University of BRISTOL
Bristol Composites Institute

Damage Models for SiC/SiC CMCs

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Background & Motivation

Questions being addressed:

1. Can the BCI models developed for woven **OMCs** be adapted for **SiC/SiC CMCs**?
2. How can the **complex damage mechanisms** of these materials be modelled efficiently and effectively?
3. At which **length scales** should these damage mechanisms be modelled?
4. Can **suitable assumptions** be made to compensate for the difficulties in characterising the various constituents and damage mechanisms?

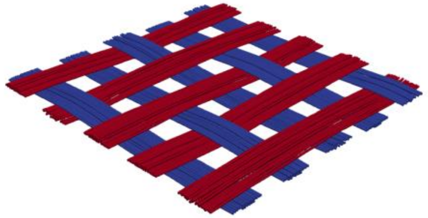
BCI / UTC Meso-scale Modelling Framework

Material Architecture

Manufacturing simulations

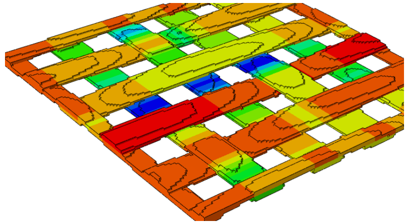
Finite element simulations

Digital elements for as-woven geometry



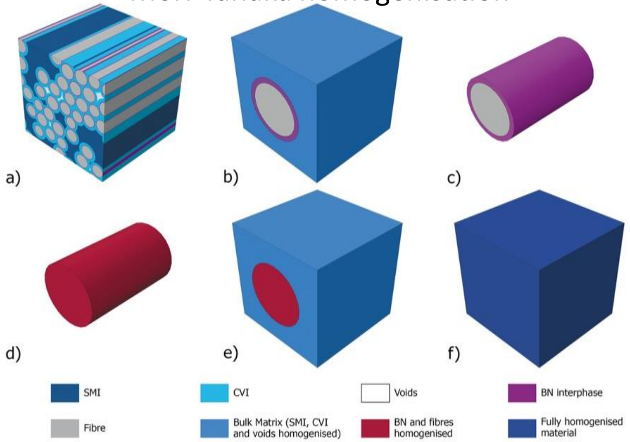
As-woven yarn surfaces extracted

Voxel models with local fibre volume fractions and fibre orientations

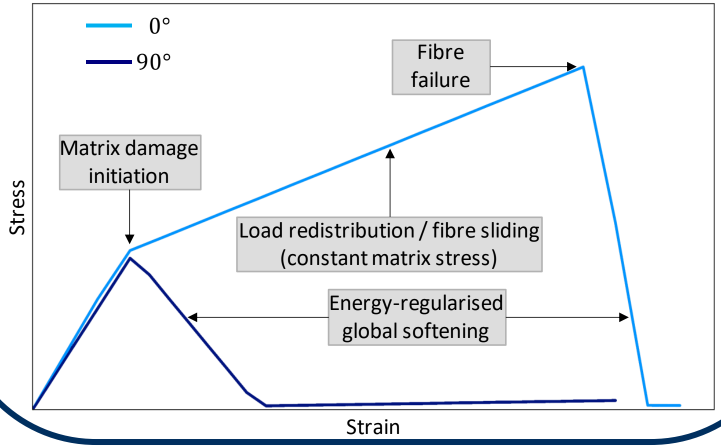


Material Models

Mori-Tanaka homogenisation

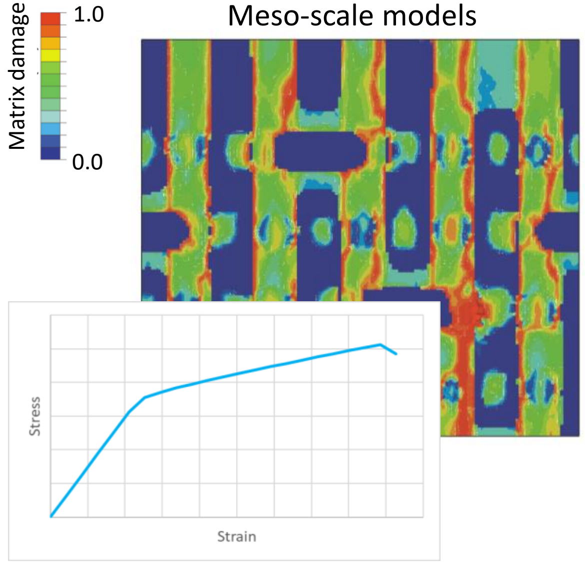


Matrix CDM model

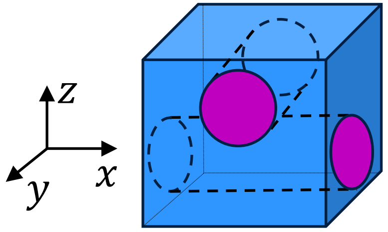


Results

Meso-scale models

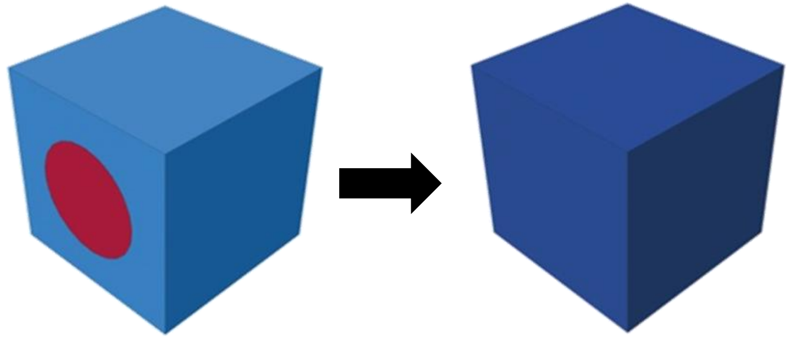


Macro-scale models



Mori-Tanaka Homogenisation

- Homogenise an inclusion (i) with its surrounding medium (m) to get a global stiffness tensor C_{homog}
- Strain concentration tensor A_{i} defines the relationship between globally applied strains and local constituent strains
- Required constituent data:
  - Elastic properties
  - Volume fraction
  - Shape of inclusion



Inclusion and matrix *Homogenised model*

Strain concentration tensor of inclusion:

$$A_{\mathrm{i}} = [I + E\, C_{\mathrm{m}}^{-1}(C_{\mathrm{i}} - C_{\mathrm{m}})]^{-1}$$

Eshelby tensor (inclusion ‘shape’)

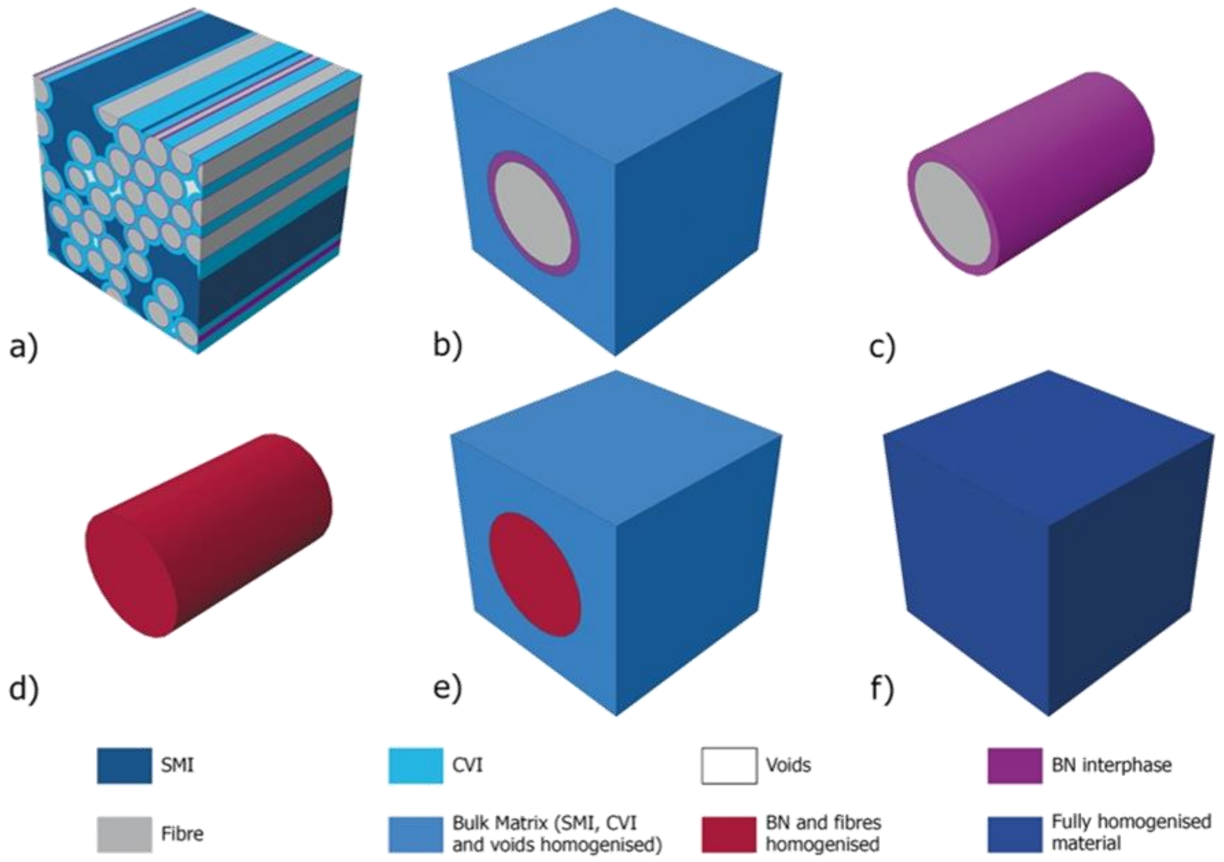
Homogenised stiffness tensor:

$$C_{\mathrm{homog}} = C_{\mathrm{m}} + V_{\mathrm{i}}\,[A_{\mathrm{i}}\,(C_{\mathrm{i}} - C_{\mathrm{m}})]$$

