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Bristol Composites Institute

Multi-scale Progressive Damage Modelling of Composite Structures using Parametric Failure Manifolds

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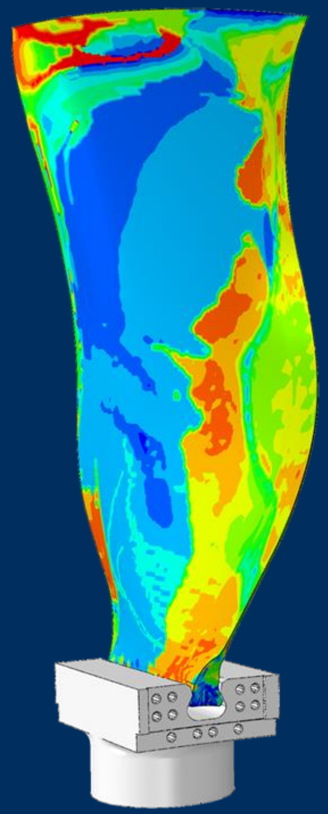
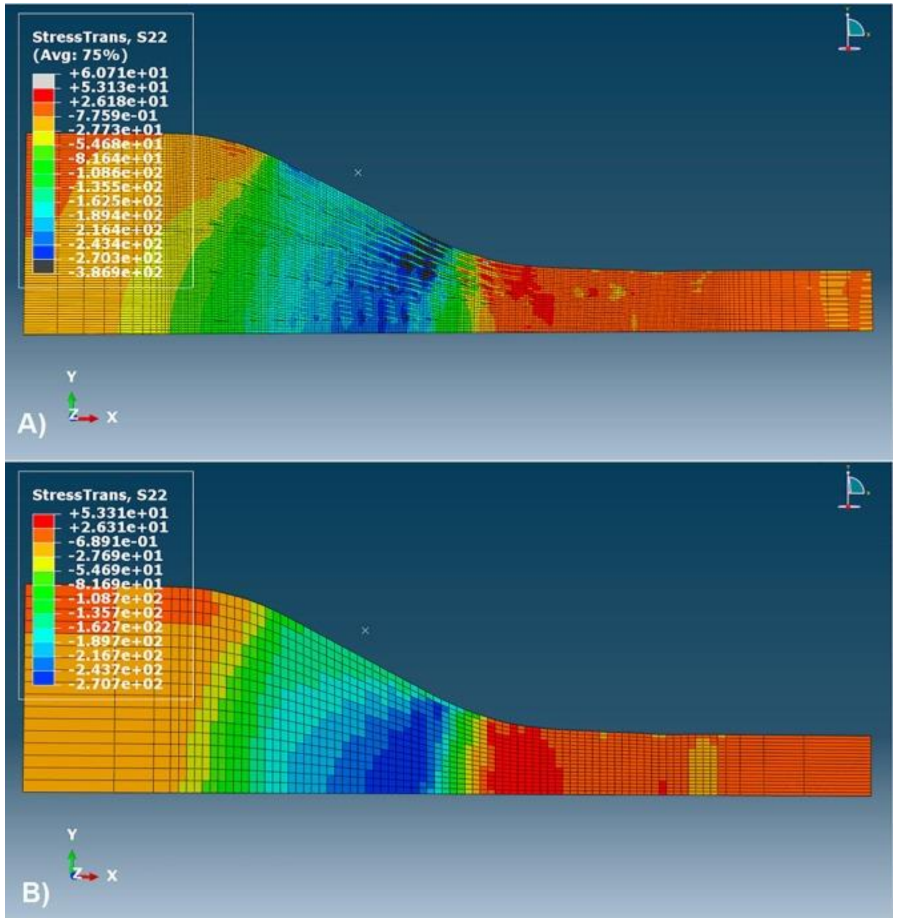
ICCM 2023 – International Conference on Composite Materials, Belfast, 30th July - 4th August 2023.



Multi-scale Challenges in Composite Structures

- Damage initiates at the smaller scales (delamination, matrix cracks, fibre failure).
- The material response is history and loading conditions dependent.
- Small scale damage progression is dependent on macro-scale structural stress re-distribution.
- Building high fidelity meso-scale models of complete structures is computationally unfeasible. Industrial scale structures could have hundreds of plies and are meters in length.
- A homogenised non-linear model of composites failure is required for structural scale modelling.

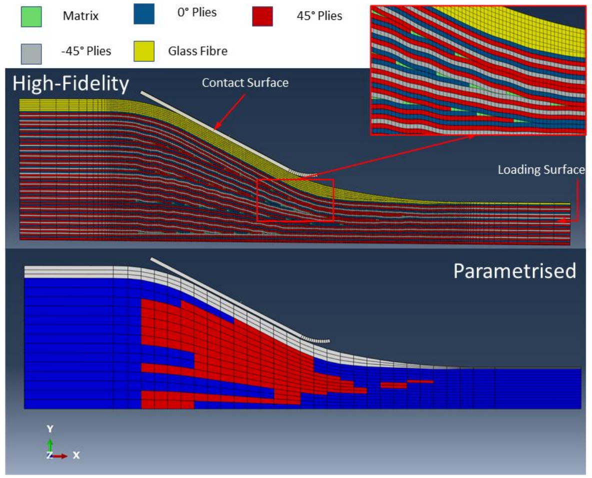


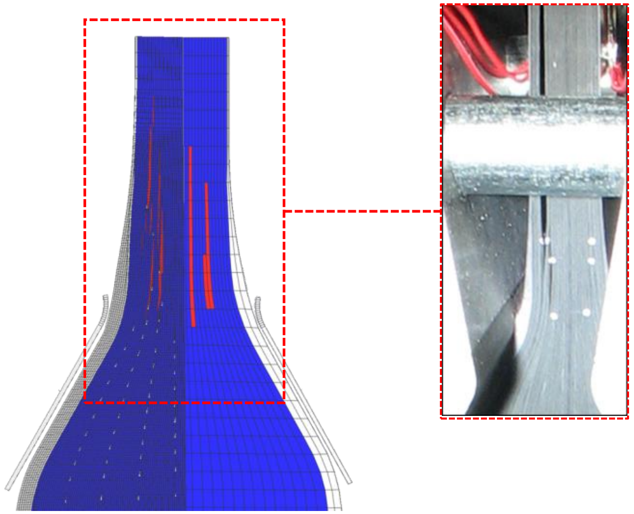
High Fidelity vs Homogenised Response

Multi-scale Challenges in Composite Structures

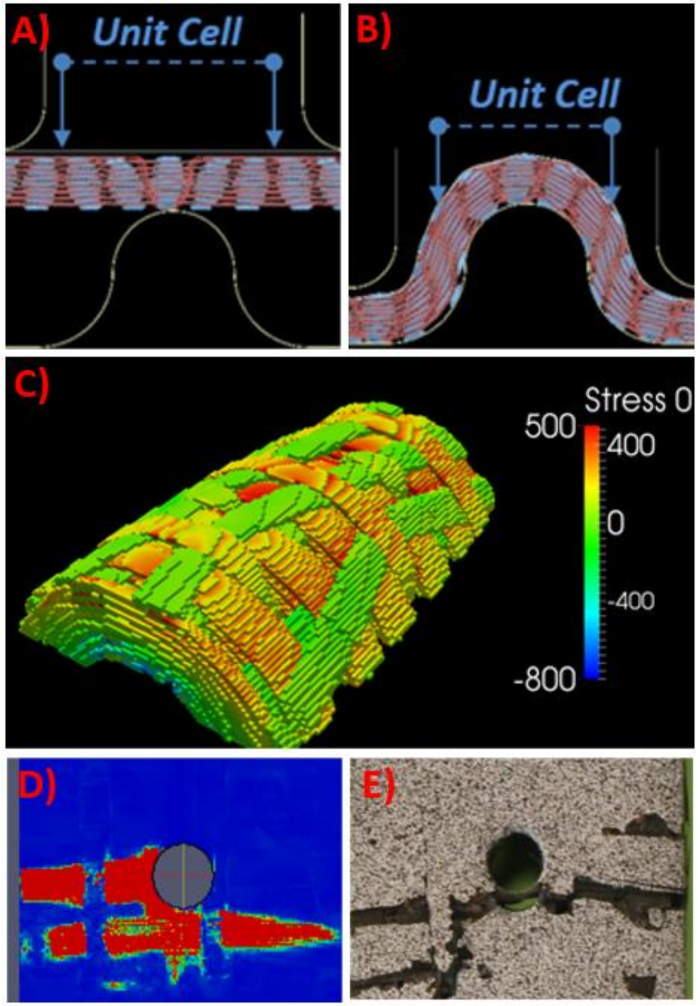
- While most composite materials can be assumed periodic, in some cases (3D Woven) the material loses periodicity during manufacture.
- A new method for parametrised structural design is needed.
- This would enable engineers to explore the design space efficiently.
- In this work a data-driven multiscale modelling approach is proposed.

