Accelerating multiscale simulations with surrogate models based on recurrent neural networks

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This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101007022.

Overview

Simulation of Composite Materials

Coupling Scales

RNN

Learning Plastic Behaviour

Learning Damaged Behaviour

Summary and Future Work

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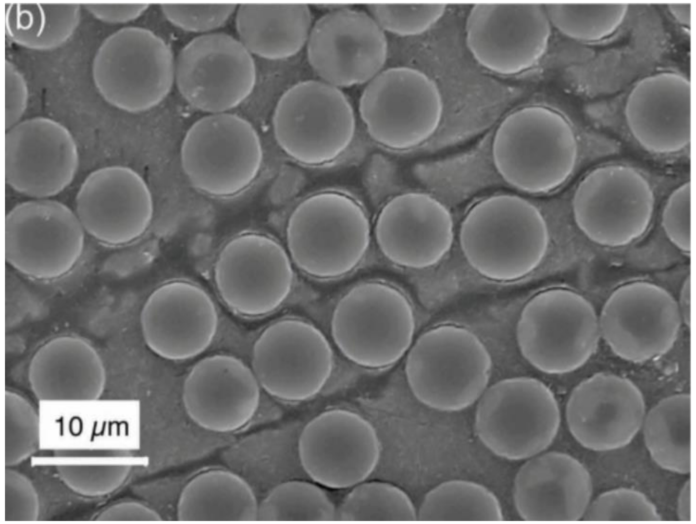
Simulation of Composite Materials

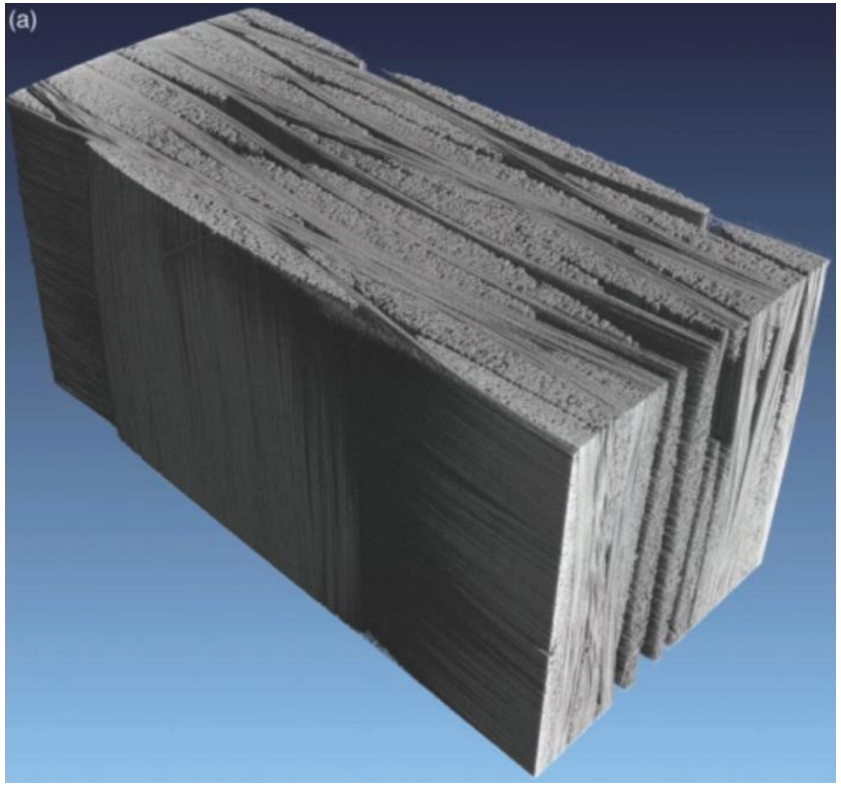
Microscale

$\sim 10^{-6}\ m$



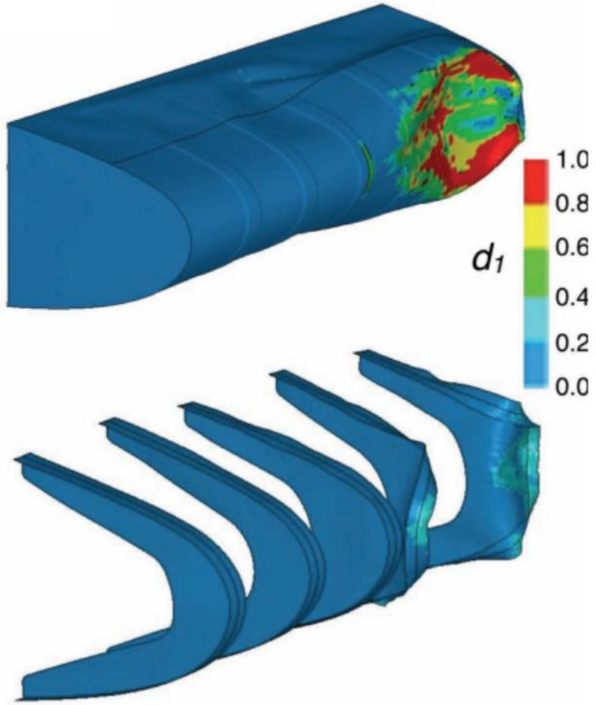
Mesoscale

$\sim 10^{-2}\ m$



Macroscale

$\sim 10^{1} - 10^{2}\ m$



LLorca, J., González, C., Molina-Aldareguía, J.M., Segurado, J., Seltzer, R., Sket, F., Rodríguez, M., Sádaba, S., Muñoz, R. and Canal, L.P. (2011), Multiscale Modeling of Composite Materials: a Roadmap Towards Virtual Testing. Adv. Mater., 23: 5130-5147.

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Simulation of Composite Materials

Microscale
$\sim 10^{-6}\ m$

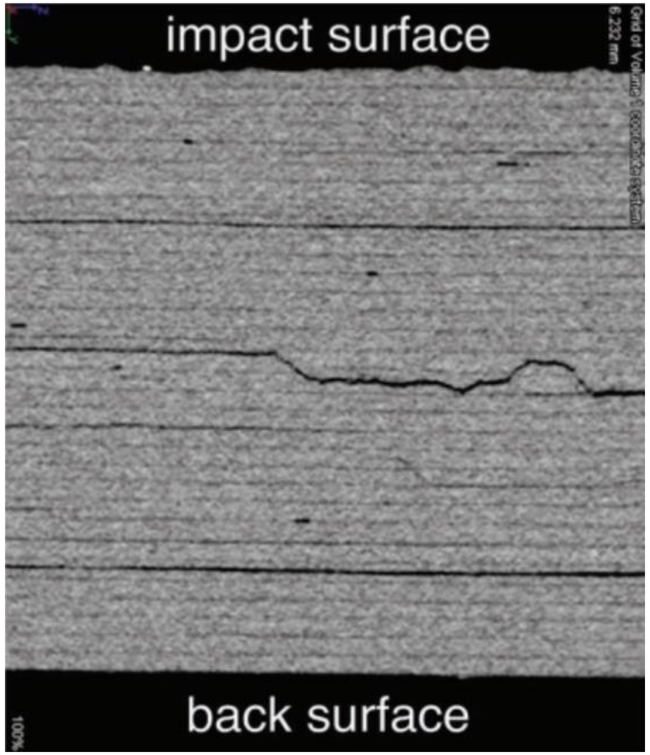
Matrix Cracking
Fibre Breakage
Fibre Kinking
Interface Decohesion