Volume fraction of inclusion

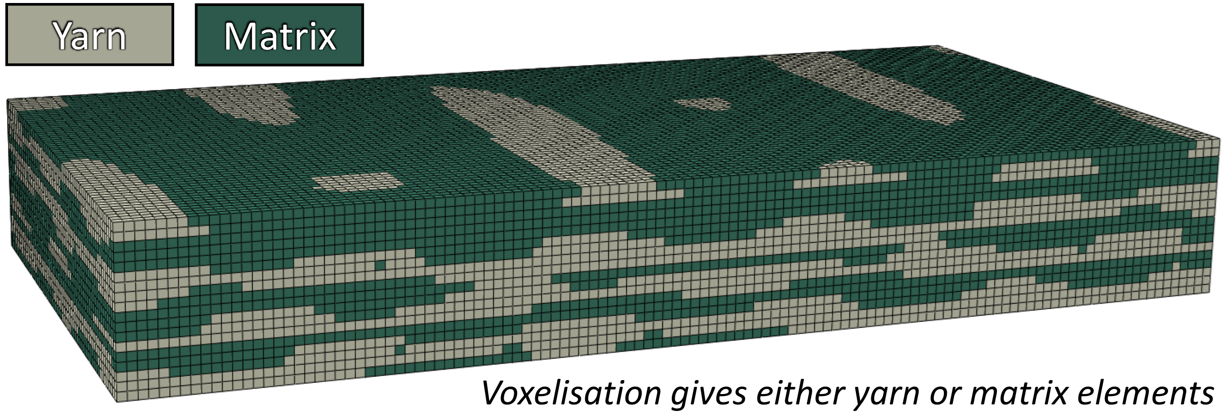
Meso-scale Models of Woven SiC/SiC CMCs

Mori-Tanaka homogenisation of CMC yarn



Meso-scale material architecture

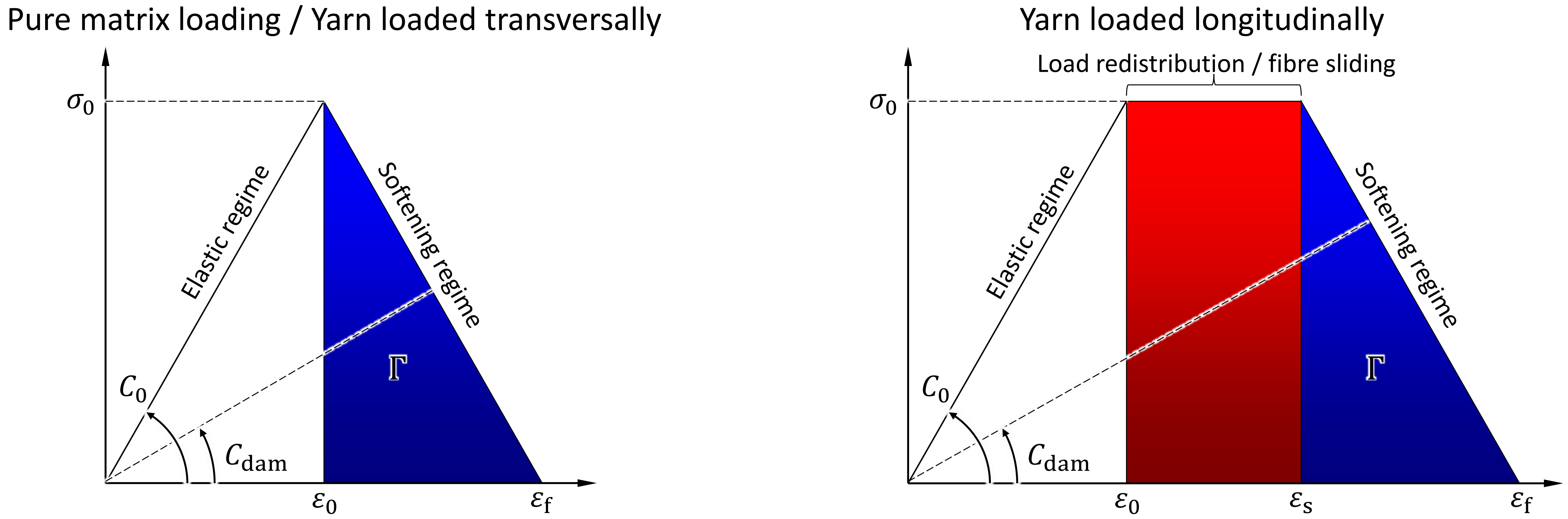
- BCI weaving and compaction models (SimTex) adapted for SiC/SiC CMCs
- Result: meso-scale voxel models containing **homogenised yarn** and **matrix** phases including local fibre volume fraction and fibre orientation



Voxelisation gives either yarn or matrix elements

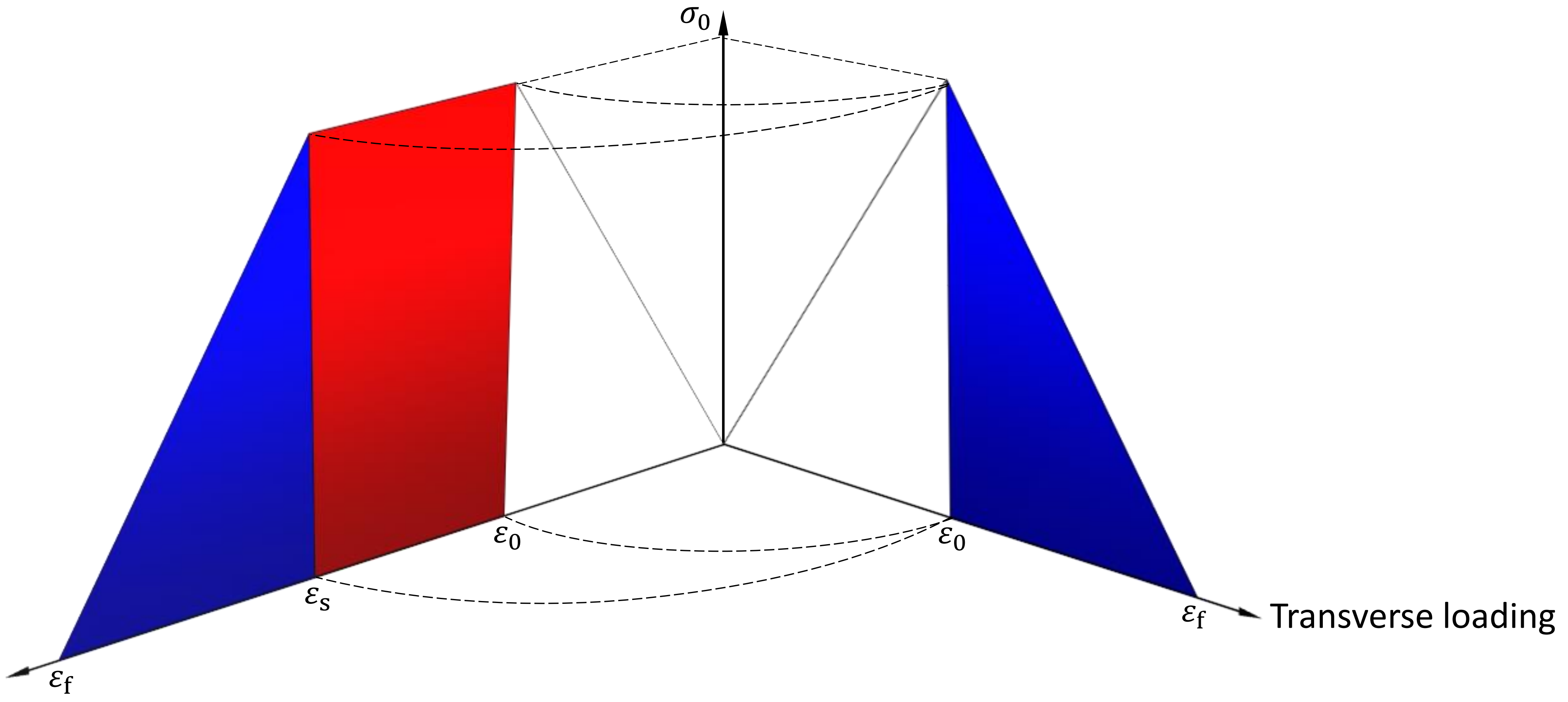
Continuum Damage Mechanics (CDM) for SiC Matrix

- Energy-regularised CDM implemented for SiC matrix in (1) ‘pure matrix’ regions and (2) matrix constituent within yarns
- Load redistribution / fibre sliding after matrix damage modelled by a **constant matrix stress** assumption (until the fibre failure criterion is met)