Periodic Materials

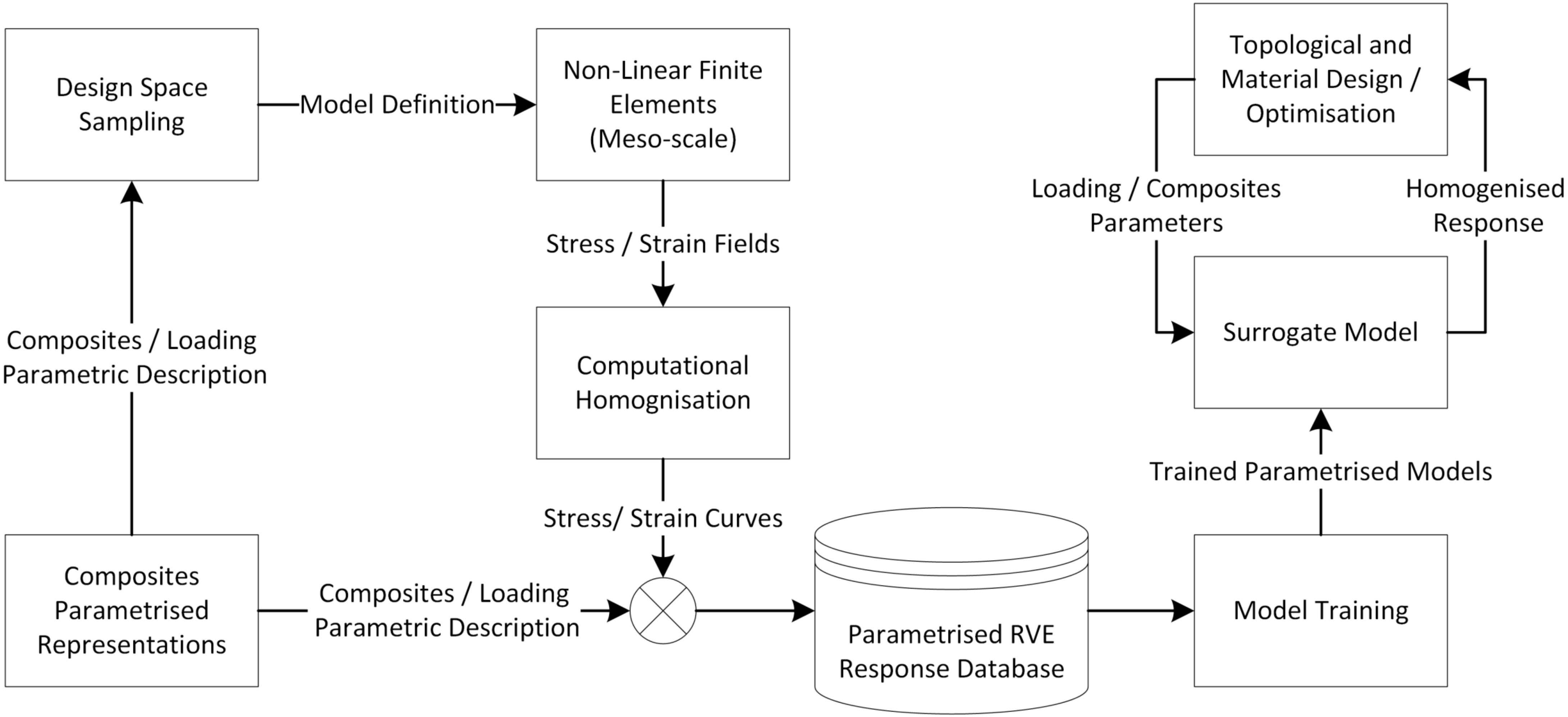




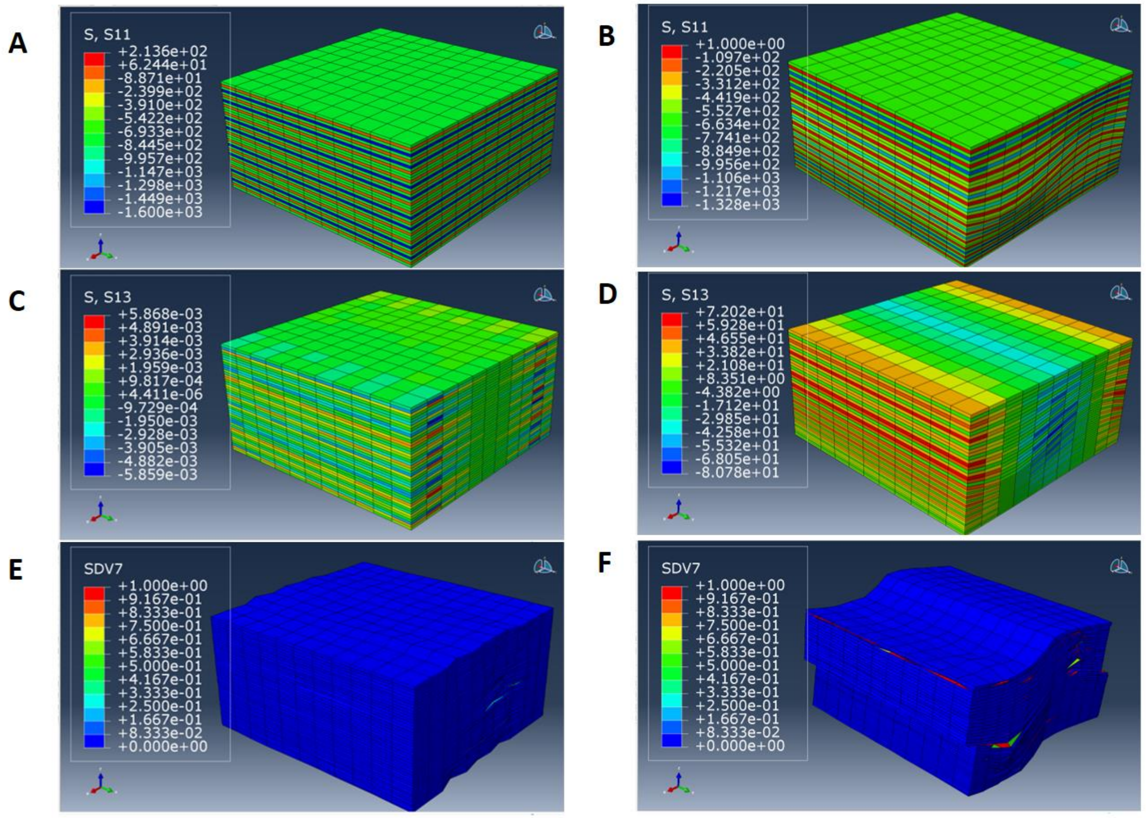
Non-Periodic Materials



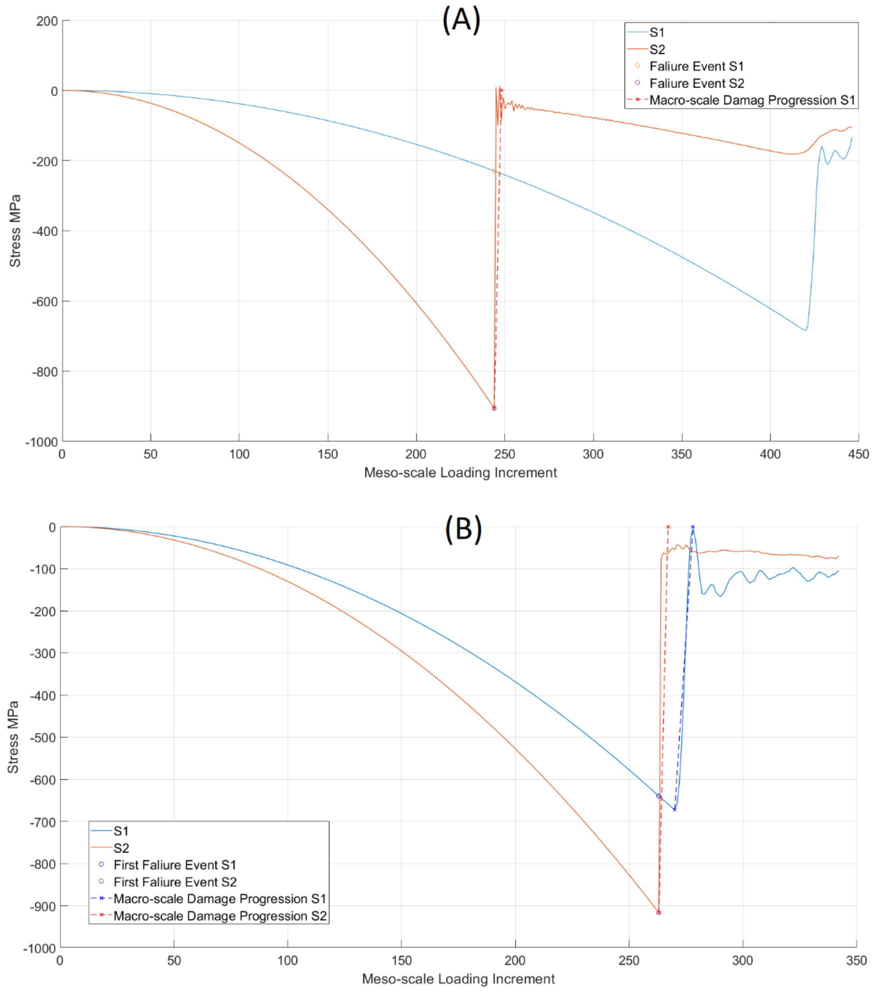
Building Parametrized Response Database



Automated failure analysis and homogenization



Unit cell results for a QI layup under in-plane compression, A) Fibre direction Stresses in a pristine RVE B) Fibre direction Stresses in an RVE with an 11° wrinkle, C) Through thickness shear stresses in pristine RVE D) Through thickness shear stresses in wrinkle RVE, E) Delamination failure in pristine RVE, F) Delamination failure in wrinkle RVE. All stresses are in MPa and are displayed in local material coordinates. The unit cell is loaded in compression in the X direction shown in figure.



Automated Analysis of homogenized Stress/ Strain Curves

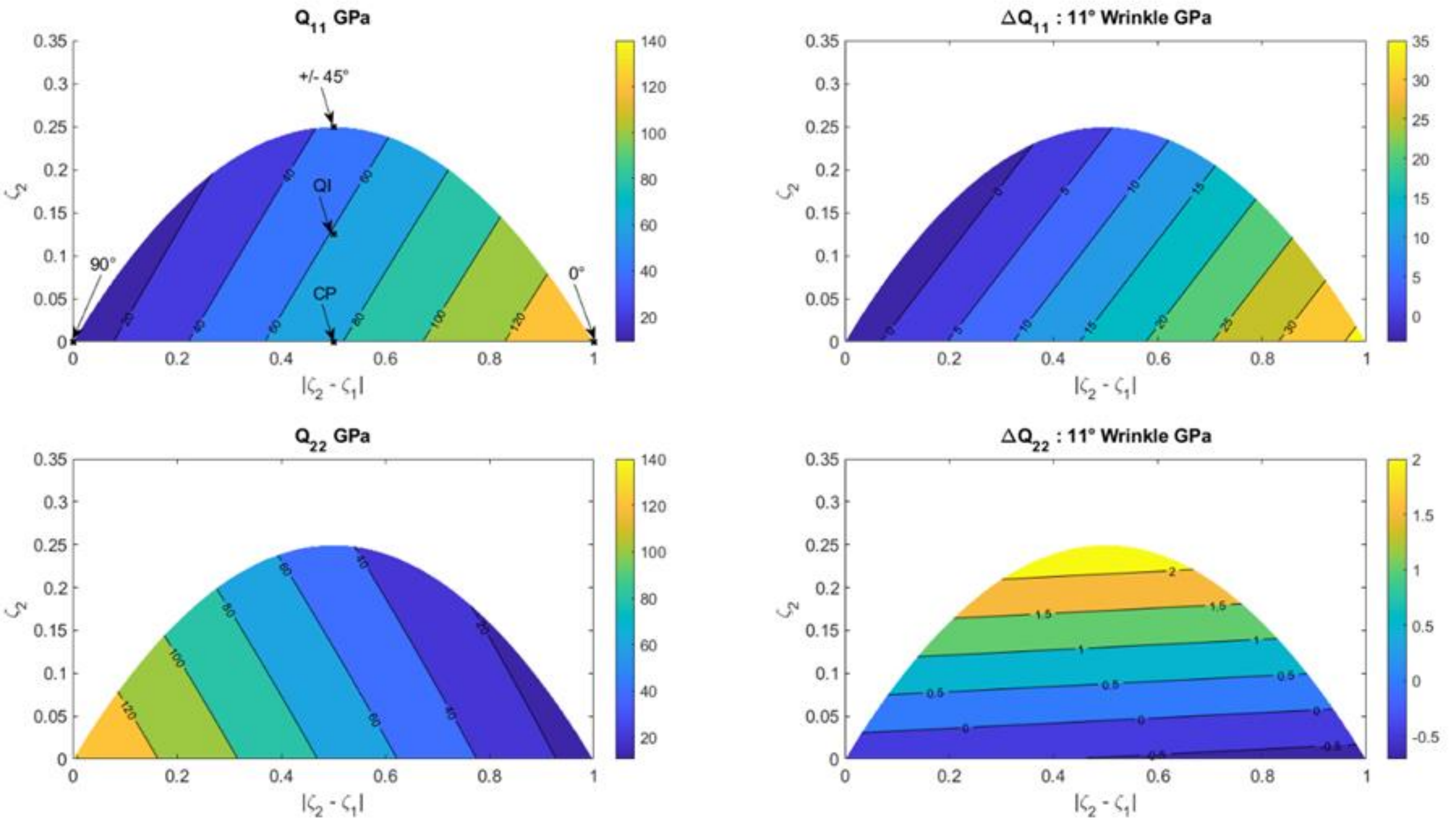
Stiffness Modelling using lamination parameters

Lamination Parameters describe the stiffness in terms of material invariants and direction cosines:

$$\zeta = \begin{cases} \zeta_1 = \dfrac{1}{h}\displaystyle\int_{-h/2}^{h/2} l_x^4 dt \\ \zeta_2 = \dfrac{1}{h}\displaystyle\int_{-h/2}^{h/2} l_x^2 dt \\ \zeta_3 = \dfrac{1}{h}\displaystyle\int_{-h/2}^{h/2} l_x^3 l_y dt \\ \zeta_4 = \dfrac{1}{h}\displaystyle\int_{-h/2}^{h/2} l_x l_y dt \end{cases}$$

Surrogate models can be trained to formulate the change in composite stiffness as the result of the presence of defects such as wrinkles:

