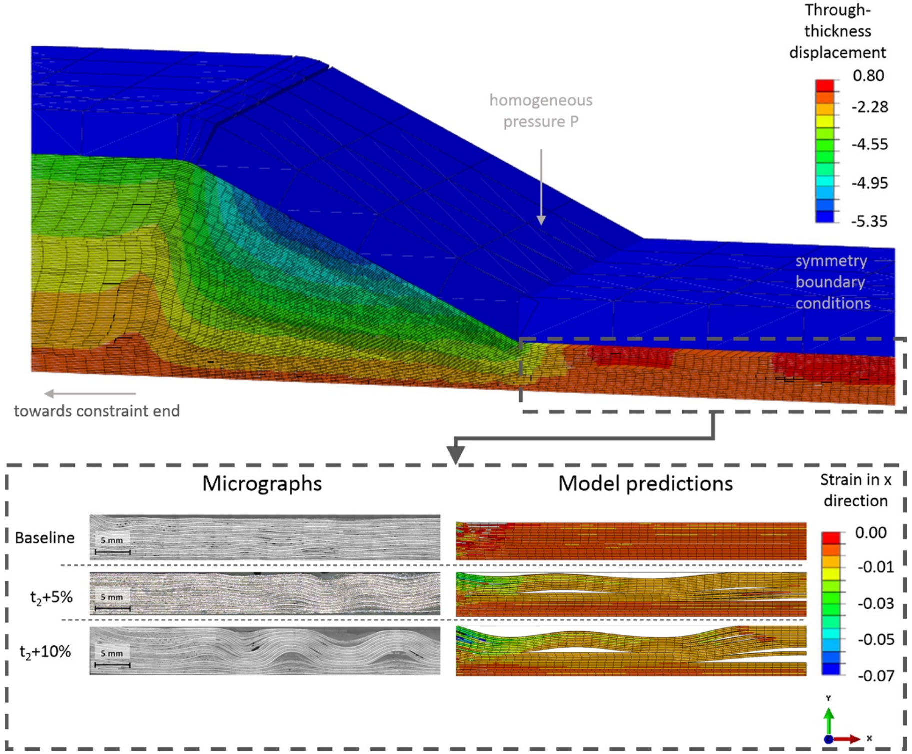


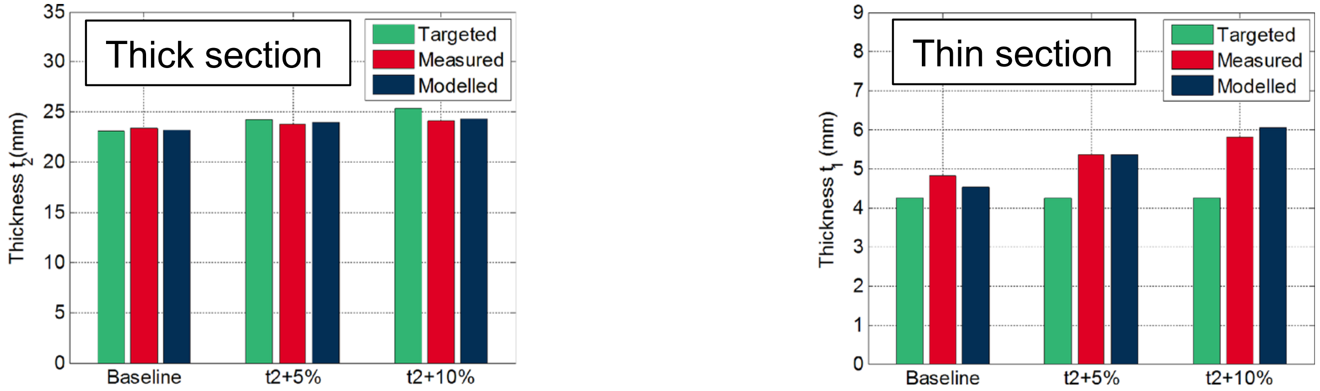
Model validation

- Very controlled experimental set-up (thermocouples, Instron and linear bearings).
- To investigate effect of variability 3 different thicknesses in the thick section were studied (baseline, +5% and +10%).
- Good agreement between model and experiments Wrinkles formation is captured. Thickness predictions were very good.



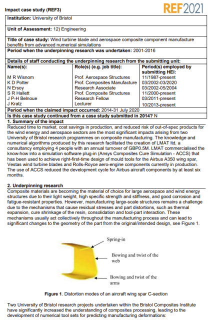






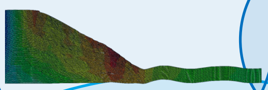
SIMPROCS WP1 ecosystem

Underlying question:
How can we improve the science so that process modelling can be useful to industry and wider society?