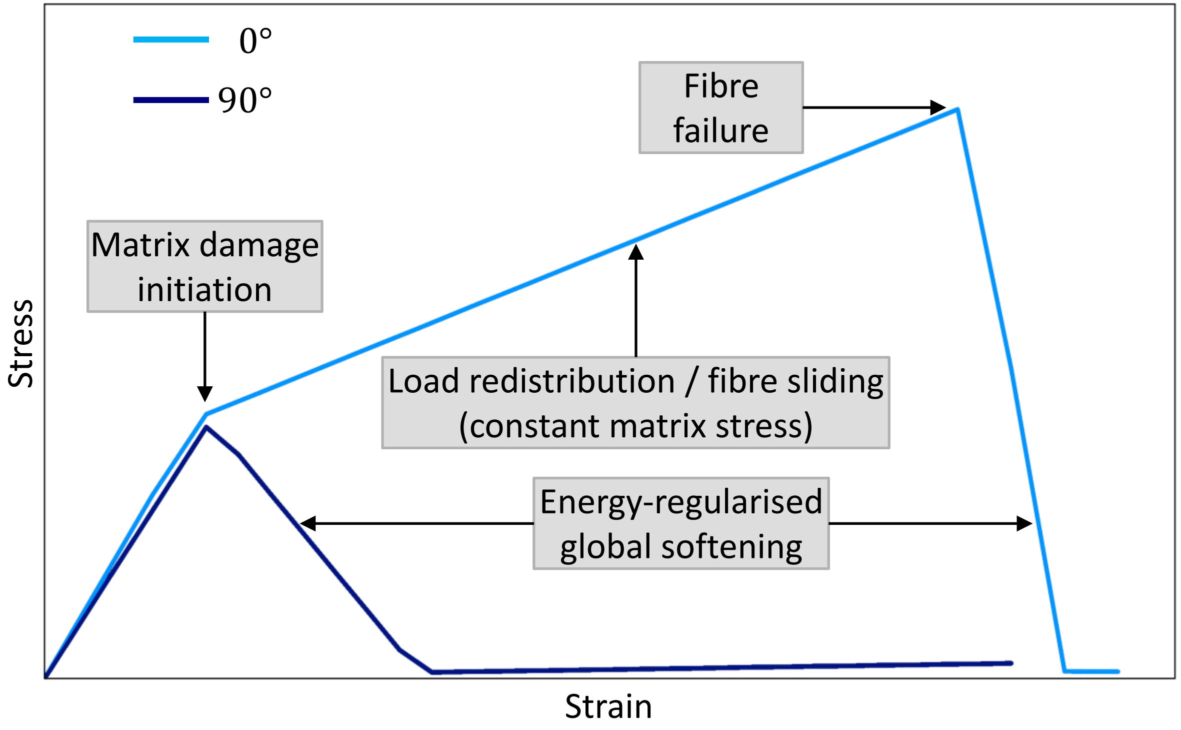
CDM for Matrix Phase Within Yarns

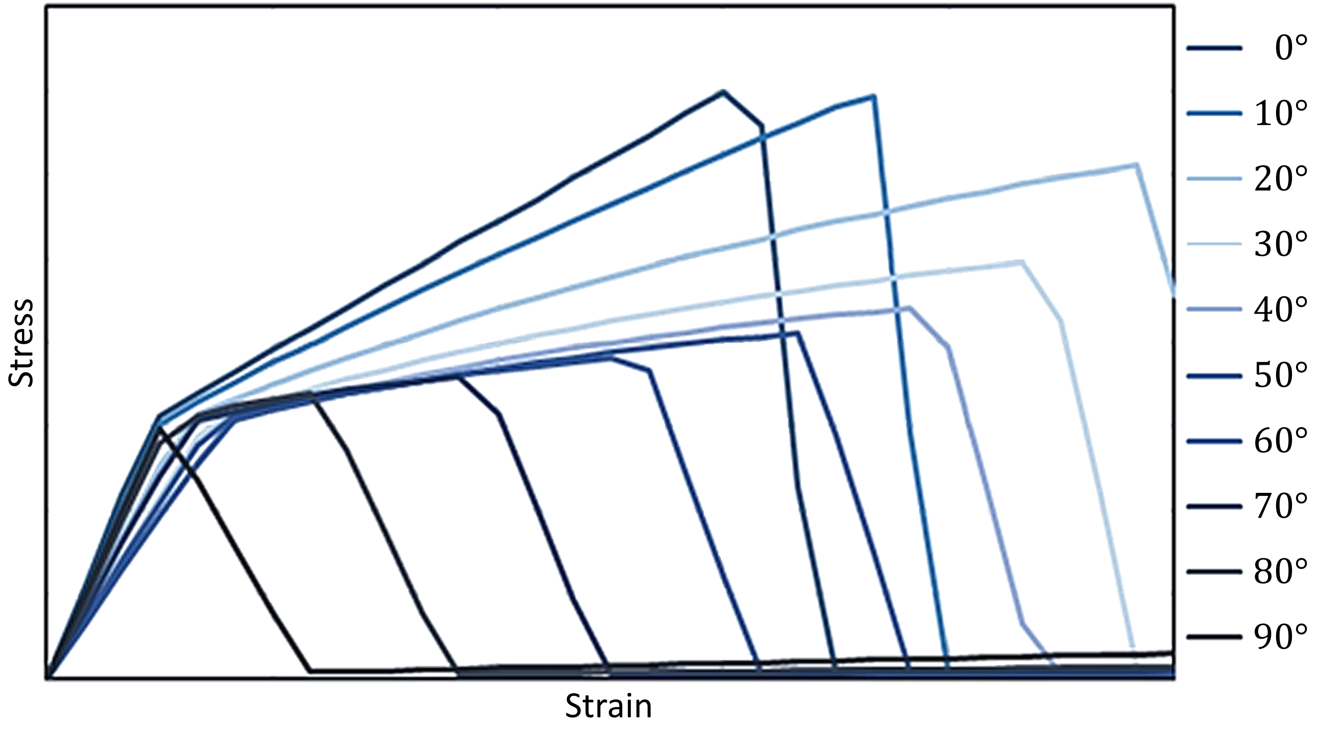
- The damage behaviour of yarns is interpolated between the longitudinal and transverse loading cases based on the local fibre orientation and strain field:



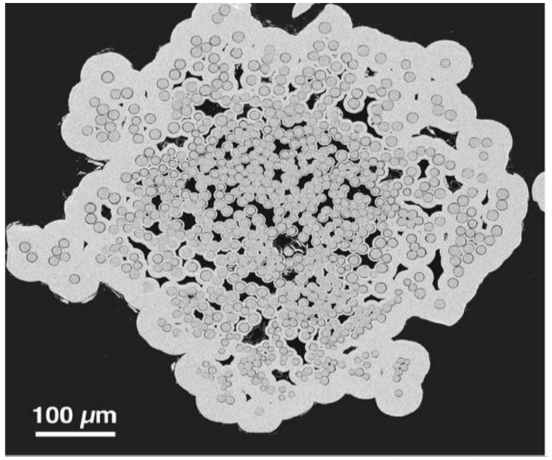
Yarn Model Verification – Off-axis Tension

- Yarn model with matrix damage verified through off-axis tension simulations
- Tangent modulus of yarns during ‘constant matrix stress’ regime in good agreement with experimental observations





Yarn Model Validation – Mini-composite Tests

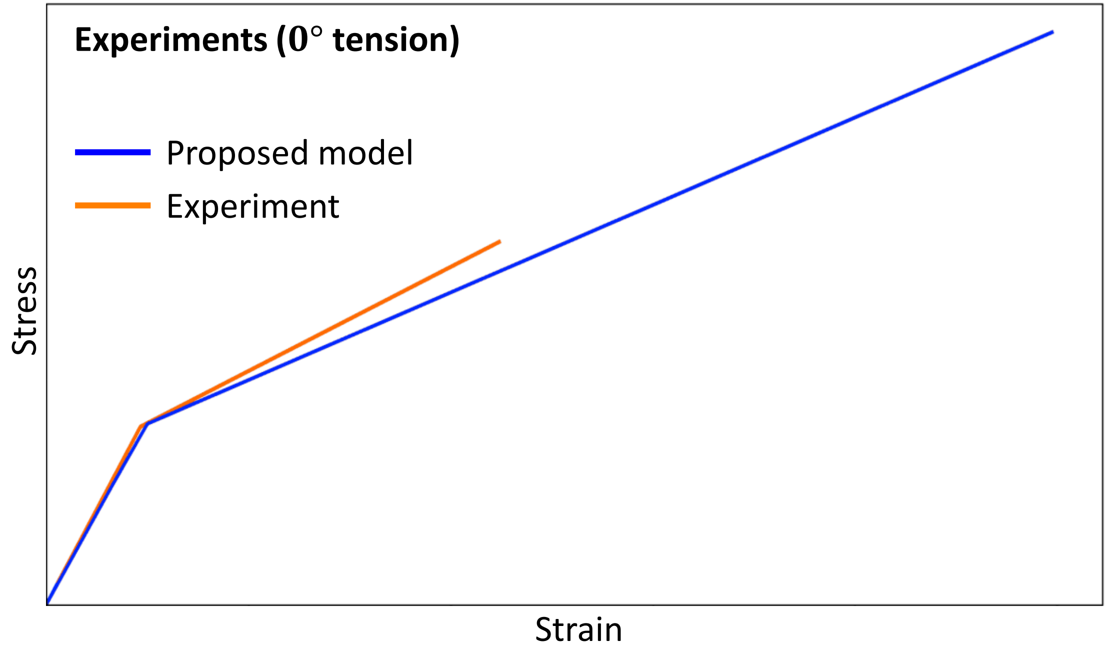


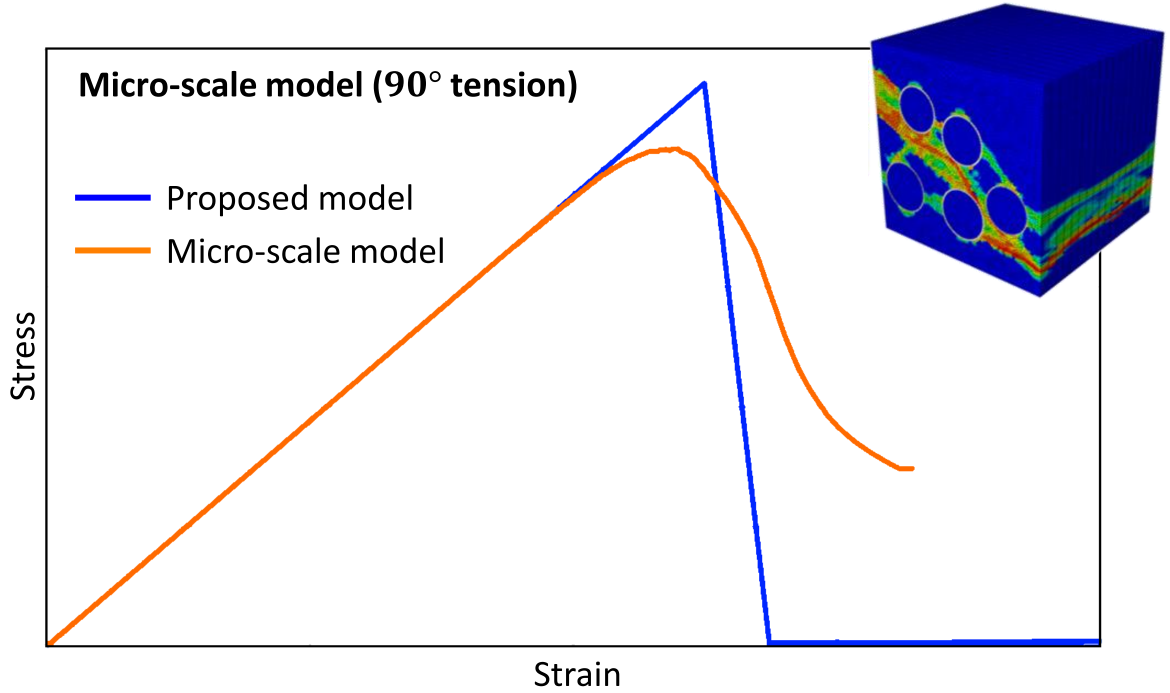
Yarn volume fractions
- Fibre - 25.8%
- BN - *Export Control*
- Void - *Export Control*
- CVI - *Export Control*