Mesoscale
$\sim 10^{-2}\ m$

Delamination

Macroscale
$\sim 10^{1} - 10^{2}\ m$

Failure



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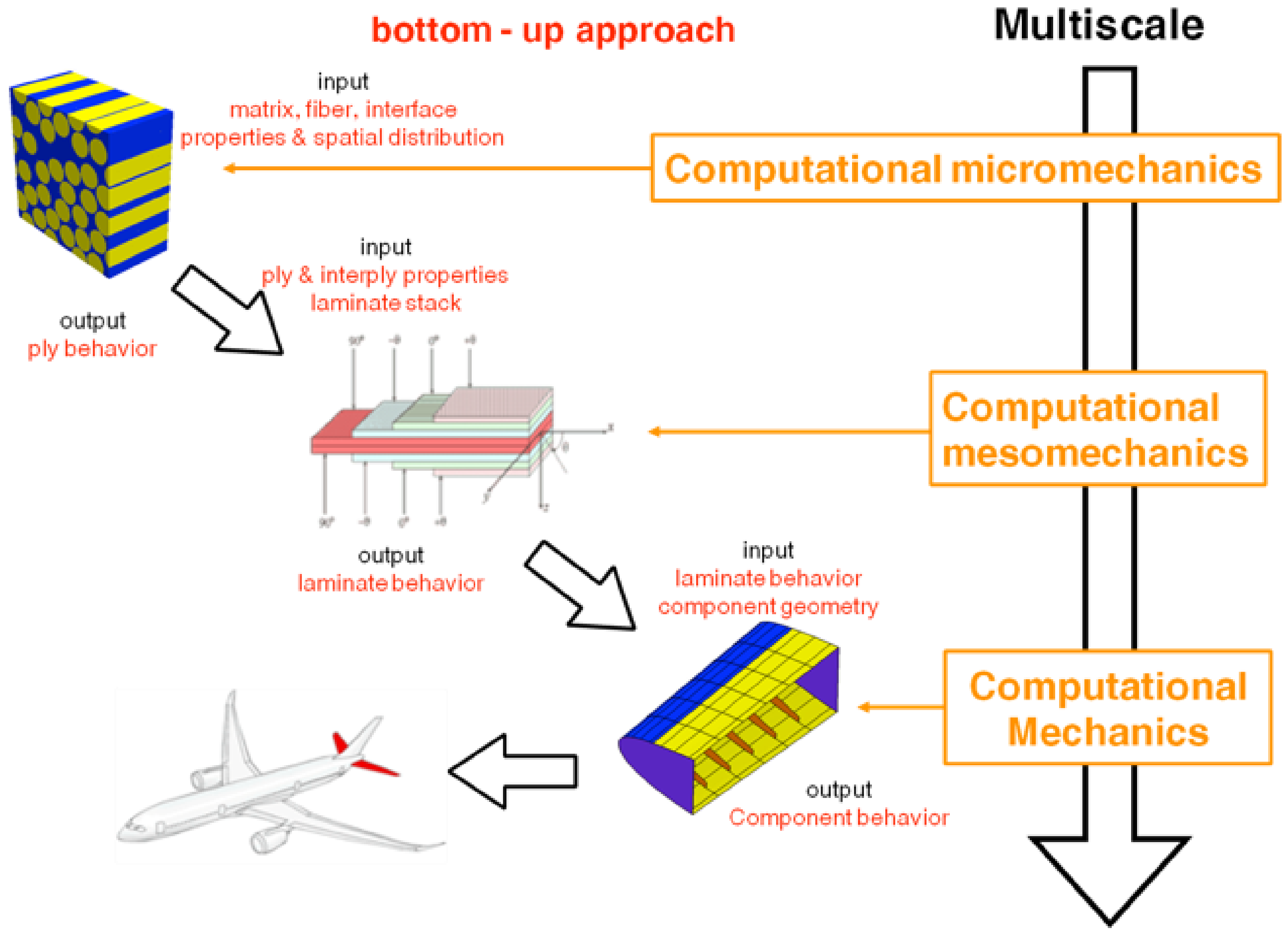
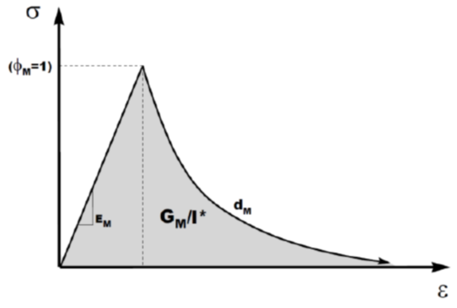
Simulation of Composite Materials

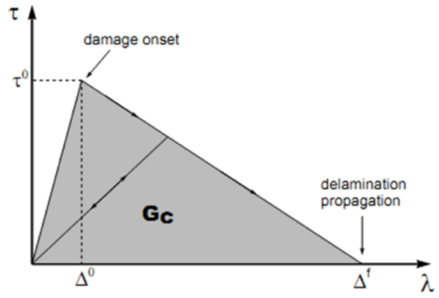
MULTISCALE SIMULATION STRATEGY



Constituve models



Ply Continuum Damage Model



Ply Interface

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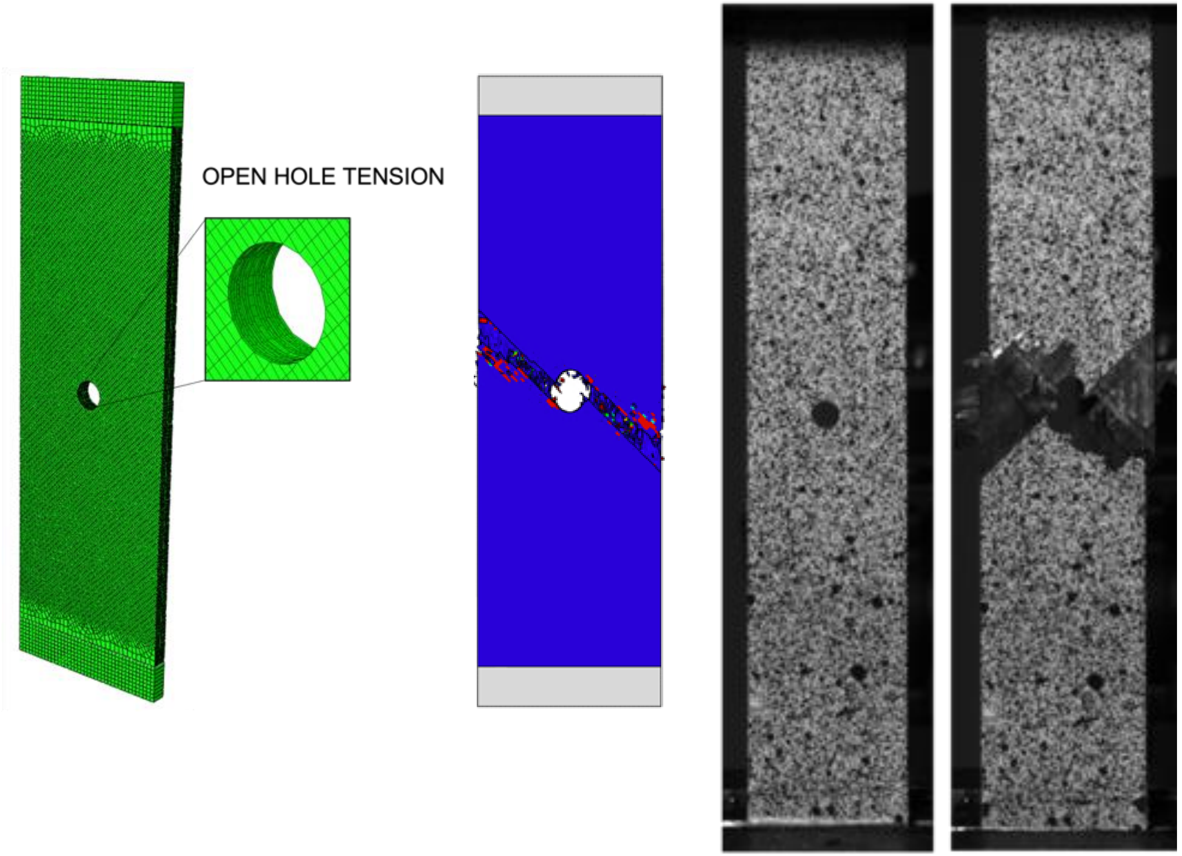
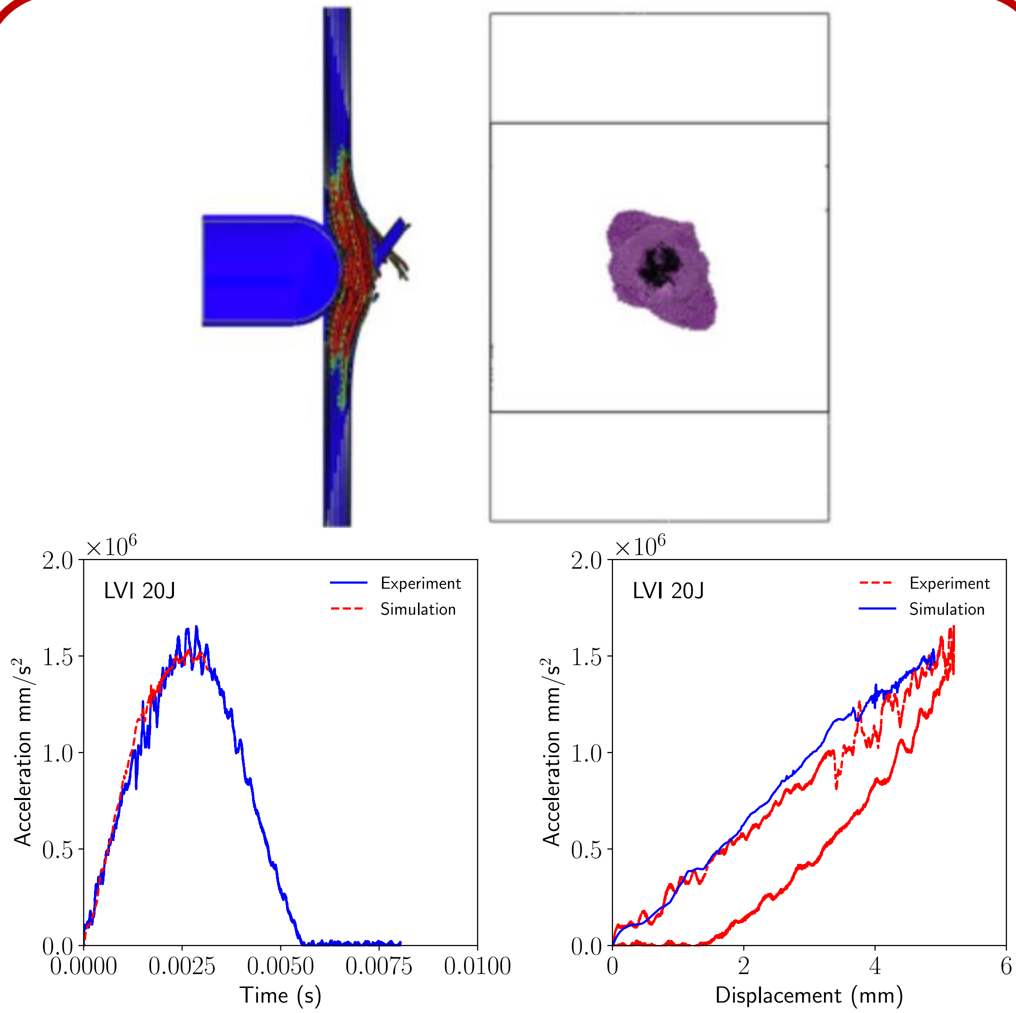
Simulation of Composite Materials