REF 2021 Impact case study

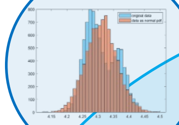
Rolls-Royce
- EngD



Rolls-Royce/NCC R&D program

NCC
- Technology Pull Through
- DETI program

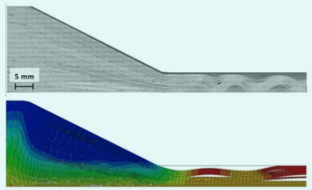
BAE Systems



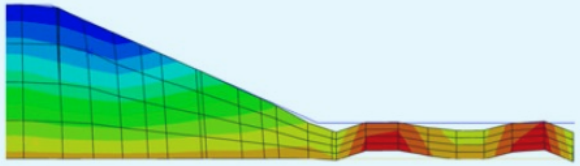
LMAT Ltd

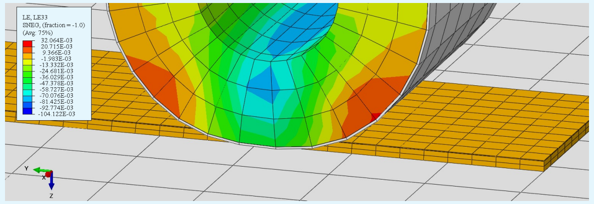
DefGen

CIMComp
EPSRC
Future Composites
Manufacturing Research Hub



SIMprocs

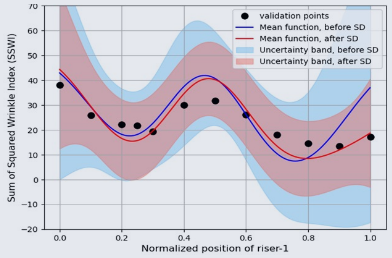




CIMComp
- Synergy project with Nottingham University

Airbus
- EngD
- EPSRC Impact Acceleration Award

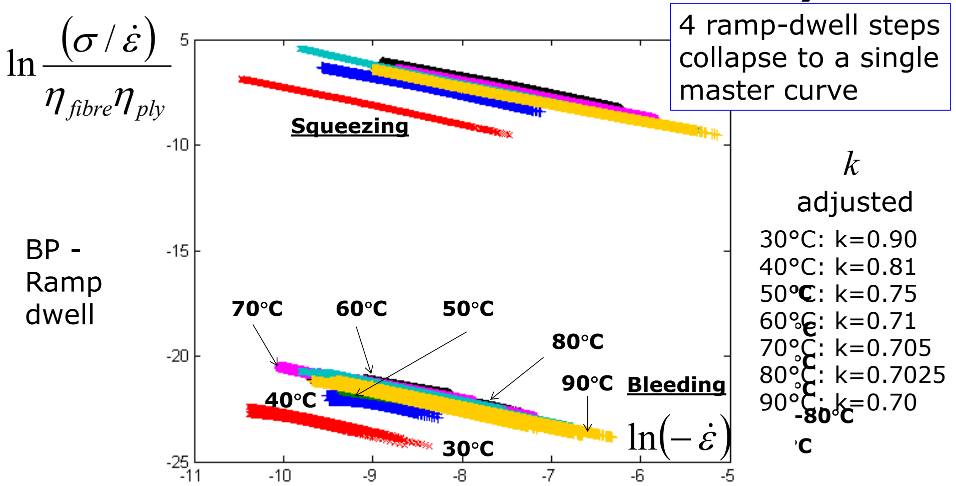
Composites: Made Faster

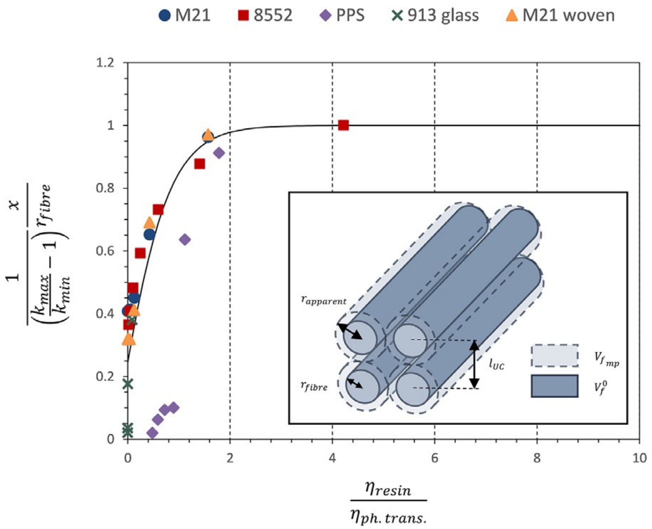


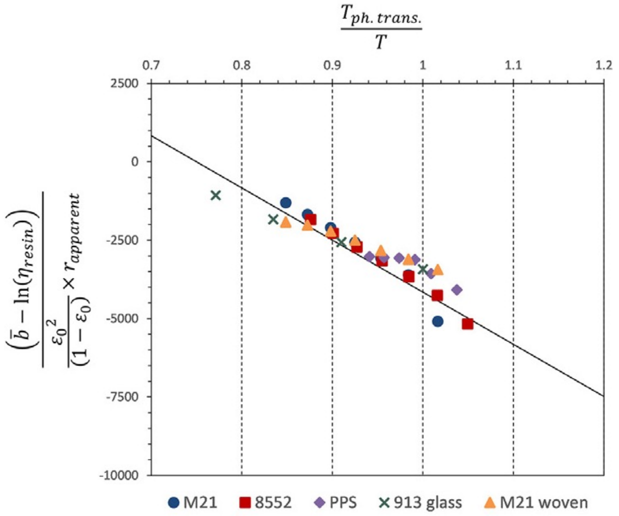
Github
- Open-source
- Vehicle for academic collaboration
- Over 30 users worldwide

Easing-off material characterisation (1/2)

- A model accounting for all the points mentioned in the previous slide was set-up.
- A parameter extraction procedure was derived.
- The ability of the model to capture the experimental data was verified.
- Later work (bottom graphs) allowed to make the model fully physical relating the material parameters to know quantity such as fibre volume fraction and resin viscosity.



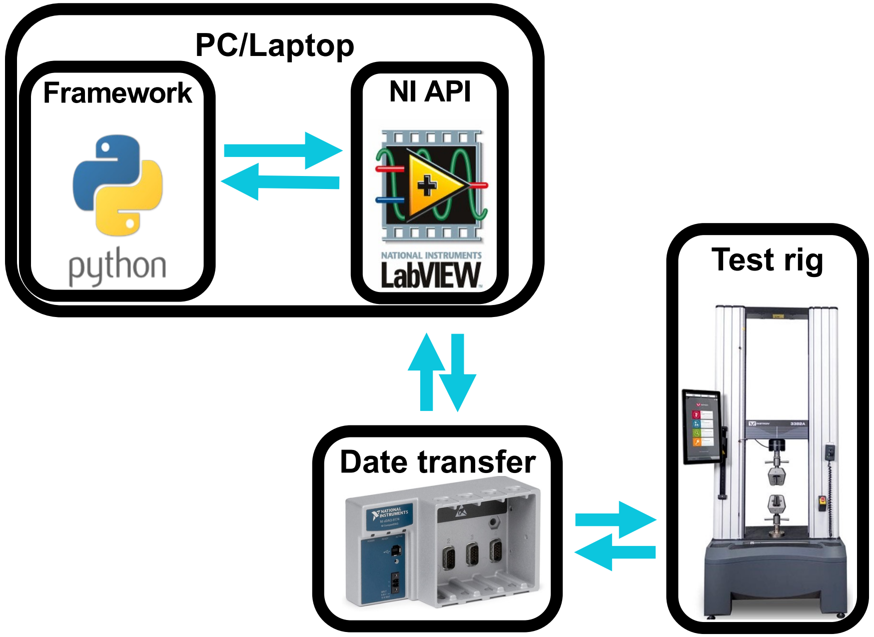




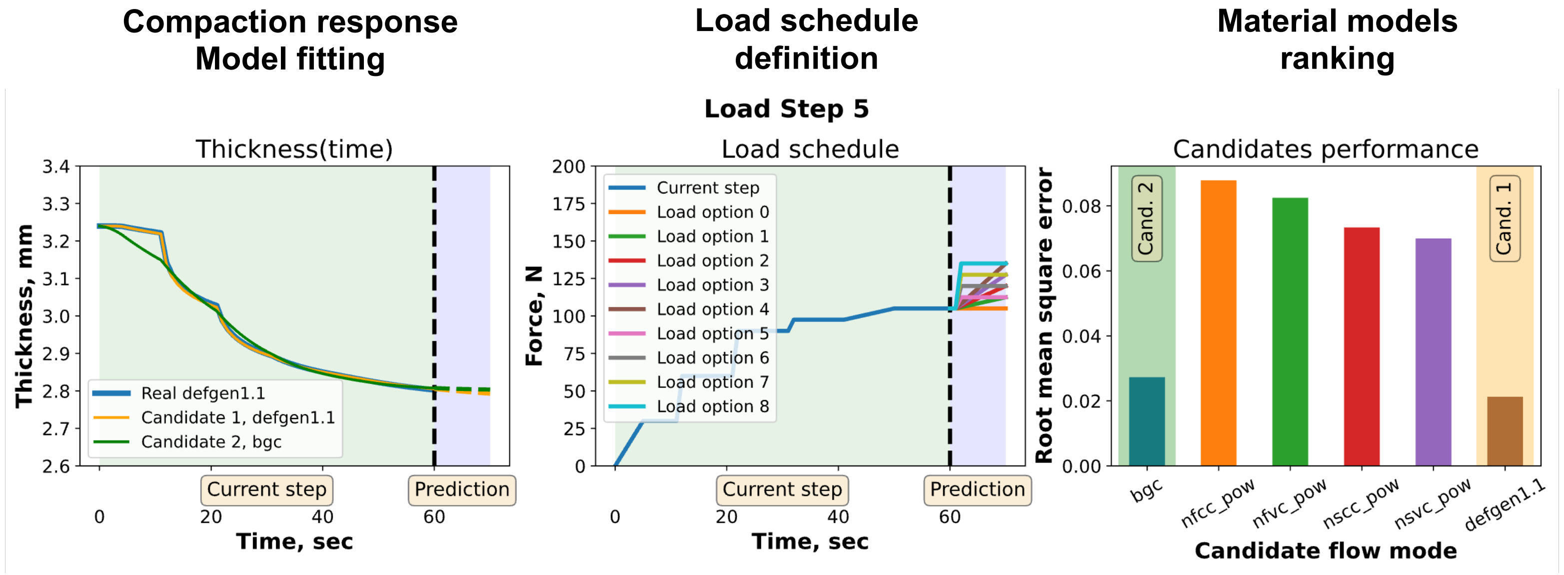
Easing-off material characterisation (2/2)