Rule of Mixtures
- $E_{[\text{yarn matrix}]}$ - *Export Control*
- $\sigma^{\max}_{[\text{yarn matrix}]}$ - *Export Control*

Constituent properties (from literature):

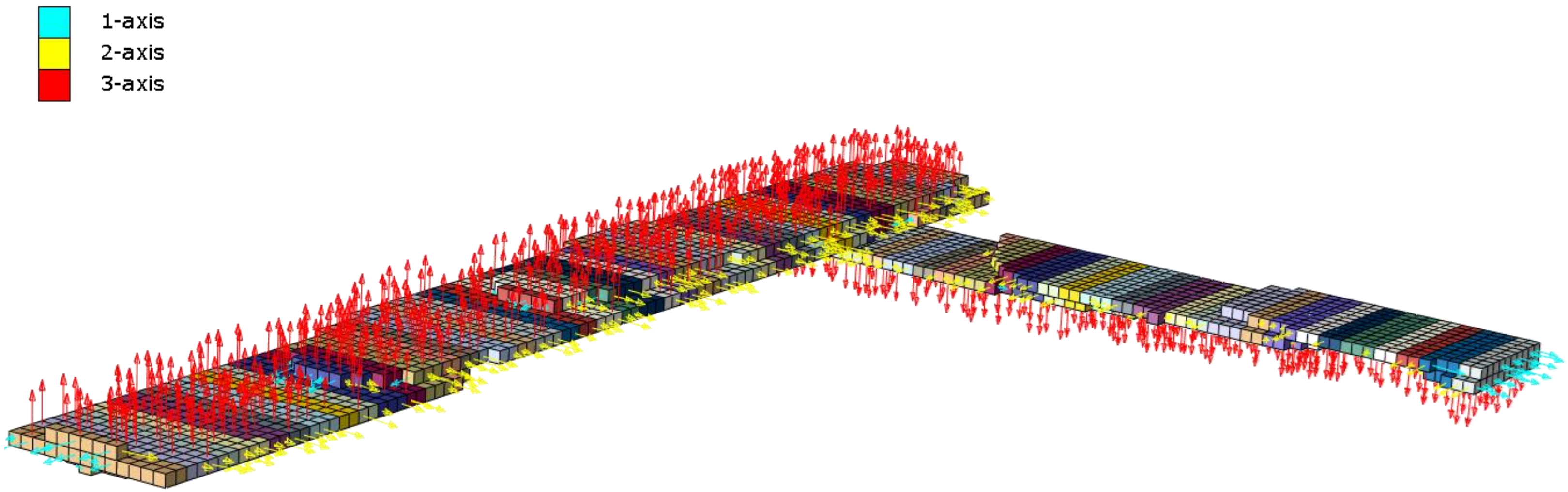
Constituent	E [GPa]	ν	$\sigma_{\max}$ [MPa]
Fibres	300	0.17	3200
CVI SiC Matrix	460	0.17	500
Boron Nitride	20	0.22	-
SMI SiC Matrix	299	0.17	170



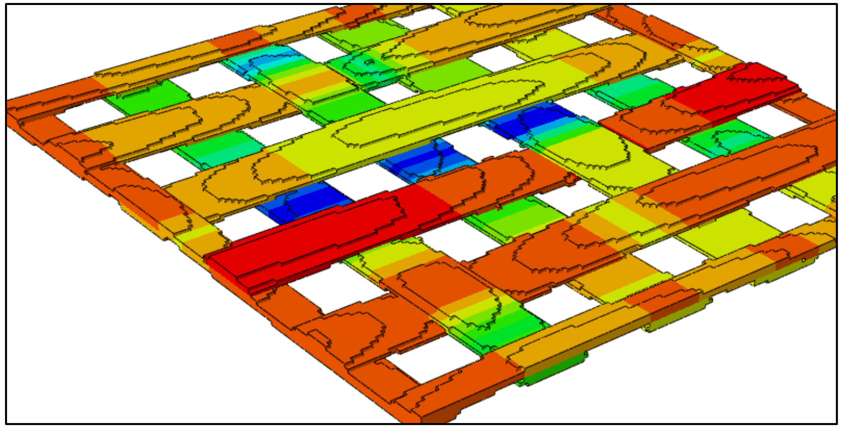


Local Fibre Volume Fractions and Fibre Orientations

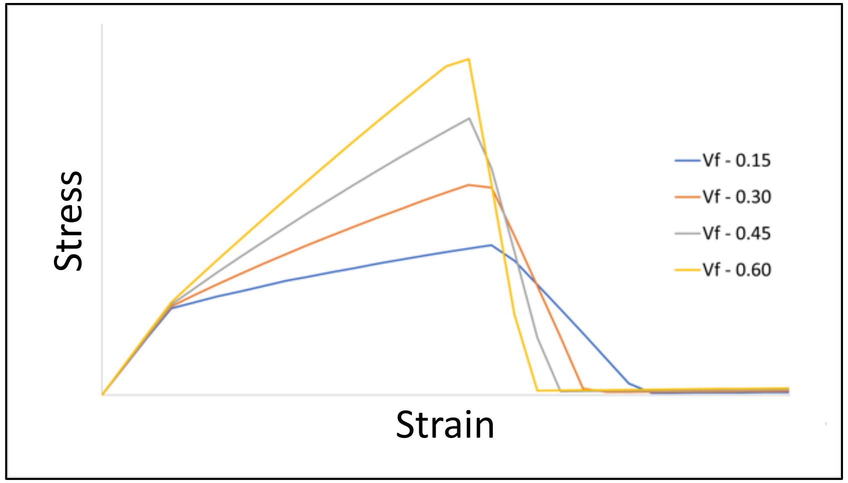
The Mori-Tanaka + CDM model is applied to individual yarns in the weave taking into account local material axes and fibre volume fractions obtained from weaving and compaction simulations (SimTex)



Individual yarns and their material orientations



Fibre volume fraction in yarn elements of meso-scale models

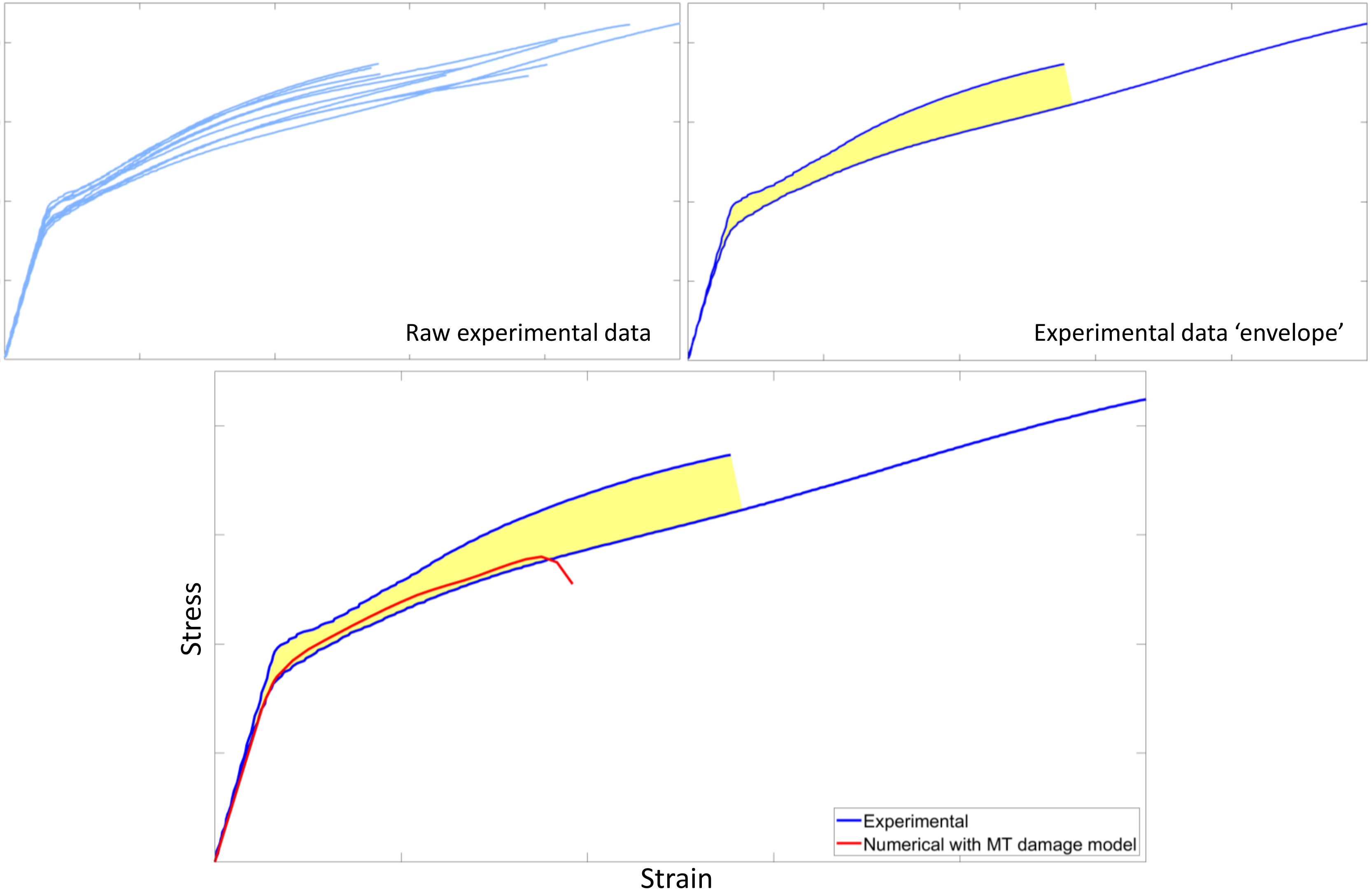


Comparison of different fibre volume fractions

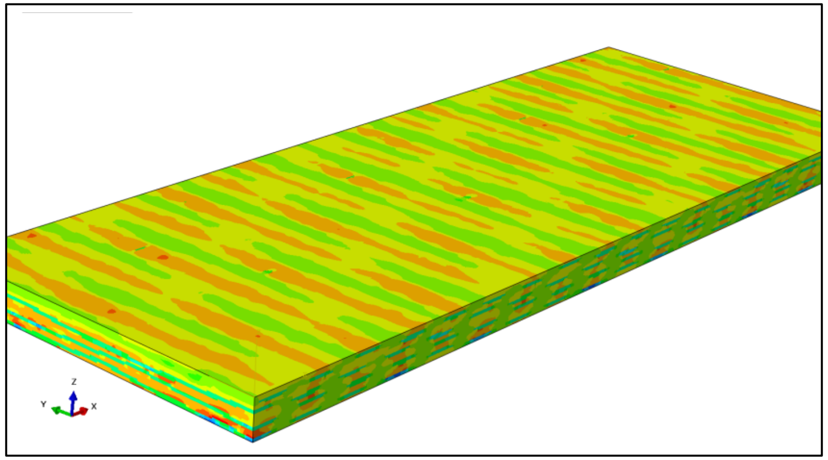
Verification and Validation Test Cases

- Unnotched tension (R-R)
  - Gauge section dimensions: 27.94 mm × 10.5 mm
  - Data recorded: Force-displacement curves
- Unnotched tension (Swansea UTC)
  - Gauge section dimensions: 7.6 mm × 3.8 mm
  - Data recorded: Force-displacement curves, SEM images (centre of gauge length)
- Open-hole tension (R-R)
  - Proprietary dimensions
  - Data recorded: Force-displacement curves, DIC maps