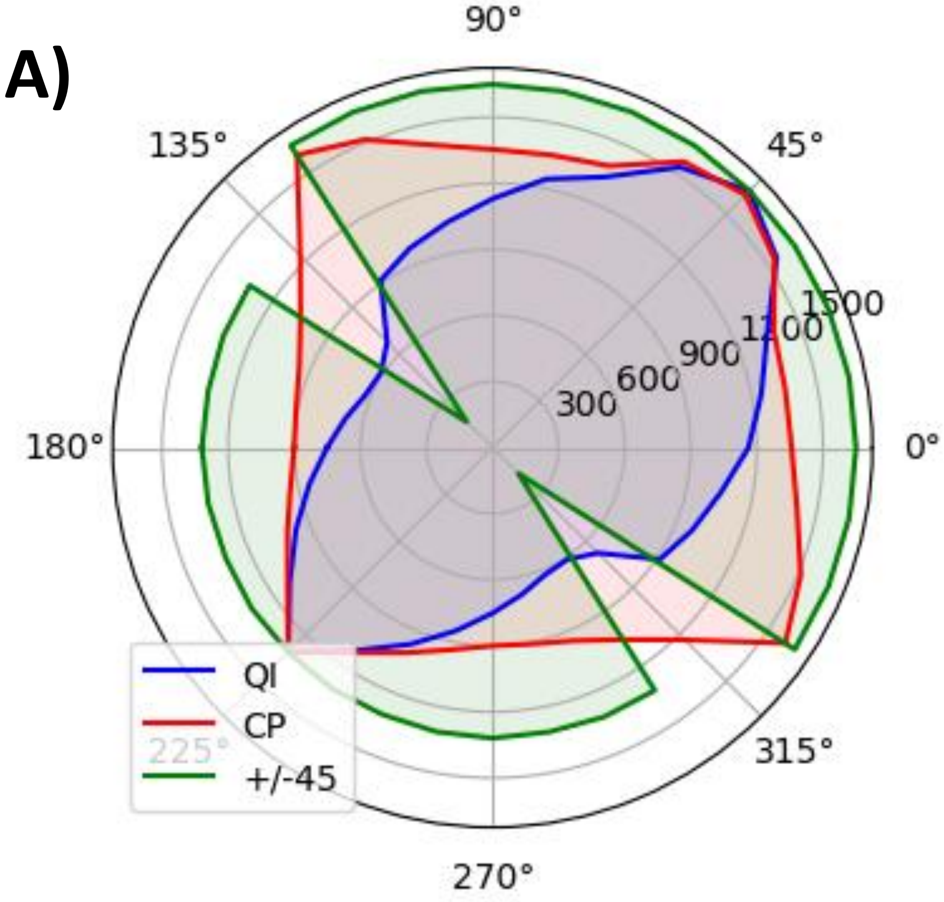
$$Q^X = Q_K^X - \Delta(\zeta)$$

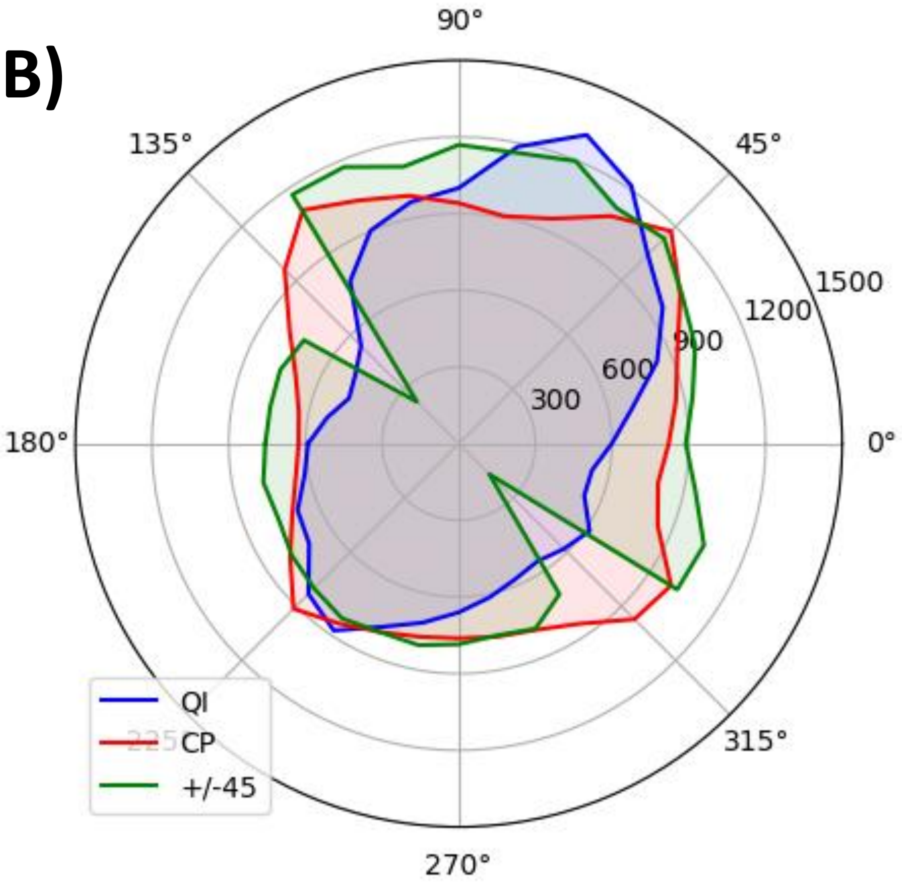


Composite Stiffness over the lamination parameters space, the impact of wrinkle presences

Multiscale surrogate modelling of the elastic response of thick composite structures with embedded defects and features. B El Said, SR Hallett - Composite Structures, 2018.

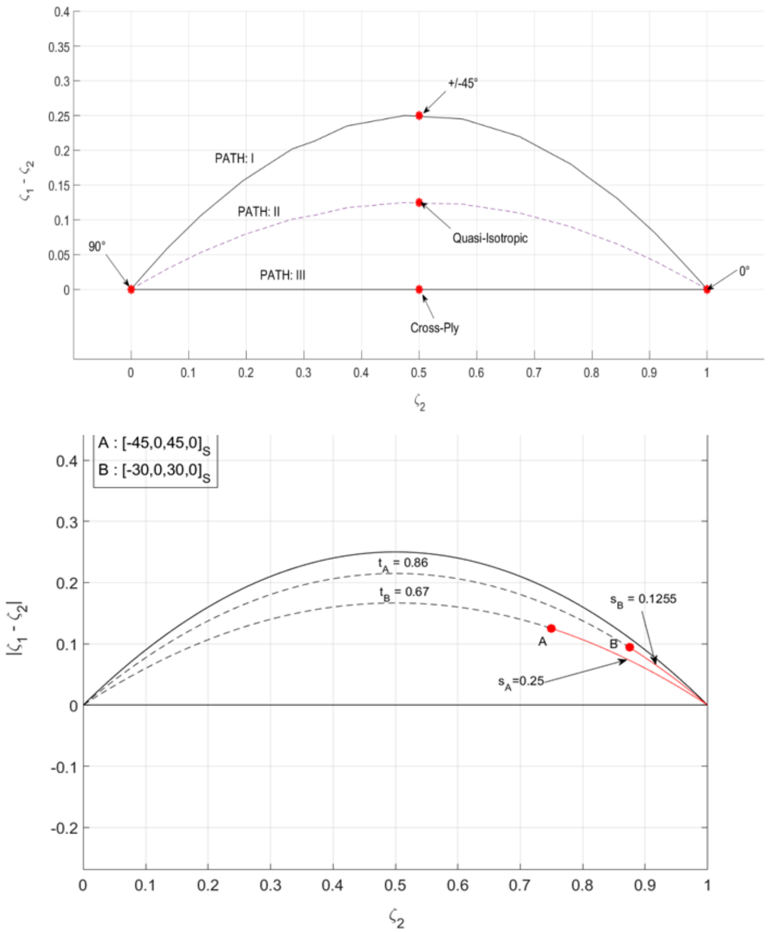
Failure Envelopes of Laminated Composites



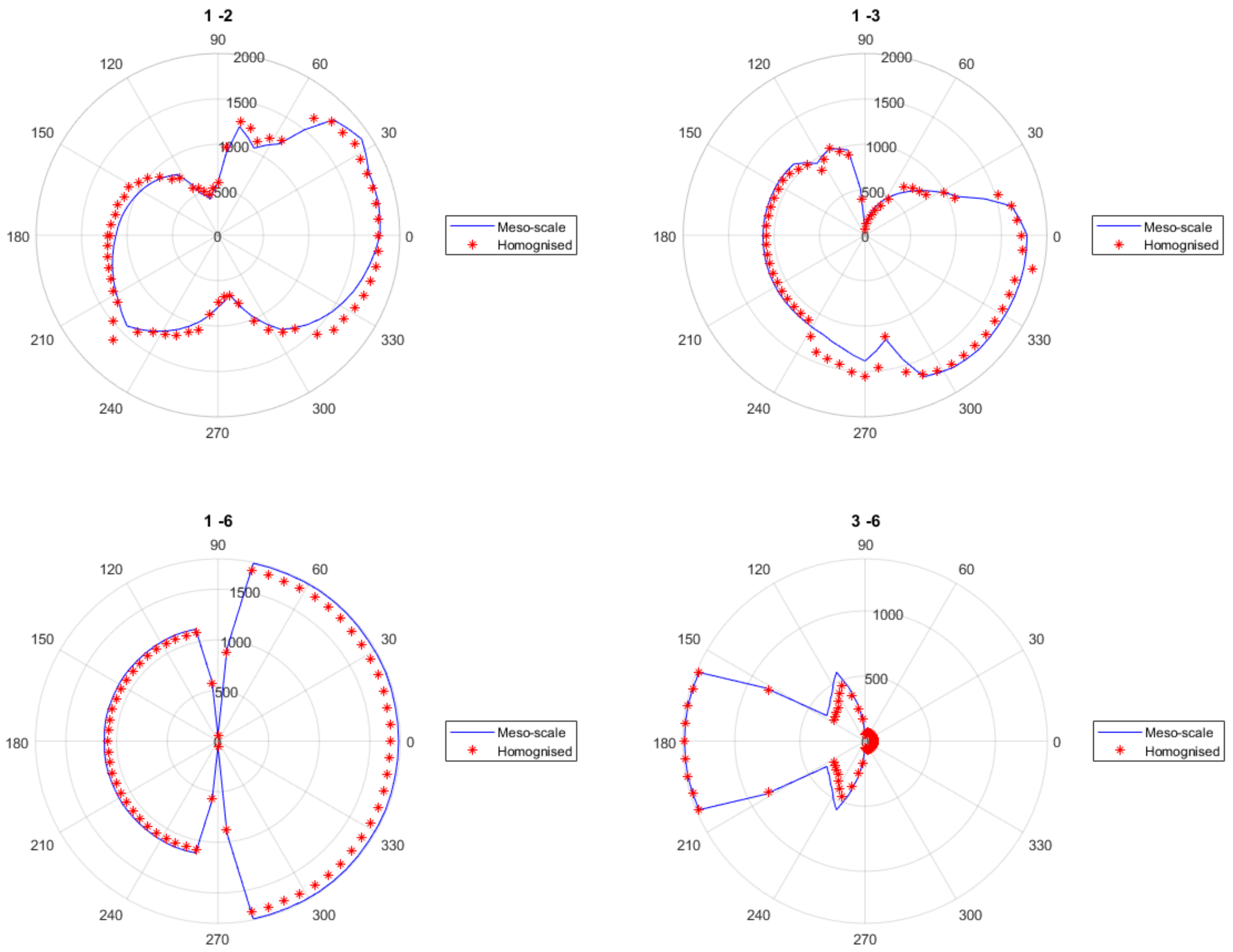


- Composite Failure data from RVE database can be mapped vs loading condition to generate failure envelopes for complete laminates.

