D-standart

Multi-scale modelling of composite structures

D-STANDART Technical Workshop,
Delft, 8 of February 2024

Bassam El Said, Peter Foster, Hanna Beketova, Giuliano Allegri(UB)

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Bristol Composites Institute

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Bristol Composites Institute, University of Bristol, United Kingdom.

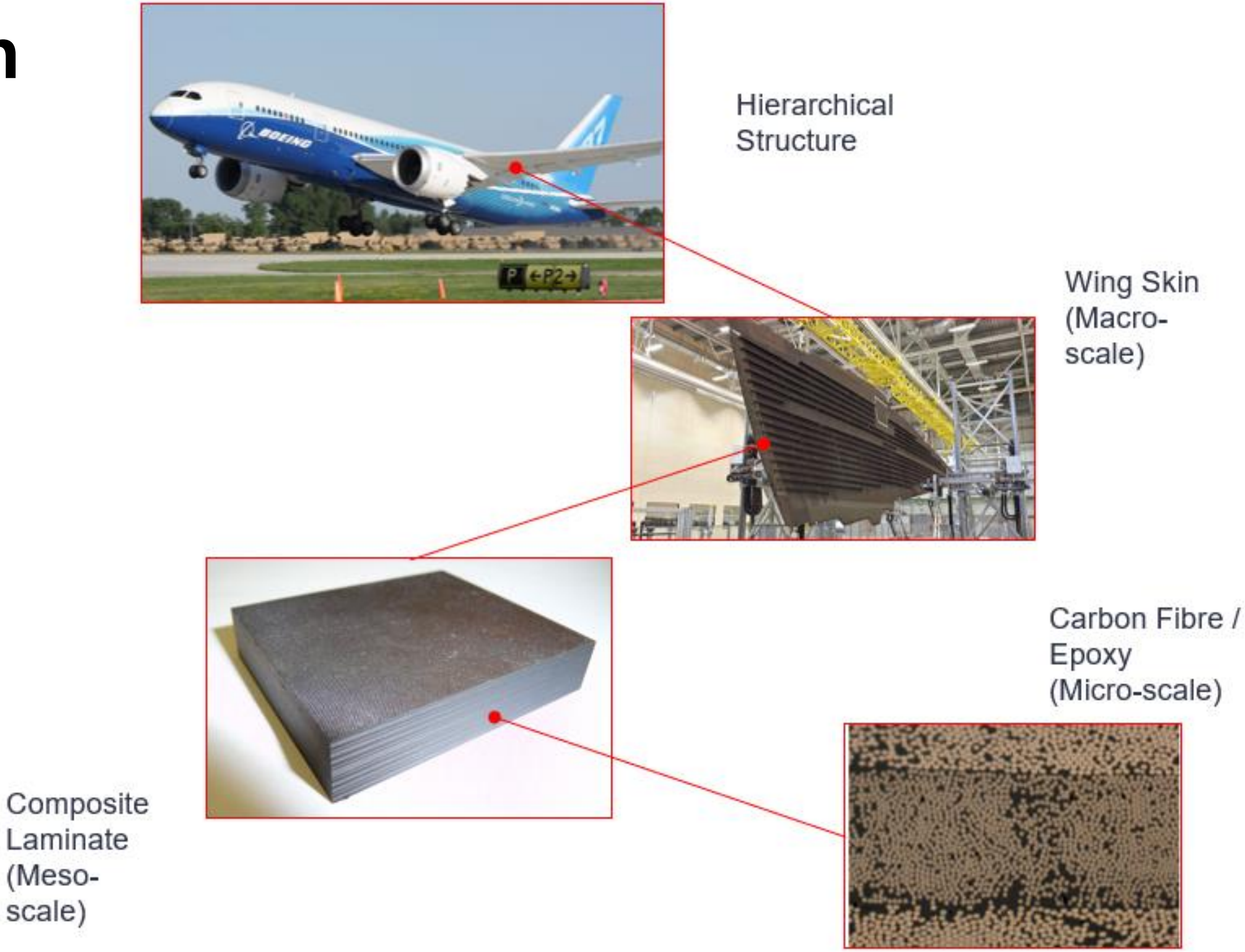
DST - Internal technical Workshop, Delft, 8 of February 2024

Research Activities

- **Multi-scale Modelling**:
  - Scale-up material constitutive models and understanding to the structural level.
  - Develop accurate and computationally efficient models of industrial composite components.
  - Quantifying the impact of defects and variabilities on structural performance (wrinkles, voids, ply-drops).
- **Data-driven Modelling**:
  - Model acceleration using various Machine Learning approaches.
  - Deep Learning model to represent material and structural geometries for rapid simulations.
- **Manufacturing simulations:**
  - Quantify the impact of manufacturing methods on structural performance.
  - Accurate modelling of material architectures for woven / NCF materials.

Multi-scale Challenges in Composite Materials

- Composite materials are hierarchal in nature: they are made from multiple level of constituents: plies, fibre, matrix, etc ..
- Linking the impact of material architecture and manufacturing processes from the fibre to the structural scale is a multi-scale modelling challenge.



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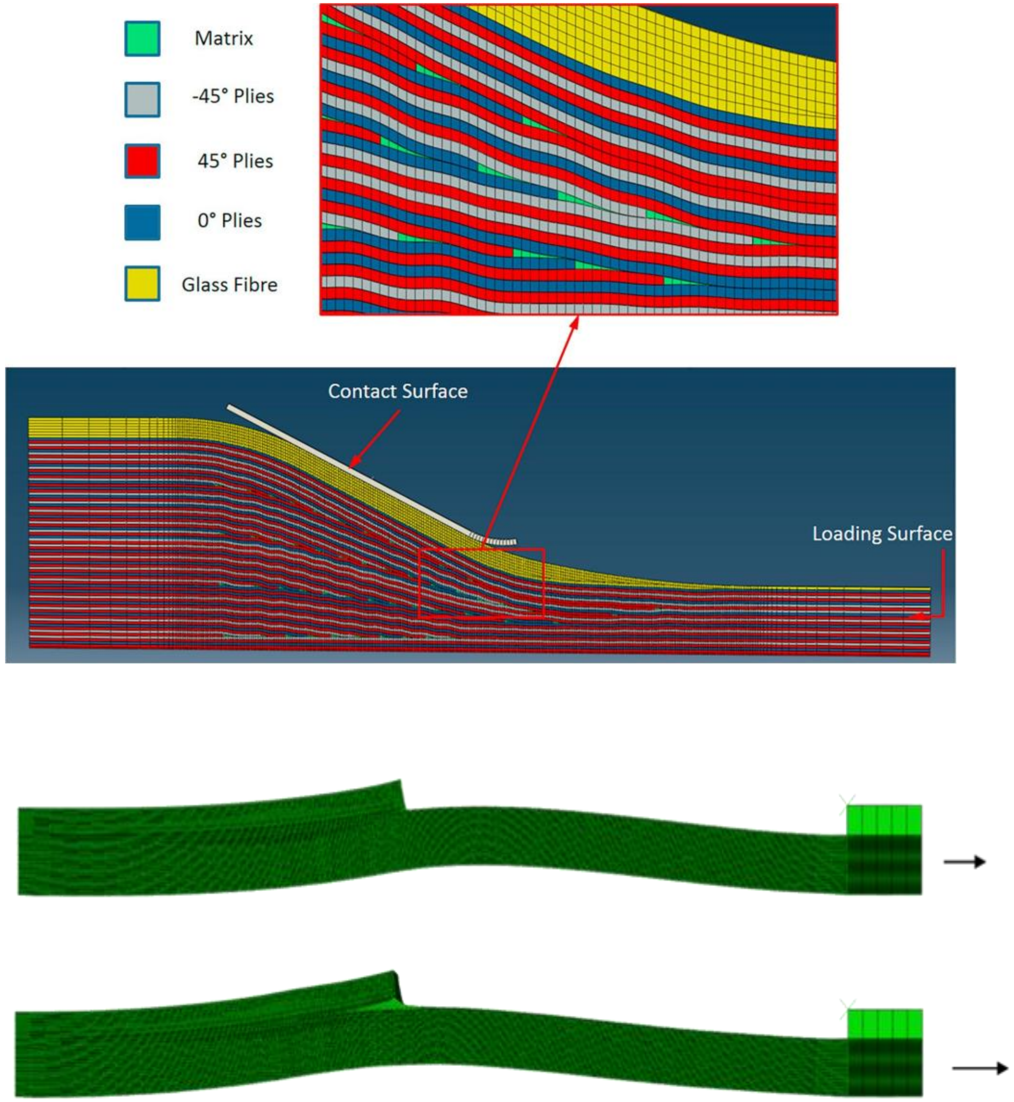
Meso-scale Modelling

From fibre to laminates

bristol.ac.uk/composites

Defects and Variabilities

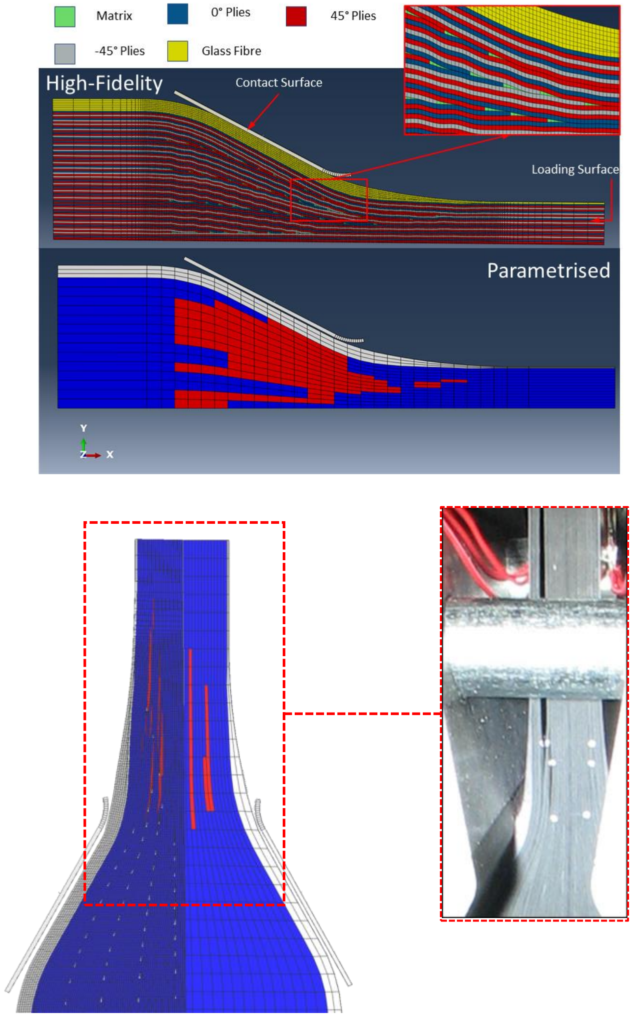
- Defects and variabilities are inevitable part of composites design and manufacturing.
- Features such as tappers create localised stress concentration, which can impact a component performance on the macro-scale.
- Manufacturing processes impact a composites internal architecture and consequently can change the part performance.
- Including these meso-scale features on the macro-scale performance is computationally challenging.



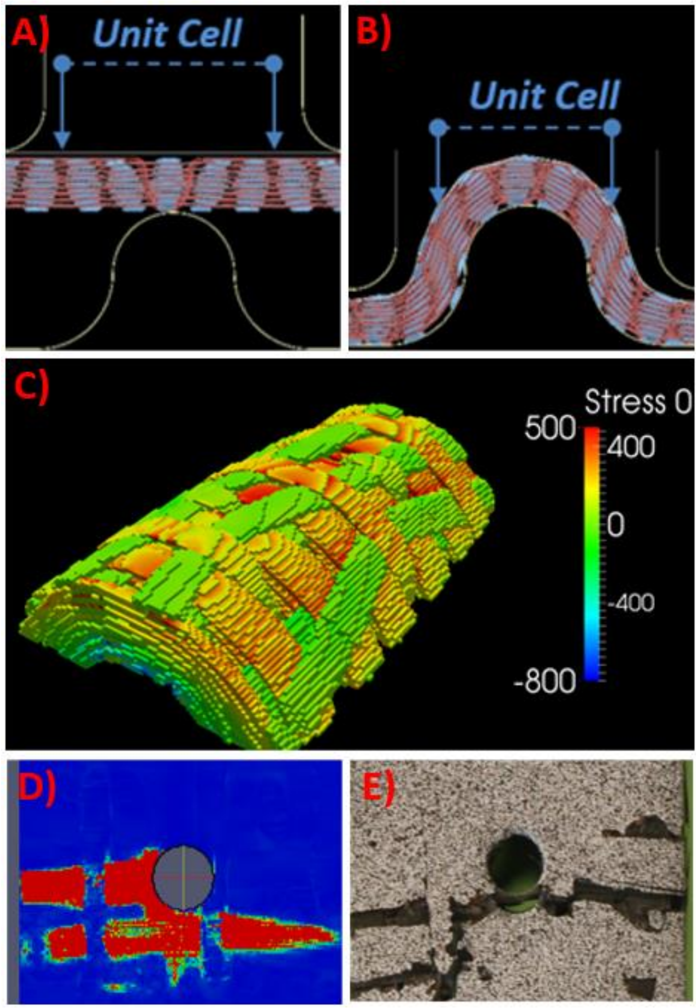
Periodic vs Non- Periodic

- While most composite materials can be assumed periodic, in some cases (3D/2D Woven + NCF) the material loses periodicity during manufacture.
- In these cases, parametrised representations of the material architecture is not straight forward.
- Experimental testing of flat coupon specimens is not directly relevant to structures with curved geometries.

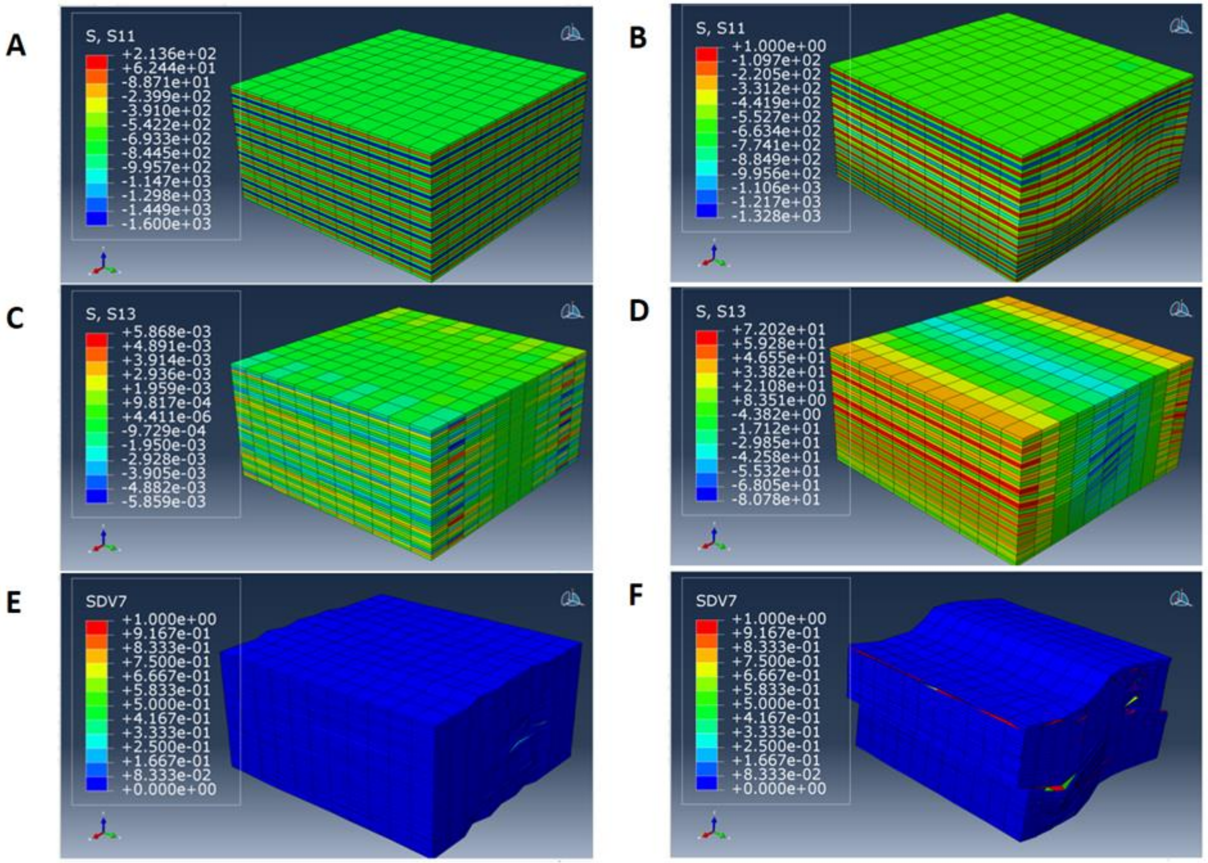
Periodic Materials



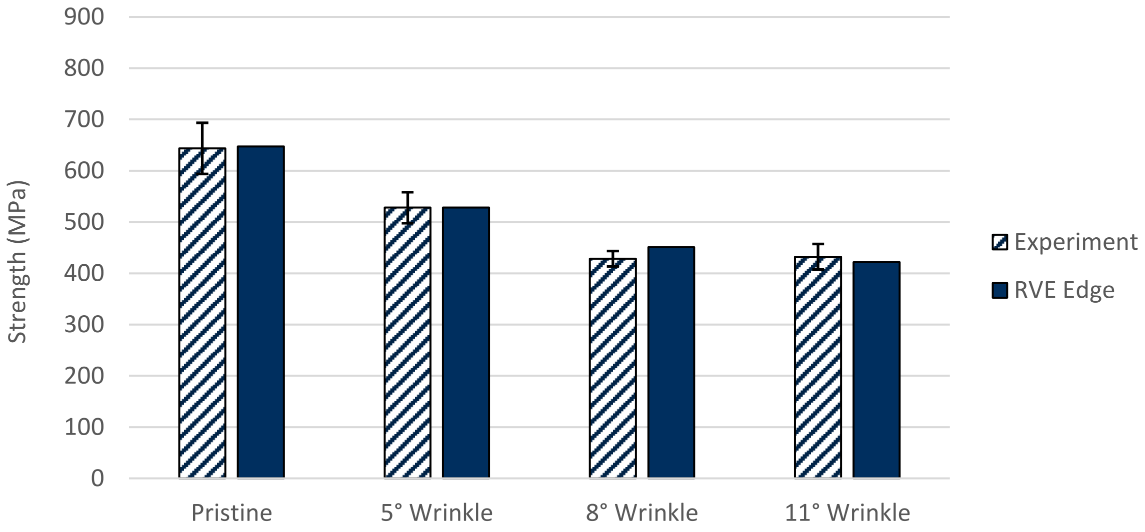
Non-Periodic Materials



Meso-scale Models: Wrinkles



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.



A comparison between the compressive strength of composites as predicted by RVE model vs Experiment [1] .