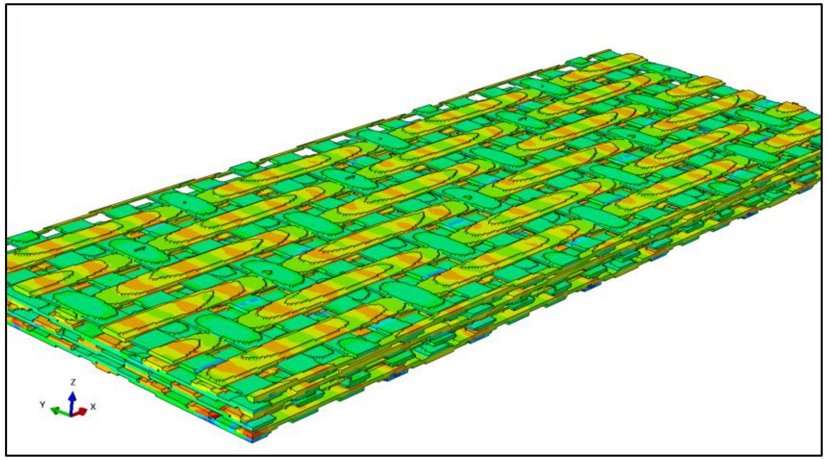
Unnotched Tension Tests – Global Stress-Strain Response



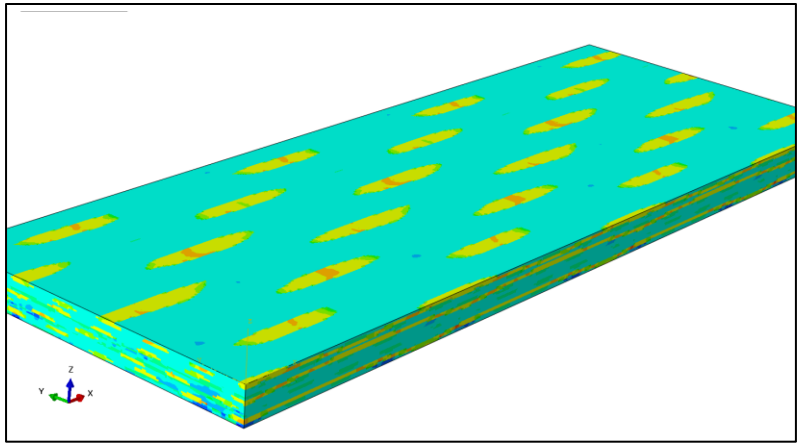
Unnotched Tension Tests – Direct Stresses σ_{11}



Composite stresses, pristine

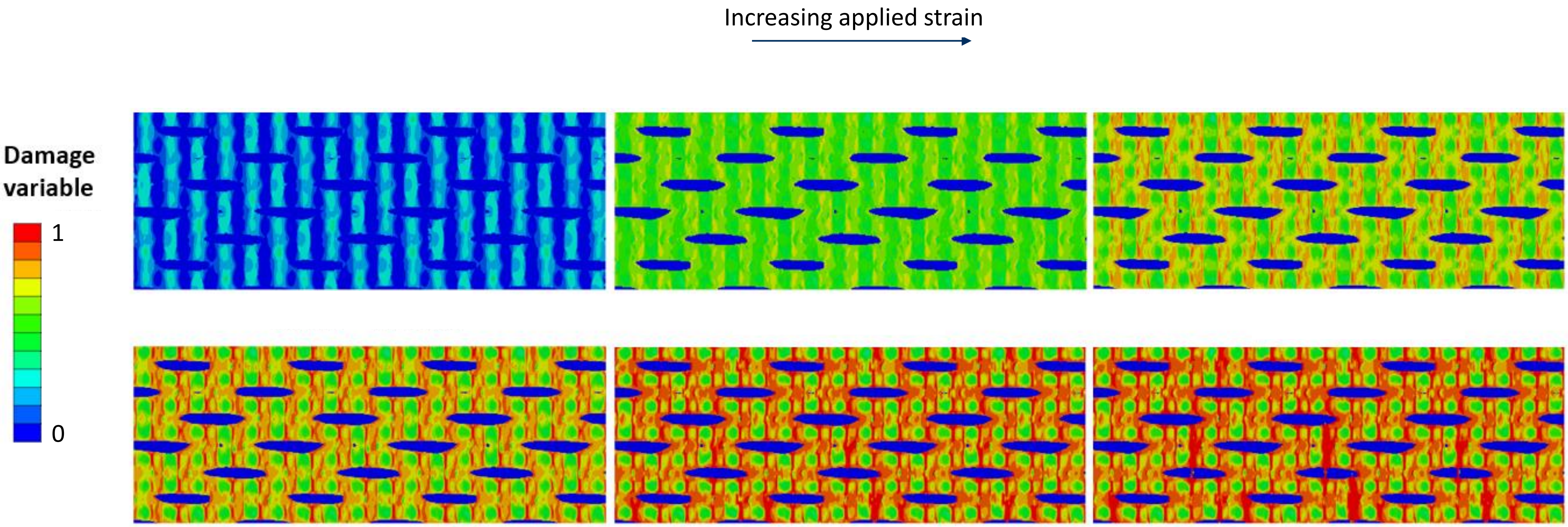


Yarn stresses, pristine

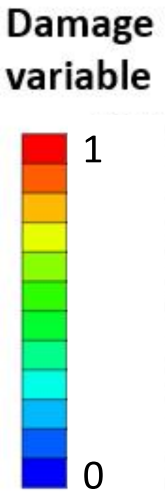


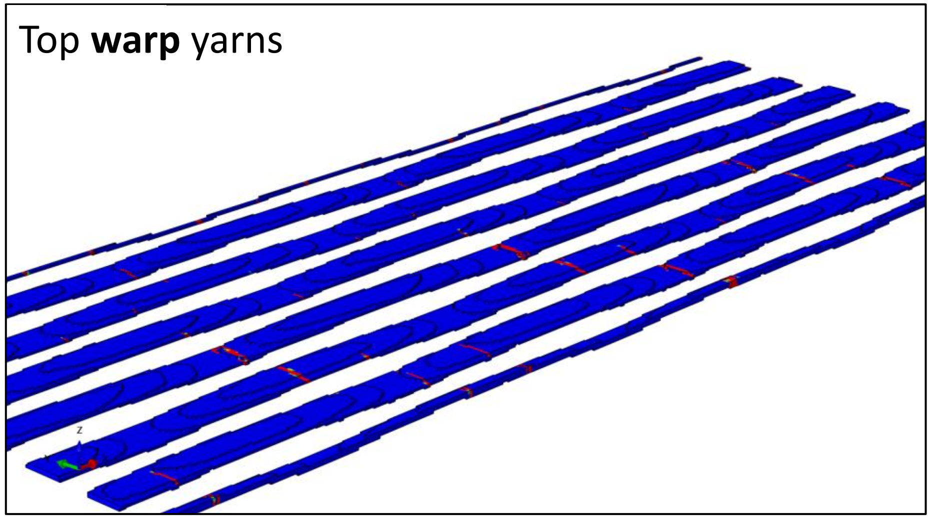
CMC textile stresses,
after bulk matrix damage

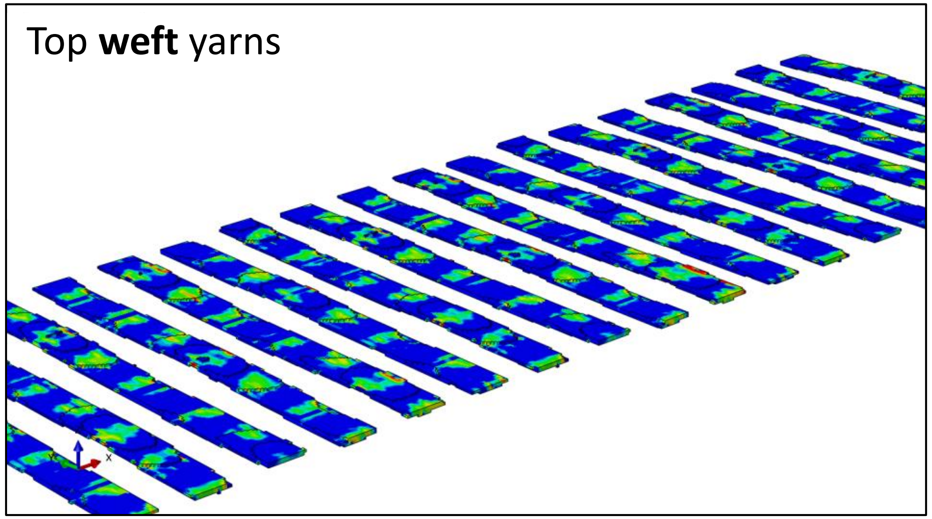
Unnotched Tension Tests – Damage Contours