- No bias towards any material behaviour model
- Removes the researcher from the process of building the characterisation test programme
- Collect sufficient amount of experimental data (data-rich programme)
- Extracts material models from experimental data and automatically builds models in the future?

Test setup

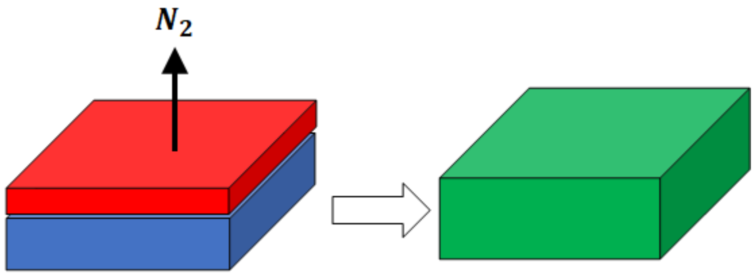


Adaptive real-time testing

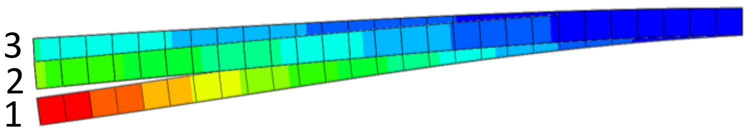


Scaling-up and speeding up the models (1/2)

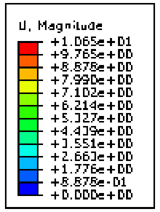
- An homogenisation procedure for laminates was developed.
- The laminate is constructed by successive homogenisation of 2 blocks.
- Interfaces are modelled as weak discontinuities of the same behaviour as a ply (DefGen model) but where the strong fibre direction is removed.
- Role of microstructural deformation on microscale behaviour is captured.

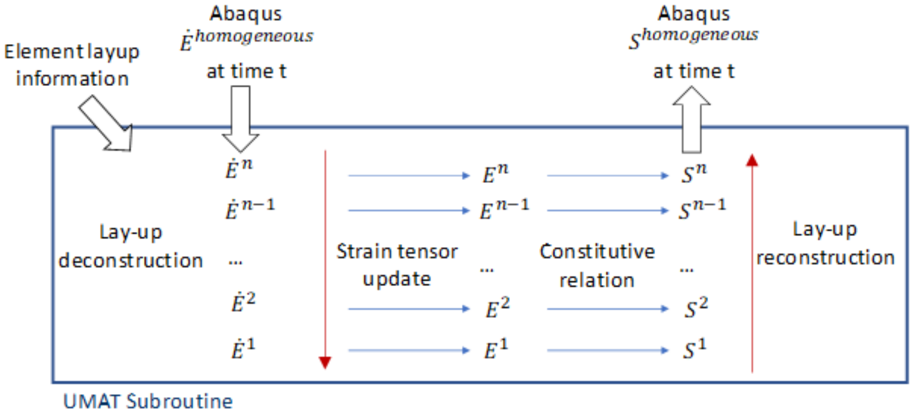


$\dot{E} = (1-f)\dot{E}^{(B)} + f\dot{E}^{(I)}$	Rule of mixture
$\dot{E}^{(I)} = \dot{E}^{(B)} + N_2\dot{\widetilde{E_1}} = \dot{E} + (1-f)N_2\dot{\widetilde{E_1}}$ $\dot{E}^{(B)} = \dot{E} - fN_2\dot{\widetilde{E_1}}$	Continuity of the strain field across the interface
$S^T\dot{E} = (1-f){S^{(B)}}^T\dot{E}^{(B)} + f{S^{(I)}}^T\dot{E}^{(I)}$	Hill-Mandel condition

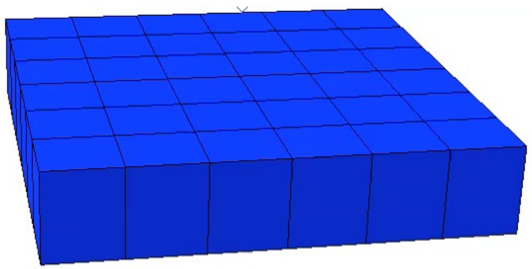


1: quasi-isotropic
2: UD
3: UD with artificially stiffened interfaces



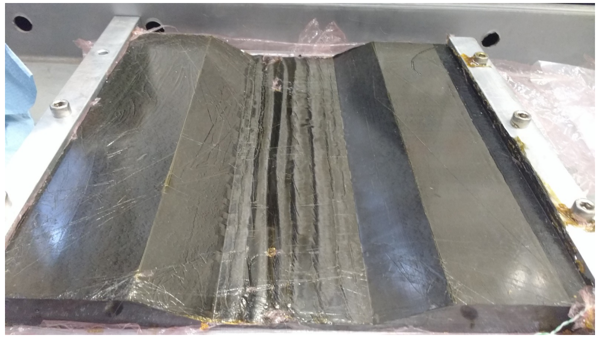


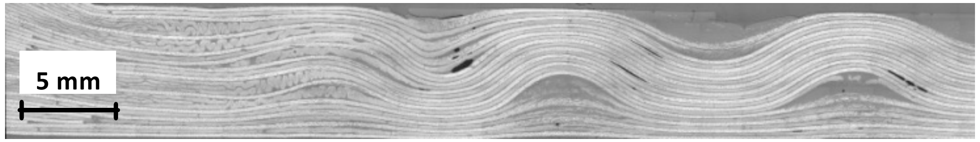
(0/20): fibres' rotation)