Quasi-static



Dynamic

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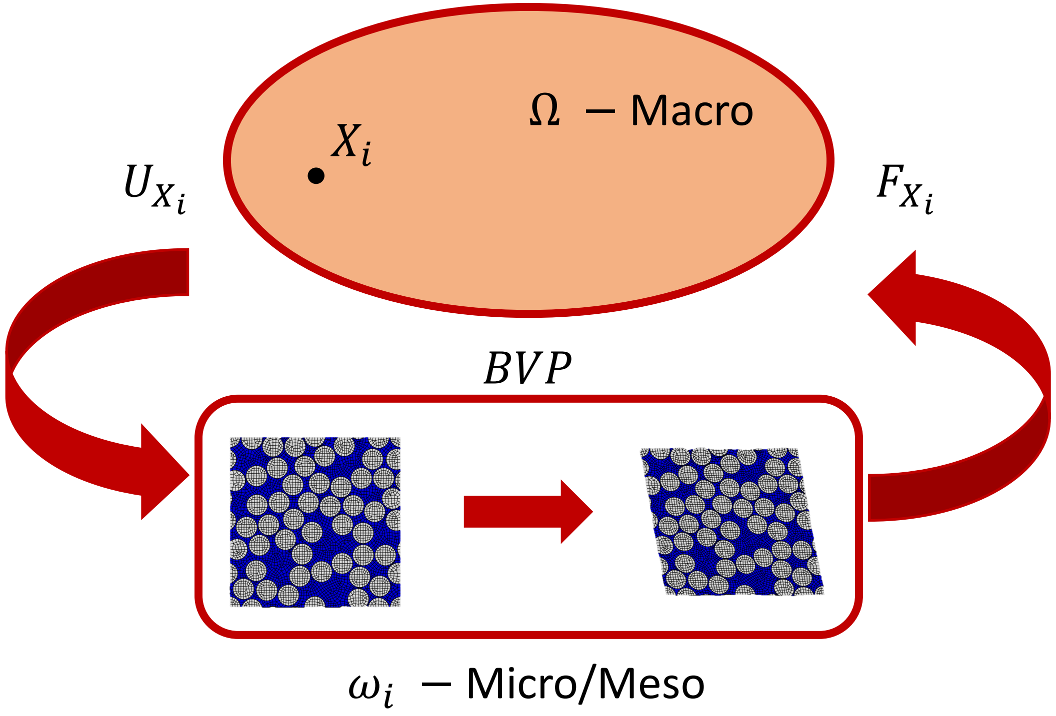
A. H. Baluch, O. Falcó, J. L. Jiménez, B. H.A.H. Tijs, C. S. Lopes,
An efficient numerical approach to the prediction of laminate tolerance to Barely Visible Impact Damage,
Composite Structures, Volume 225, 2019

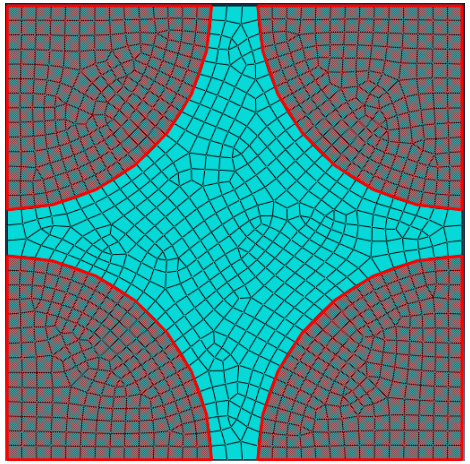
Coupling Scales. Surrogate model based on NNs

FE^2- Concurrent



Computationally Expensive

Representative Volume Elements are simple



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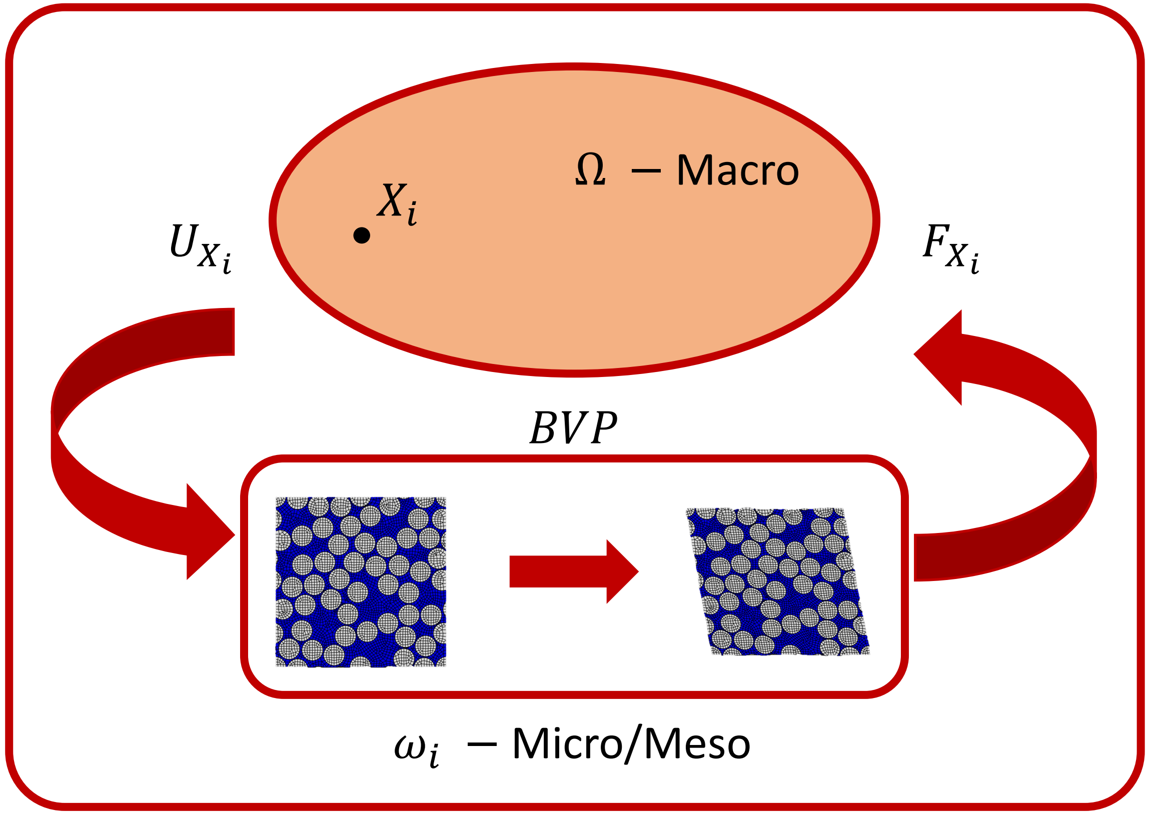
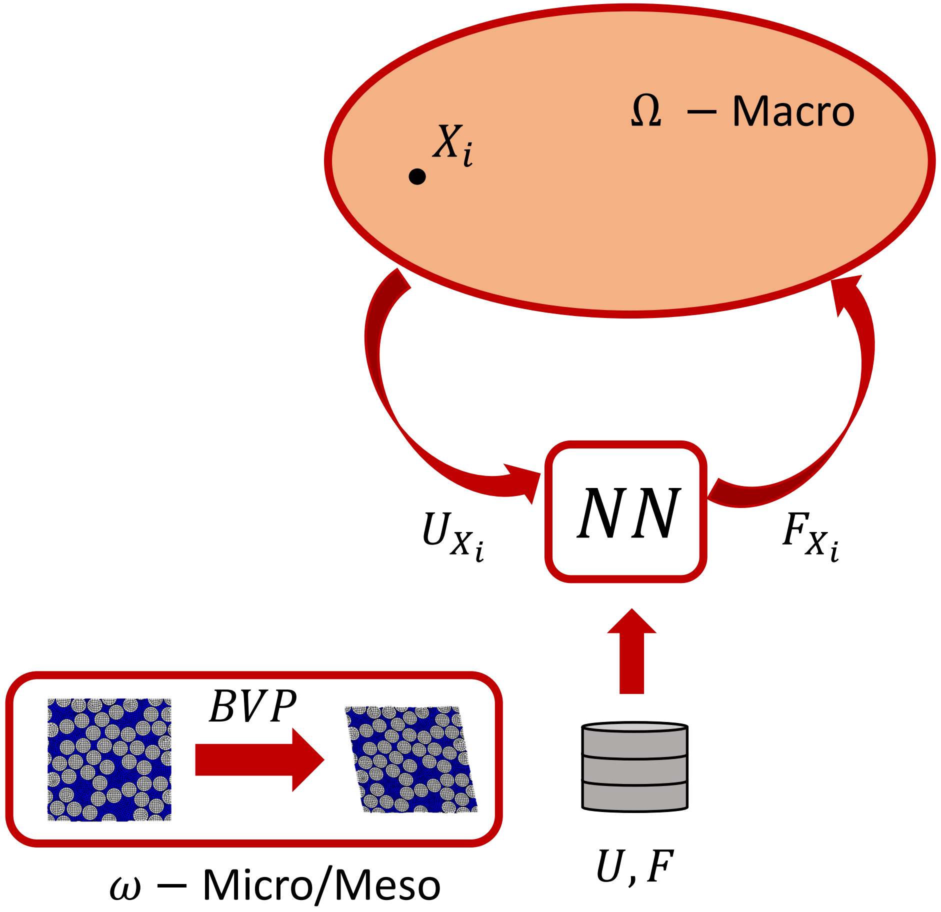
Coupling Scales. Surrogate model based on NNs