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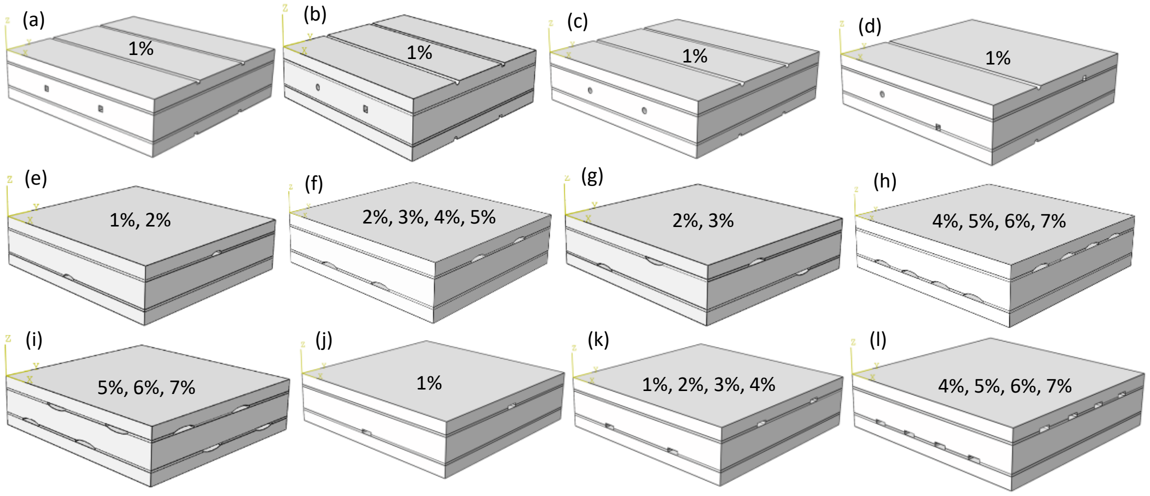
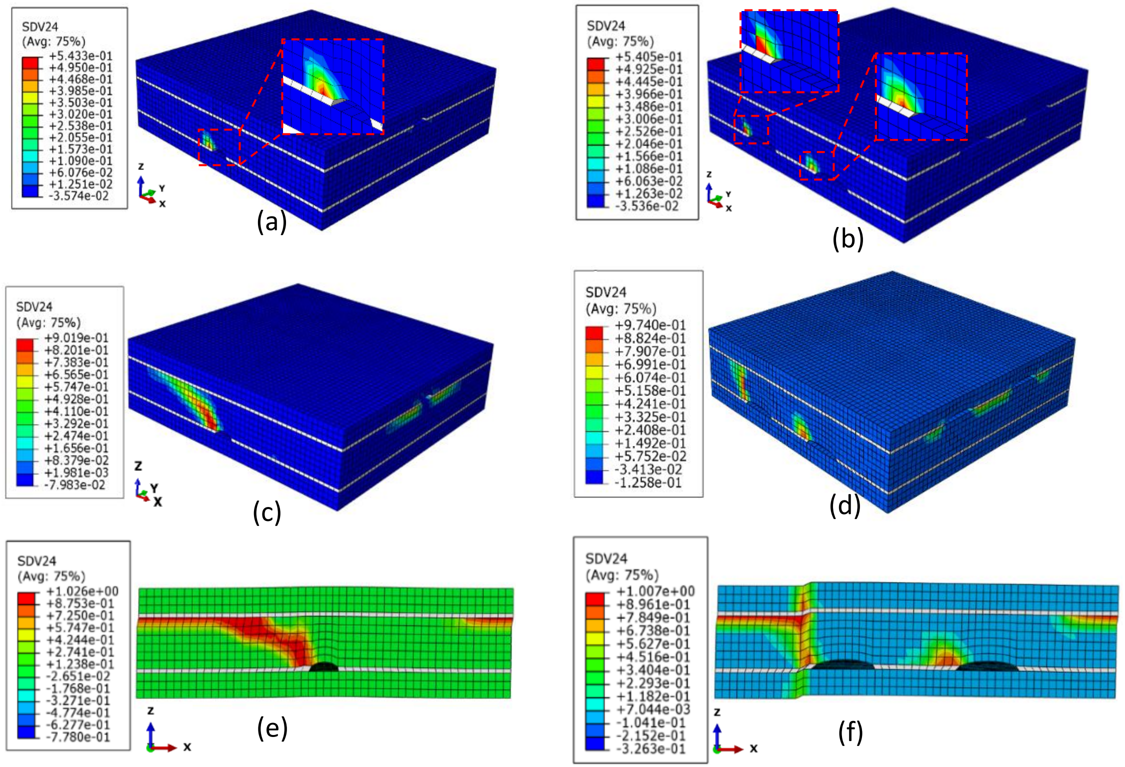
[1] - Mukhopadhyay, S., M.I. Jones, and S.R. Hallett, Compressive failure of laminates containing an embedded wrinkle; experimental and numerical study. Composites Part A: Applied Science and Manufacturing, 2015.

Meso-scale Models: Voids

- The meso-scale RVE approach can be used to study a wide variety of material architecture and defects.



Schematic of RVE models containing 1%-7% void volume fraction.



Damage contours of RVE models containing: (a) 1% void content and (b) 4% void content at early stage of damage initiation; (c) 1% void content and (d) 4% void content at the step where in-plane shear stress reaches the maximum value; (e) 1% void content and (f) 4% void content at a time step that damage propagates through the entire ply.

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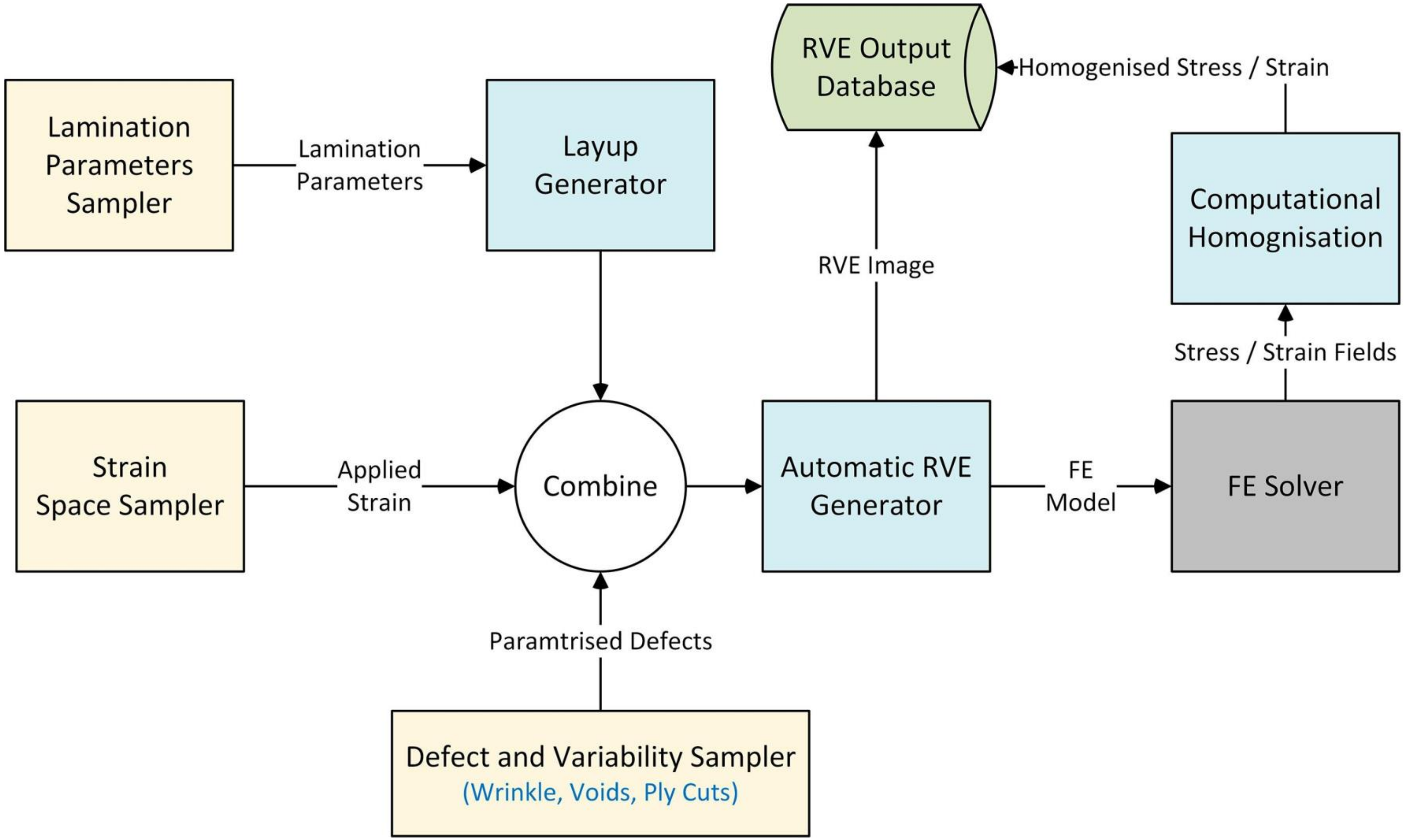
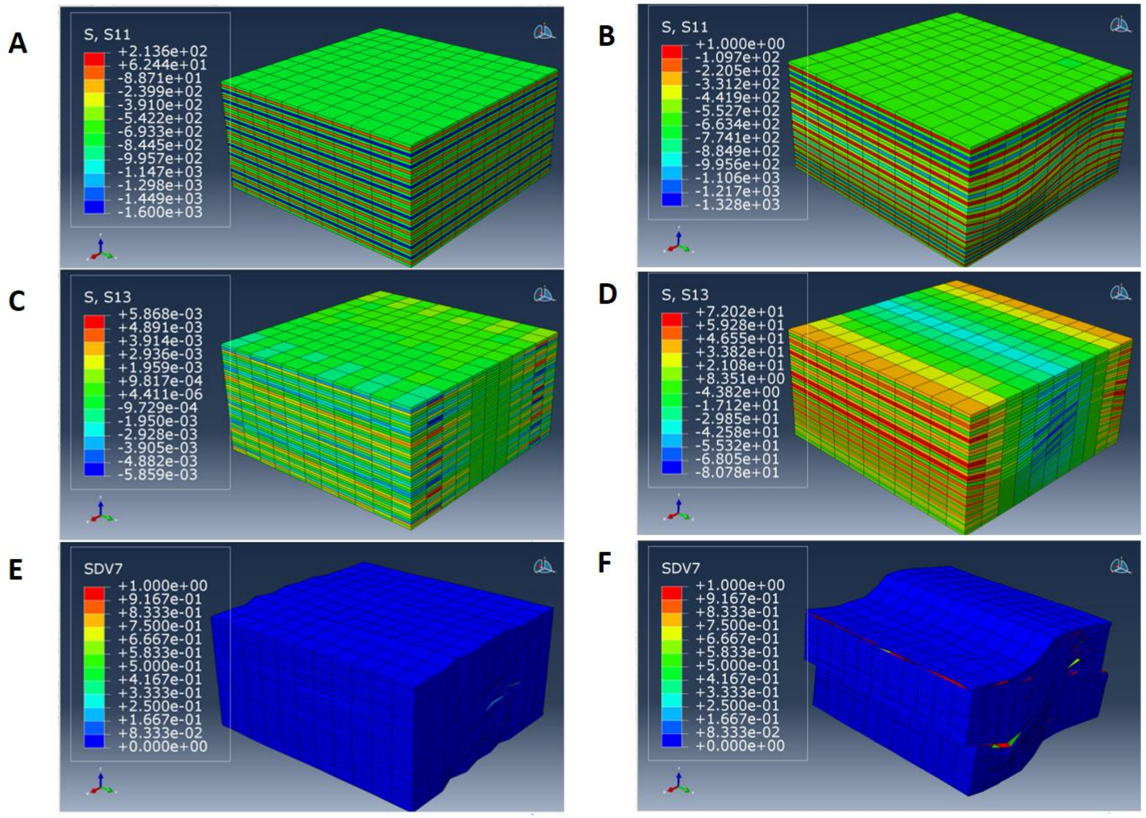
Transition to Macro-scale

From laminates to components

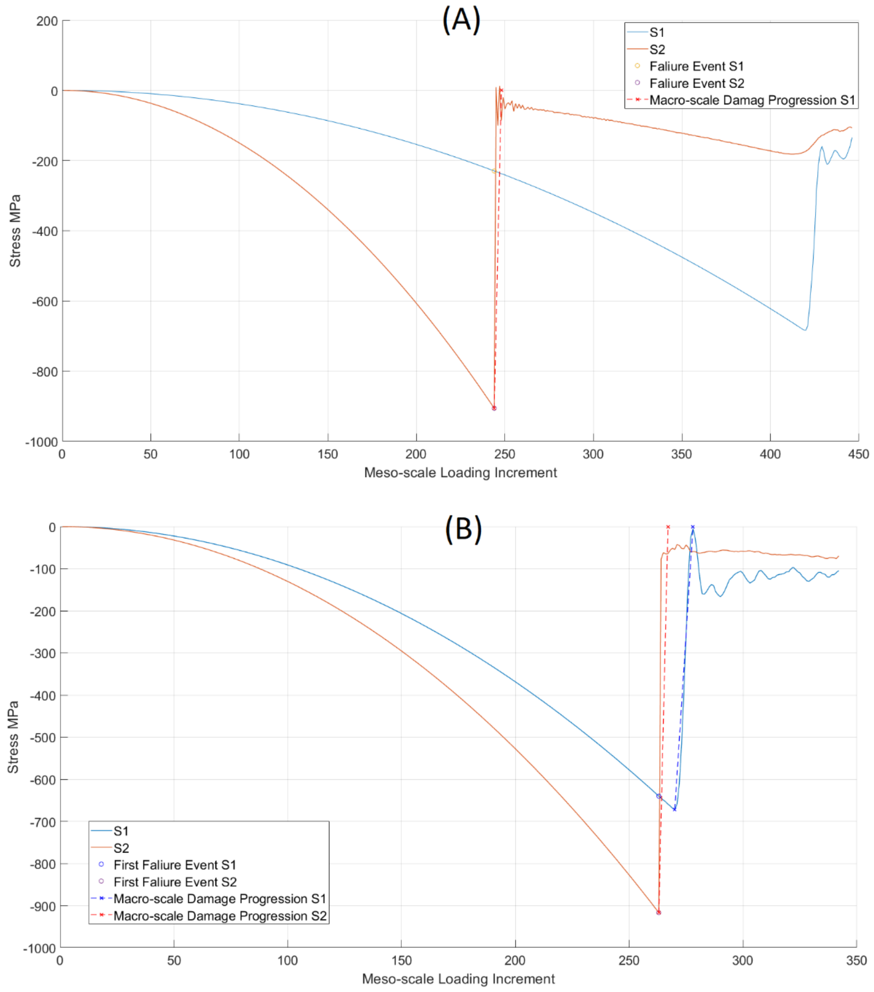
Building Parametrized Response Database



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

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El Said, B. and S.R. Hallett, Parametric failure manifolds for laminated composites. Composite Structures, 2020. 253: p. 112798.

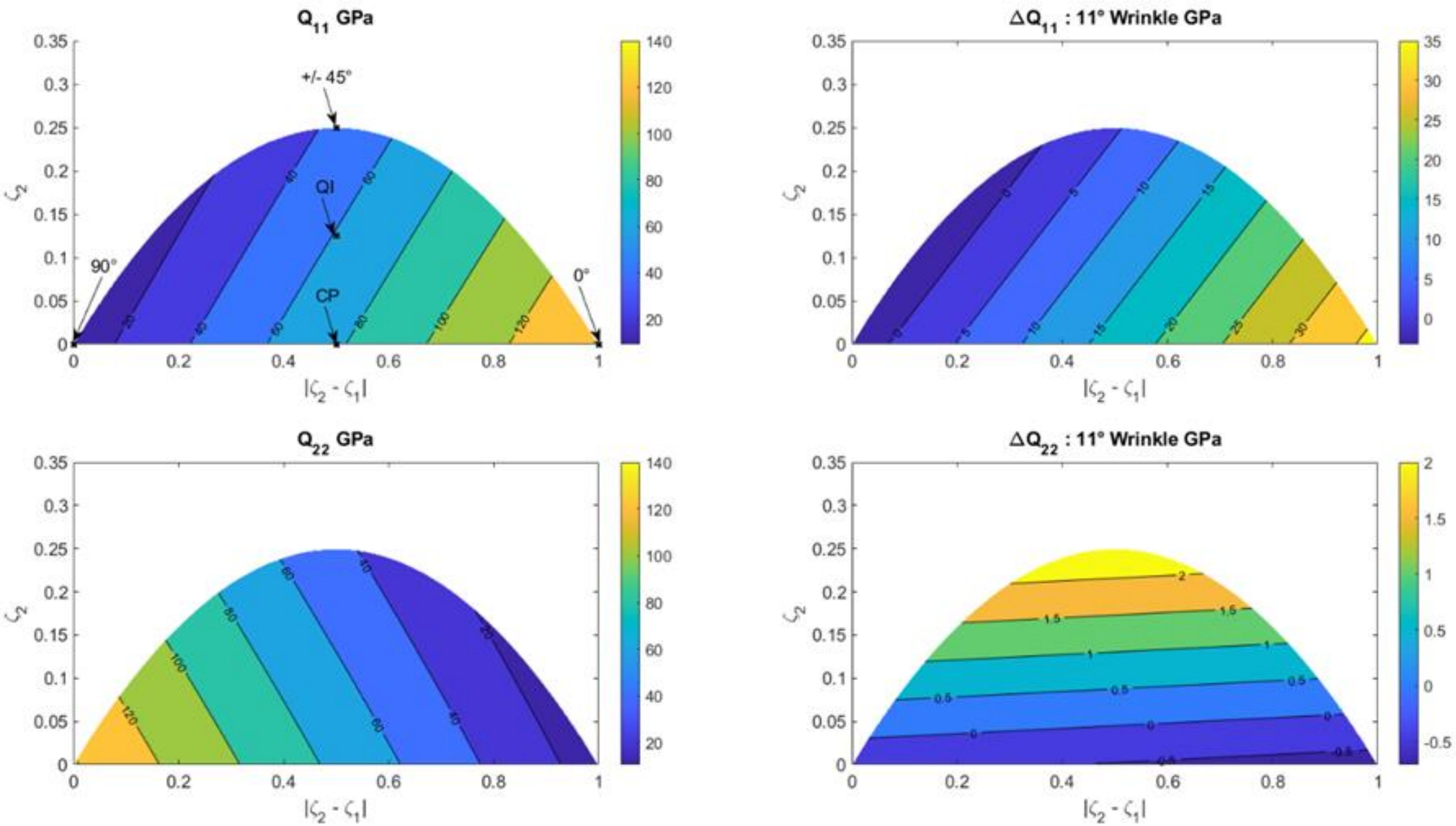
Stiffness Modelling using lamination parameters

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:

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



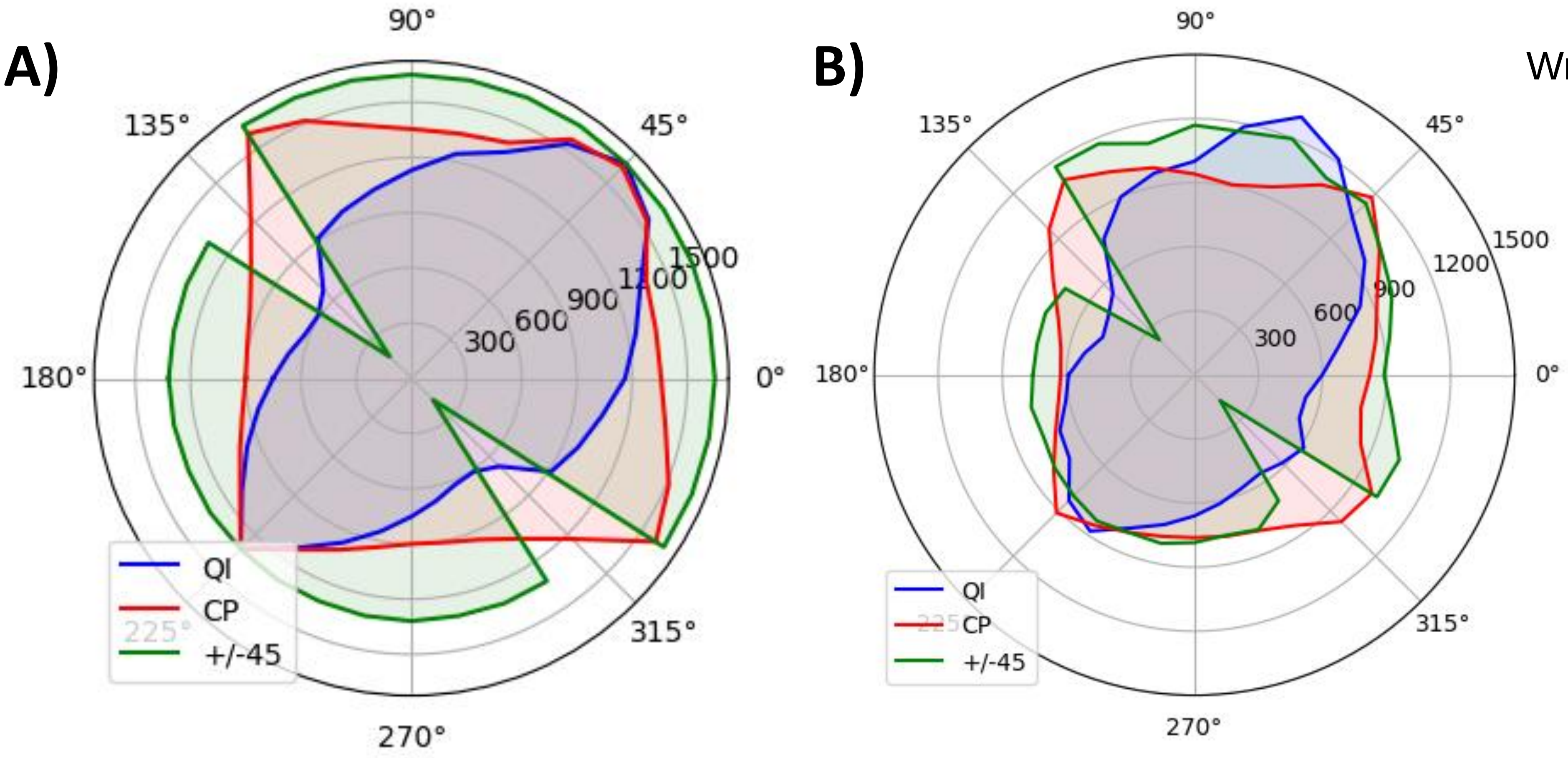
Composite Stiffness over the lamination parameters space, the impact of wrinkle presences

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

Pristine

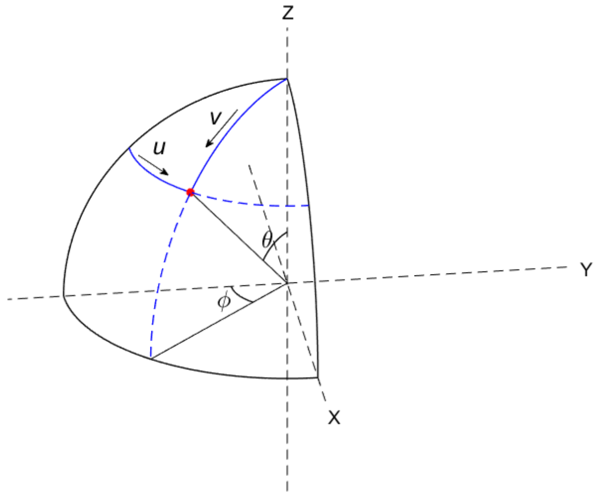
Wrinkle 8°



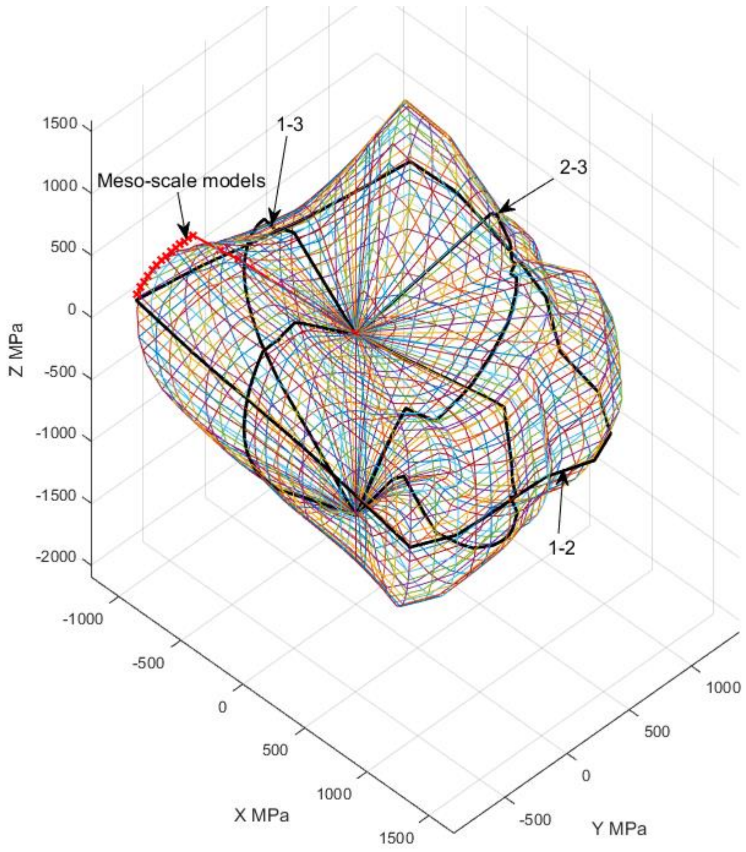
- Composite Failure data from RVE database can be mapped vs loading condition to generate failure envelopes for complete laminates.

Tri-Axial Failure Manifolds for Laminated Composites

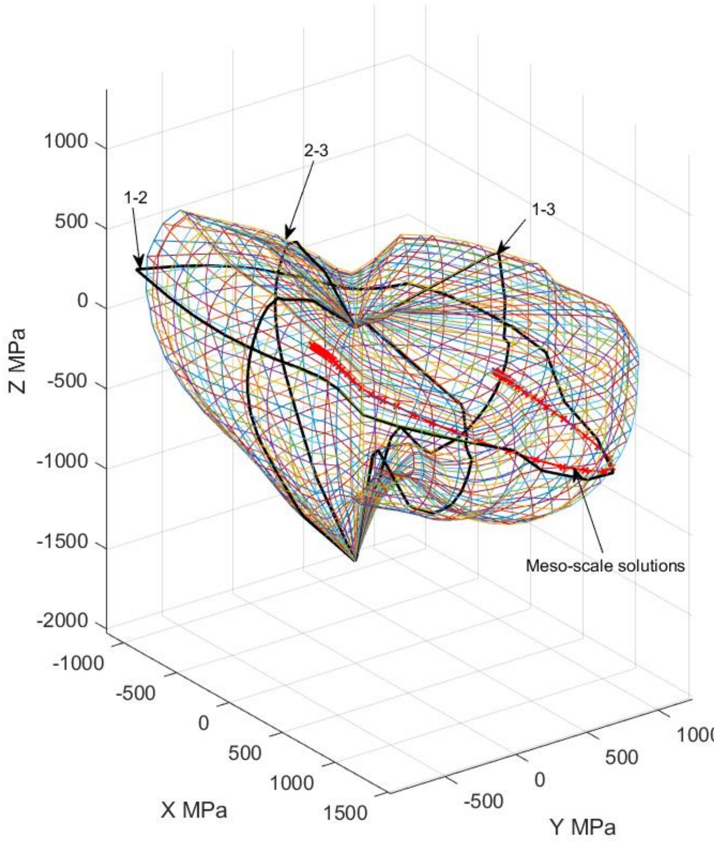
- Bi-axial failure envelopes can be considered the intersection of a 3D failure manifolds with the principal plans.
- Using the intersection and the surface computability conditions a full 3D failure manifold can be



Schematic description of Failure Manifolds



Failure Manifold for Cross-Ply

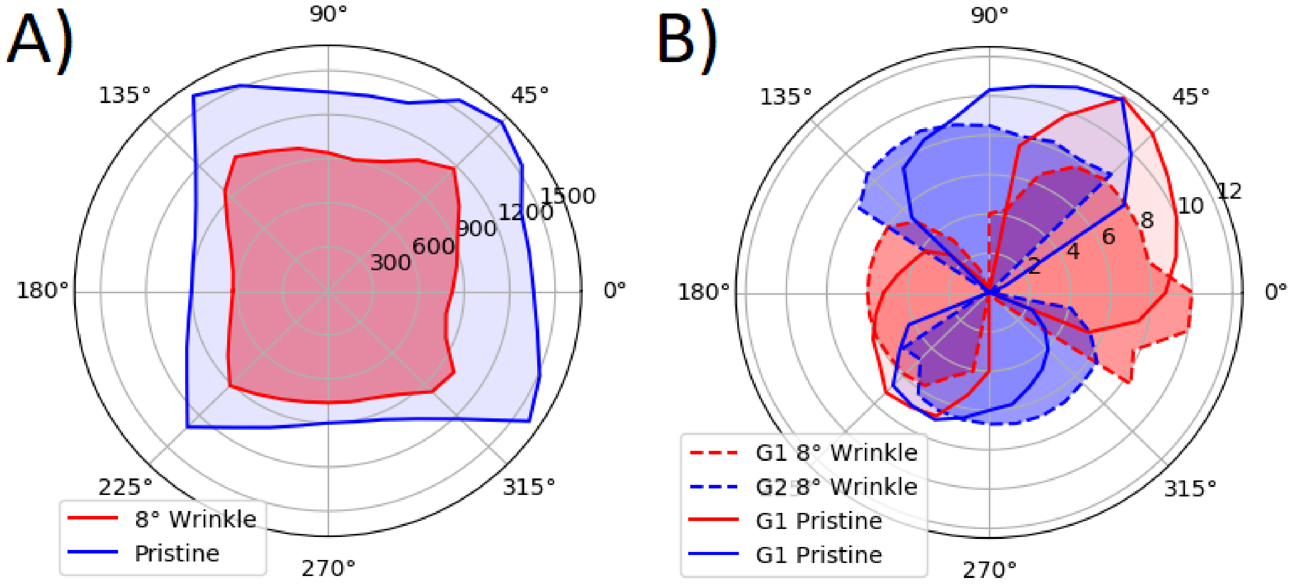


Failure Manifold for Quasi-Isotropic

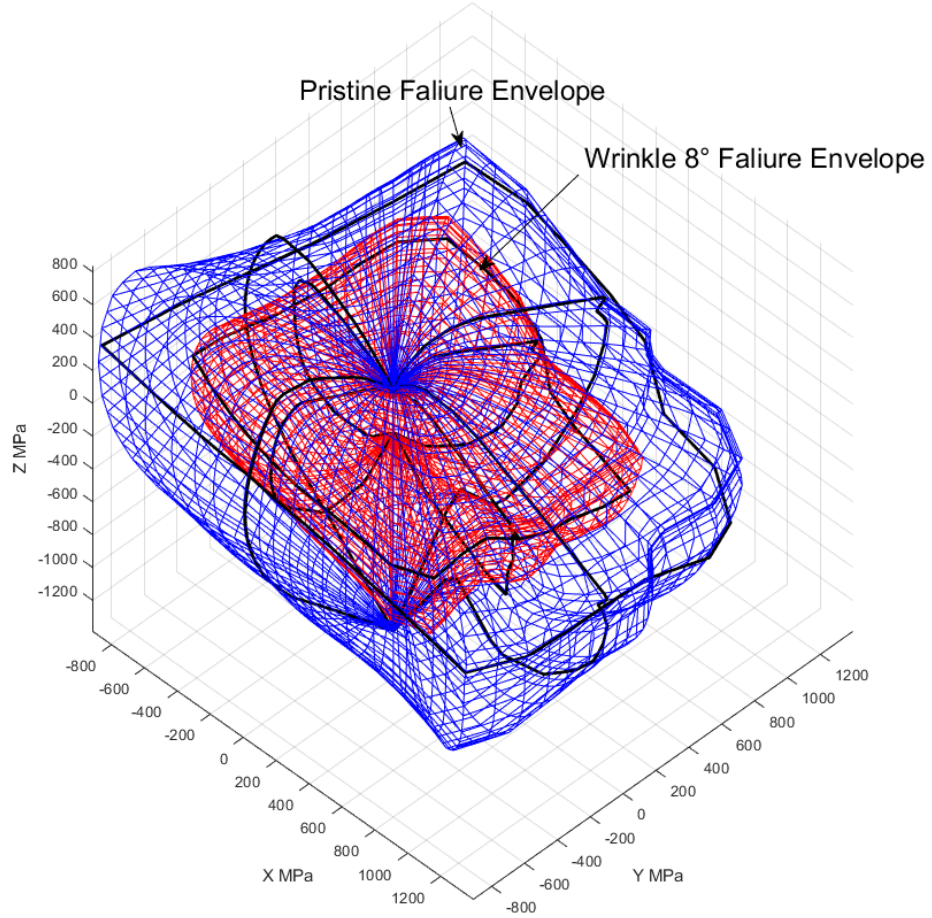
El Said, B. and S.R. Hallett, Parametric failure manifolds for laminated composites. Composite Structures, 2020. 253: p. 112798.

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.



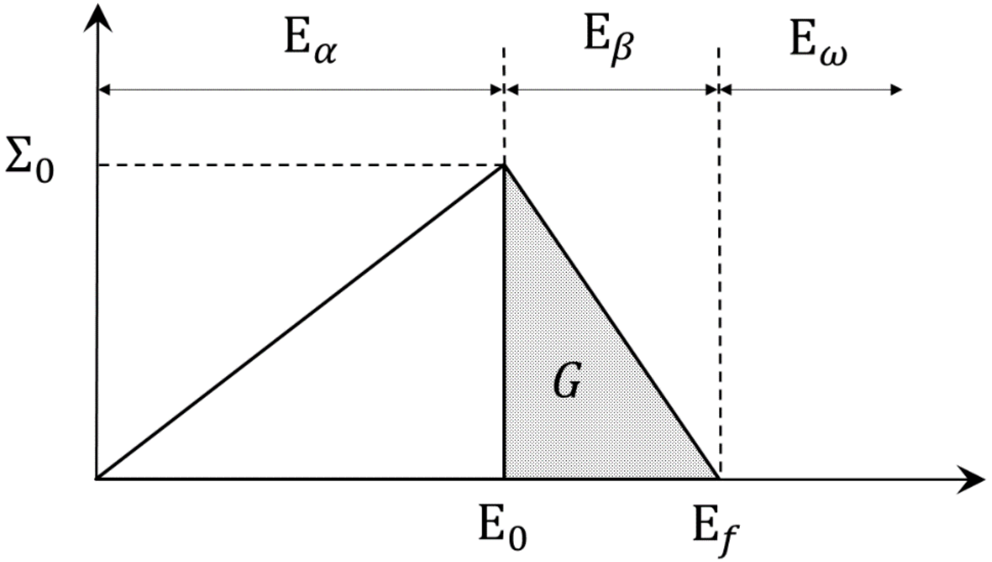
Failure envelopes for a Cross-Ply layup (A) with the associated regularization energy,(B) pristine vs 8° wrinkle



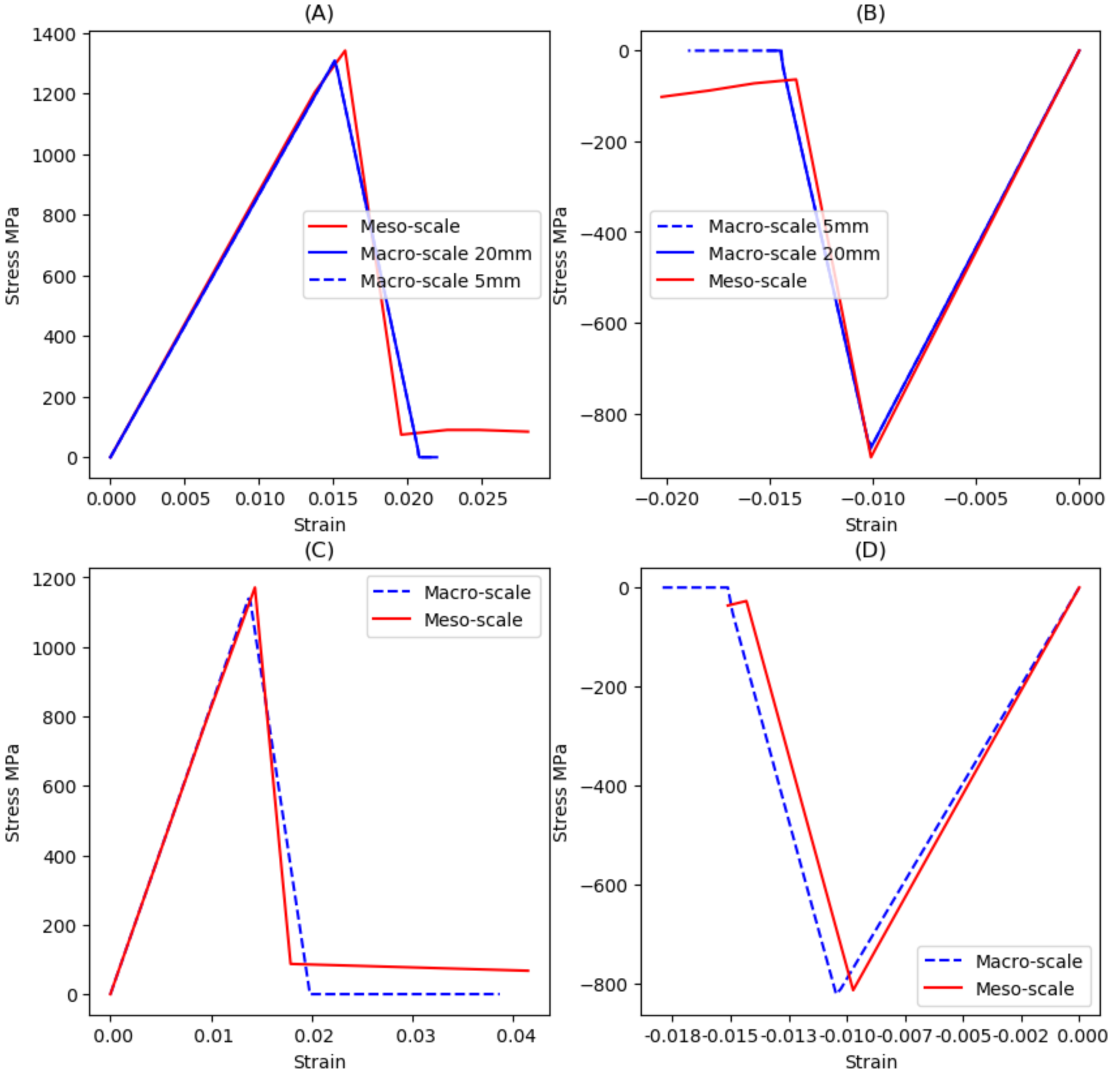
A comparison of 3D failure manifolds for cross-ply layup, wrinkle vs pristine

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.