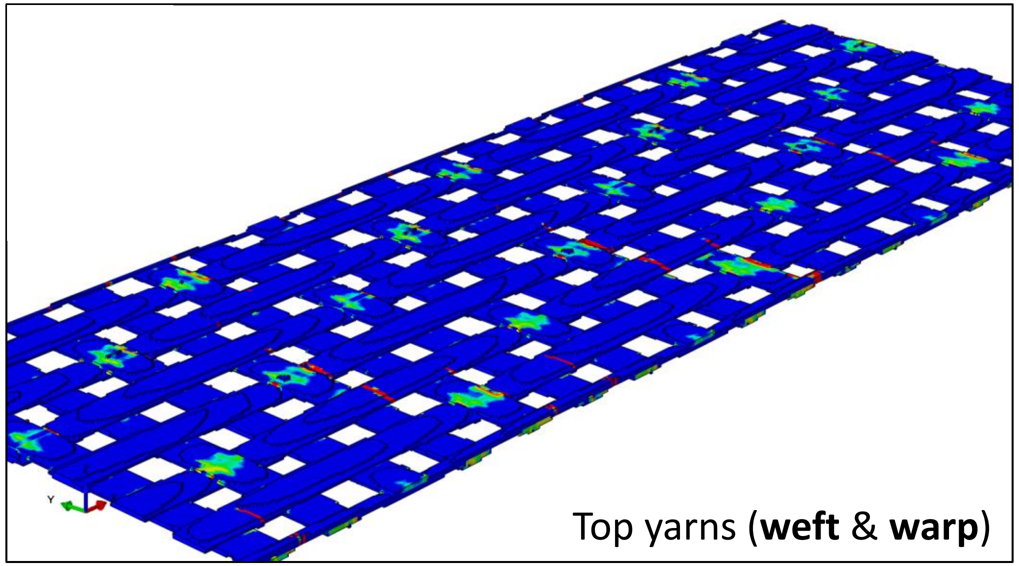


Unnotched Tension Tests – Yarn Damage at Final Failure



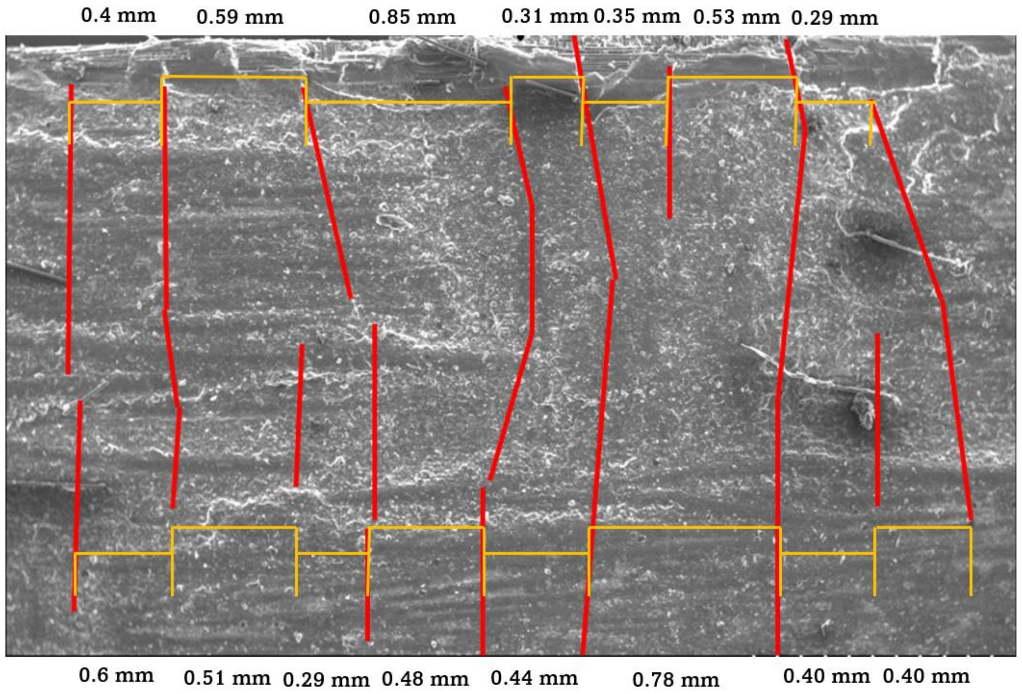


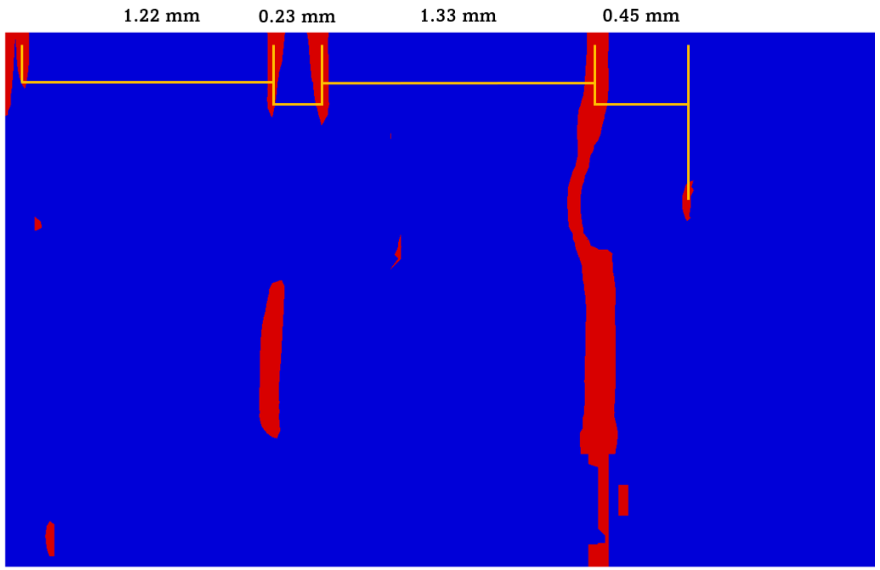


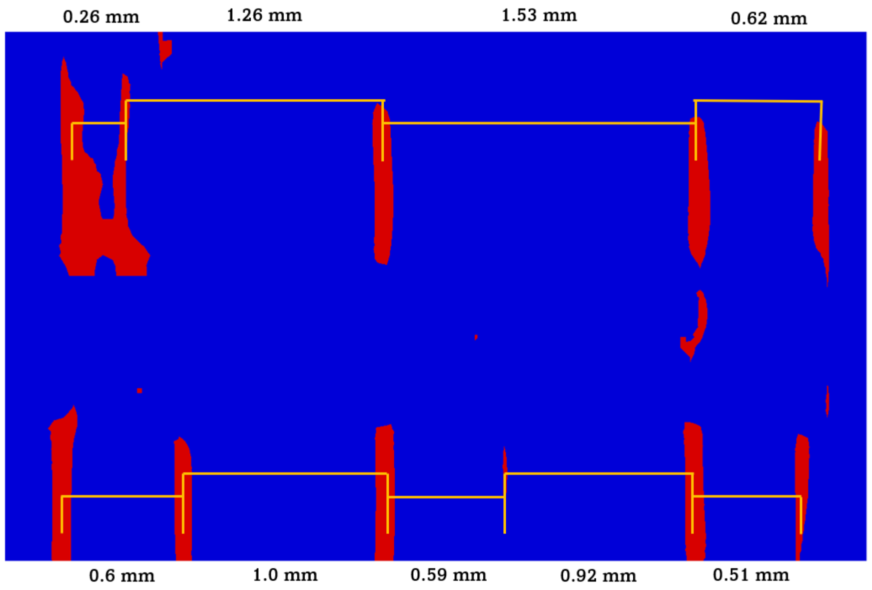


SEM Evidence (Swansea UTC)

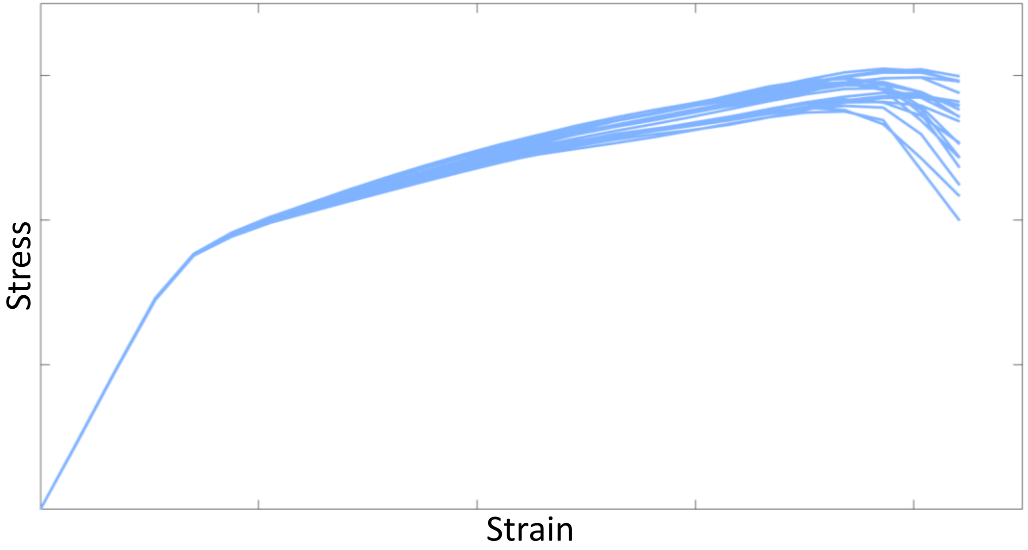
- Crack orientations and spacing measured by SEM at increasing loads and at final failure (shown here)
- Similar 'tram-track' shaped cracks in both cases
- Experiments show more closely-spaced cracks → models assume a homogeneous bulk matrix (without particles or pure Si)