FE^2- Concurrent





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Recurrent Neural Networks

Elastic

$$\boldsymbol{\sigma}(t_i) = f\ (\boldsymbol{\varepsilon}(t_i))$$

Damaged Behaviour

$$\boldsymbol{\sigma}(t_i) = f\ (\boldsymbol{\varepsilon}(t_0, t_1, \ldots, t_{i-1}, t_i))$$

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Recurrent Neural Networks

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Damaged Behaviour

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hidden state:

$$\boxed{\mathbf{h}_t \in R^{h_{units} \times 1}}$$

$$W_{xh} \in R^{h_{units} \times n_x}$$

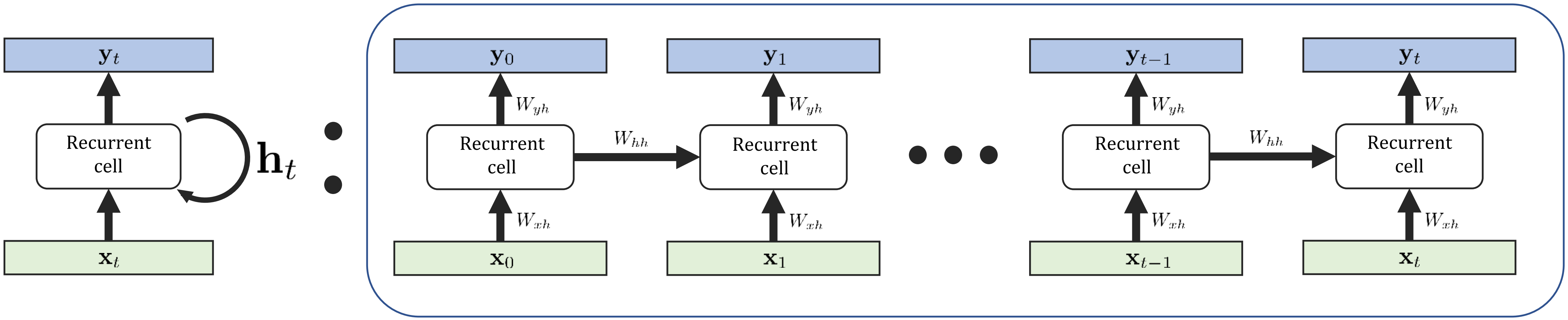
$$W_{hh} \in R^{h_{units} \times h_{units}}$$

$$W_{yh} \in R^{n_y \times h_{units}}$$

$$\mathbf{h}_t = tanh\left(W_{xh}\mathbf{x}_t + W_{hh}\mathbf{h}_{t-1}\right)$$

$$\mathbf{y}_t = W_{hy}\mathbf{h}_t$$

Initialization : $\mathbf{h}_0 = \bar{0}$



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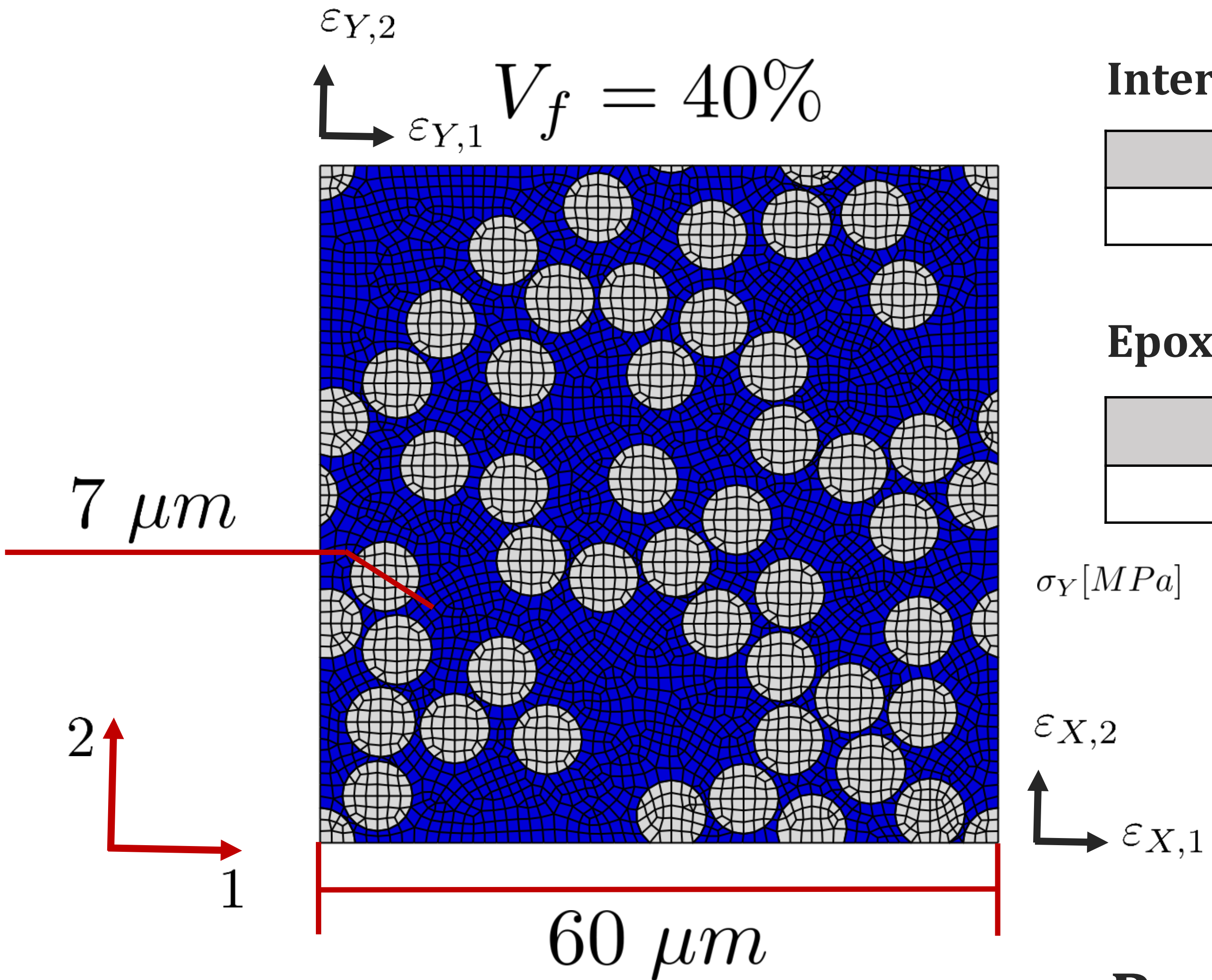
FE Model. Representative Volume Element