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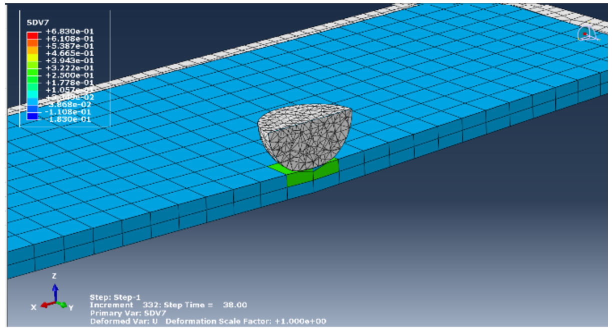
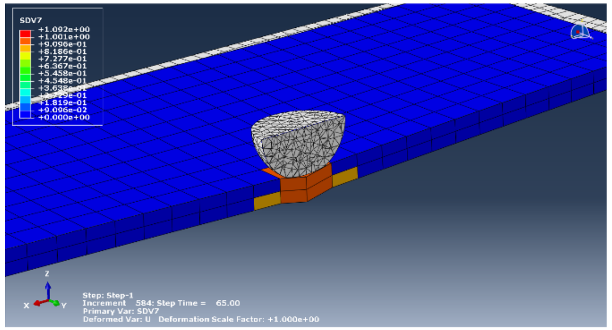
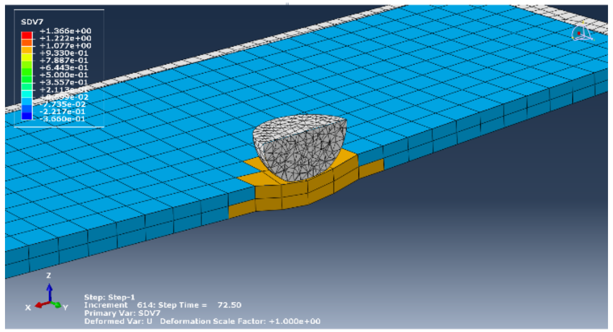
Application : Static Indentation/ Low Speed Impact

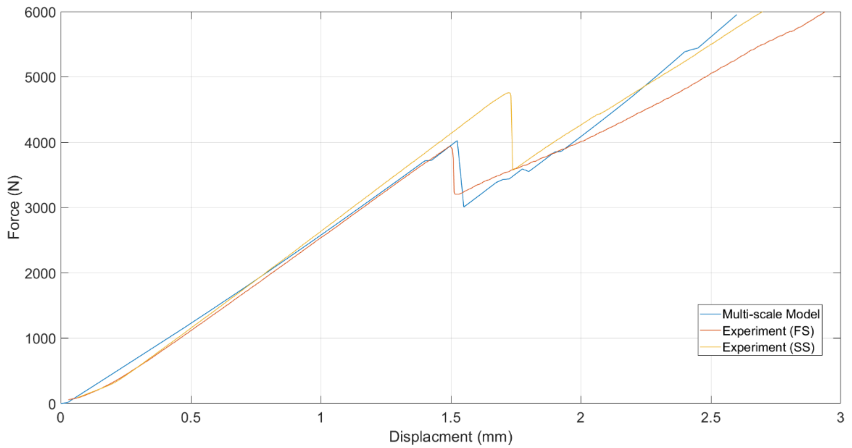
Static indentation multiscale model



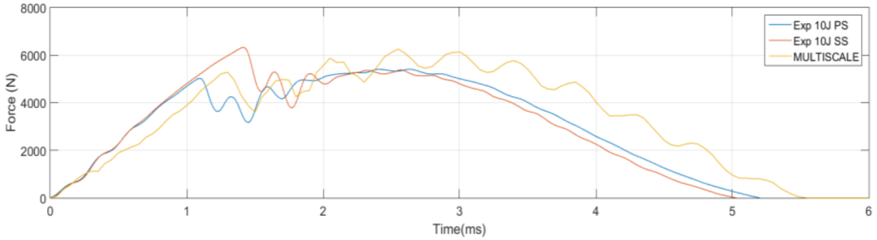


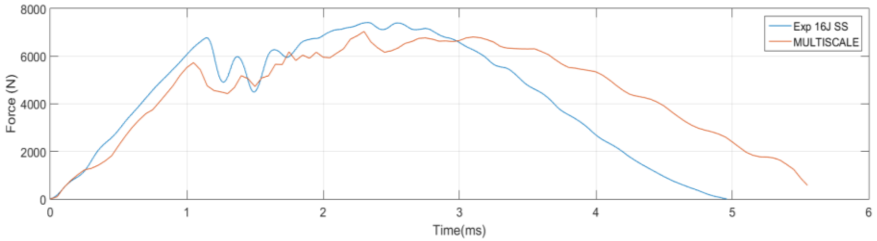


Static indentation force displacement curves, multi-scale vs Experiment

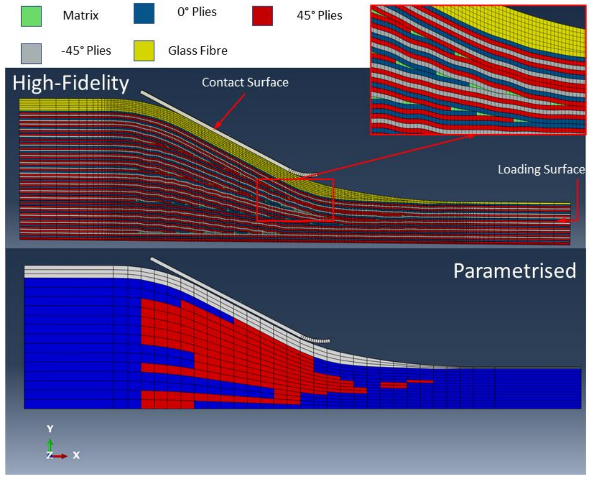


Low speed impact, multi-scale vs experiment



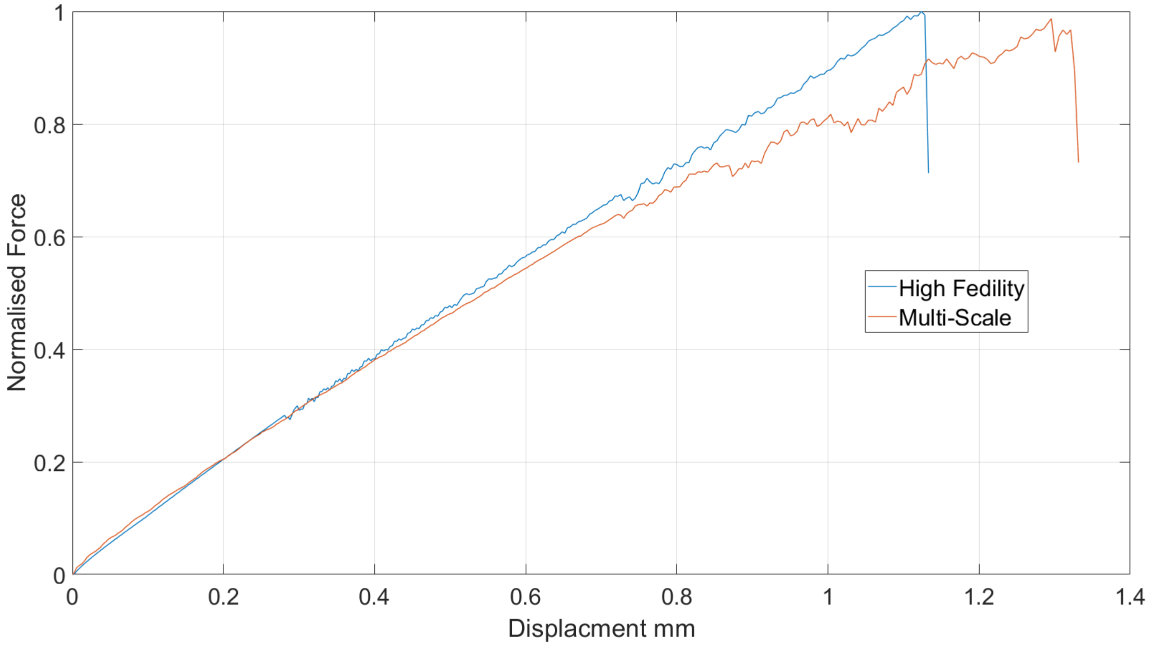


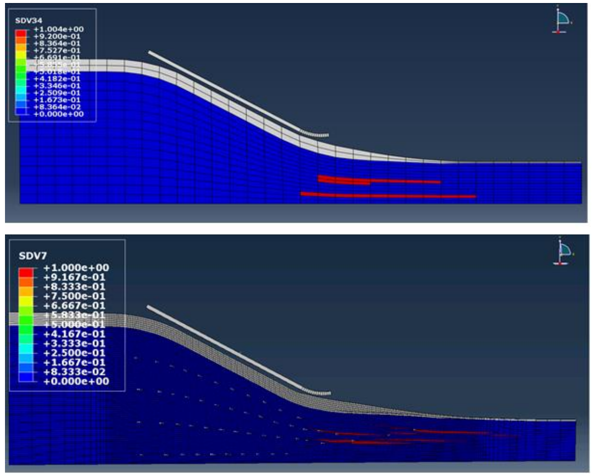
Application: Complex composite structures



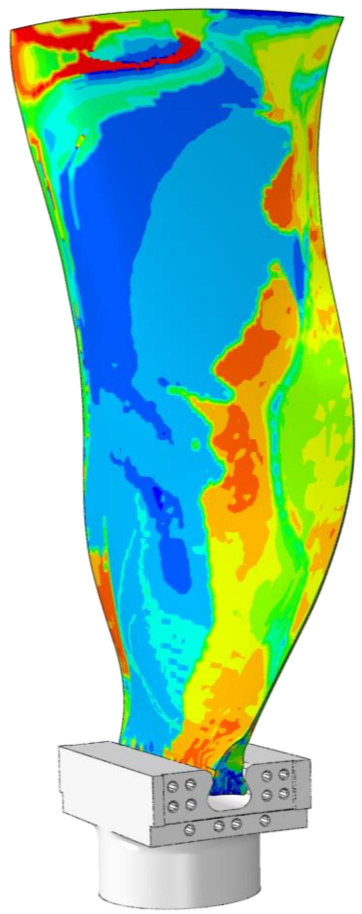
Model Setup for a tapered specimen

Normalized Force vs Displacement for a tapered specimen





Failure Morphology fidelity vs macro-scale



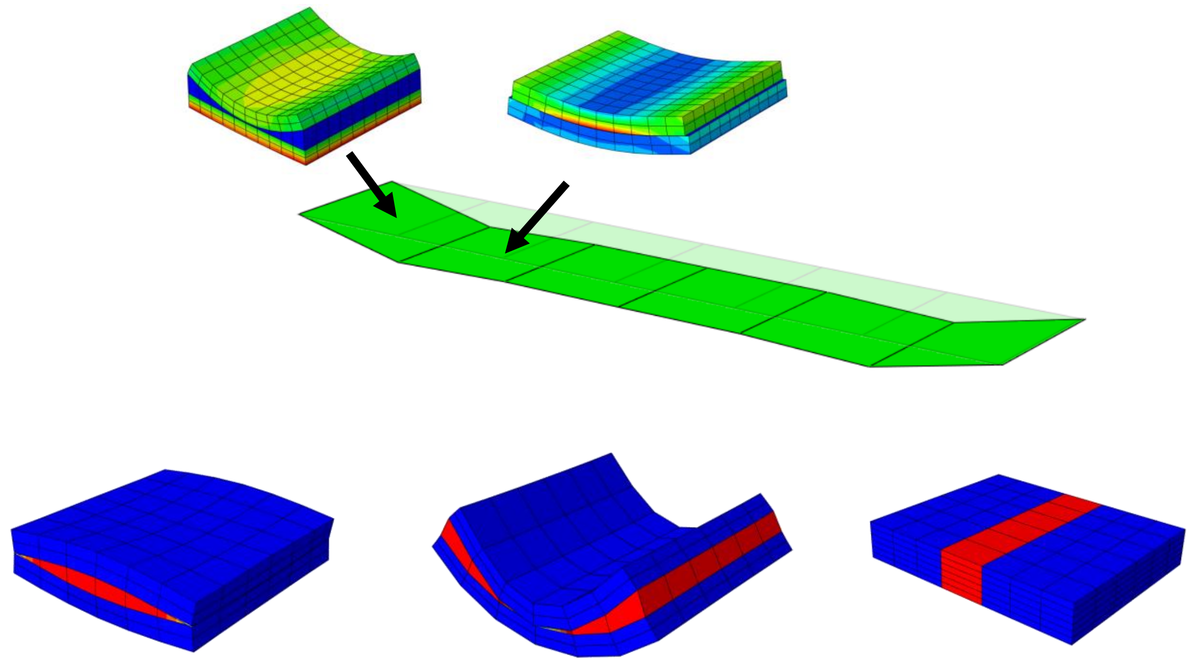
Industrial scale application

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

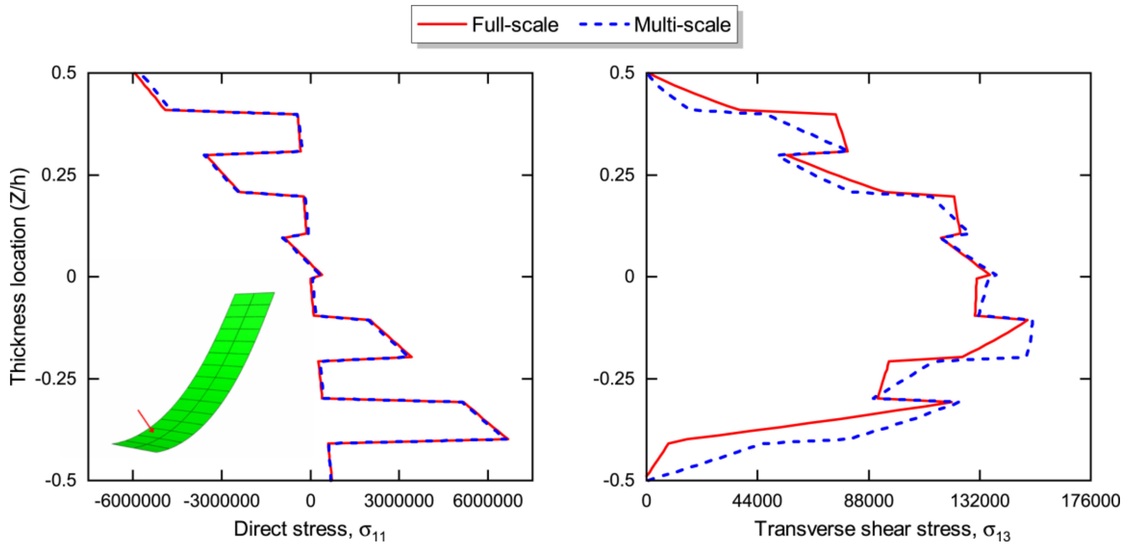
Data-driven multi-scale framework for shell models

- 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.

Example application: FE2 of plate under end moments



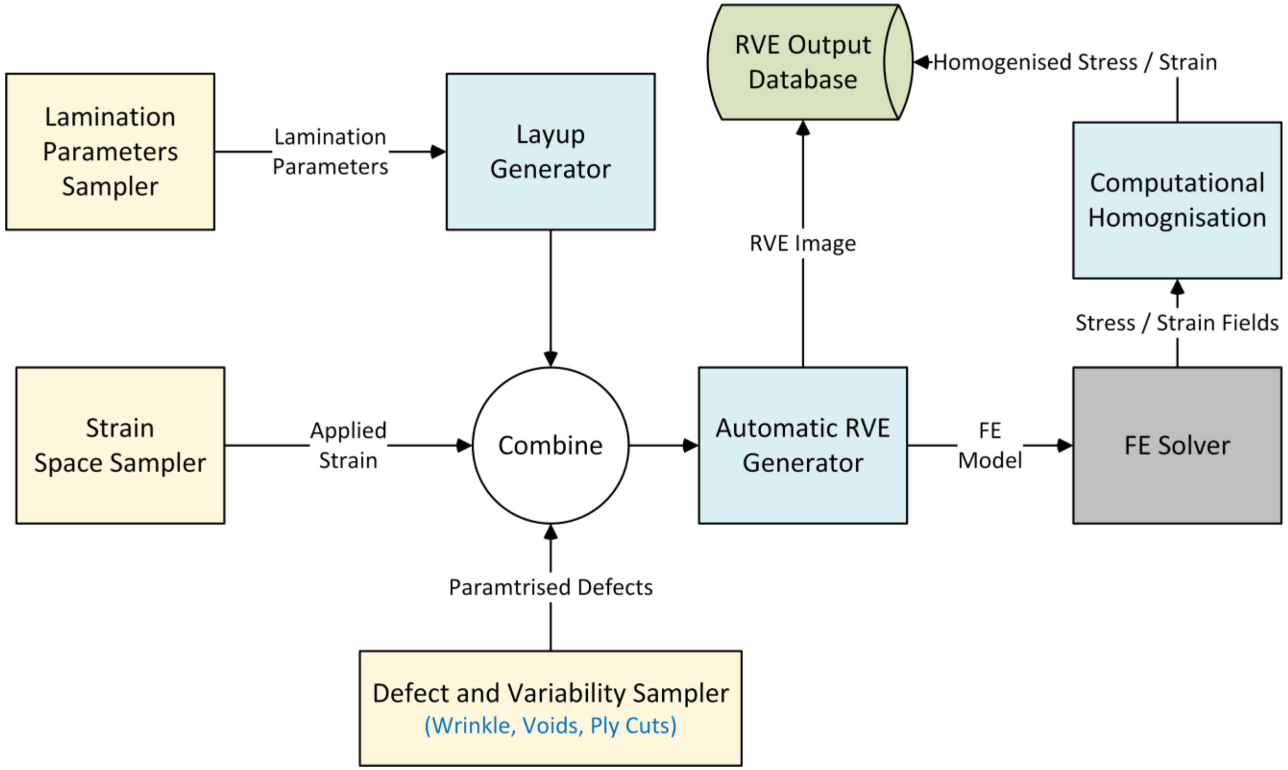
Delamination buckling under compression *Delamination under bending* *Matrix cracking under tension*



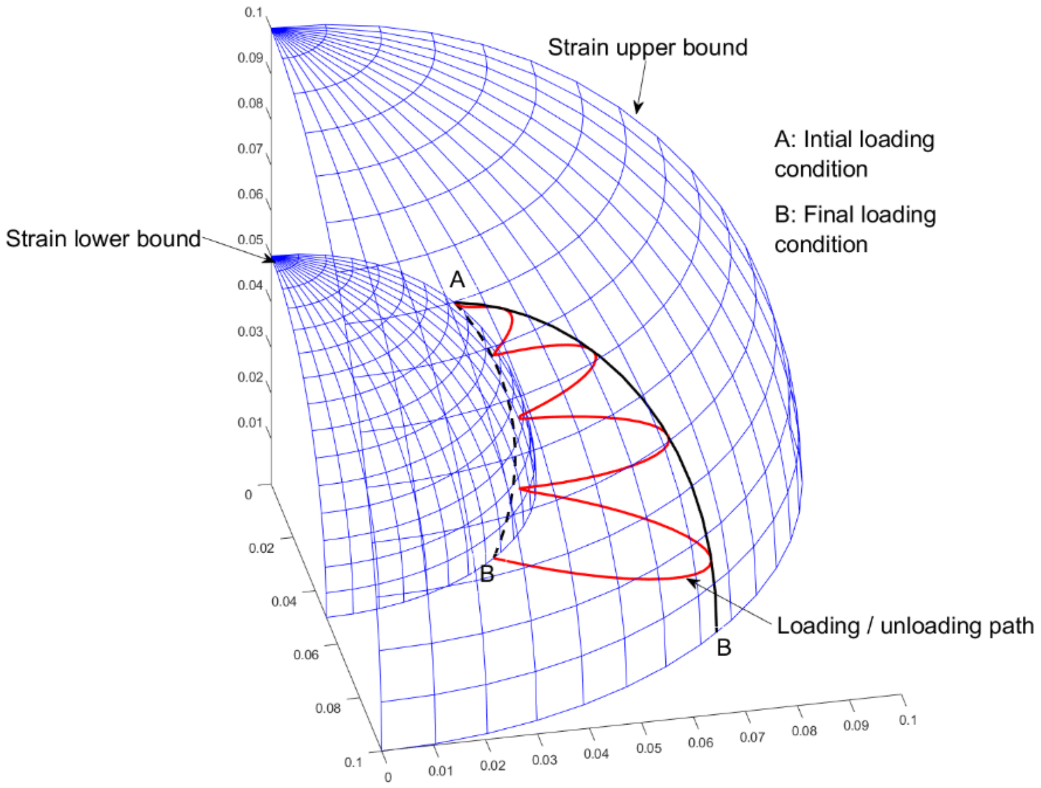
Through-thickness distribution of σ_{11} (left) and σ_{13} (right) in the thick cross-ply laminate under bending.