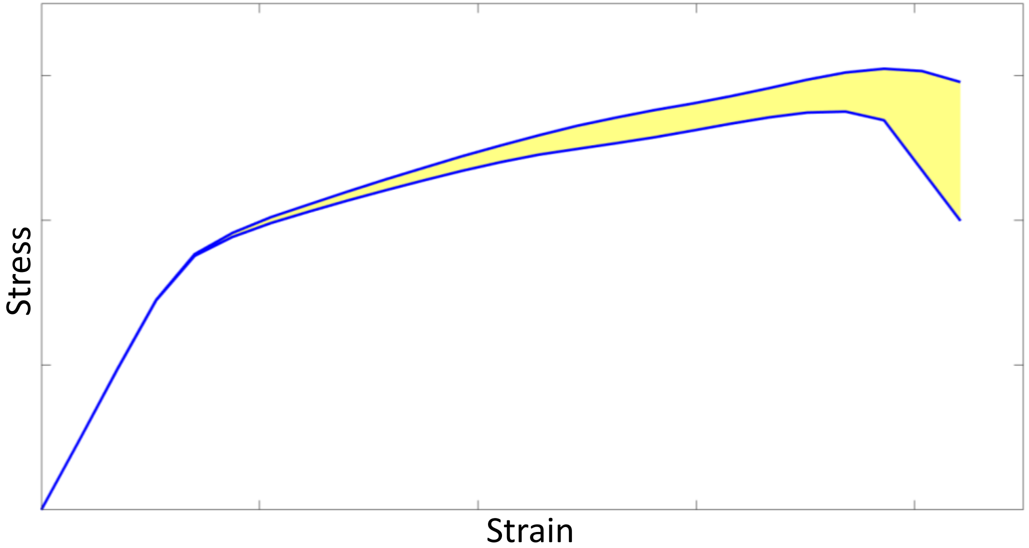




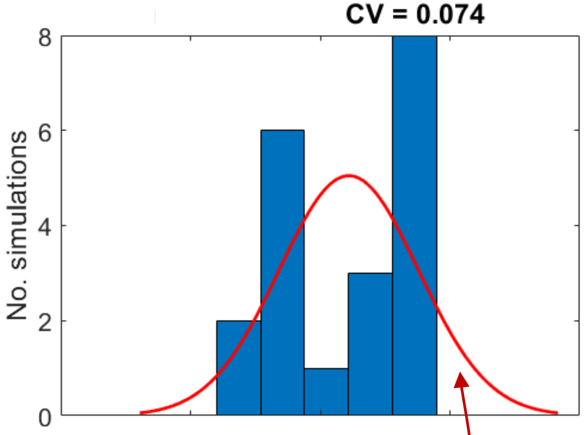


Sensitivity Study – Random Yarn Shifting

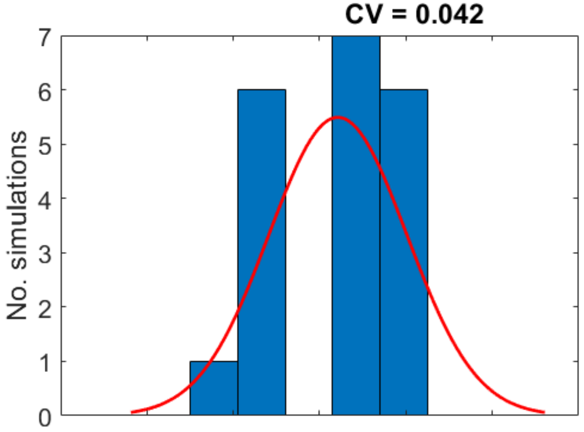




Proposed modelling framework enables the study of **manufacturing variabilities** such as random 'shifting' between adjacent yarns

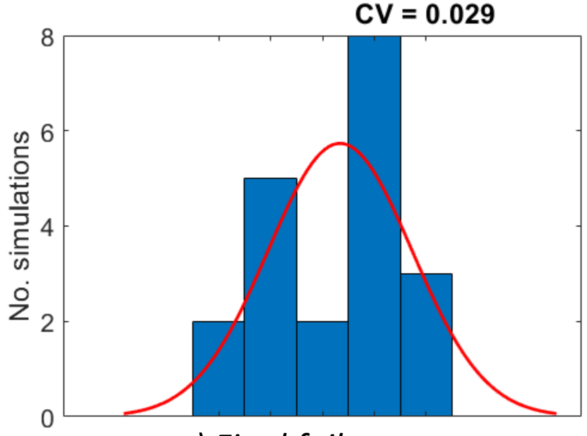


a) Tangent modulus



b) Final fail strain

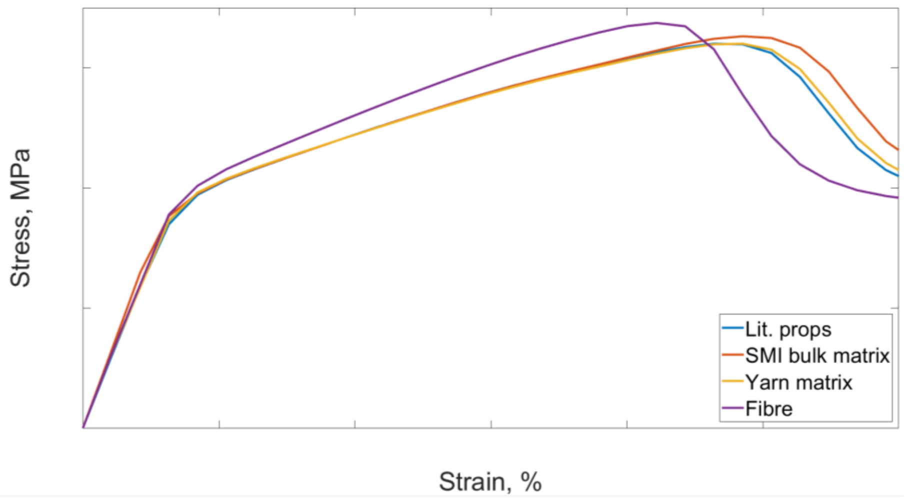
Assuming a normal distribution, for 99.8% of yarn shifting cases the tangent modulus varies within ±44.5% of the mean value



c) Final failure stress

Sensitivity Study – Constituent Properties

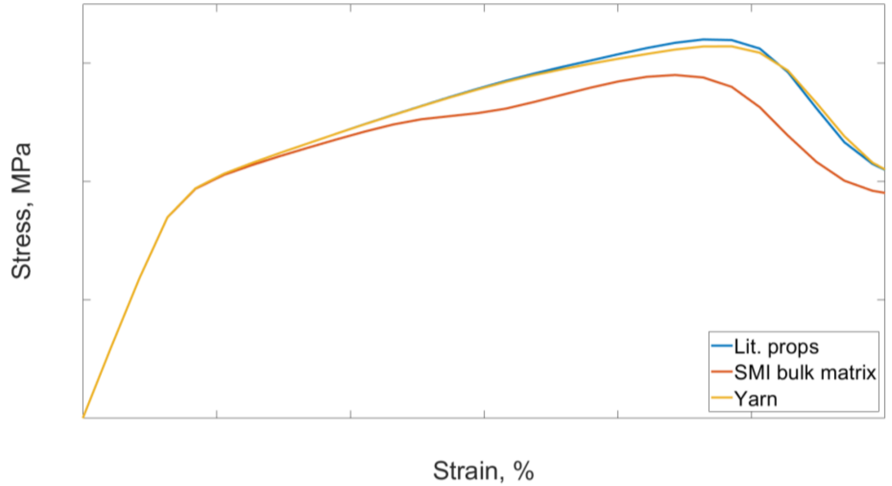
Modulus, +20%



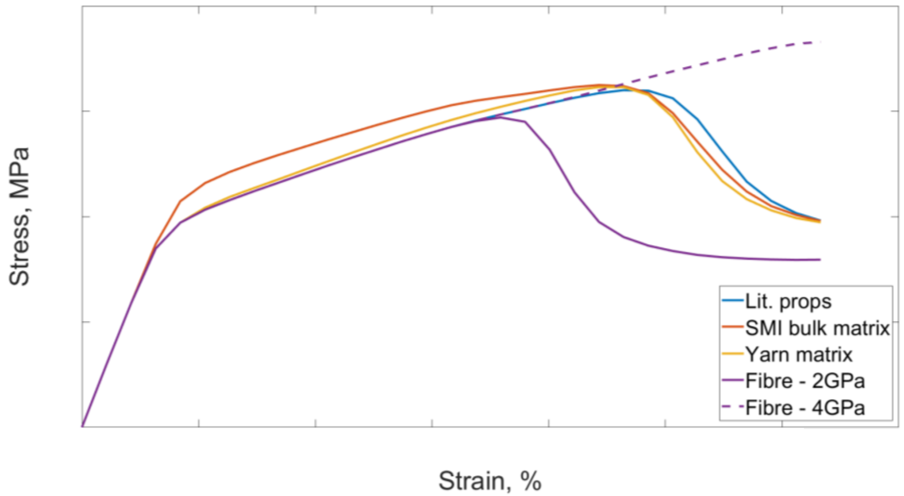
Proposed modelling framework enables the study of **material variabilities**

- SMI bulk matrix properties have a significant influence on the CMC properties
- Fibre modulus has a significant influence on CMC tangent modulus
- Variation in fibre strength properties reported in literature can change CMC failure strain by up to 100%