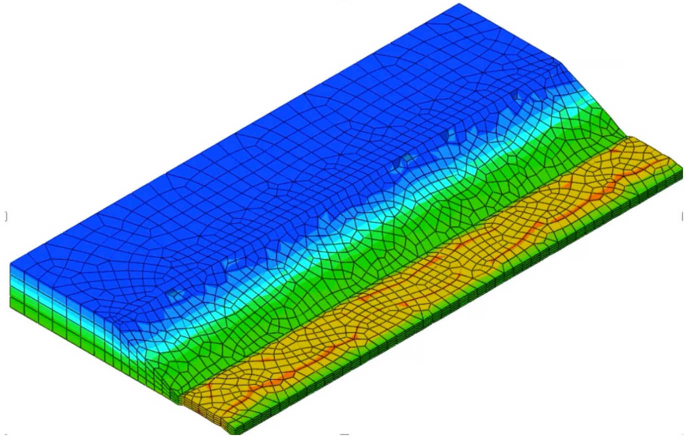


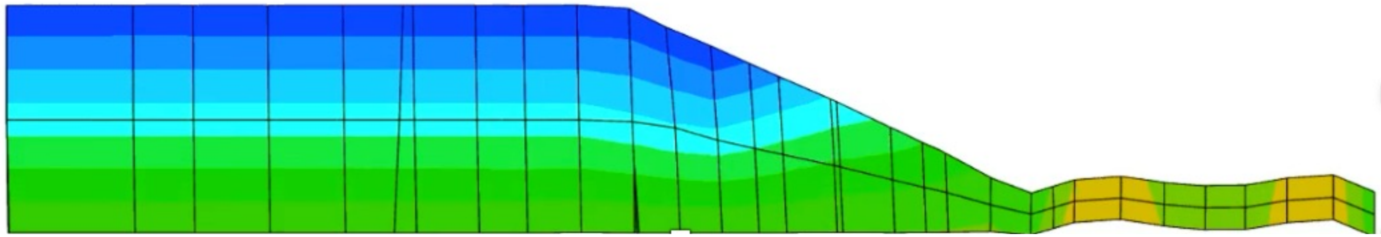
Scaling-up and speeding up the models (2/2)

- Considerable speed gain is obtained comparing with the ply-by-ply approach i.e. the run time is reduced from 2.5 weeks to 20 mins for the DefGen taper.
- This is due to the sharp decrease of the total amount of degree of freedom but also the use of elements with better thickness to width ratio and, above all, the removal of most contacts.



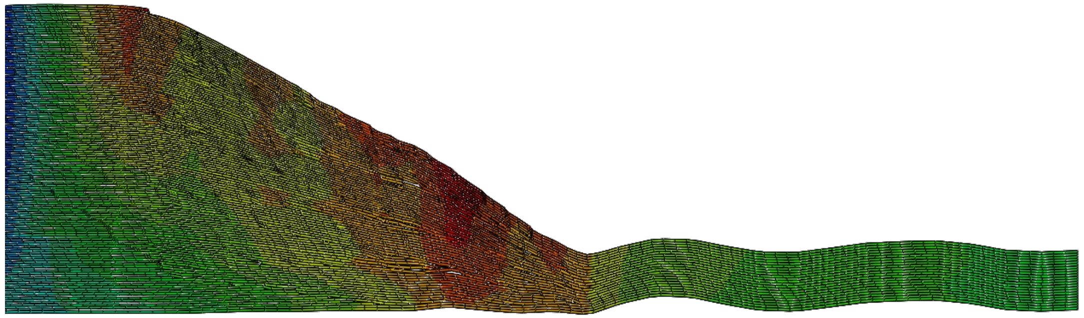




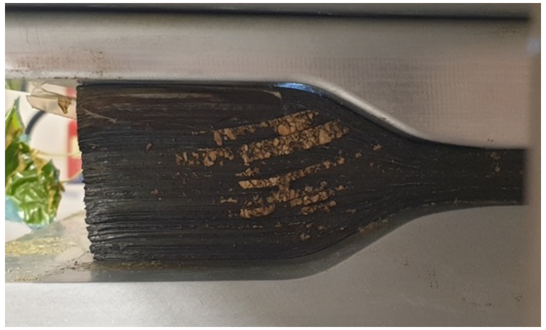


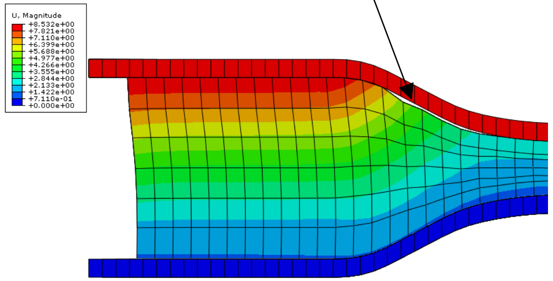
RR-sponsored EngD

- Established without any doubt that the ply-by-ply approach is not fit to problems of industrial scale.
- Derived tools allowing to recover ply-by-ply resolution.
- Demonstrated how useful process simulation tools could be.
- Investigated the effect of variability on part manufacturing robustness.