Failure Envelopes of Laminated Composites



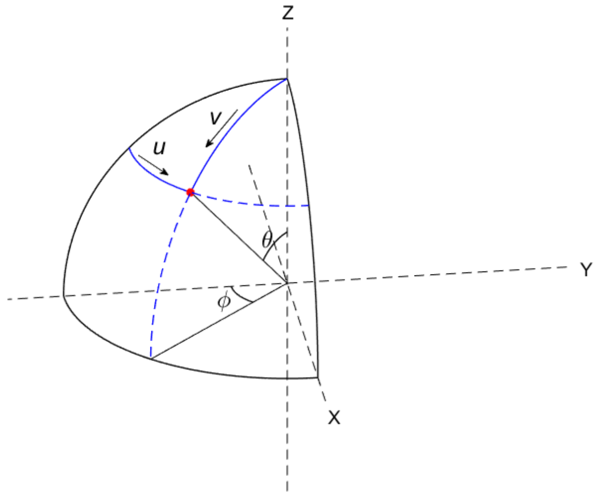
Design Space for symmetric laminated composites



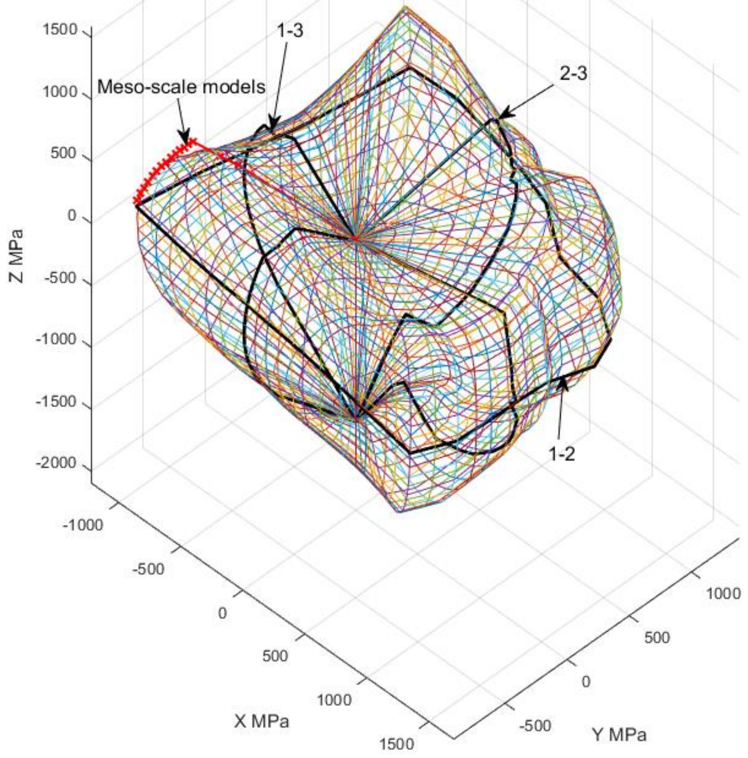
Failure Envelopes for [-45,45,0]

Tri-Axial Failure Manifolds for Laminated Composites

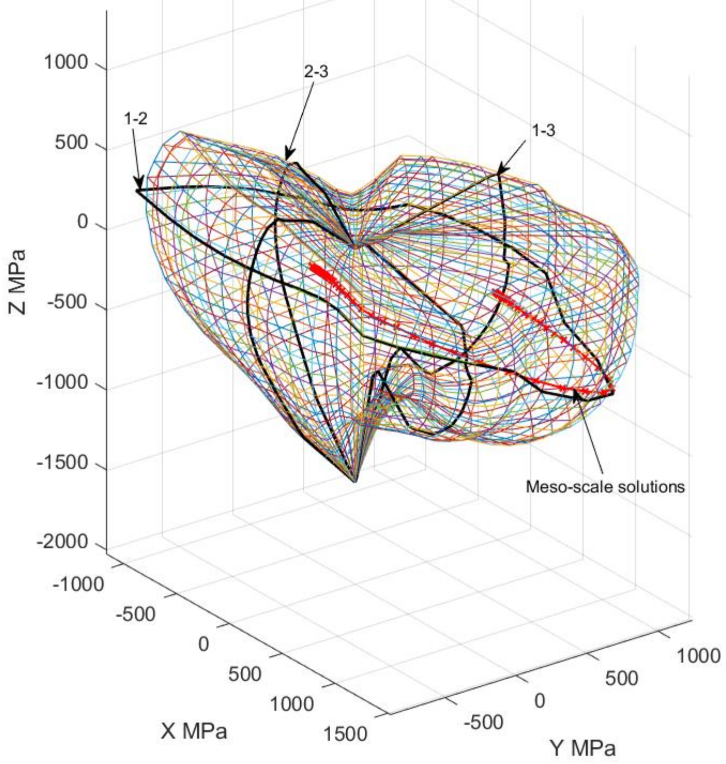
- Bi-axial failure envelopes can be considered the intersection of a 3D failure manifolds with the principal plans.
- Using the intersection and the surface computability conditions a full 3D failure manifold can be



Schematic description of Failure Manifolds



Failure Manifold for Cross-Ply

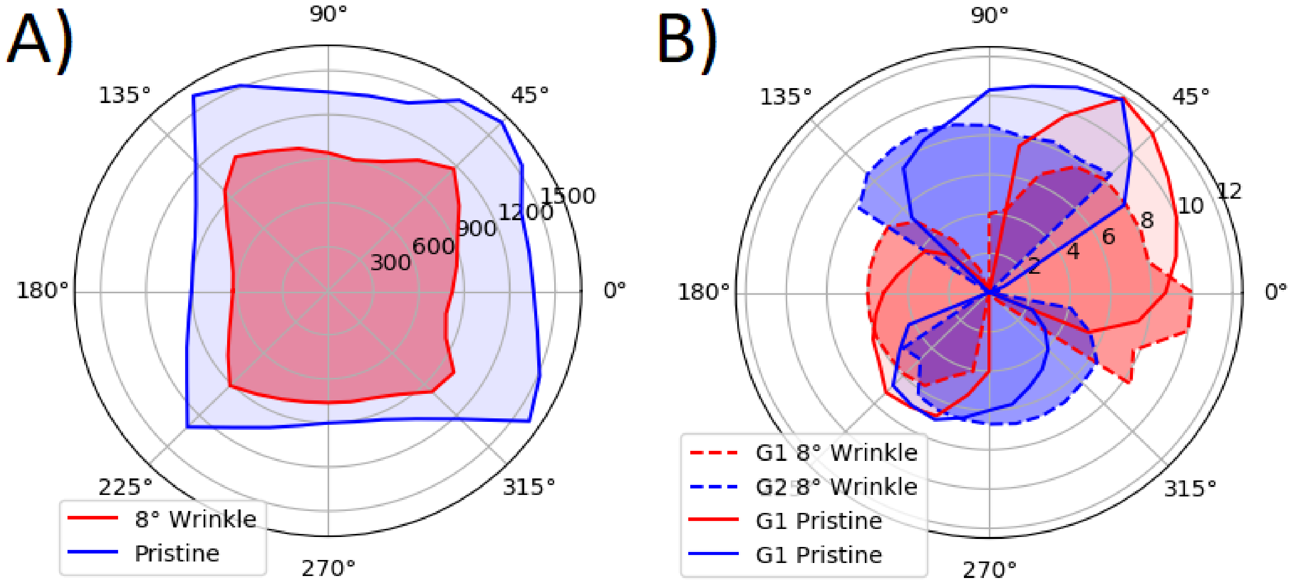


Failure Manifold for Quasi-Isotropic

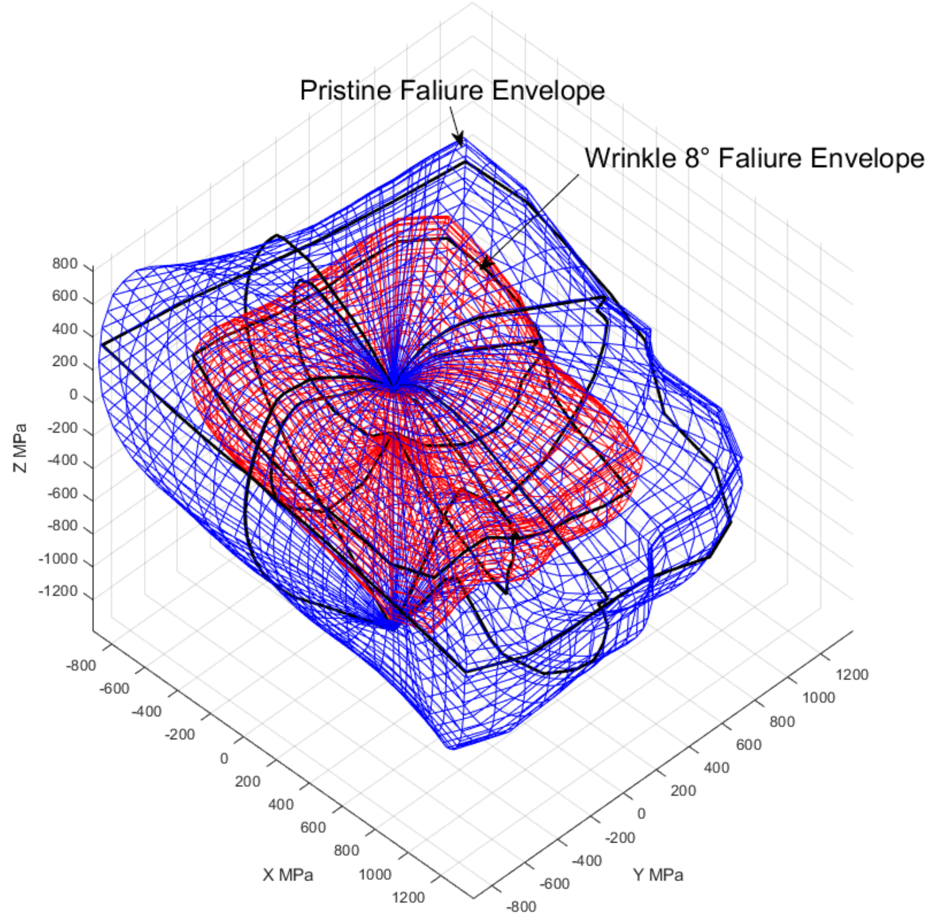
Parametric failure manifolds for laminated composites. B El Said, SR Hallett - Composite Structures, 2020

Progressive Damage Modelling on the Structures Scale

- Similar failure envelopes can be developed for composites containing various types of defects.
- Apparent fracture energy is extracted from the RVE stress/strain response and mapped to loading conditions.