Intermediate Modulus Carbon Fibres

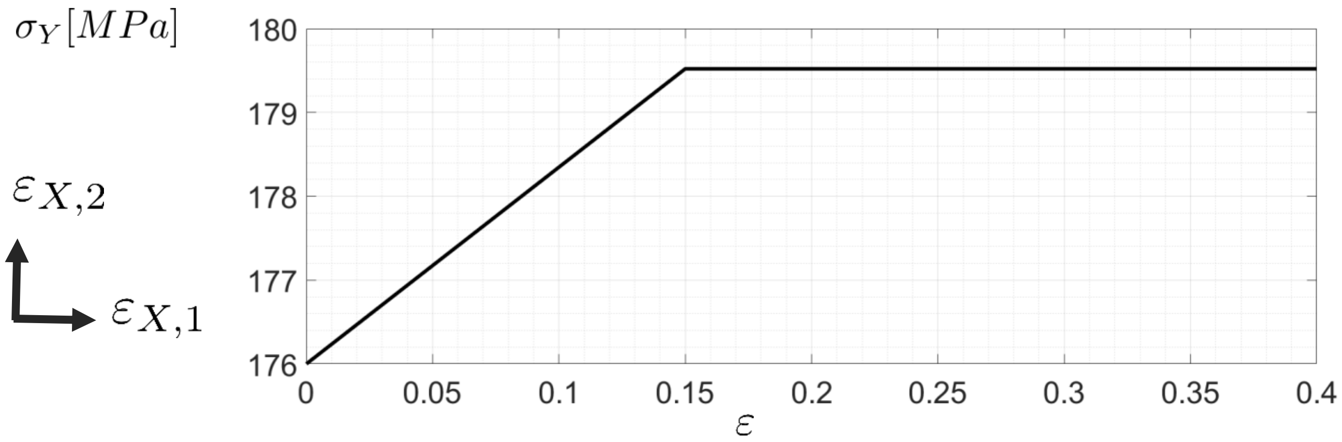
$E_T[GPa]$	ν_T
13.00	0.40

Transversally Isotropic

Epoxy Resin

$E[GPa]$	ν
5.07	0.35

Isotropic



Periodic Boundary Conditions

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Dataset Generation. Generation of strain history paths

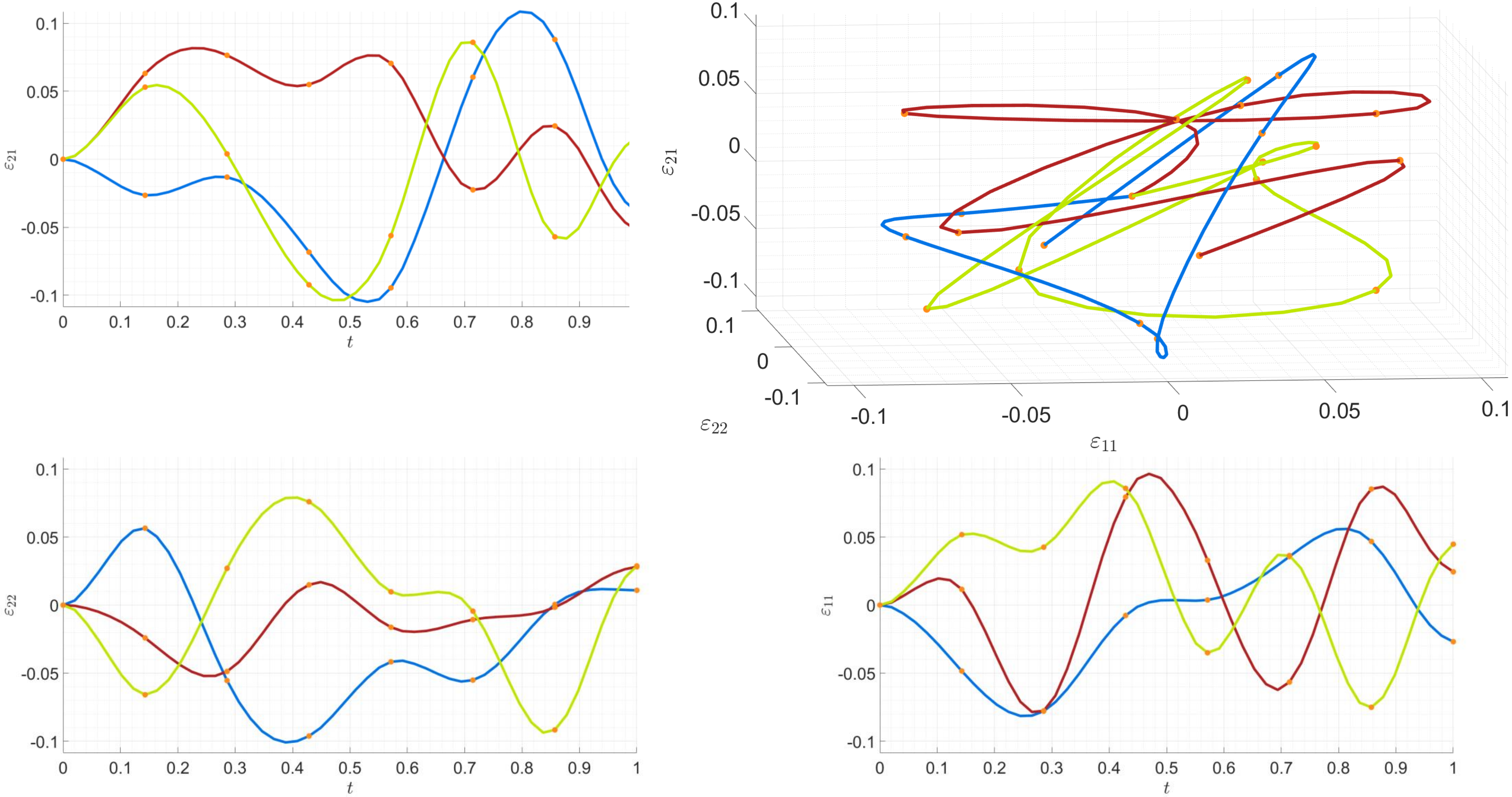
Abaqus
(Implicit Solver)

$t \in [0,1]$

$\varepsilon \in [-0.1, 0.1]$

1000 paths

N = 8



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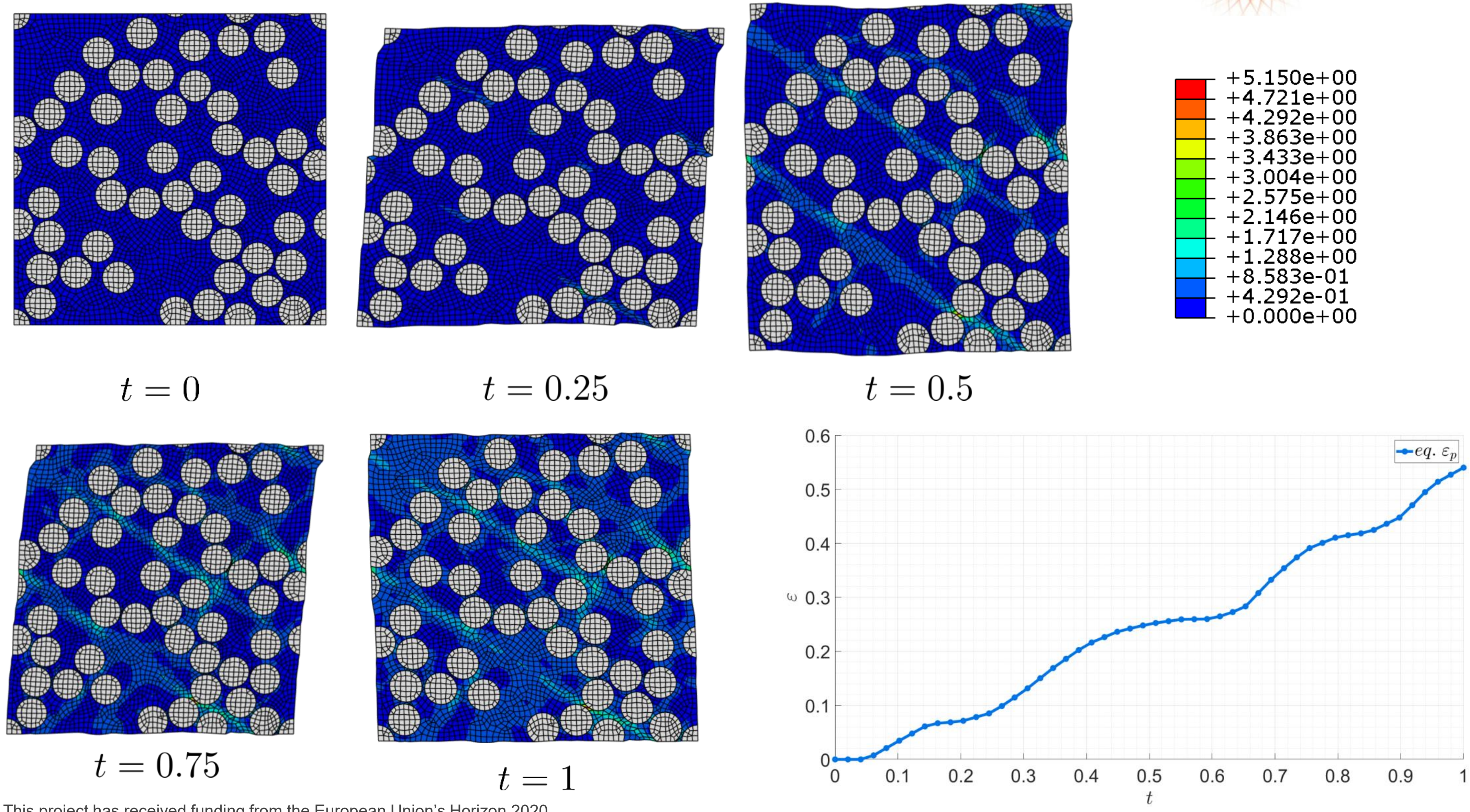
Dataset Generation. Accumulated Plastic Strain