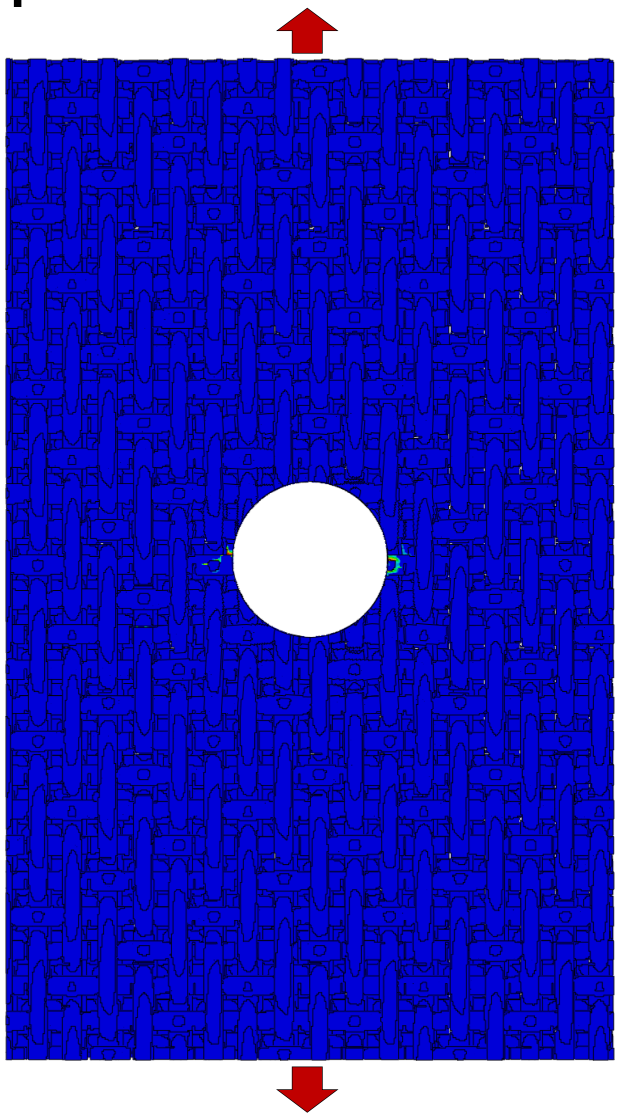
Fracture toughness, -50%



Strength, +20%

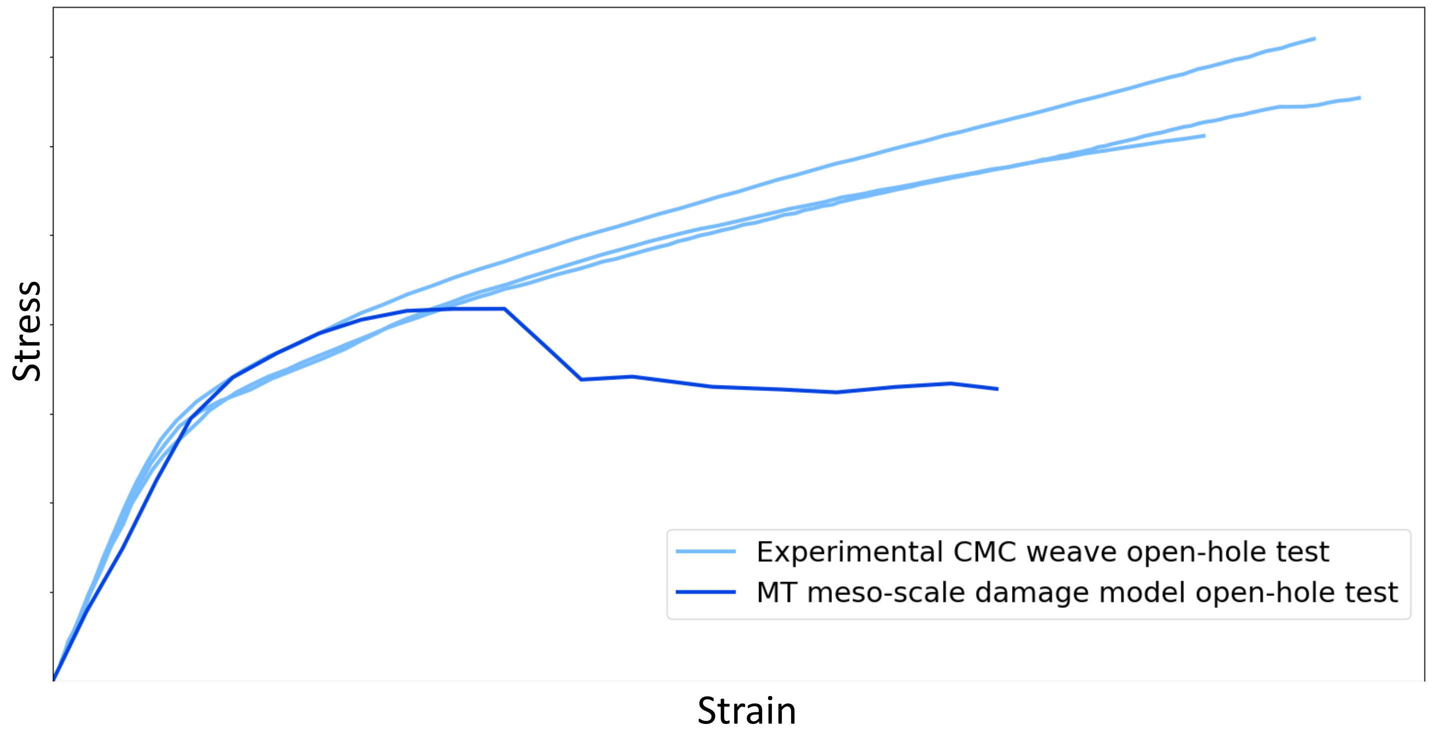


Open-Hole Tension Tests



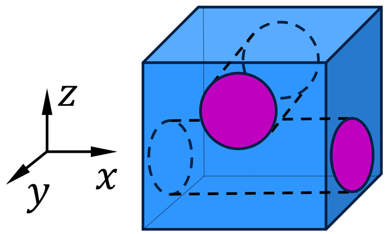
The modelling framework was also applied to feature-level open-hole tension tests

- Very large models ran on Bristol's HPC facilities
- For large applied strains the model overestimates the extent of damage, consistently with uniaxial tension results
- Open-hole tests believed to be highly sensitive to manufacturing variabilities

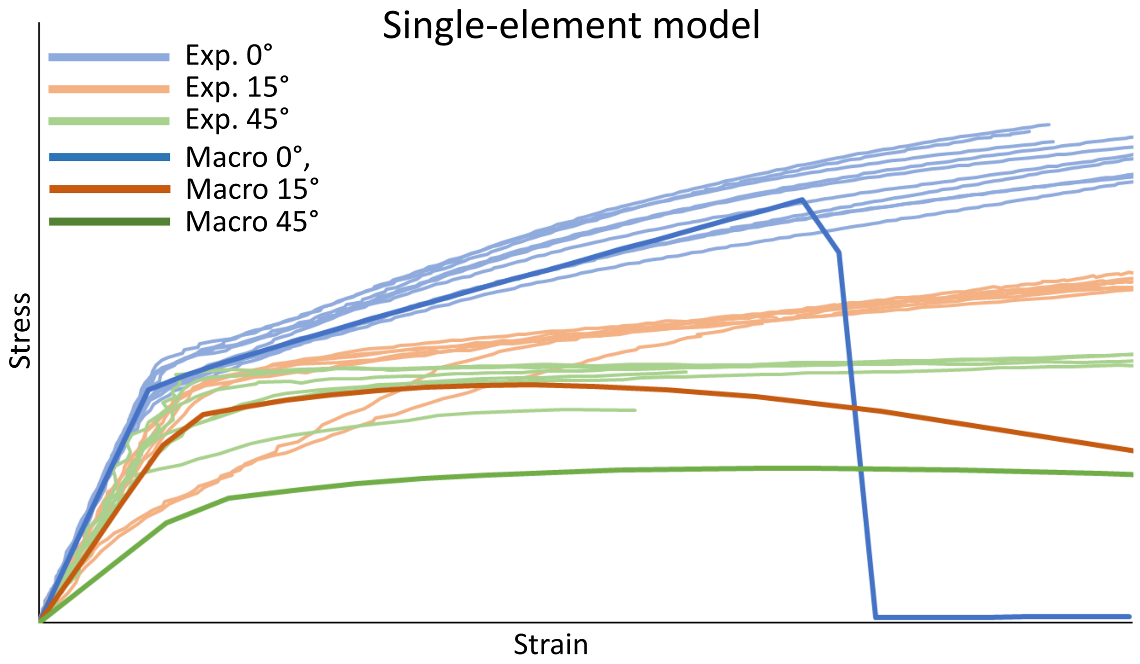


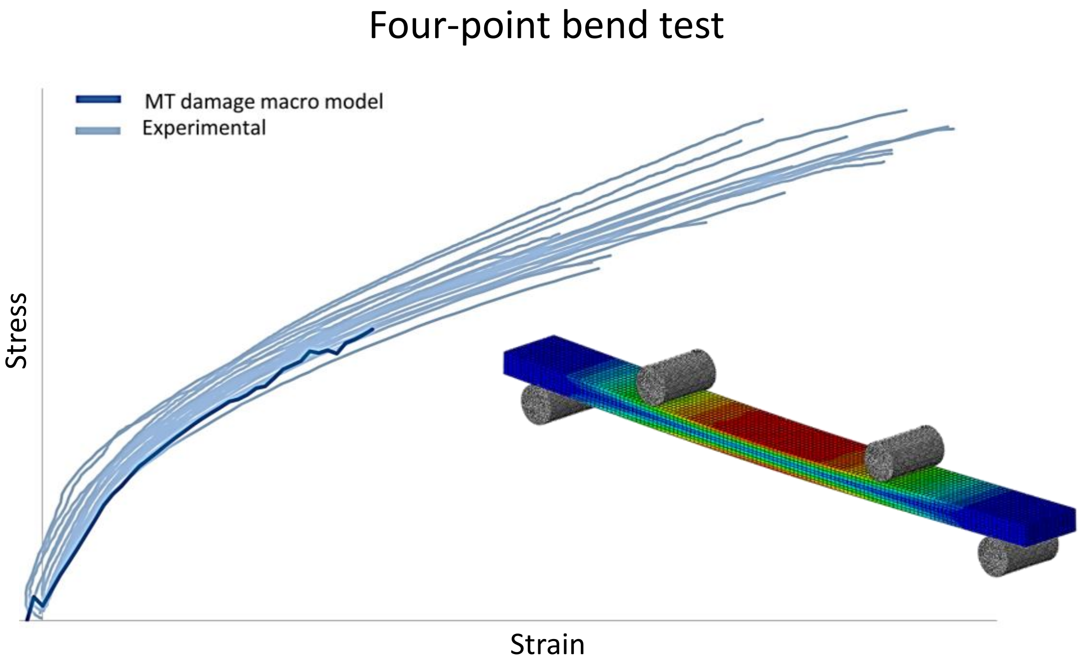
Homogenised Macro-scale Material Model

- Homogenised macro-scale model suitable for component-scale analyses
- Fibre inclusions at 0° and 90° to simulate weave
- Underlying weave structure may be considered using fibre and interphase (0° and 90°) plus CVI and SMI volume fractions



Model extended to multiple fibres





Summary

- A 3D meso-scale material damage model for woven CMCs was developed which takes constituent properties, volume fractions and fibre architecture as input
- Assumptions made to account for complex damage mechanisms and limited material data are suitable at this stage
- Combined with weaving & compaction models give good agreement with experiments

Future work

- Further experiments required to validate meso-scale model
- Stochastic properties for bulk matrix to better match the real micro-structure
- Material model currently being extended to include thermal, environmental, creep and fatigue effects

Acknowledgements

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