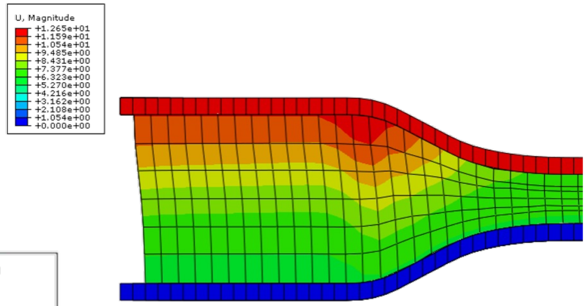


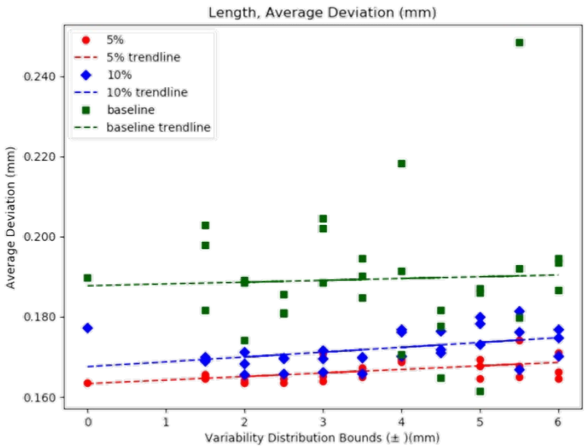
Baseline

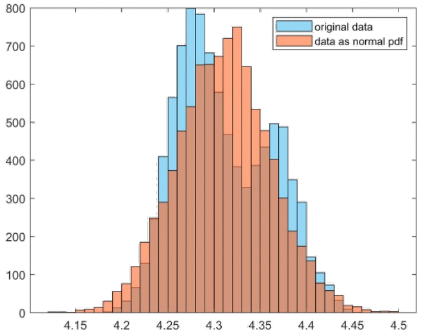




Ply length extended by 10%



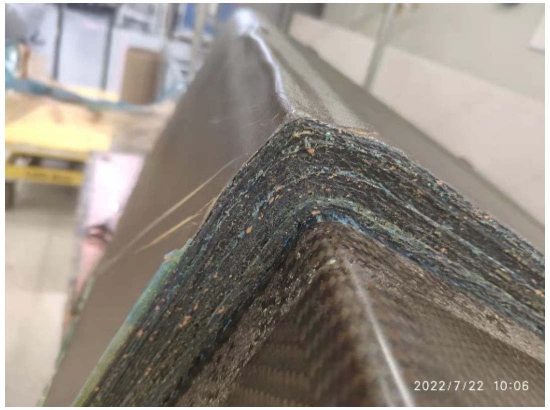


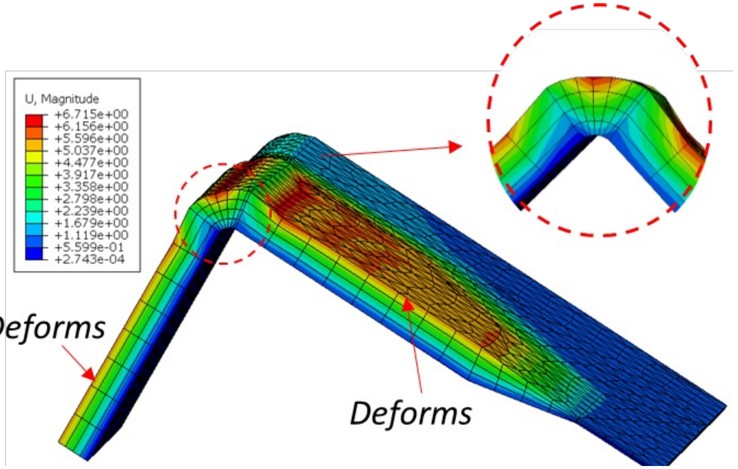


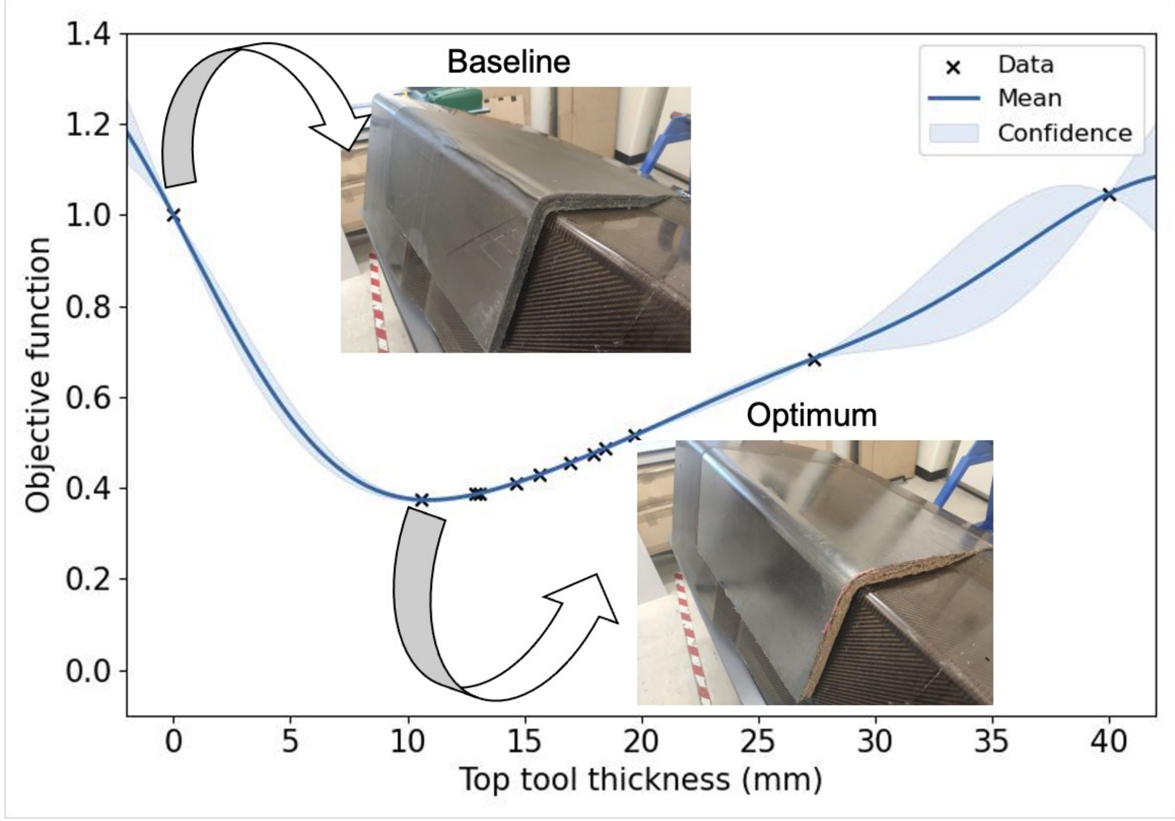
Process Optimisation (Yi Wang's talk)

DIGITAL ENGINEERING TECHNOLOGY & INNOVATION

- Fully automated workflow for model creation, part thickness and fibre path prediction and tooling optimisation of composite parts.
- Further validation of the model for parts of increased size and complexity.

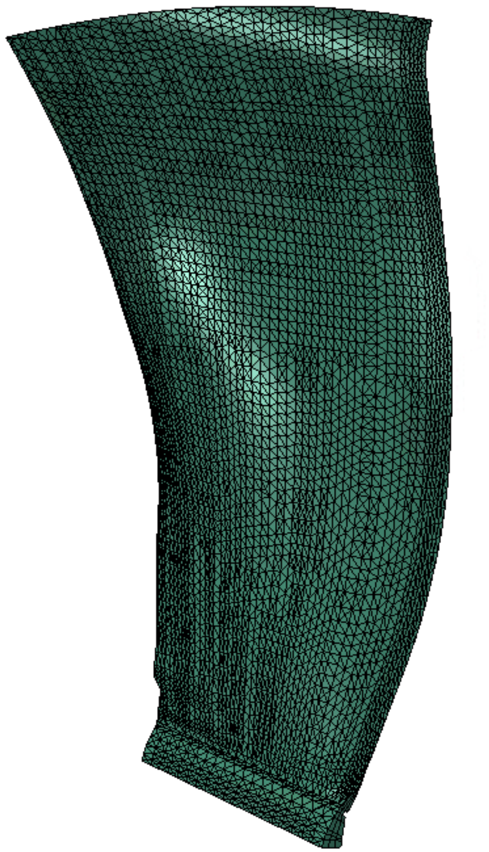






Use in industry and societal impact

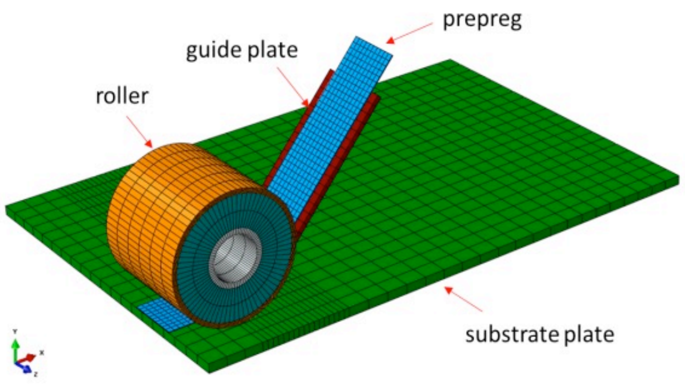
- RR R&D contract to NCC for improvement of the robustness of the processing of composites blades.
- UoB compaction tools are used to help re-design some of the tooling used to cure the blade.
- Subcontract to UoB for pre-processor adjustment and support with software.
- RR-supported EngD student now carries some of this work as an NCC employee.