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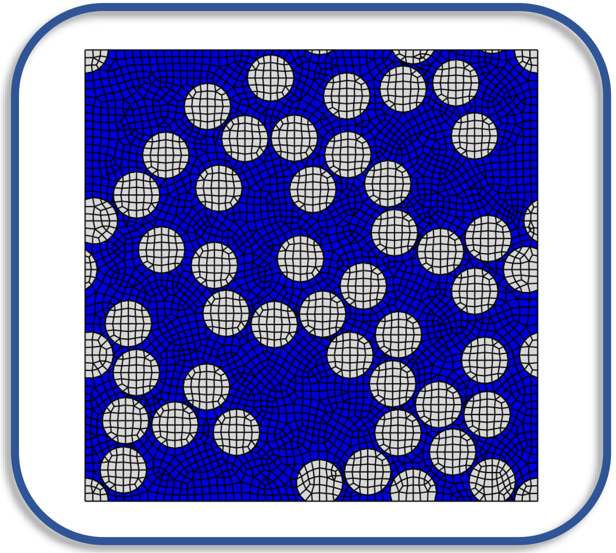
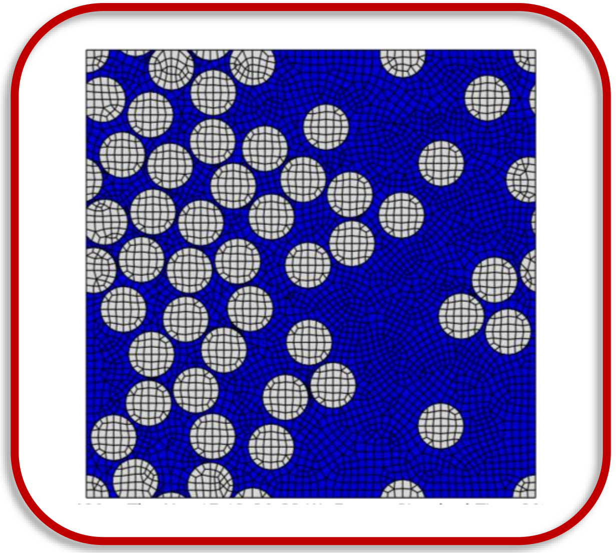
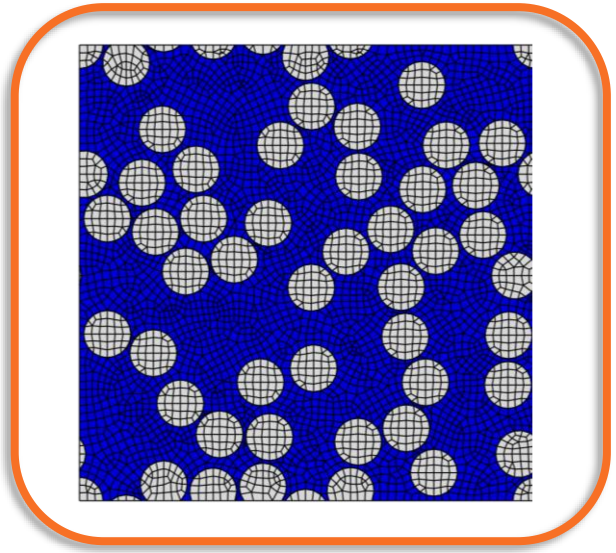
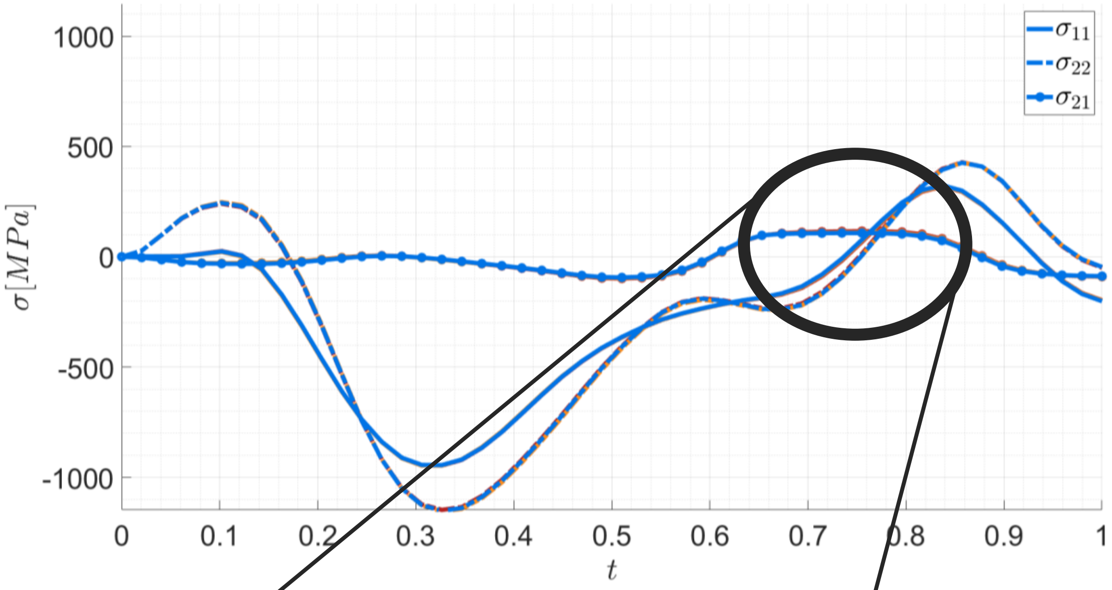
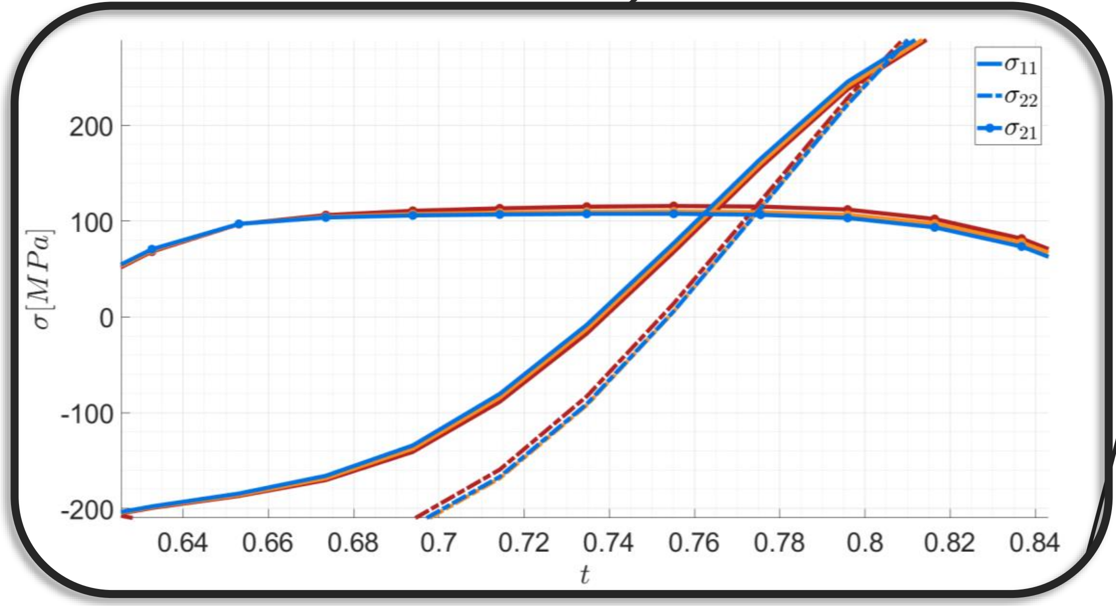
Dataset Generation. Effect of Fibre's Distribution











$$\approx 0.66\%$$

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Neural Network. Architecture