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

Design Space Sampling for Deep Learning



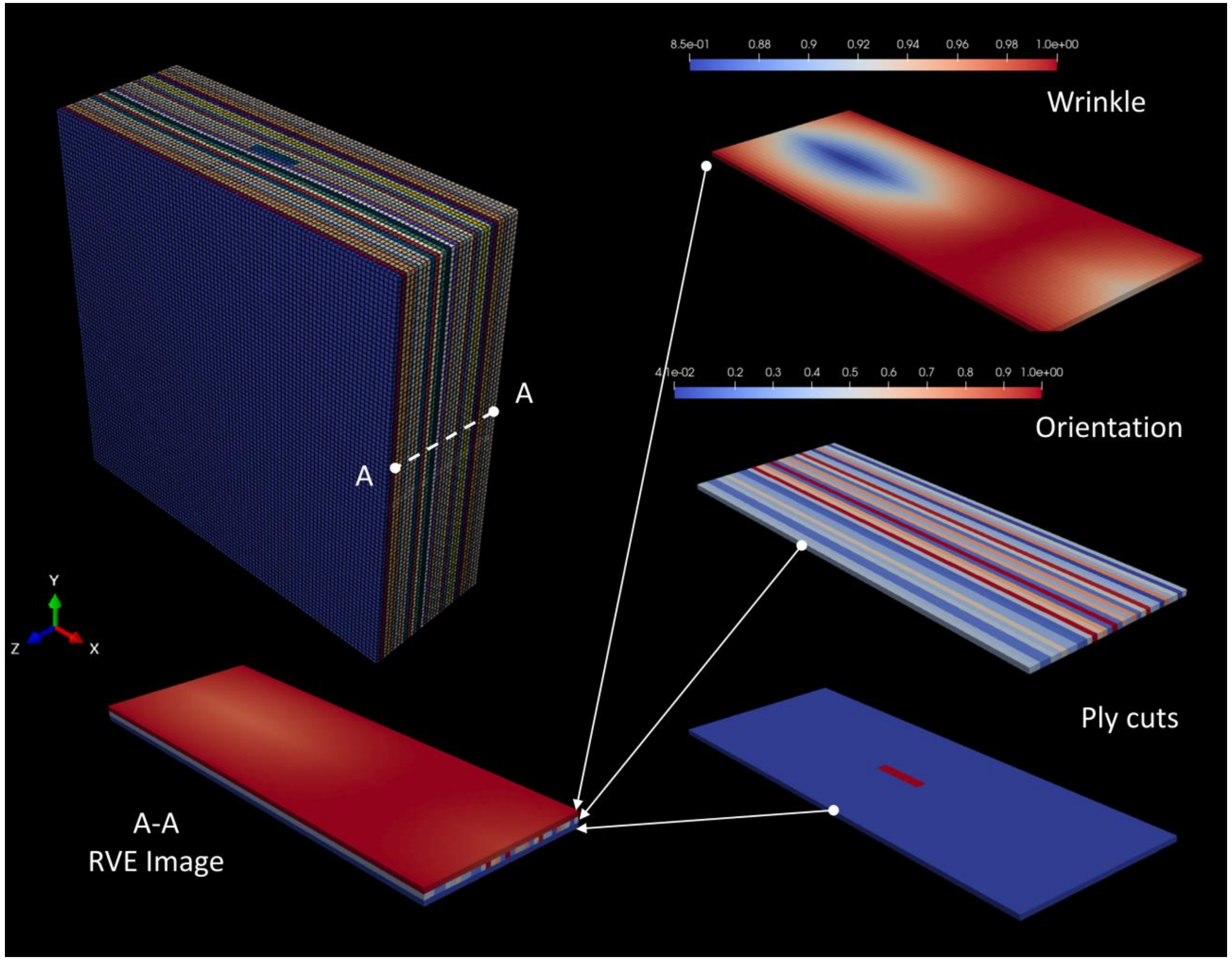
Overview of RVE database generation (3075 RVE, 500K Readings)



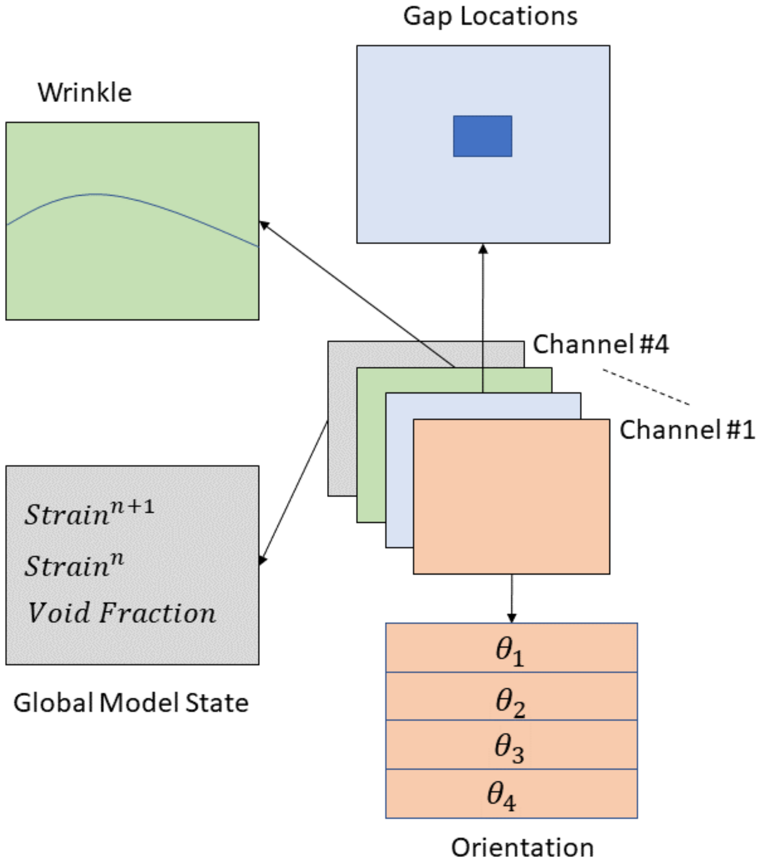
Strain space sampler

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

DRCN Network Input

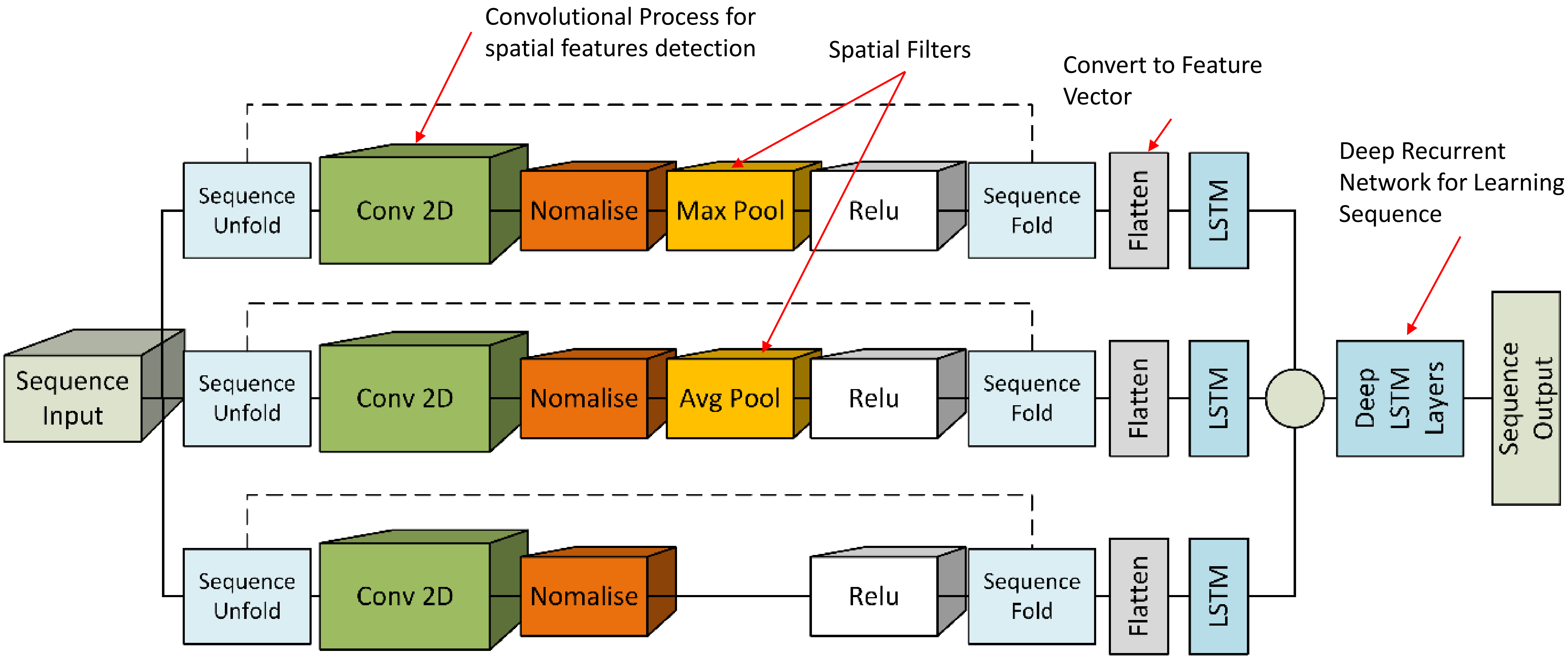


Example RVE with wrinkle



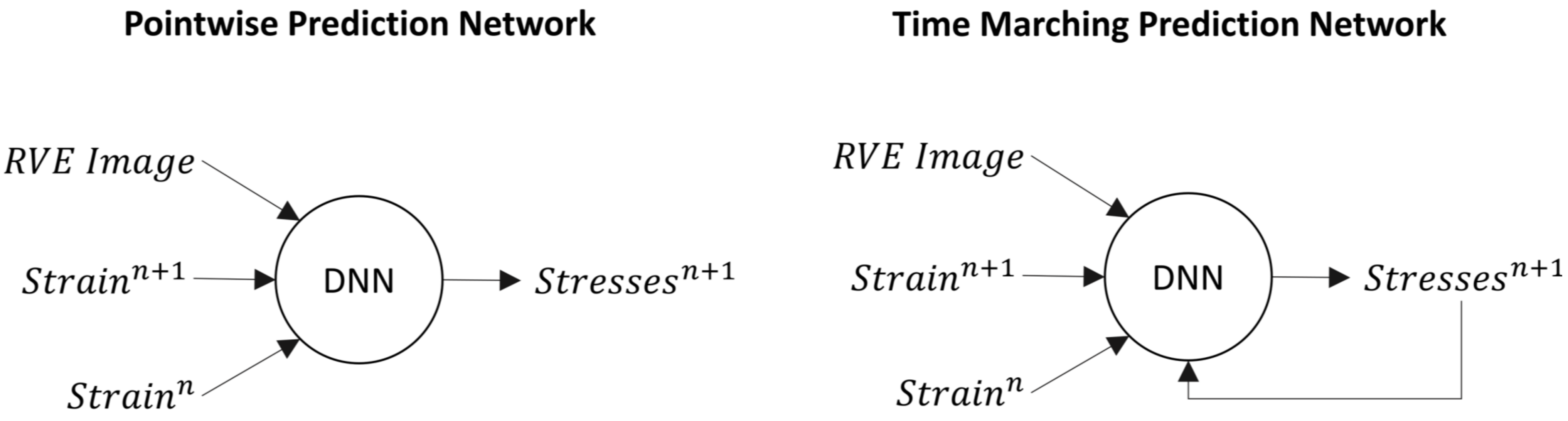
Structure of RVE input image used for DRCN Network training

Deep Recurrent Convolutional Natural Network



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

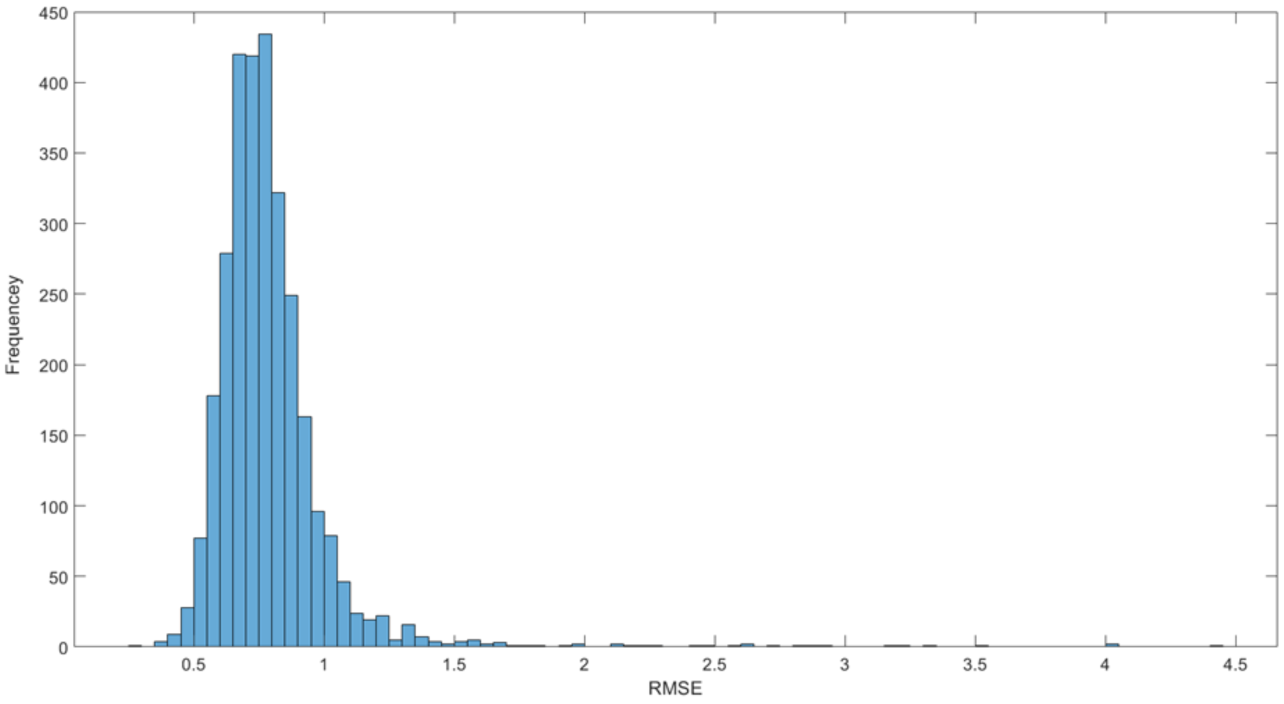
DRCN Problem Formulation



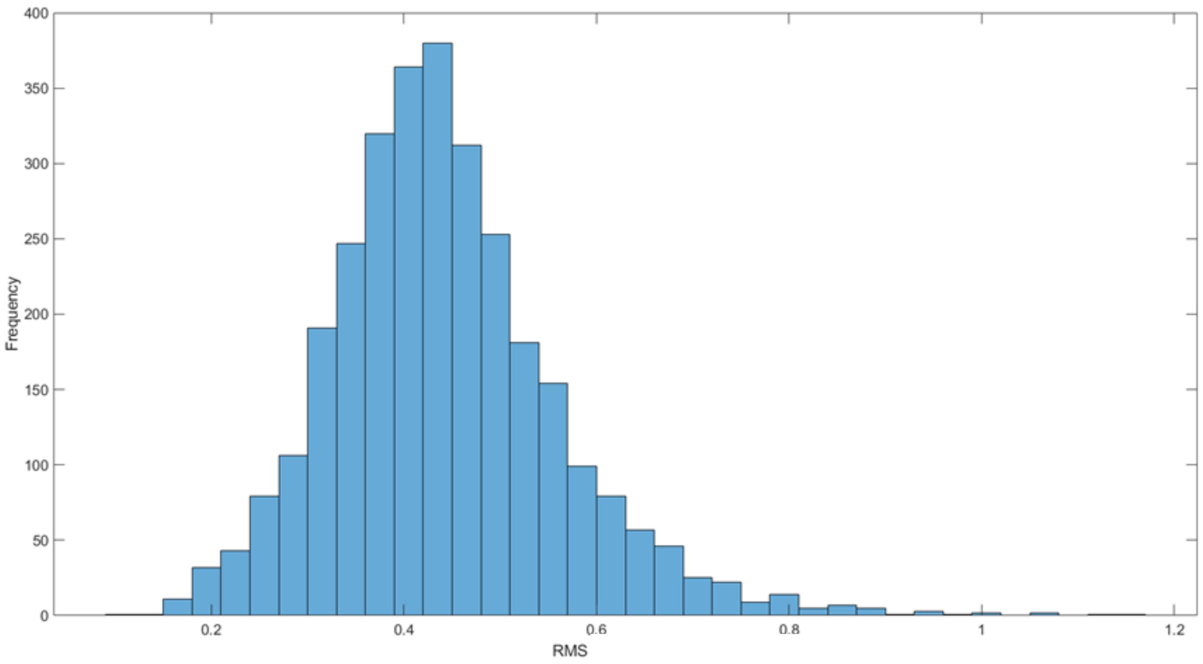
- There are two approaches to formulate the composites performance prediction problem.
- The approaches are analogues to a total strain formulation approach and a gradient formulation approach

Training Results

- Both network are showing good accuracy with T-DRCN showing better performance.