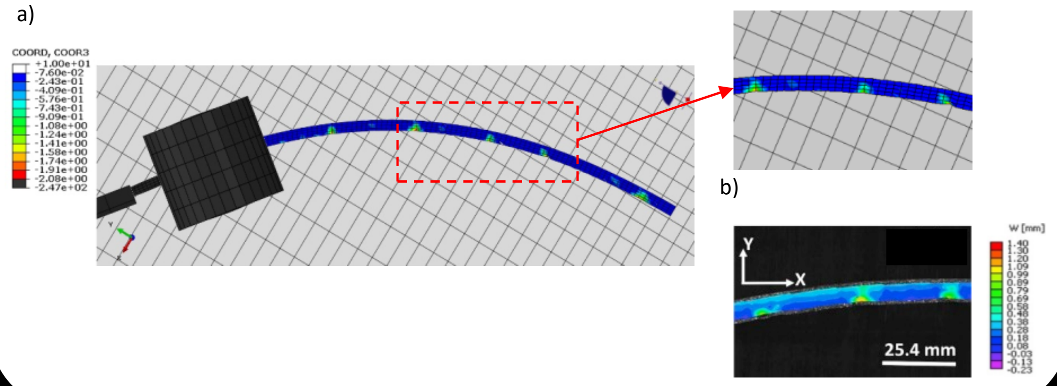
Automated Fibre Placement simulations (1/5)

- AFP simulation platform was built on the FE model from TU Munich.
  - Result of a productive outcome from a two week visit to TUM by Jonathan.
  - Validated kinematics and thermal models.
  - Fully parameterised.
  - Lacked proper mechanical behaviour.
- Provided us with the blueprint to develop our own framework and build on some of the weaknesses.
- Good quantitative predictions of defects generation when compared with literature

Original TUM AFP model

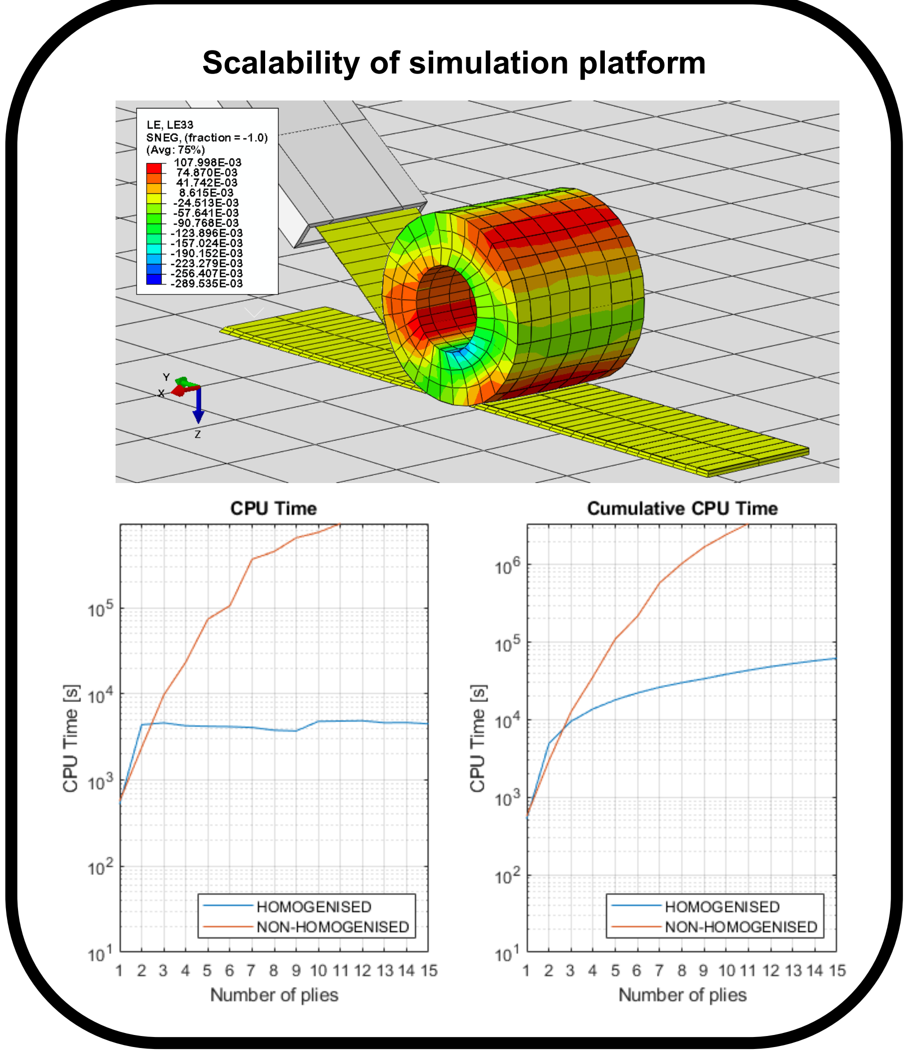


Platform validatation



Automated Fibre Placement simulations (2/5)

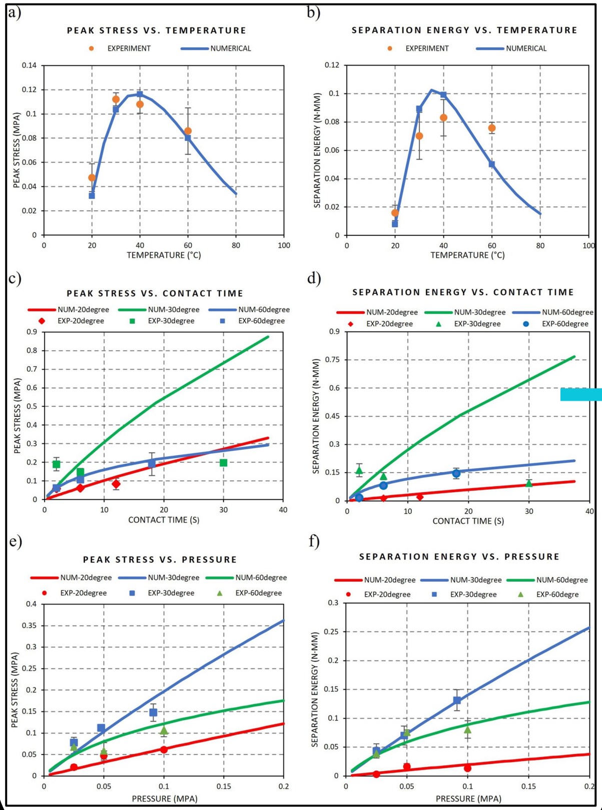
- Current state-of-the-art AFP platform is built on ABAQUS, includes:
  - Sequentially-coupled STANDARD model, for investigating the process for a single lay-up.
  - Isothermal STANDARD model linked with AFP power curves and on-the-fly substrate bulk homogenisation, for investigating compaction.
  - Isothermal EXPLICIT model, for steering.
- Prepreg and roller material models characterised over a wide range of processing conditions.