Recurrent Neural Network Arquitecture

- 1 Recurrent Cell : 100 hidden units
- Fully Connected Layer

$\sim$12k parameters

Mean Squared Error

$$m.s.e = \frac{1}{N}\sum_{i=1,N}\left(\mathbf{y}_{t,i} - \bar{\mathbf{y}}_{t,i}\right)$$

Mean Absolute Error

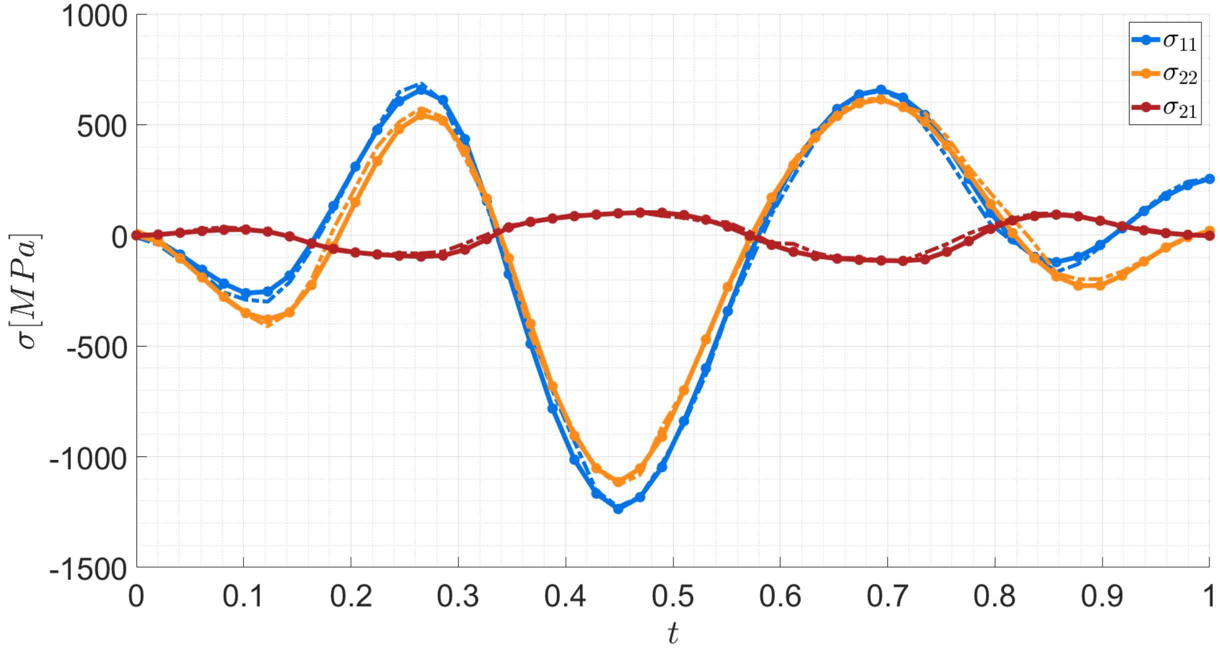
$$m.a.e. = \frac{1}{N}\sum_{i=1,N}\left|\mathbf{y}_{t,i} - \bar{\mathbf{y}}_{t,i}\right|)$$

Train Set

m. s. e.	m. a. e.
0.9419	13.18

Test Set

m. s. e.	m. a. e.
1.005	13.24



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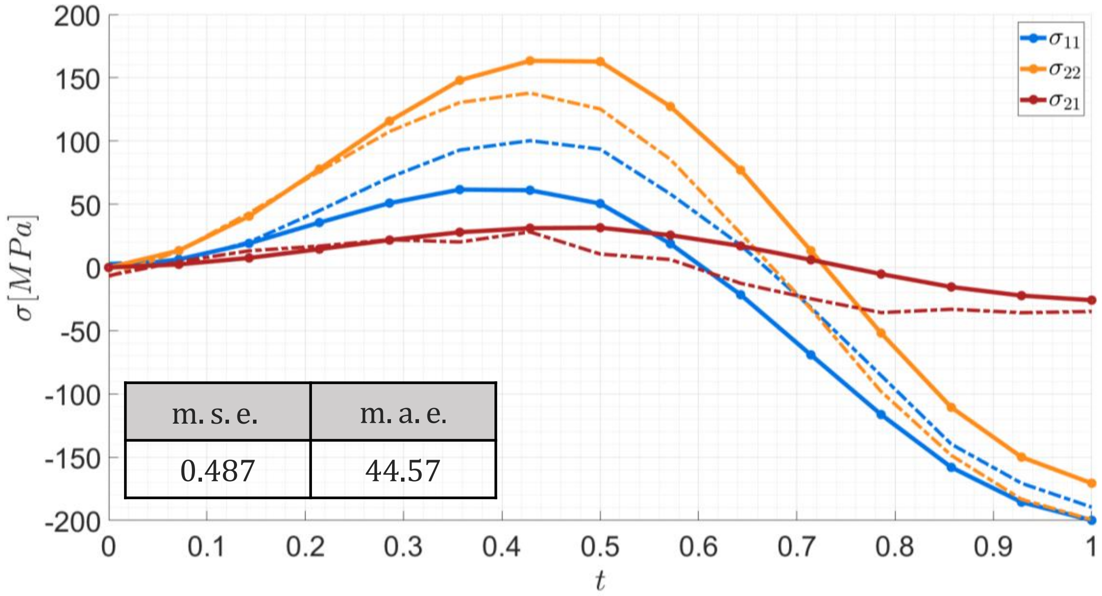
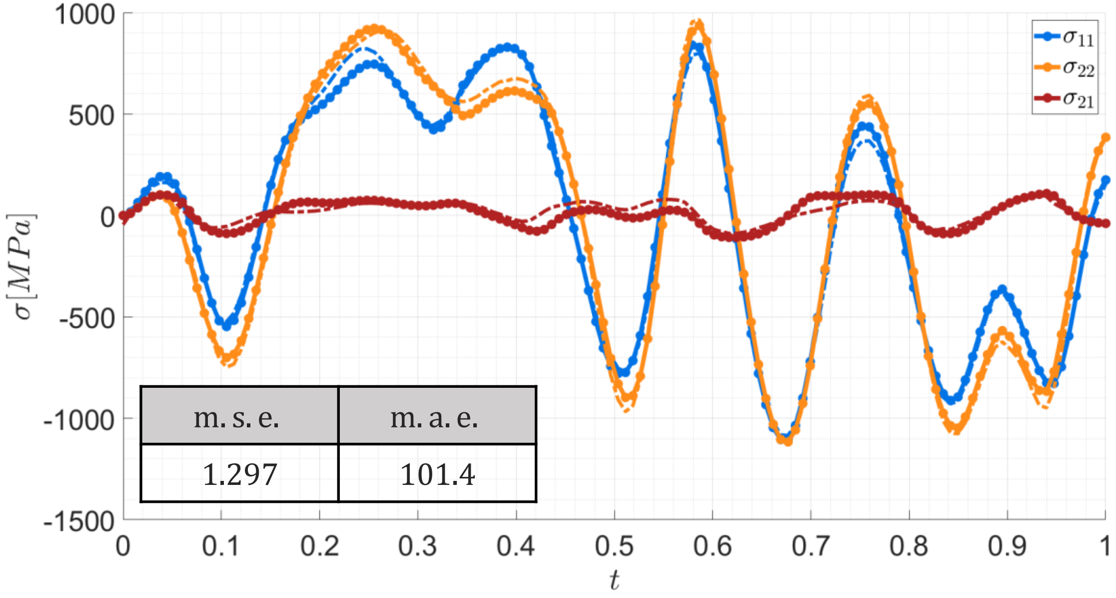
Results. Model Validation