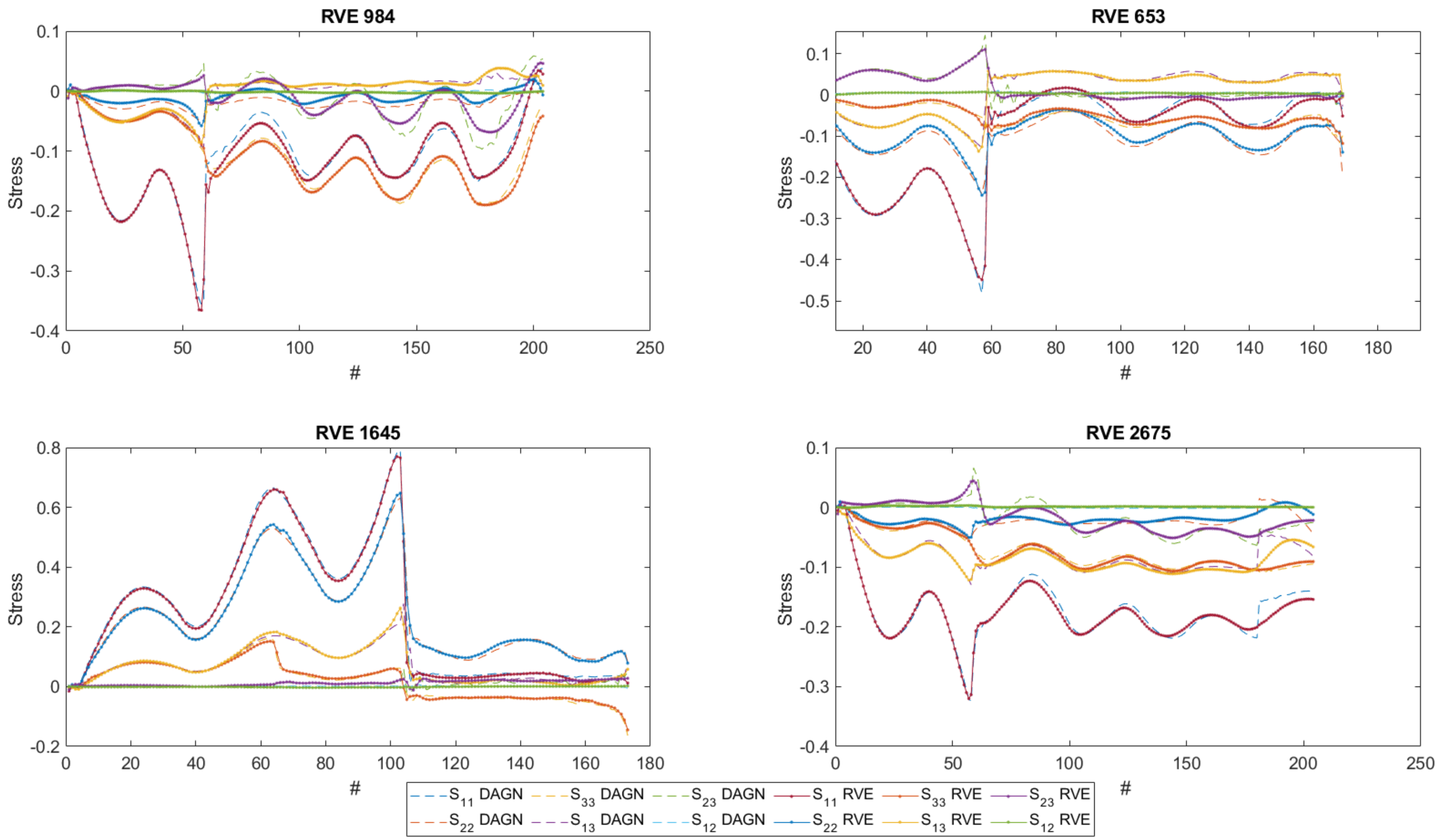
P-DRCN RMSE



T-DRCN RMSE

DRCN Results

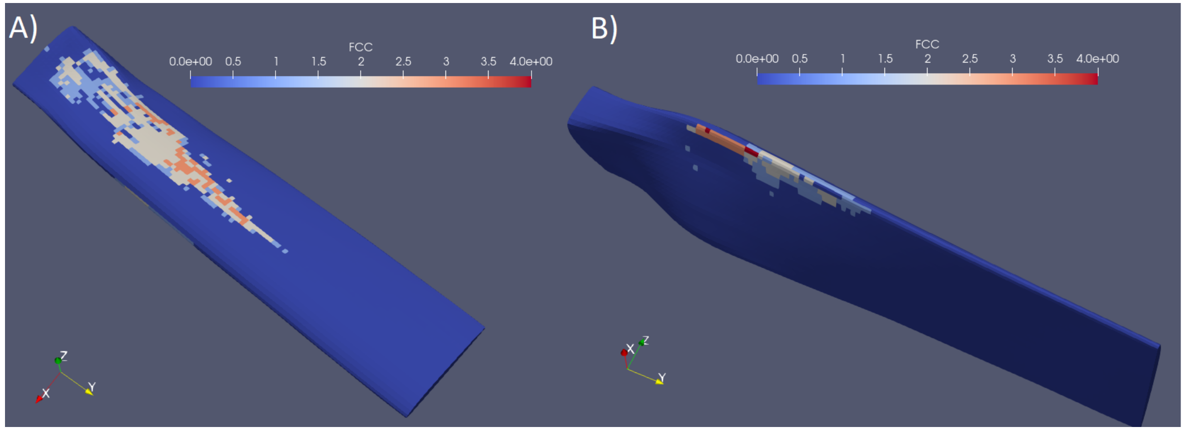
Example RVE response predictions



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

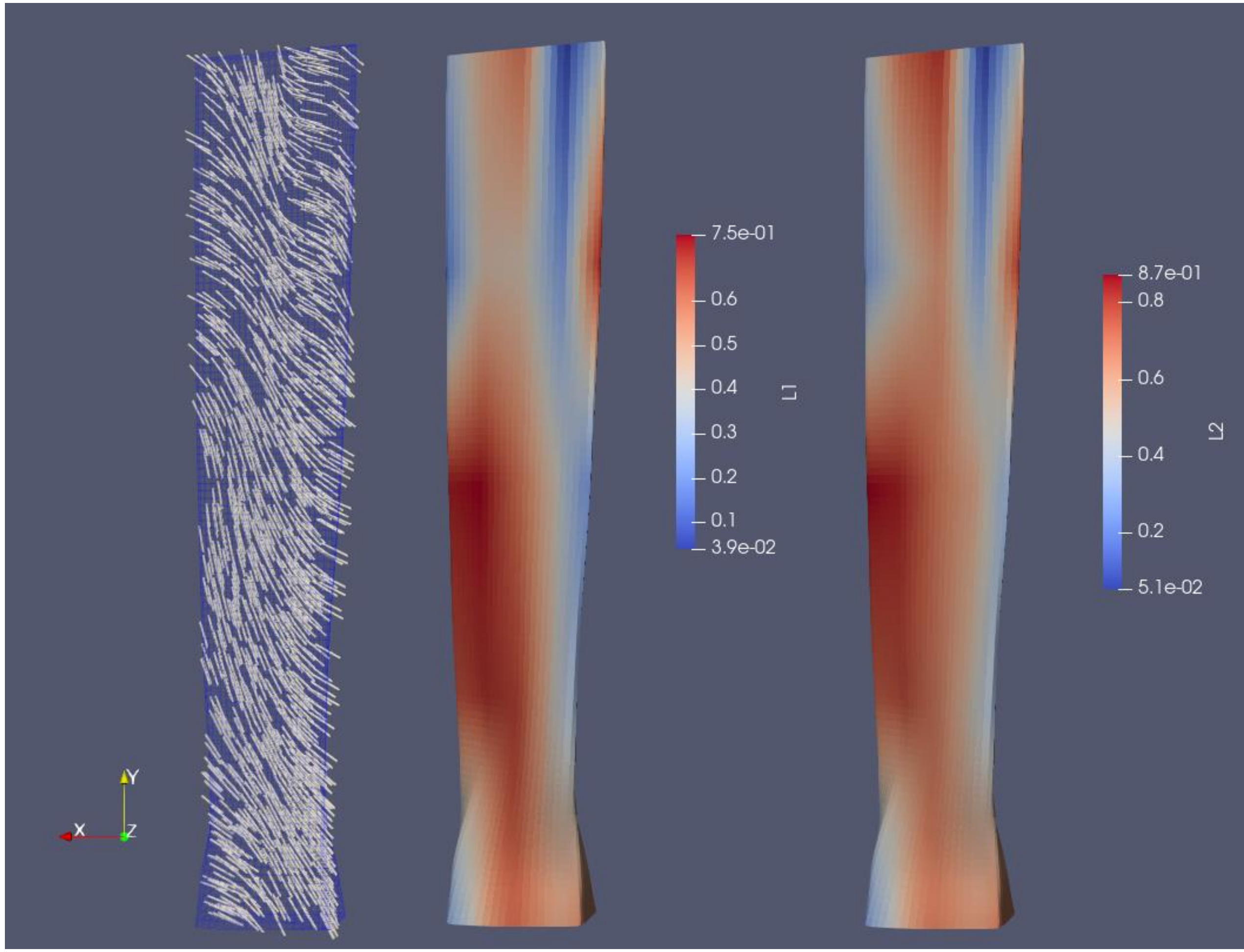
Structural Design and Optimisation

- 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.



Damage initiation prediction using failure manifolds and linear FE.

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



UKRI Engineering and Physical Sciences Research Council

CERTEST

CERTIFICATION FOR DESIGN: RESHAPING THE TESTING PYRAMID

University of BRISTOL

UNIVERSITY OF BATH

University of Southampton

UNIVERSITY OF EXETER

AIRBUS

BAE SYSTEMS

ROLLS ROYCE Rolls-Royce

GKN AEROSPACE

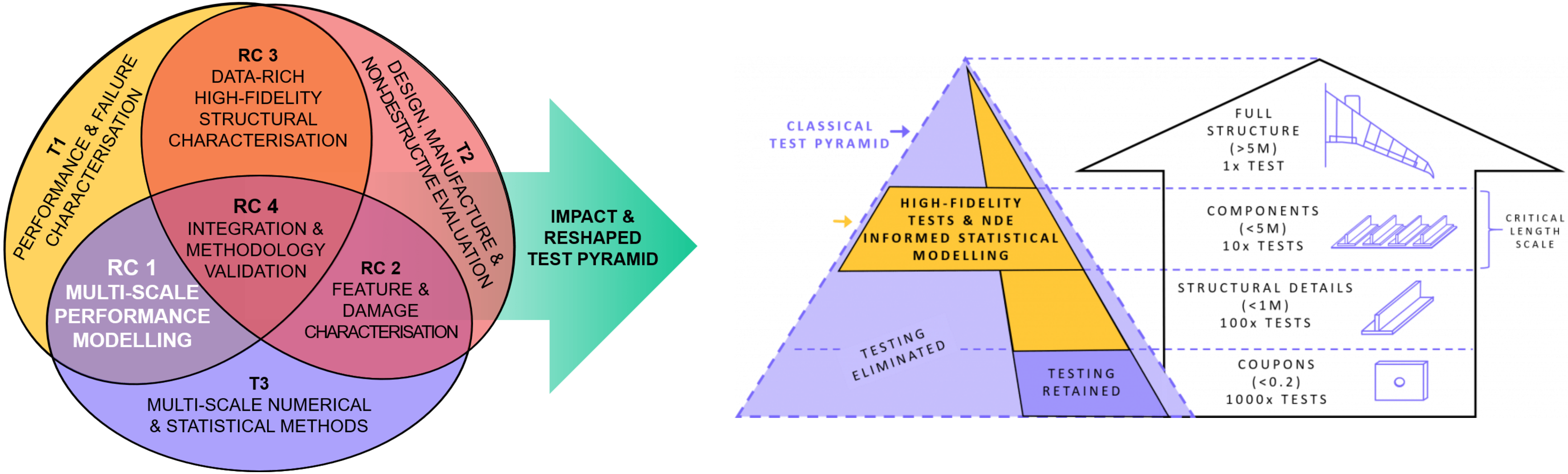
NATIONAL COMPOSITES CENTRE

cfms

The Alan Turing Institute

CerTest Mission Statement

The project aims to develop new approaches for integrated high-fidelity structural testing and multi-scale statistical modelling through Design of Experiments and Bayesian Learning.



[Certest – Certification for Design: Reshaping the Testing Pyramid (composites-certest.com)](composites-certest.com)

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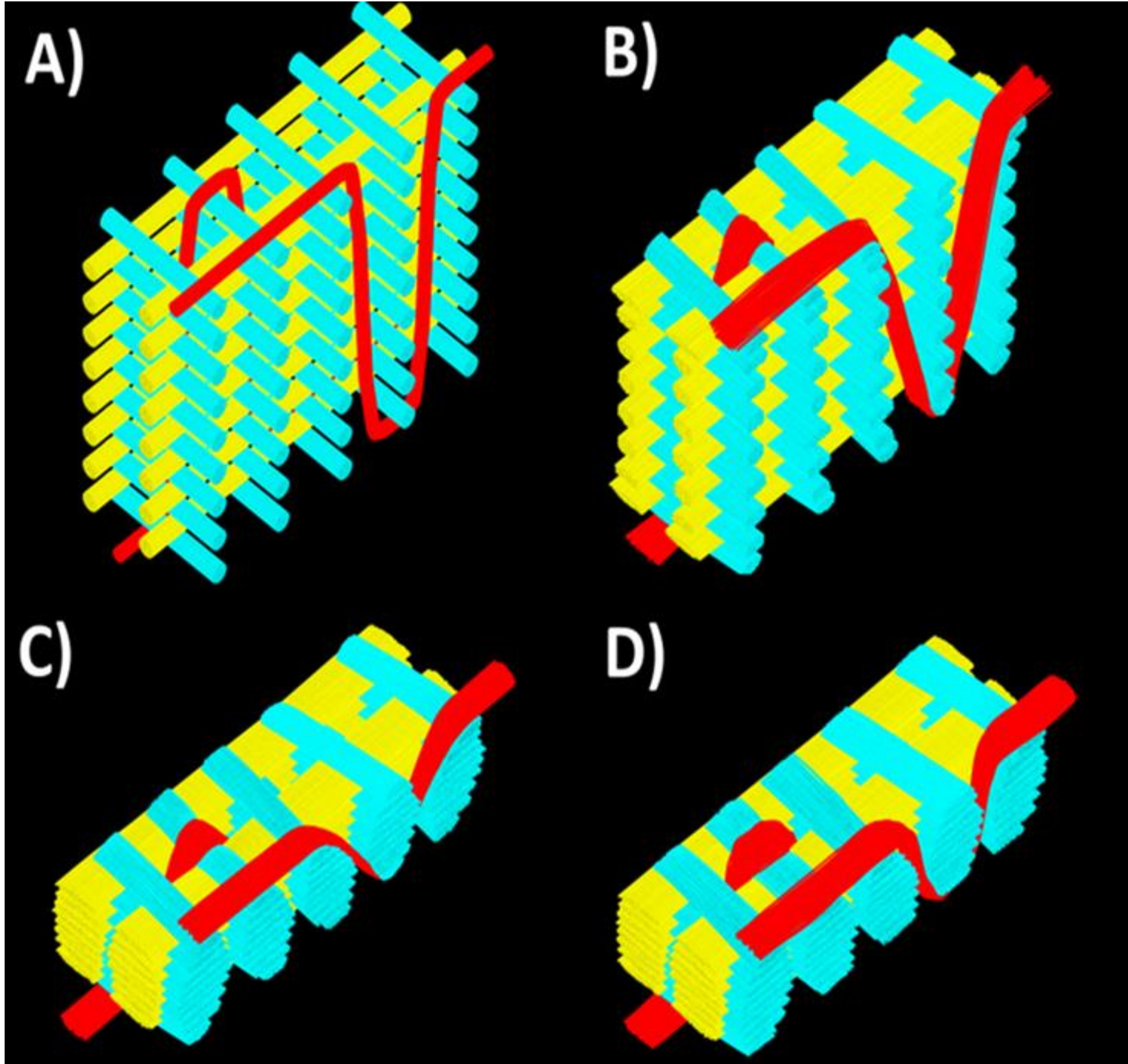
Non-Periodic Materials

3D/2D Woven and NCF

Non-periodic: woven Composites

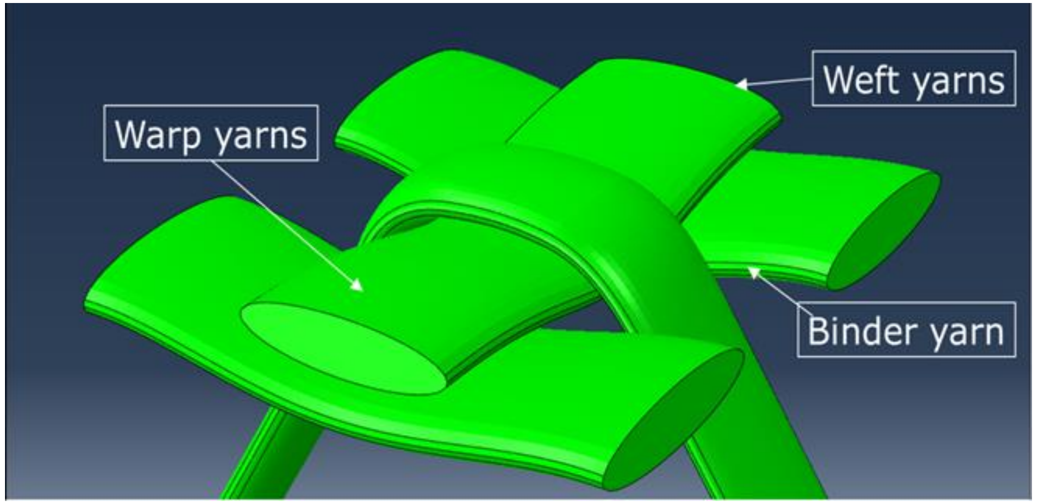
- 3D weaving is the generic term applied to woven fabric preforms with 3rd direction reinforcement
- Complex fabric structures are produced with many internal “architectures” possible.
- 3D woven fabrics can offer cost reduction due to near-net-shape preforms
- 3D Woven composites offer increased through-thickness strength, toughness, and impact performance.