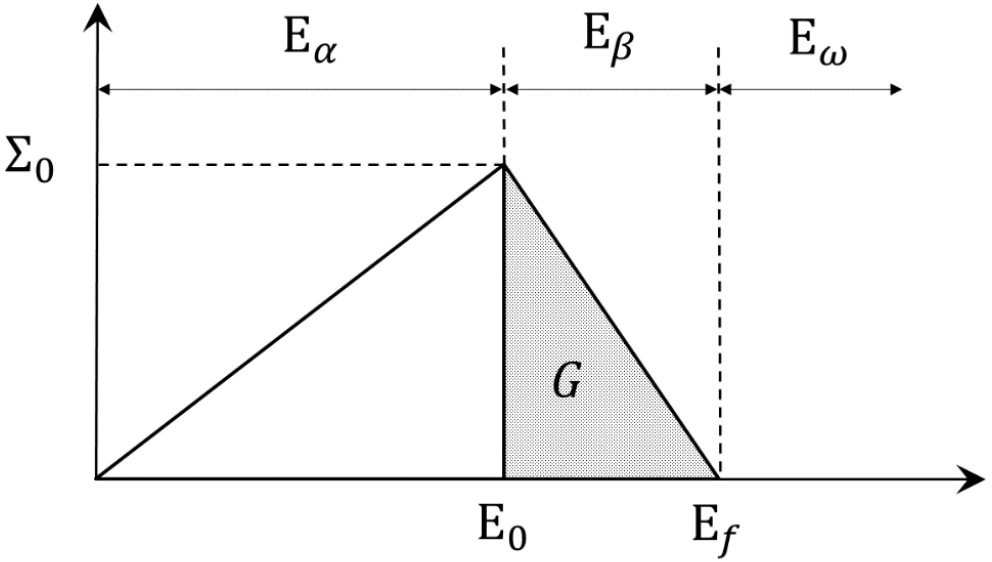
Failure envelopes for a Cross-Ply layup (A) with the associated regularization energy,(B) pristine vs 8° wrinkle



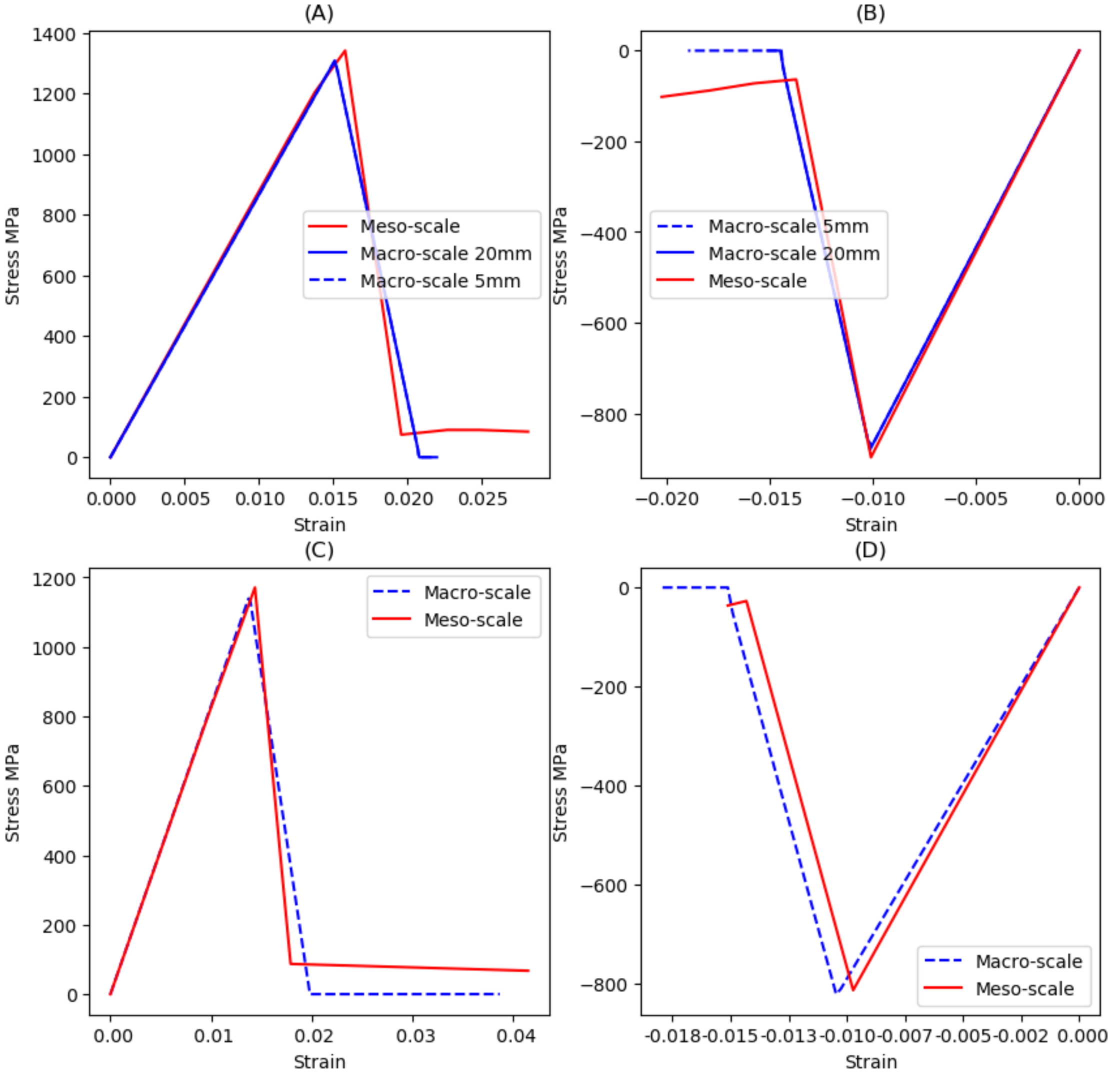
A comparison of 3D failure manifolds for cross-ply layup, wrinkle vs pristine

Application: Single Element Tests

- A number of uni-axial and bi-axial single element test were conducted for a QI layup.
- The test compares a macro-scale element of different sizes vs the results of a full meso-scale RVE.



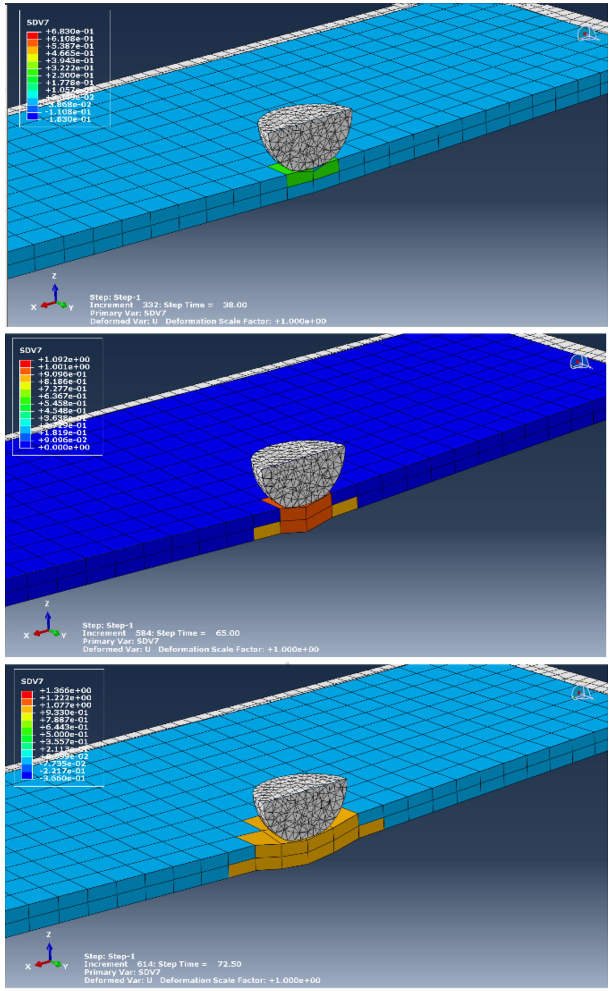
Macro-scale bilinear damage law



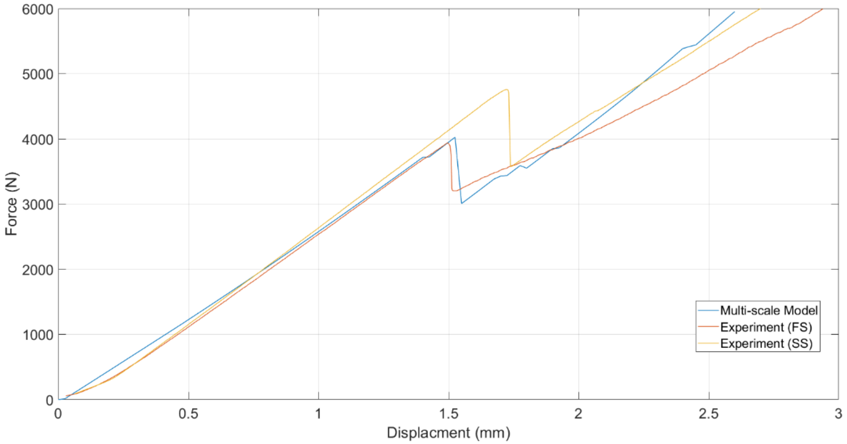
Single Element Tests for Qi Layup. A) Response in 1 direction under pure tension, B) Response in 1 direction under pure compression, C) Response in 1 direction under combined bi-axial tension/compression, D) Response in 2 direction under combined bi-axial tension/compression.

Application : Static Indentation/ Low Speed Impact

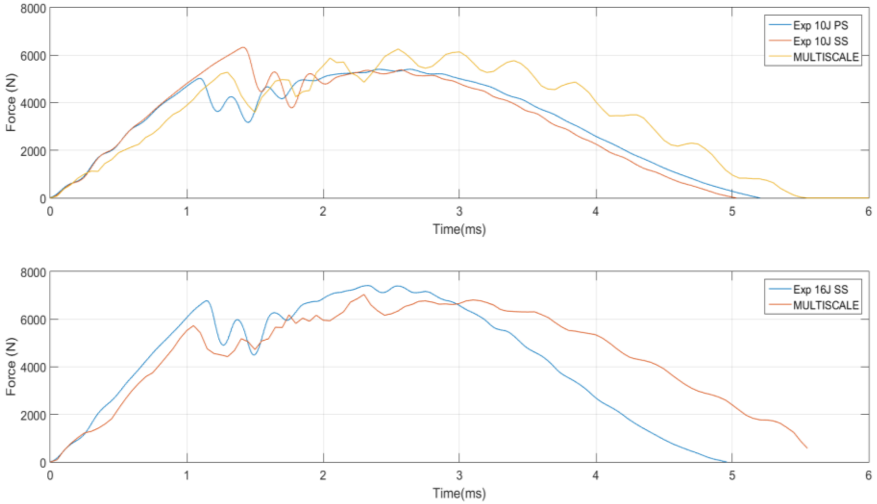
Static indentation multiscale model



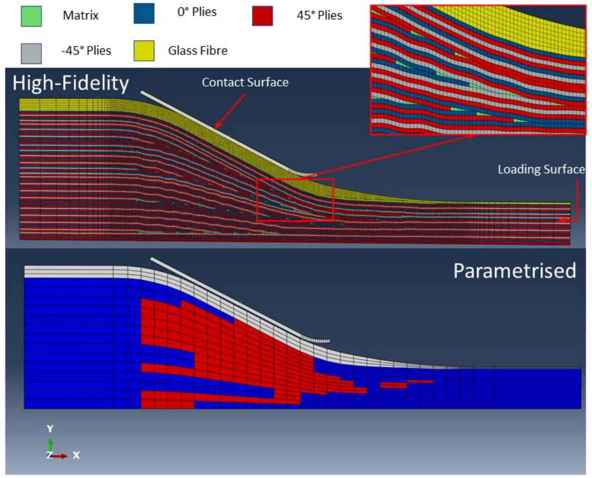
Static indentation force displacement curves, multi-scale vs Experiment