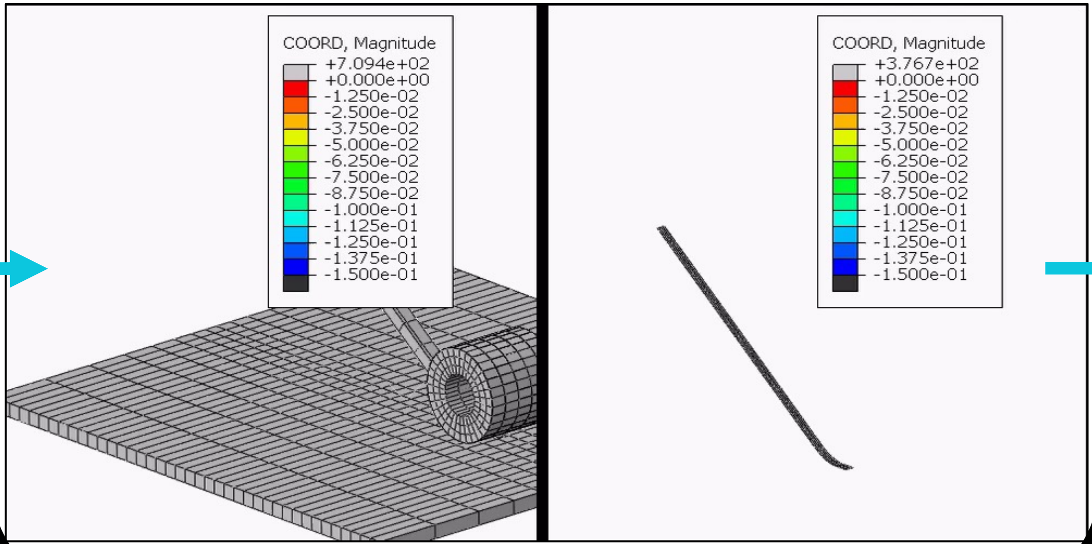
Automated Fibre Placement simulations (3/5)

Investigating the effect of process conditions on lay-up quality

Prepreg tack model



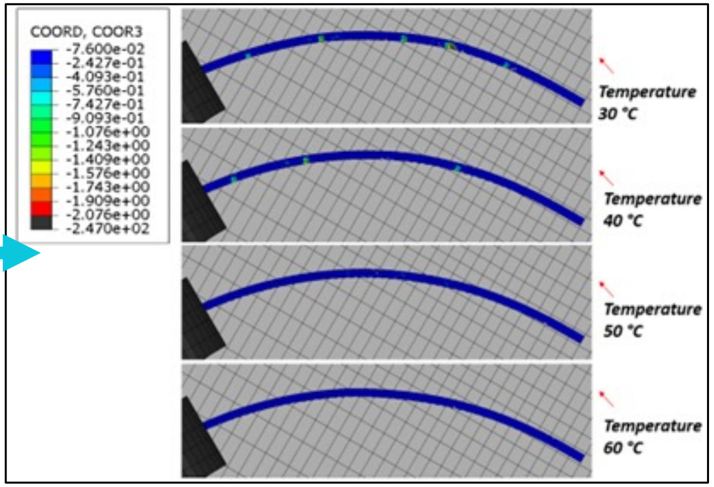
Simulation platform



In-plane shear model

Bending model

Virtually explore lay-up process

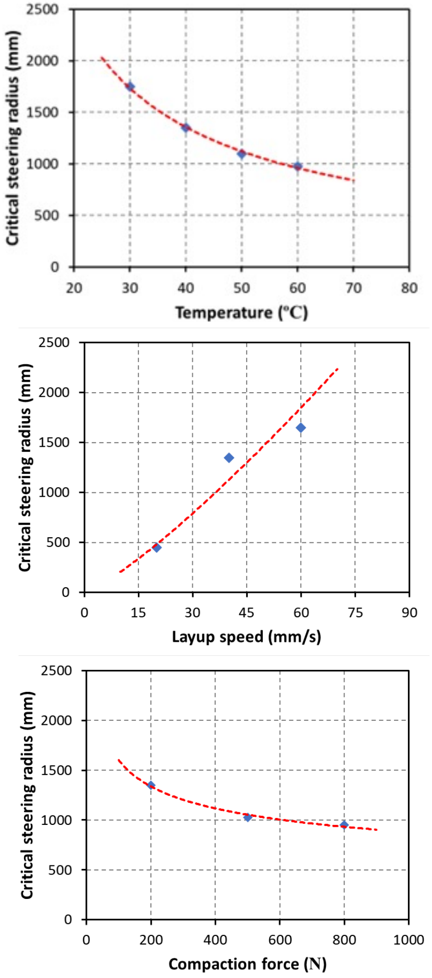


***Out-of-plane wrinkle < 1 ply thickness**

Demonstrated by Dr Yi Wang

Automated Fibre Placement simulations (4/5)