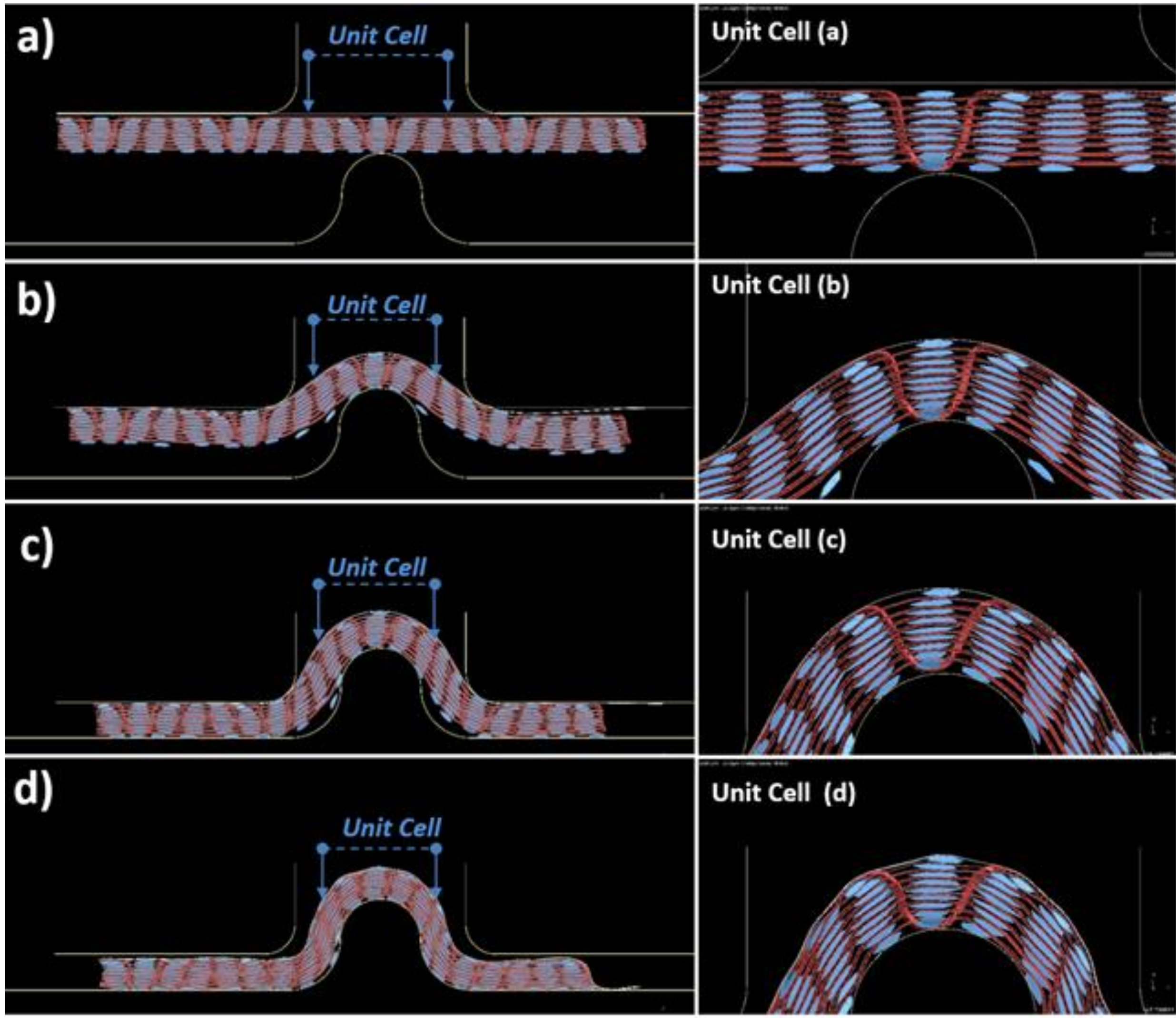
Digital Weaving Simulation of 3D Woven Composites

Non-Periodic Composites Structures

- 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.

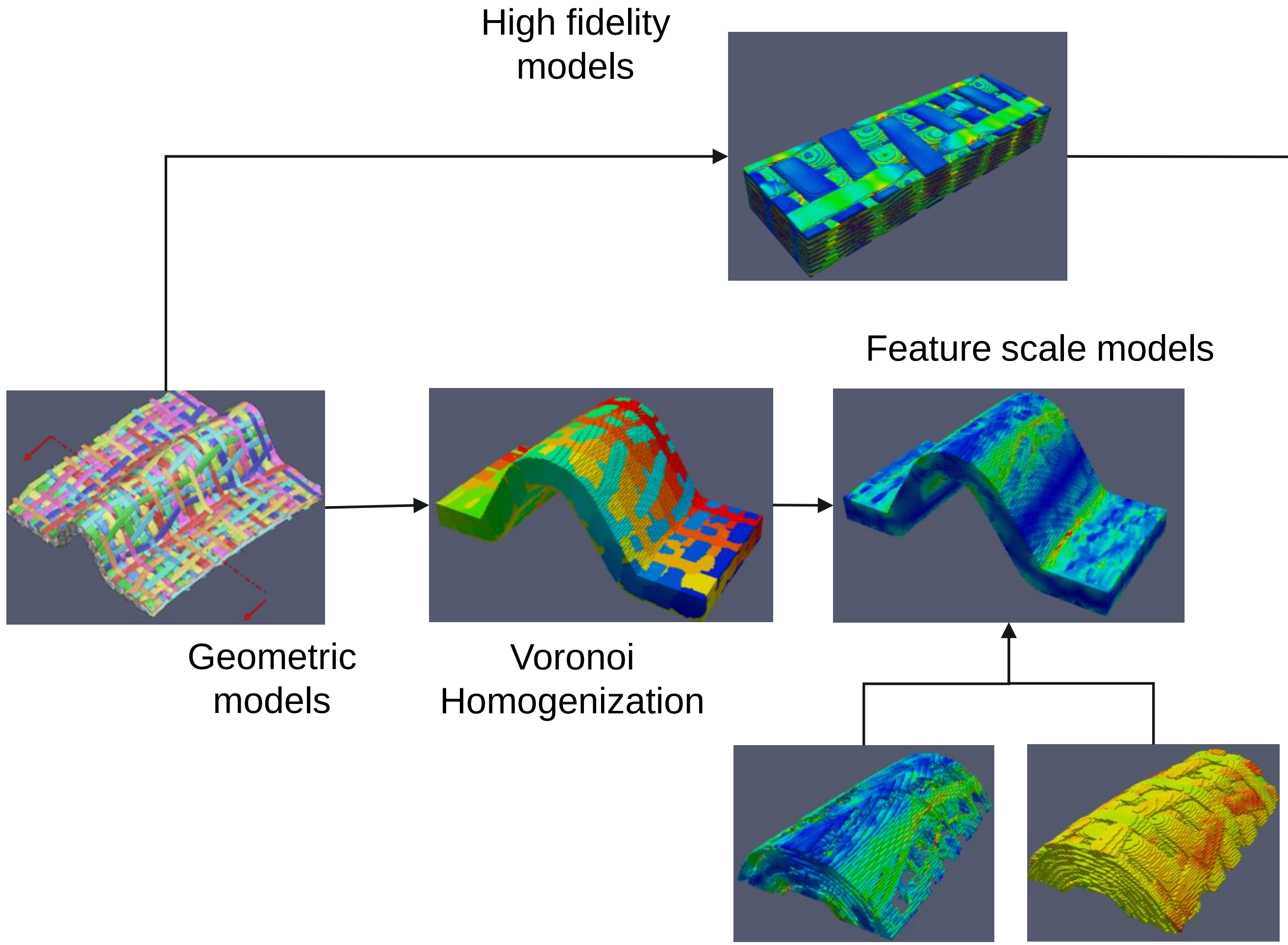


Binder Yarn Deformations

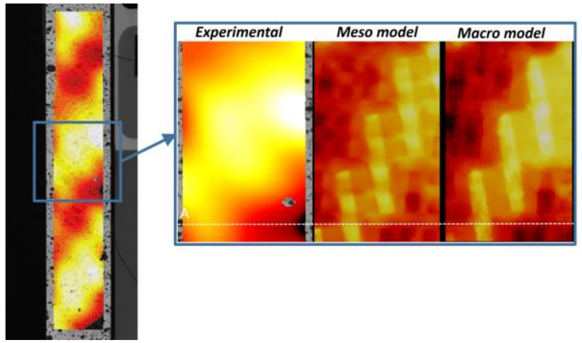


Internal architecture deformation during draping

Multi-scale Modelling of 3D Woven Composites – Stiffness



Experimental Verification



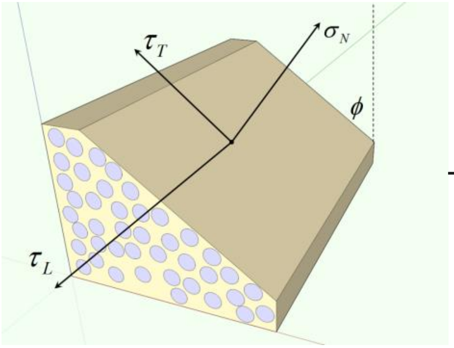
- The modelling framework is capable of :
- Automatic generation of high-fidelity model based on realistic geometries of 3D woven composites.
- Homogenization of high-fidelity models to generate and solve feature scale models.
- Iterative global/local analysis combining homogenized and high-fidelity representations.
- All functionalities have been verified against experimental results

El Said, Bassam, et al. "Multi-scale modelling of strongly heterogeneous 3D composite structures using spatial Voronoi tessellation." *Journal of the Mechanics and Physics of Solids* 88 (2016): 50-71.

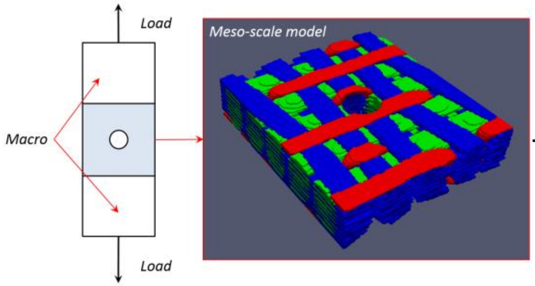
Multi-scale Modelling of 3D Woven Composites – Damage

- The multi-scale framework implements phenomenological damage models to understand damage initiation, damage progression, failure loads and morphology

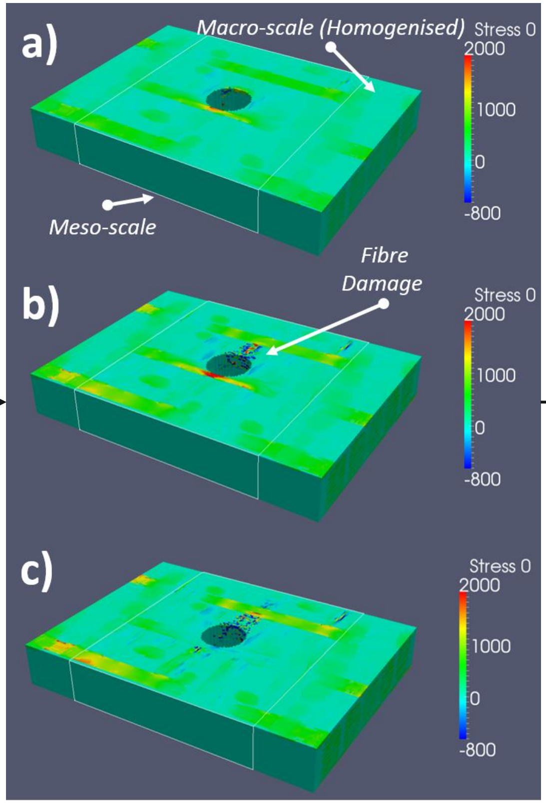
Phenomenological damage models



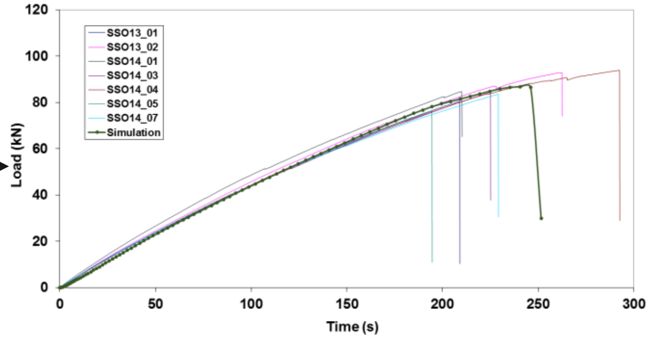
Virtual test setup



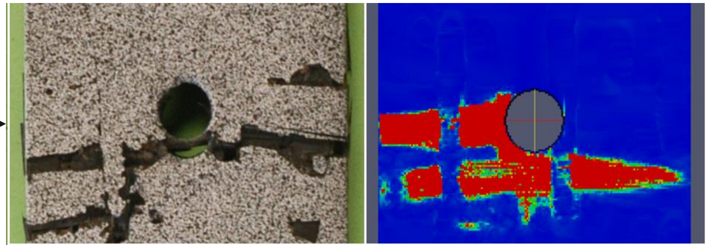
Damage initiation , progression and stress redistribution



Prediction and verification of failure loads



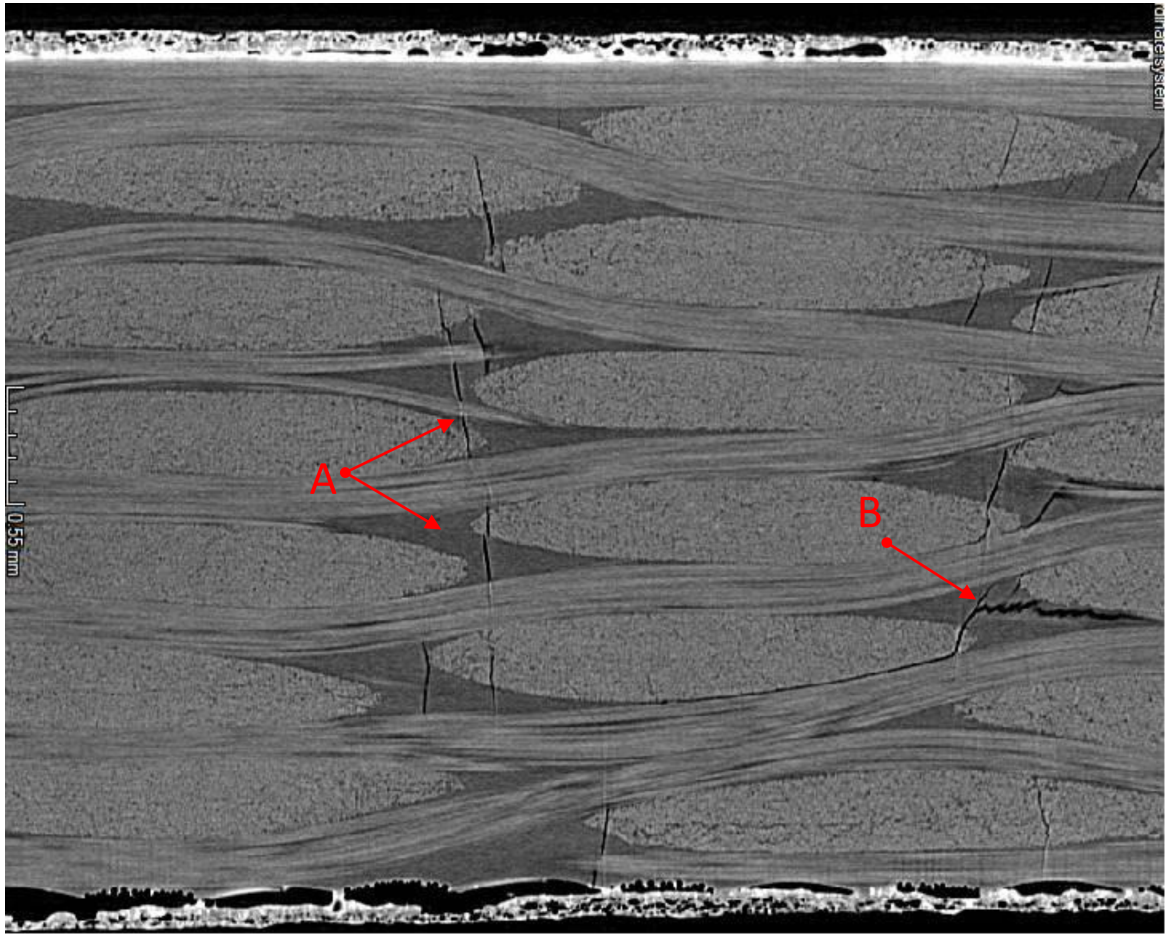
Prediction and verification of failure morphology



El Said, Bassam, et al. "An iterative multiscale modelling approach for nonlinear analysis of 3D composites." *International Journal of Solids and Structures* 132 (2018): 42-58.

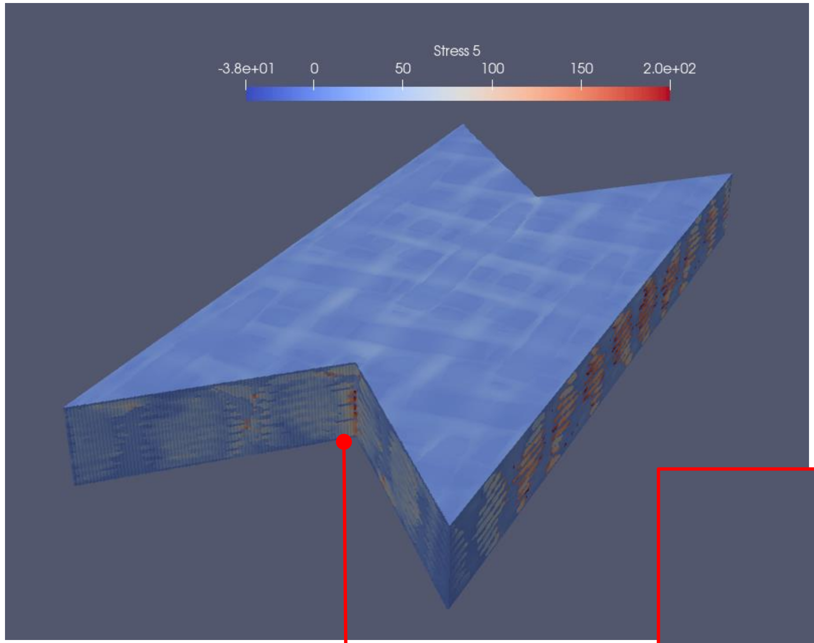
Experimental investigation of Unit Cell Interaction Effects

CT-Scan of interrupted tests at 80% UTS for a layer to layer 3D woven carbon/ epoxy composite.