Low speed impact, multi-scale vs experiment

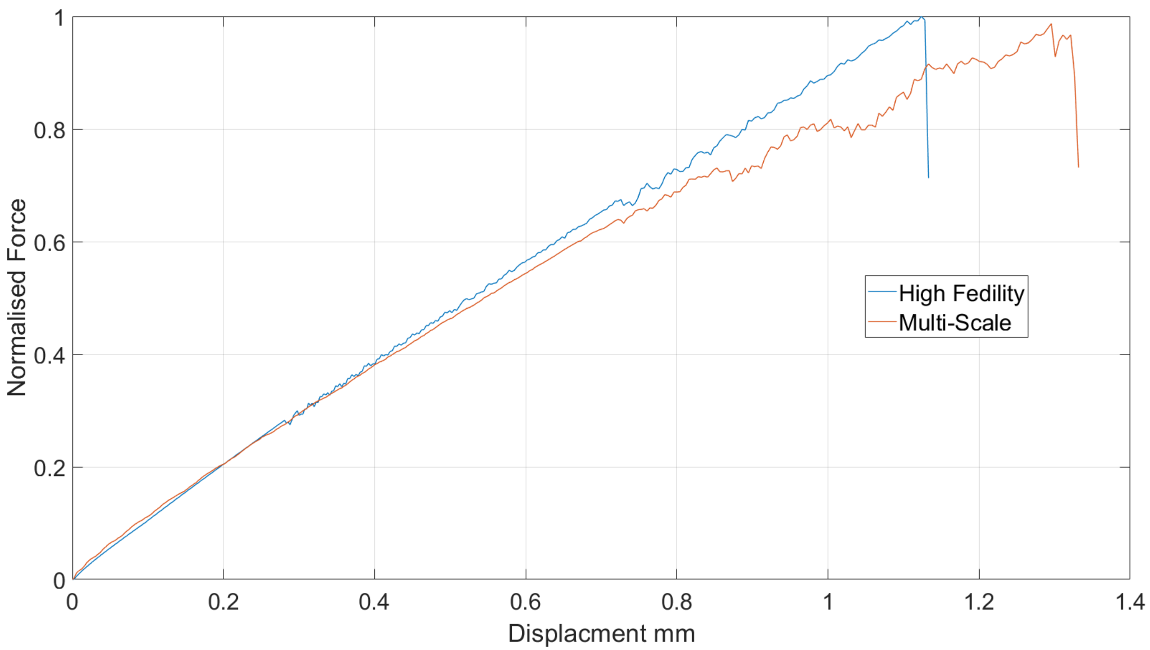


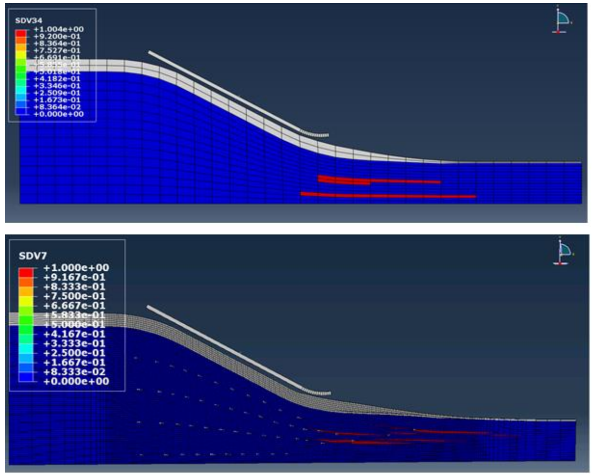
Application: Complex composite structures



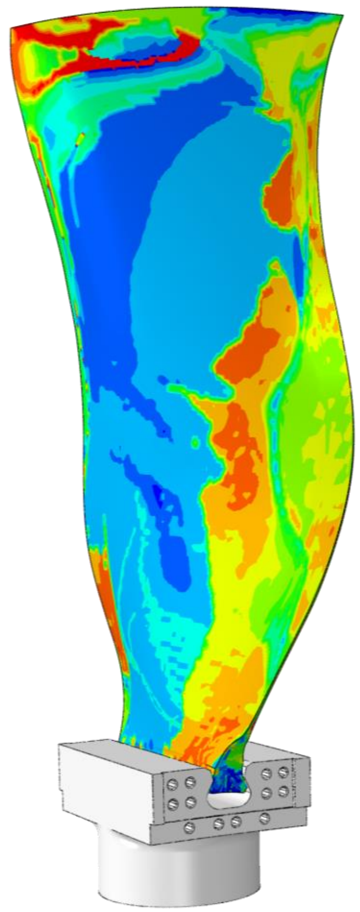
Model Setup for a tapered specimen

Normalized Force vs Displacement for a tapered specimen





Failure Morphology fidelity vs macro-scale



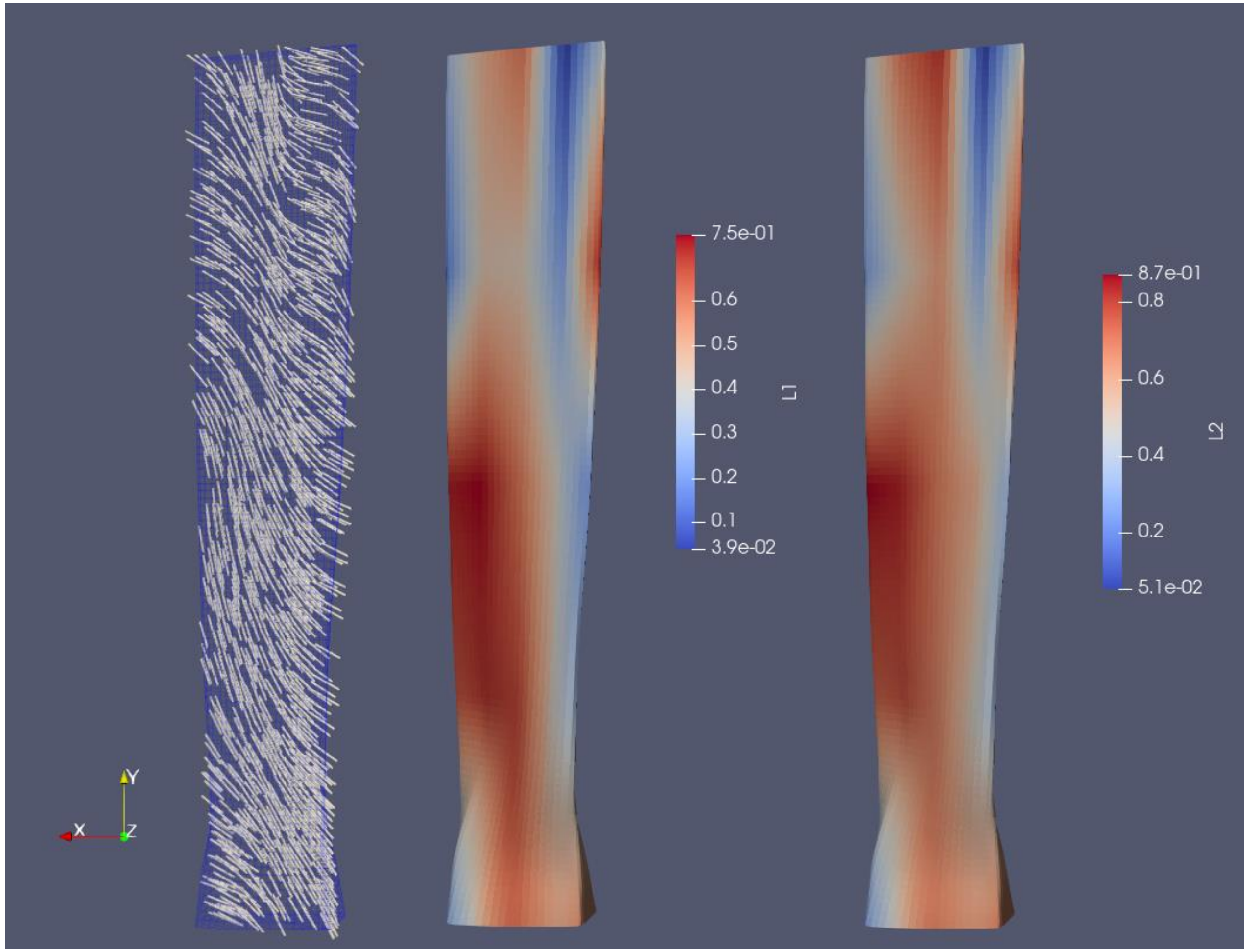
Industrial scale application

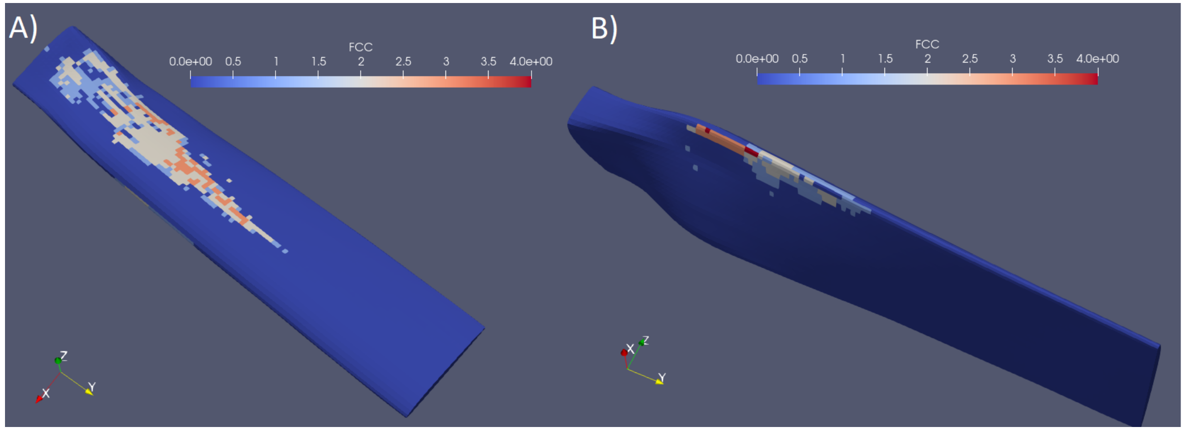
Multiscale surrogate modelling of the elastic response of thick composite structures with embedded defects and features. B El Said, SR Hallett - Composite Structures, 2018.

Structural Design and Optimisation

- This is a powerful tool for composites structural design and optimisation, where structural geometries and material layup can be optimised simultaneously.
- Lays the foundation for application of Deep Learning approaches for more complex material behaviour.

Layup and geometry optimization of a composite wind tunnel blade tunnel blade



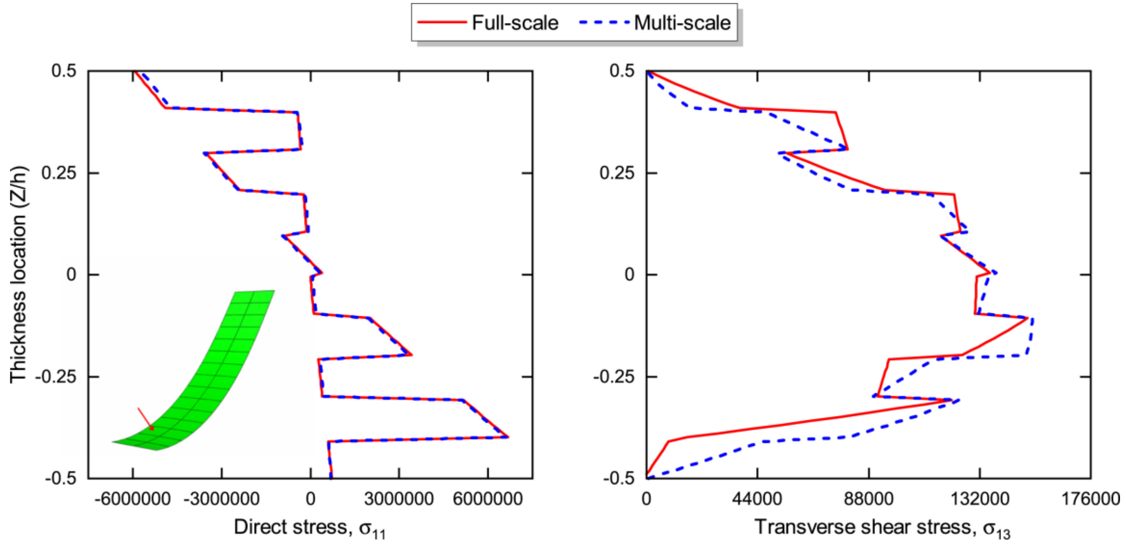


Damage initiation prediction using failure manifolds and linear FE.