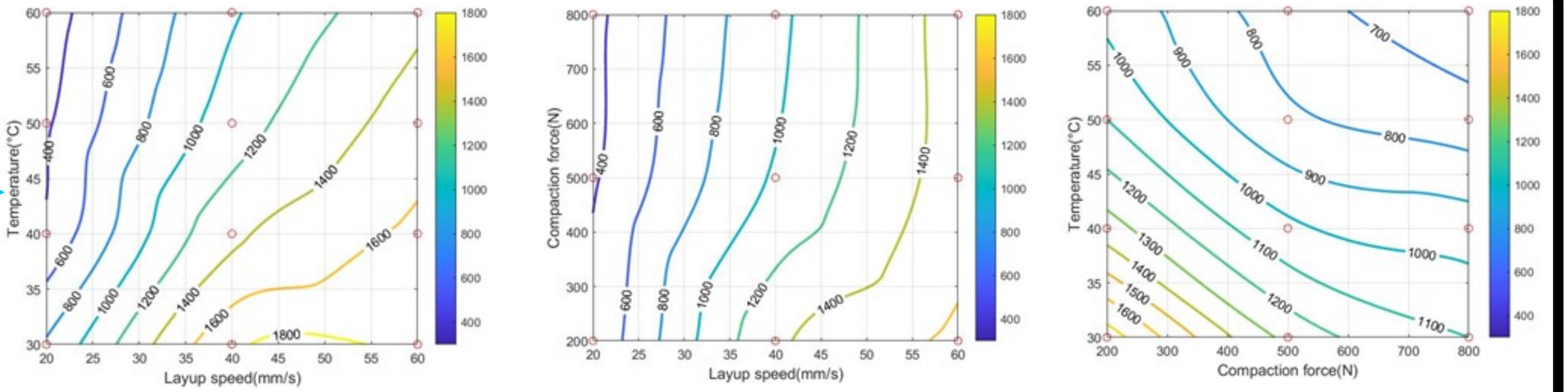
Find process limits



~~**Investigating the effect of process conditions on lay-up quality**~~

Optimisation of process conditions the required lay-up quality

Extend the process limits to a process map

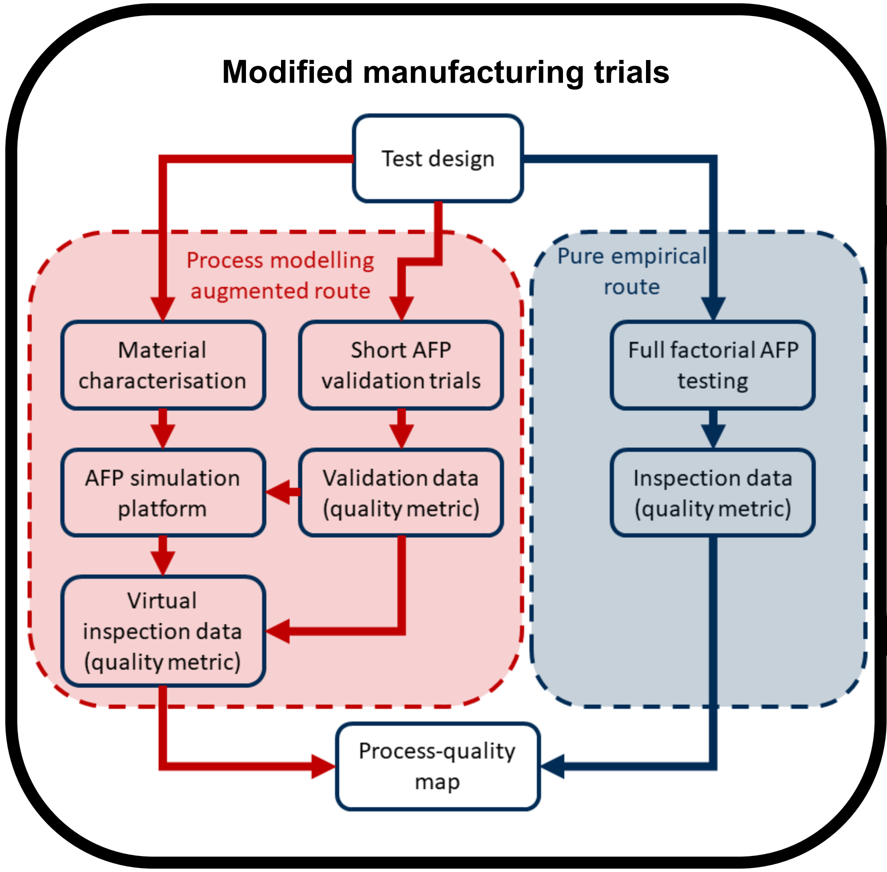


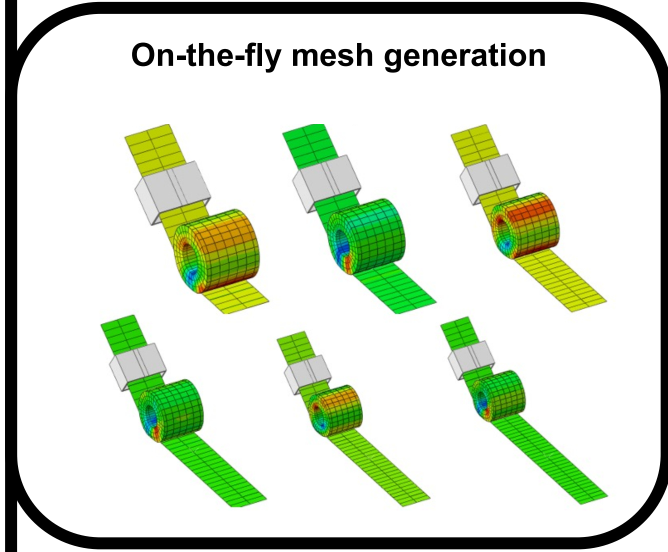
We know how sensitive the dials are, but how easy are they control during lay-up?

Demonstrated by Dr Yi Wang

Automated Fibre Placement simulations (5/5)

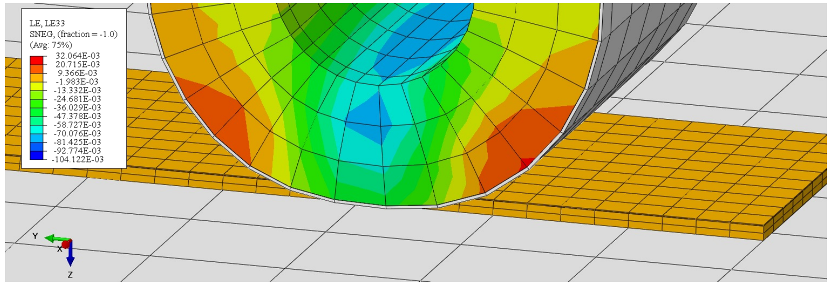
- Capable of capturing the influence of wide range of processing conditions on lay-up quality and setting process limits.
- The process map can give guidance to current AFP projects or be used a first approximation.
- Future work includes more validation, addition of complex geometry lay-ups and smart process map exploration.

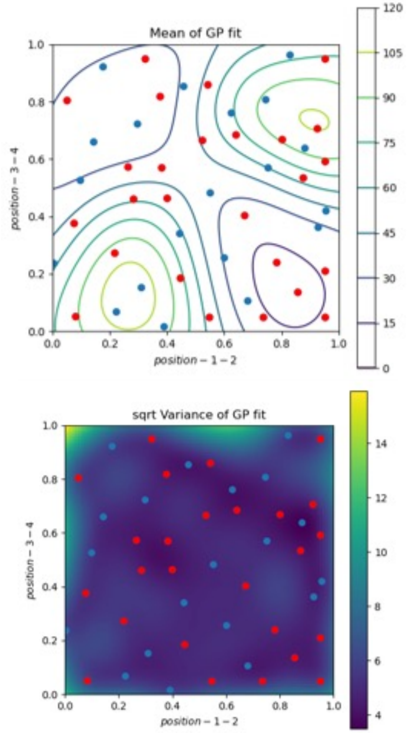


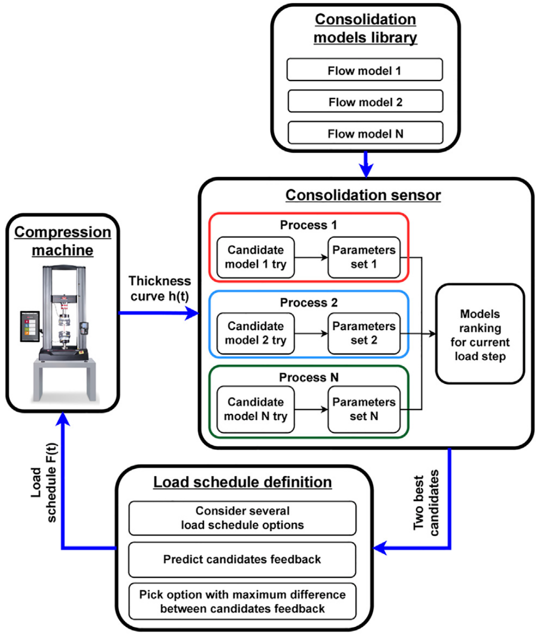


Lessons learnt and where next?

- Good example of how government research funding can benefit industry and the wider society.
- Industry-inspired research can make for great low TRL work.
- Sustainability of funding is important for work across the TRL scales.
- Demonstration that digital engineering can play a role in improving manufacturing process robustness
- Where next?
  - Automated Fibre Placement
  - Link to failure models
  - Data but in a slightly different way (i.e., quality over quantity)
  - Machine-model interaction







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SIMprocs

UKRI Engineering and Physical Sciences Research Council