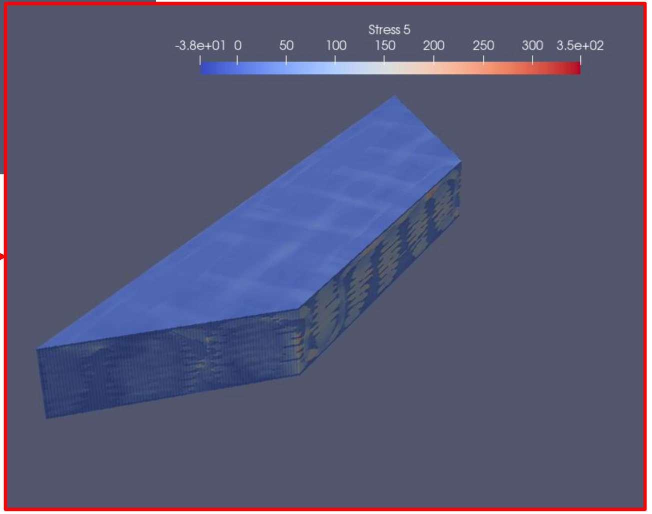


A: Matrix cracks
B: Debonding damage

Modelling 3D Woven Composites with Complex Geomtries

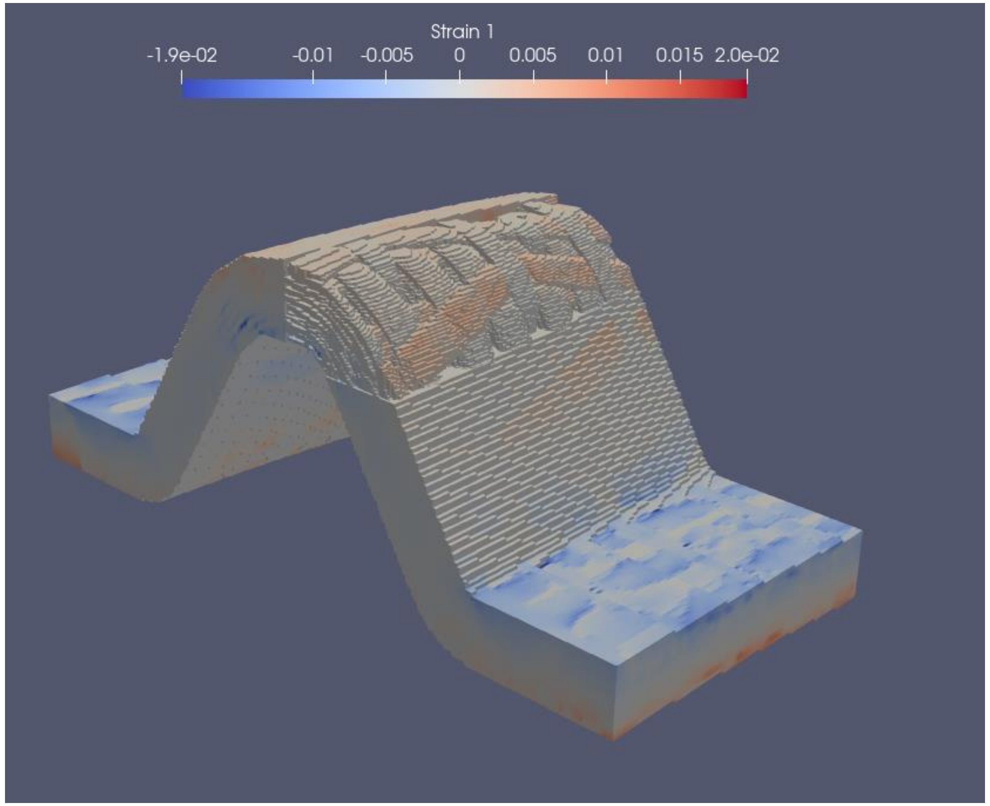


Shear stresses on a v-notch specimen



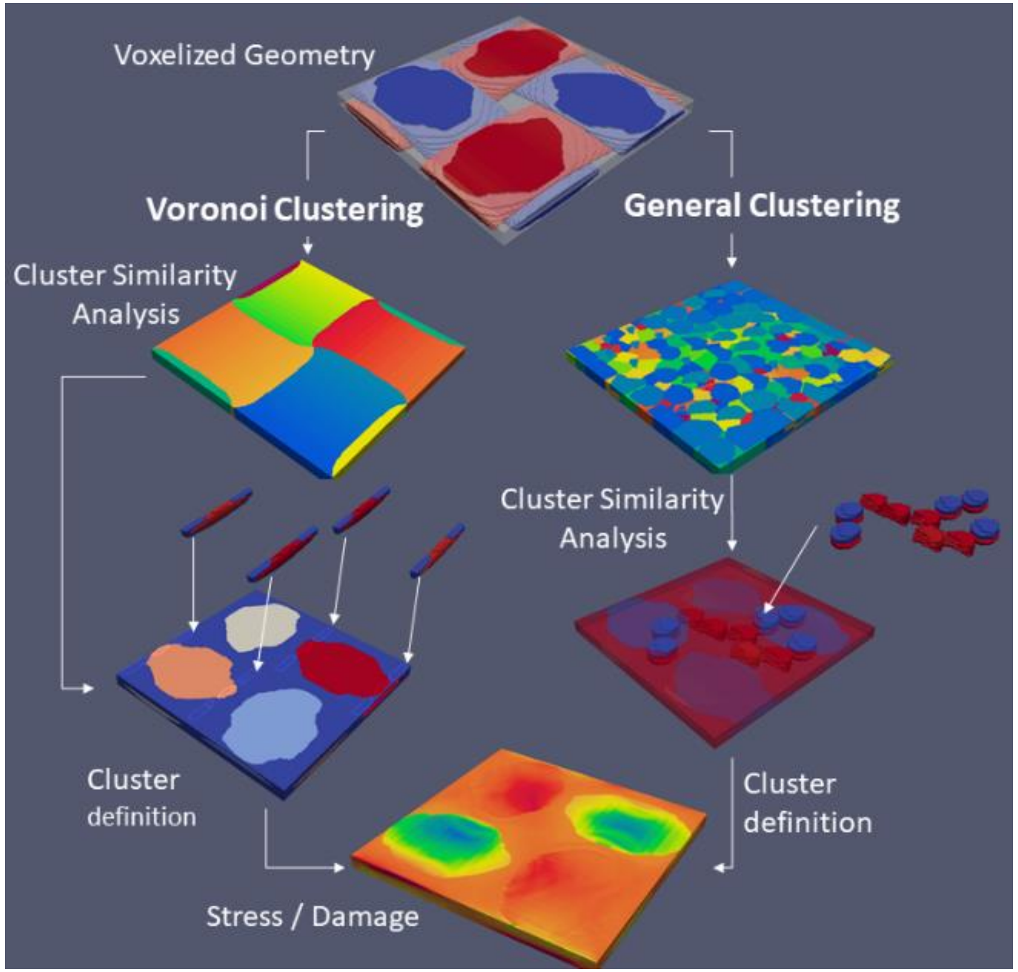
A cut-view through the critical section

Axial Stresses on a humpback bridge specimen

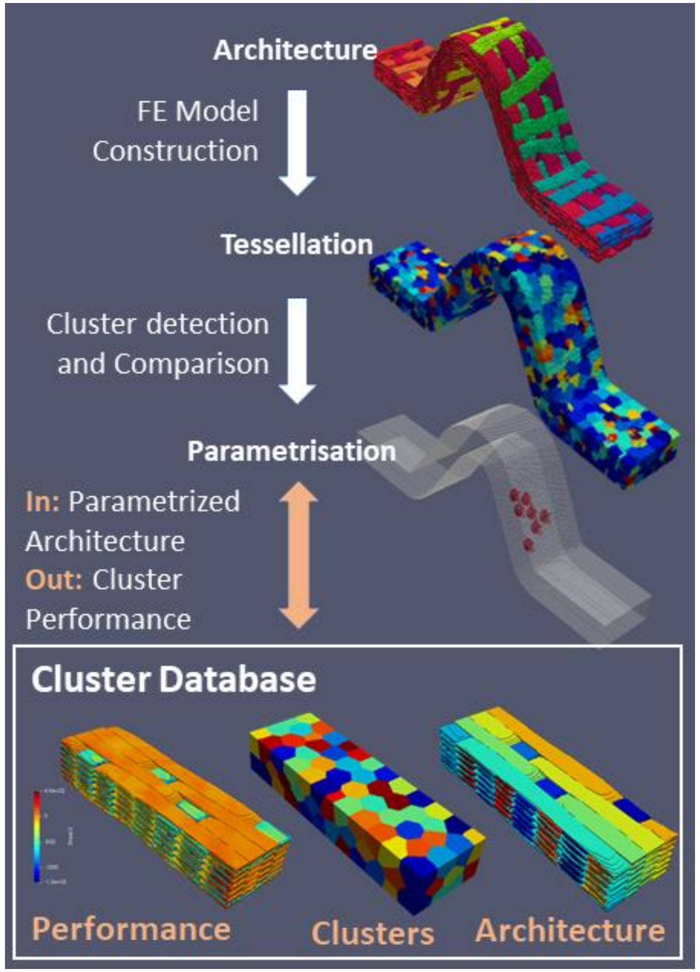


Hybrid Statistical / Deterministic Multi-scale Modelling

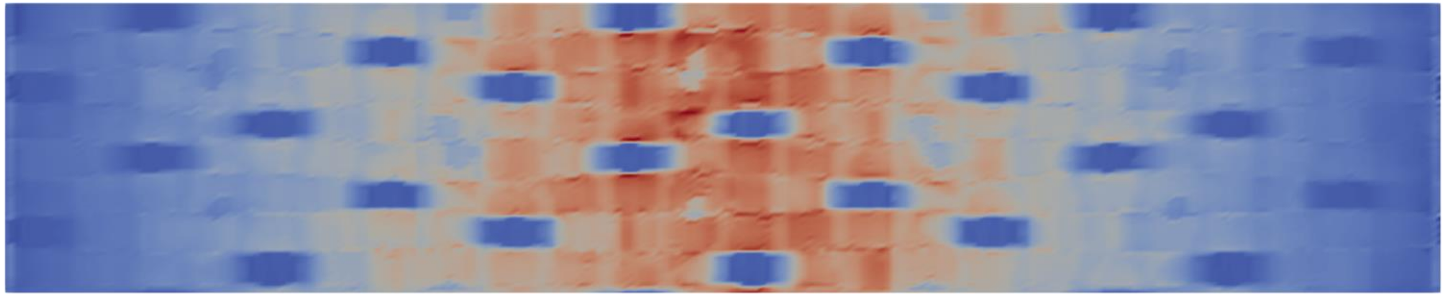
Populating Material Cluster Database



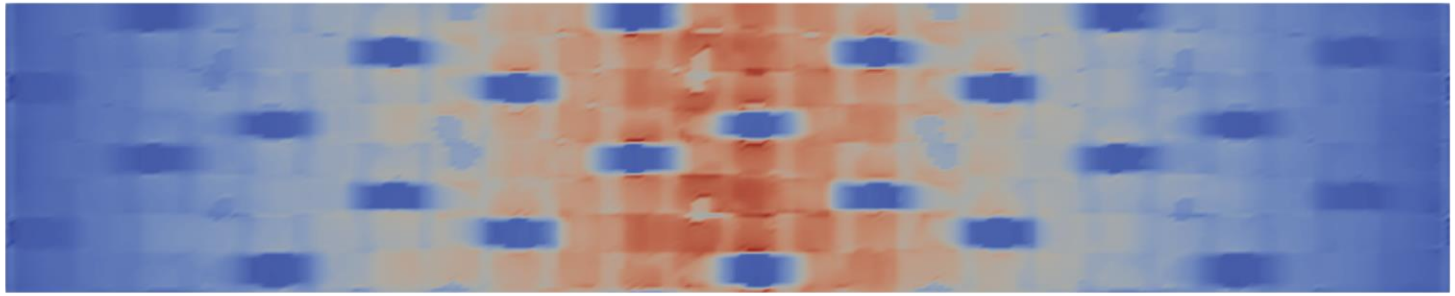
Structural Scale Simulation



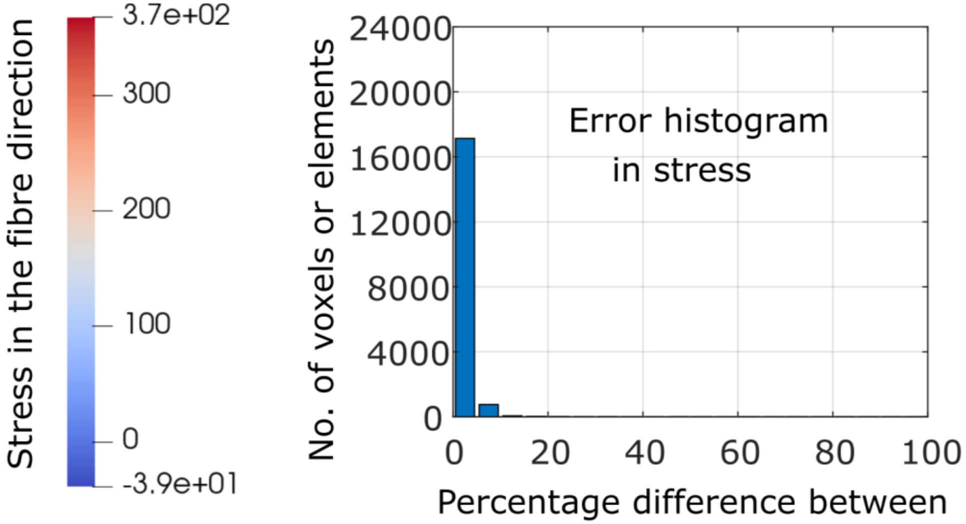
Material Clustering for Non-periodic Composites



Macro-scale modelling using data clustering and image registration



Meso-scale modelling with yarn and matrix definition



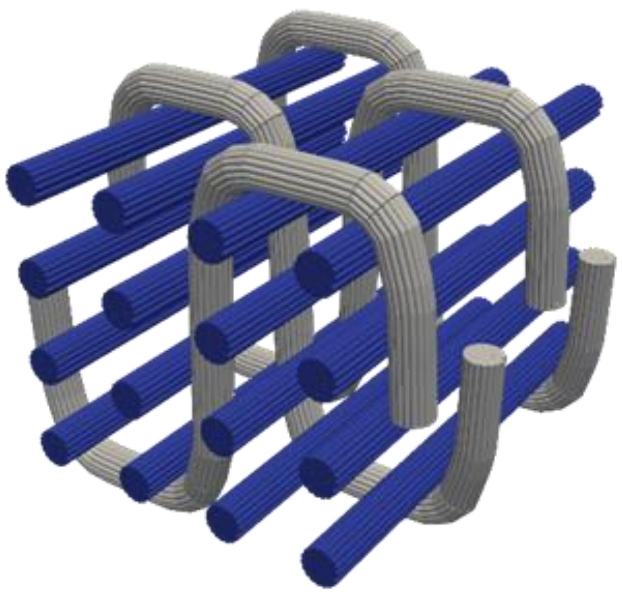
J Selvaraj and B El Said, Multiscale modelling of strongly heterogeneous materials using geometry informed clustering
International Journal of Solids and Structures, 2023

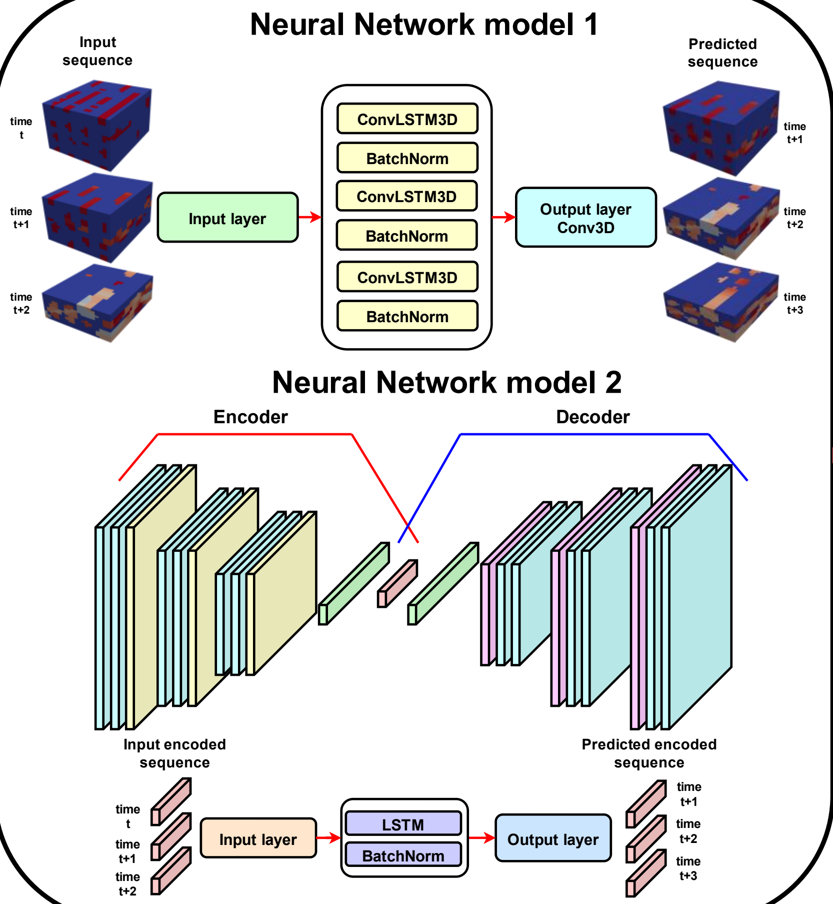
3D Woven Manufacturing Simulation

- A Deep Learning framework of instantaneous generation of woven materials models.

Input

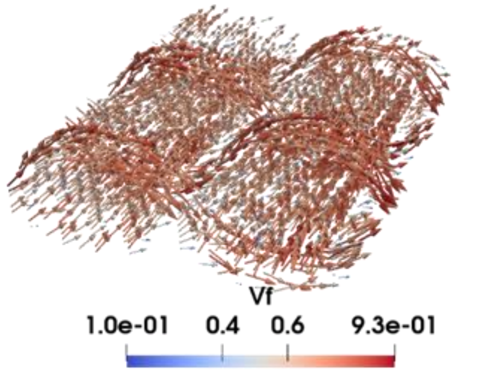
Initial 3D weave map



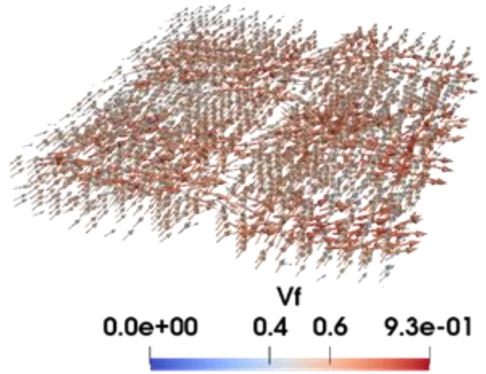


Predicted 3D compacted architecture

Prediction 1



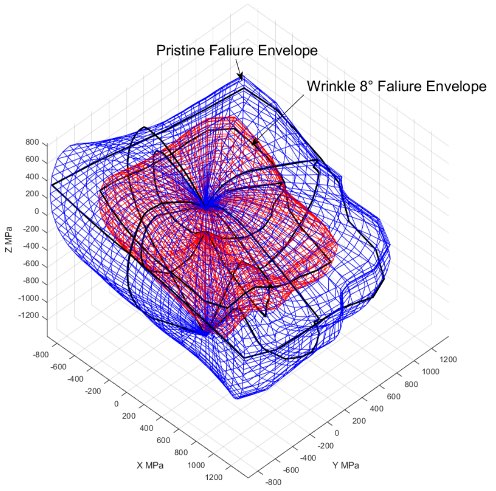
Prediction 2

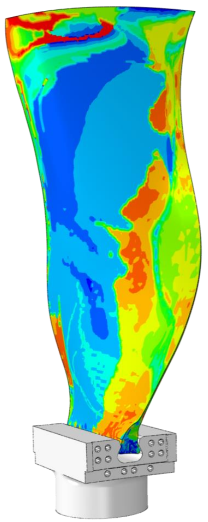


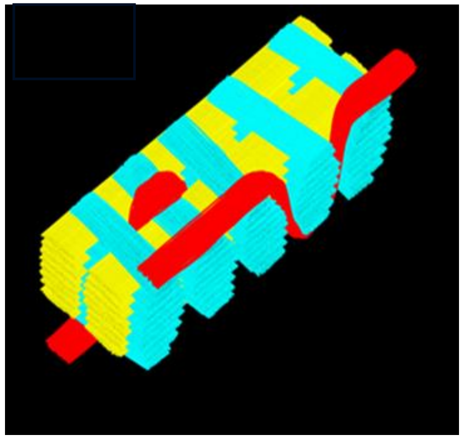
https://dx.doi.org/10.2139/ssrn.4625867

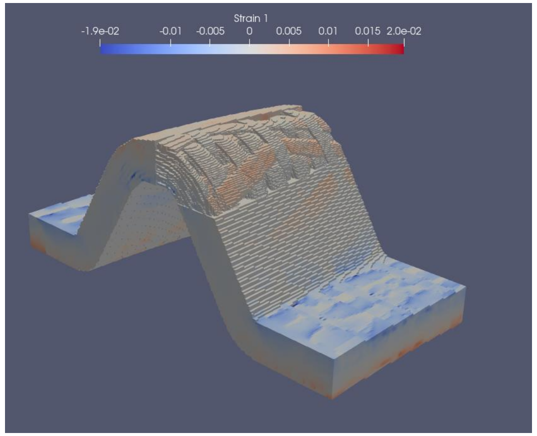
Summary

- An integrated set of multi-scale data-driven approaches for composites simulation.
- Link across the length scales and applicable to industrial problems.
- Covers a wide variety of materials: Laminated, Woven , NCF.
- Strong link to manufacturing simulation and experimental characterisation.









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Questions ?

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standart
for Durability Modelling of Composites

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