B El Said, Predicting the non-linear response of composite materials using deep recurrent convolutional neural networks, International Journal of Solids and Structures 2023

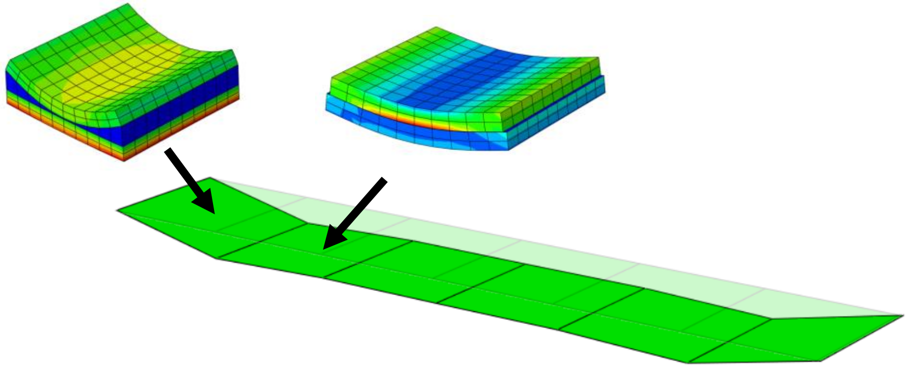
Data-driven multi-scale framework for shell models

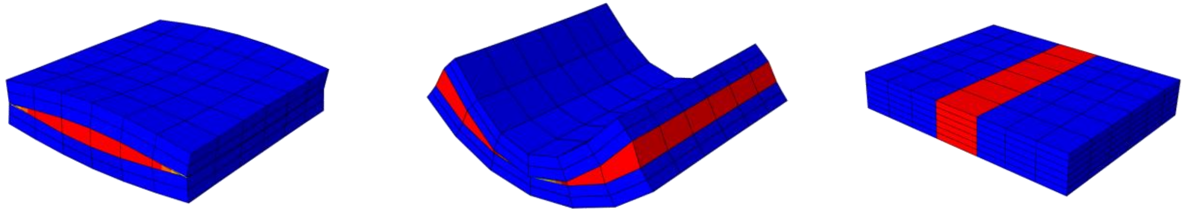
- A framework which maintains spatial information and accounts for length-scale effects during homogenisation.
- The RVE spans the full shell thickness. The framework is compatible with macro-scale shell models, taking into account material and geometric nonlinearities.
- Accurately captures the through thickness shear stresses and consequently can homogenise delamination.



Through-thickness distribution of σ_{11} (left) and σ_{13} (right) in the thick cross-ply laminate under bending.

Example application: FE2 of plate under end moments





Delamination buckling under compression

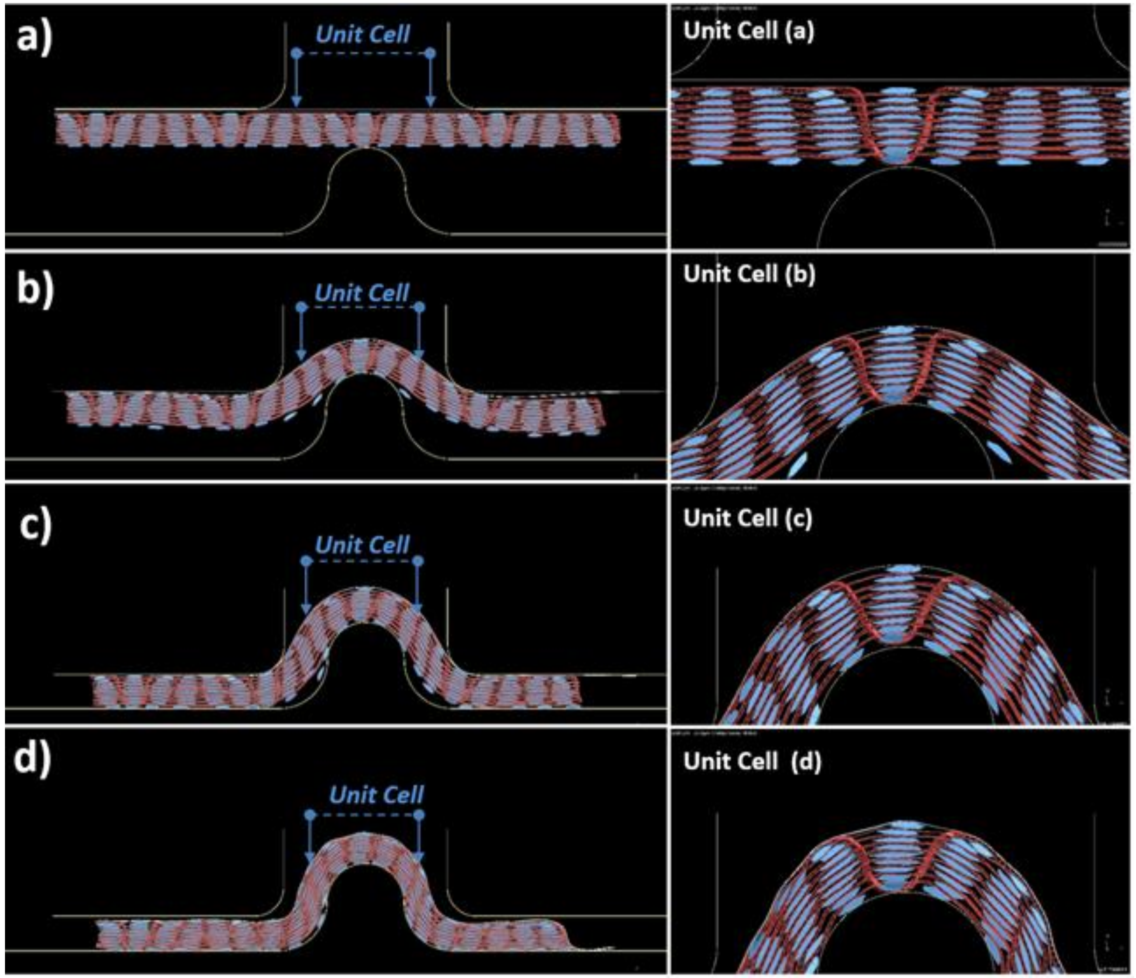
Delamination under bending

Matrix cracking under tension

A kinematically consistent second-order computational homogenisation framework for thick shell models. AKW Hii, B El Said - Computer Methods in Applied Mechanics and …, 2022

Multi-scale modelling of Non-periodic Composites

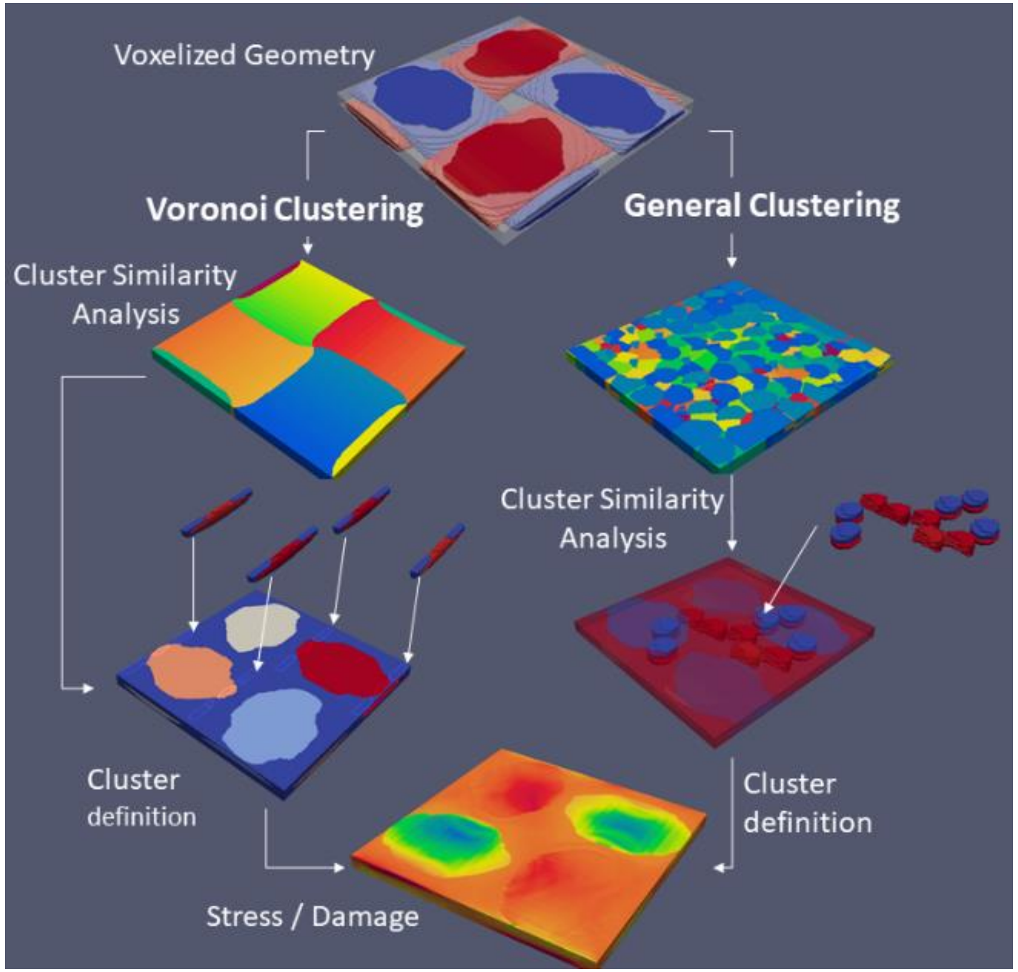
- During manufacturing, 3D Woven preforms deform to conform to the structure geometry.
- The unit cell, which are originally periodic, experience localised deformation leading to a non-periodic architecture.
- This would require a modelling approach not based on RVE.



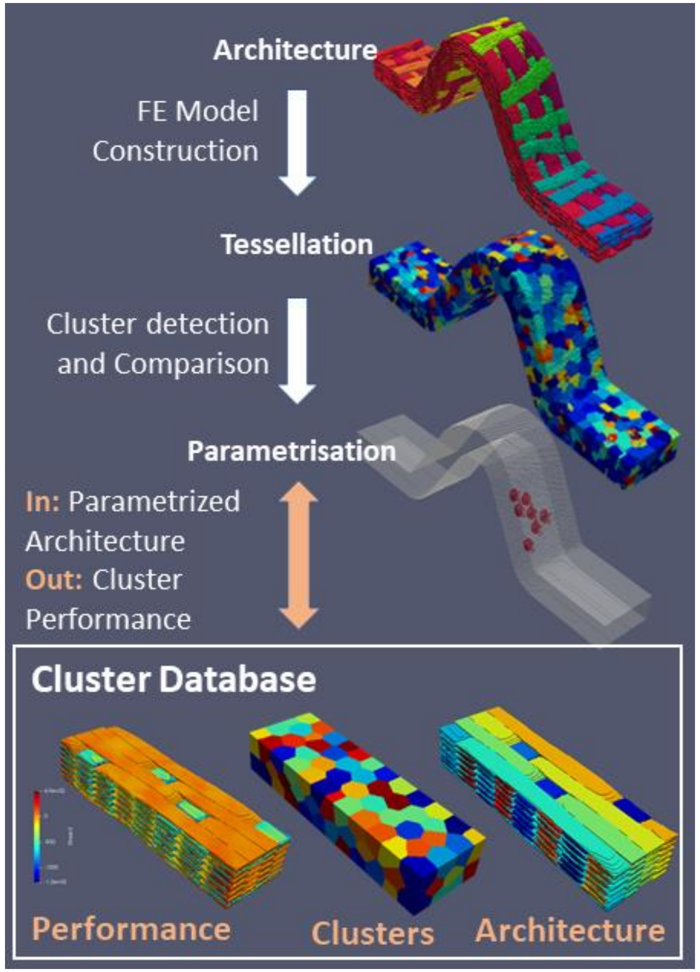
Internal architecture deformation during draping

B El Said, F Daghia, D Ivanov, SR Hallett , An iterative multiscale modelling approach for nonlinear analysis of 3D composites, International Journal of Solids and Structures, 2018.

Material Clustering for Non-periodic Composites

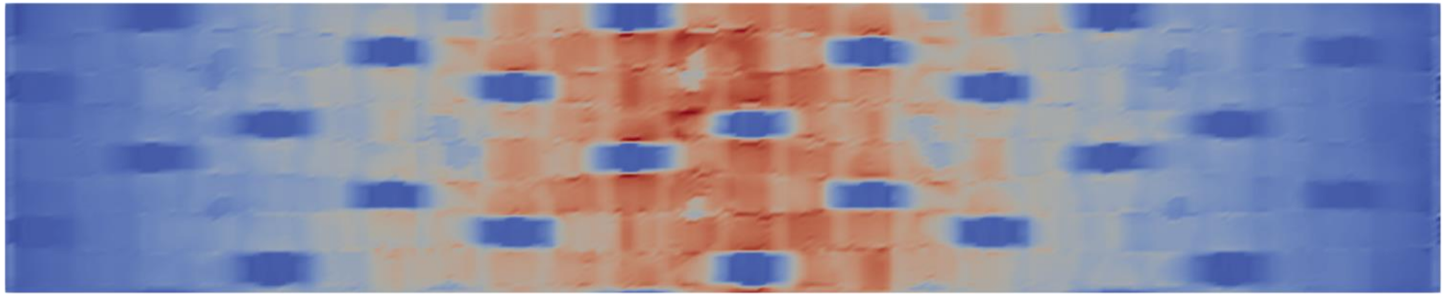


Populating Material Cluster Database

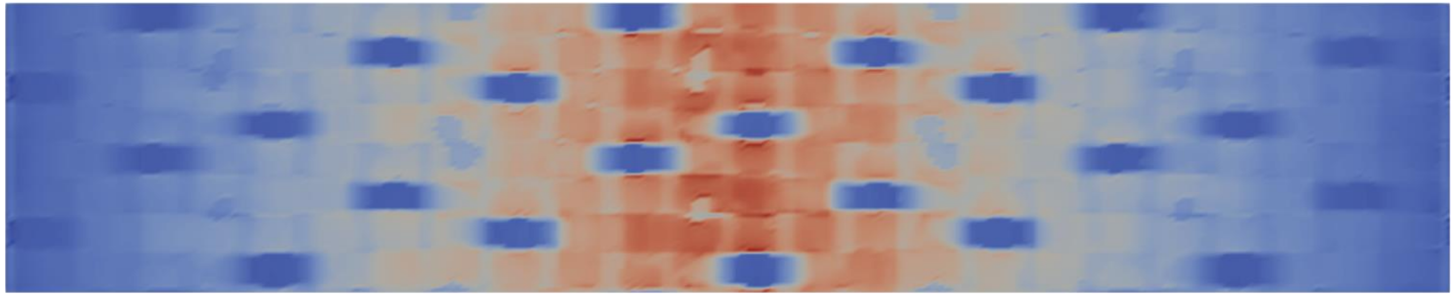


Structural Scale Simulation

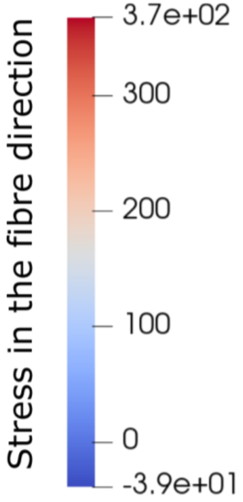
Material Clustering for Non-periodic Composites

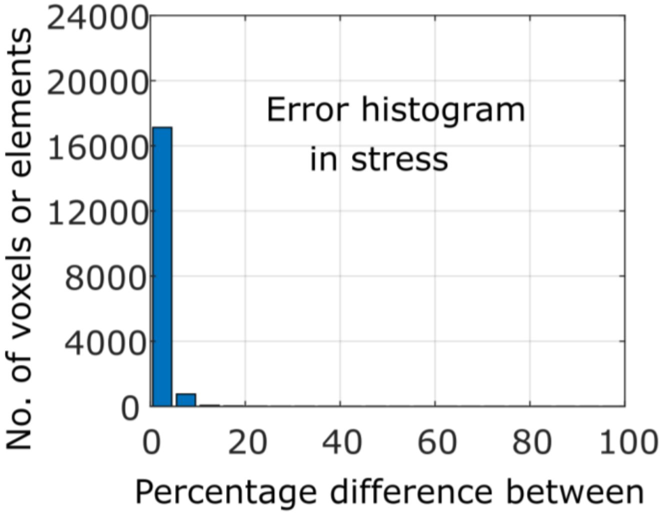


Macro-scale modelling using data clustering and image registration



Meso-scale modelling with yarn and matrix definition

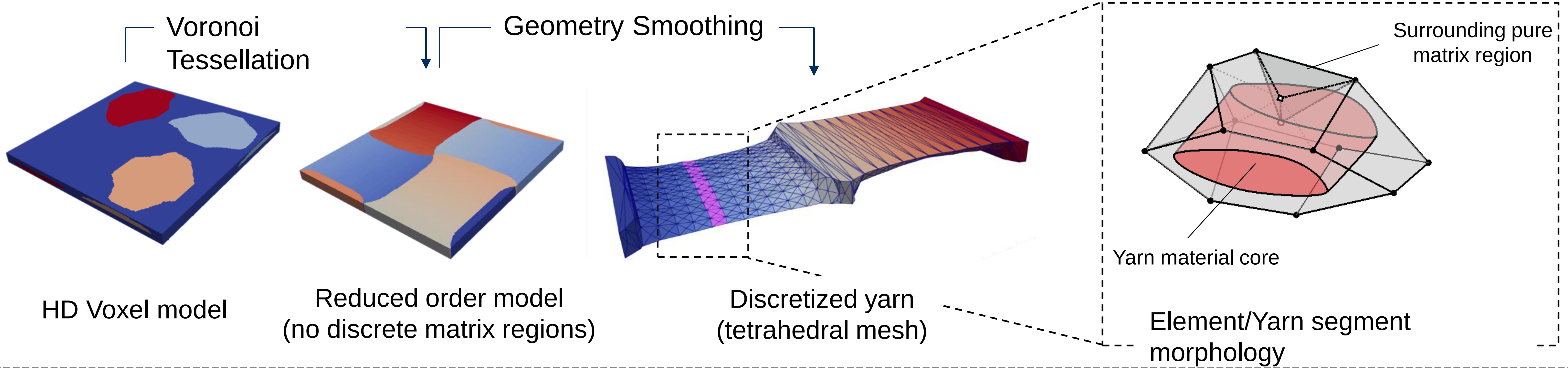




J Selvaraj and B El Said, Multiscale modelling of strongly heterogeneous materials using geometry informed clustering International Journal of Solids and Structures, 2023

From Material Cluster to Polyhedral Elements

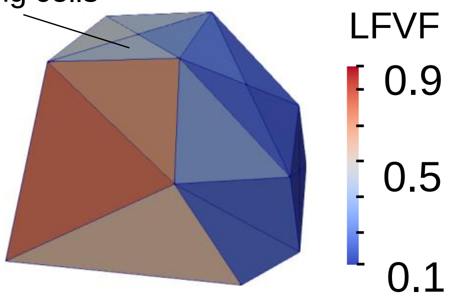
Reduced order model creation



Polyhedral element formulation

Cell based Smoothed Finite Element Method (CSFEM).

Bi-material homogenisation material model [1].



Example of local element fibre volume fraction

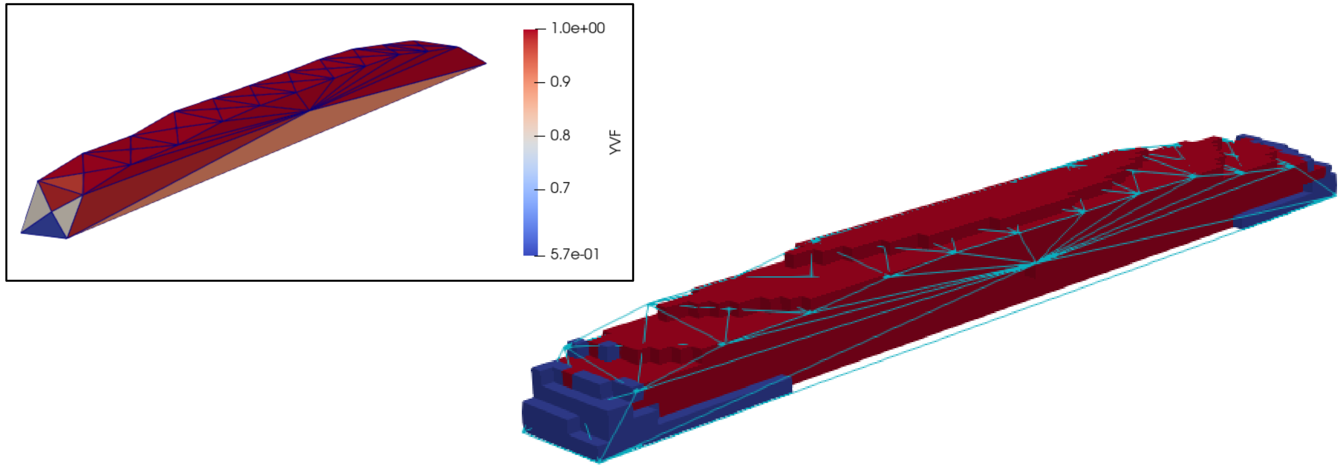
Local Fibre Volume Fraction (LFVF) on each subcell considered.

Promising computational times for coupon and feature scale models.

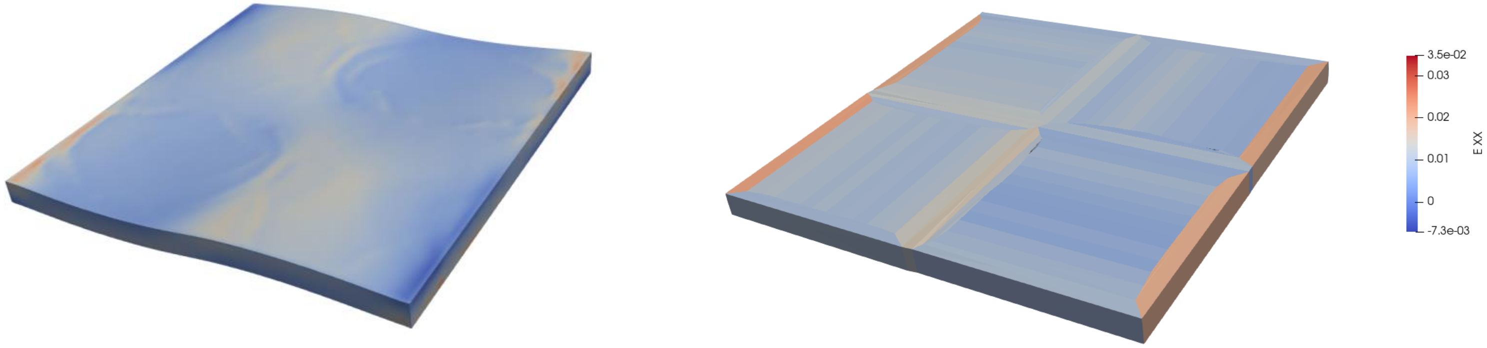
Benchmark Model

The polyhedral model framework was applied on a 2D plain woven representative volume element (RVE) model.

- Model characteristics compared to voxel model:
  - Number of elements: **108** (195,132)
  - Number of nodes: **741** (514,188)
  - Model Fibre Volume Fraction: **0.647** (0.650)
- Computational time:
  - CPU time: 0.2 sec (**6.5 sec**)



Calculation of Local Yarv Volume Fraction on the smoothing subcell level.



Comparison of the x component strain map on warp loaded 2D plain woven RVE between the voxel model and the polyhedral mesh model.

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