Pure Elastic Behaviour



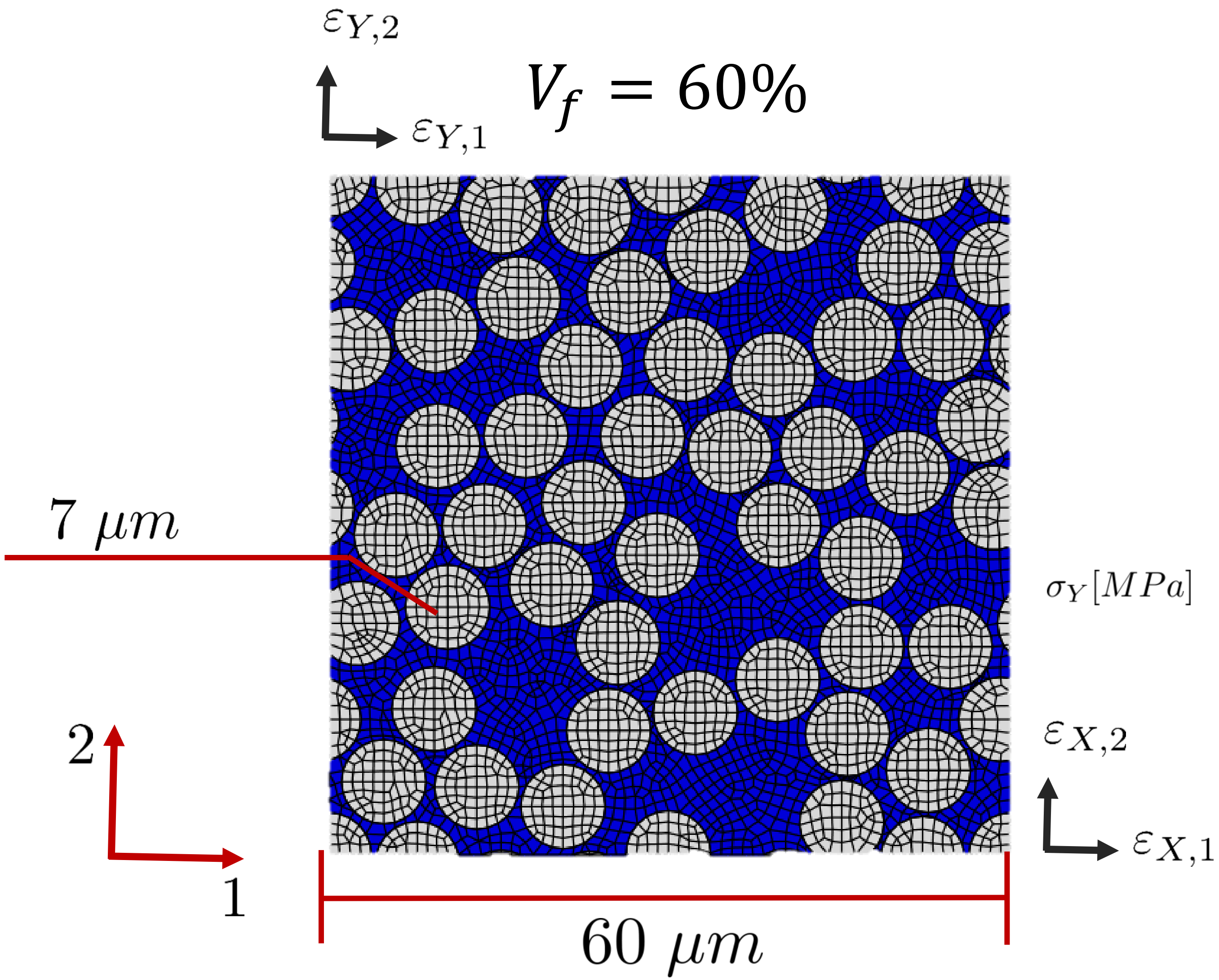
m. s. e.	m. a. e.
0.487	44.57

Longer History



m. s. e.	m. a. e.
1.297	101.4

FE Model. Cohesive Properties & Matrix Damage



Matrix-Fibre Interface:

Cohesive Elements

Matrix:

Plasticity

Damage

Periodic Boundary Conditions

Strain Paths:

$t \in [0,1]$

$\varepsilon \in [-0.012, 0.012]$

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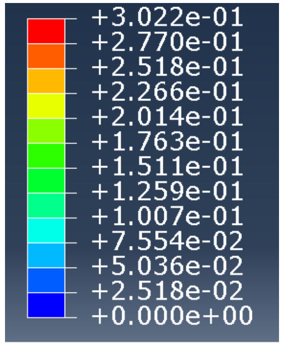
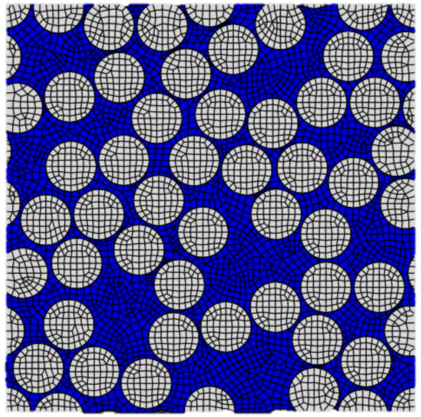
Damage Evolution

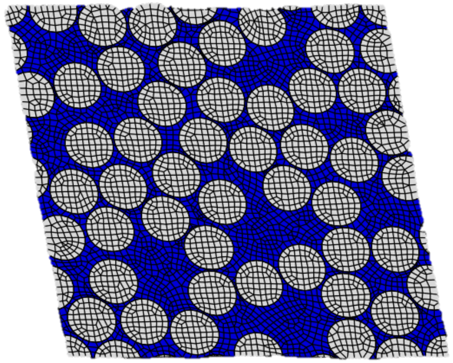
Surro

Tensile Damage

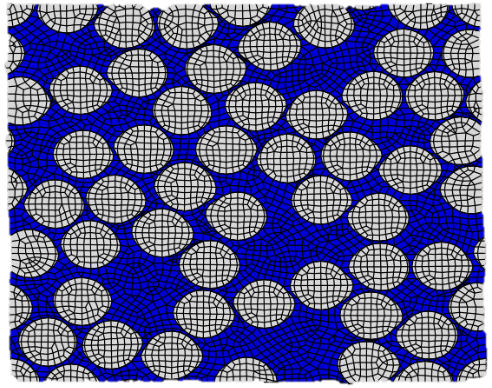




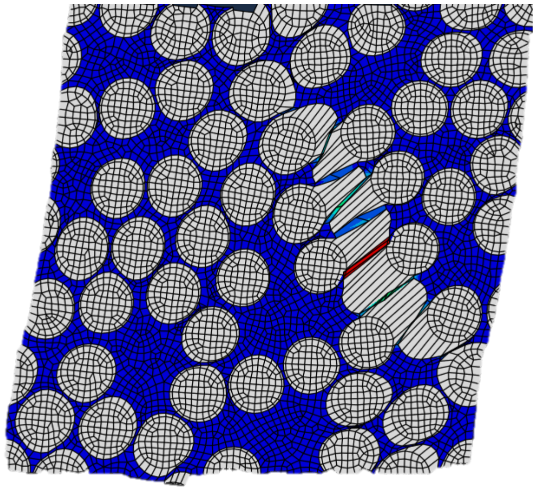
$t = 0$



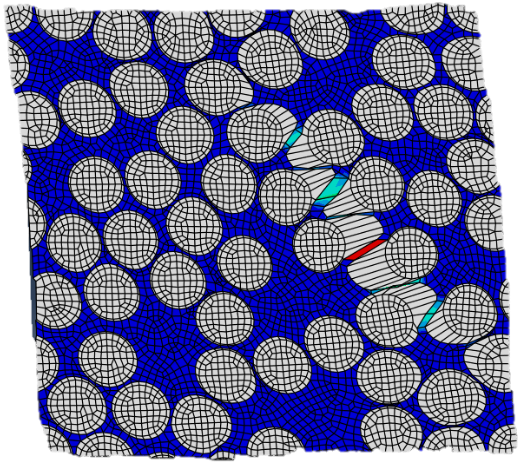
$t = 0.05$



$t = 0.16$



$t = 0.67$



$t = 0.83$

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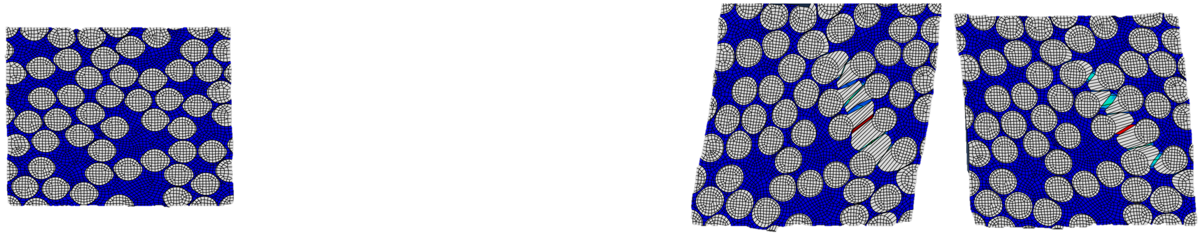
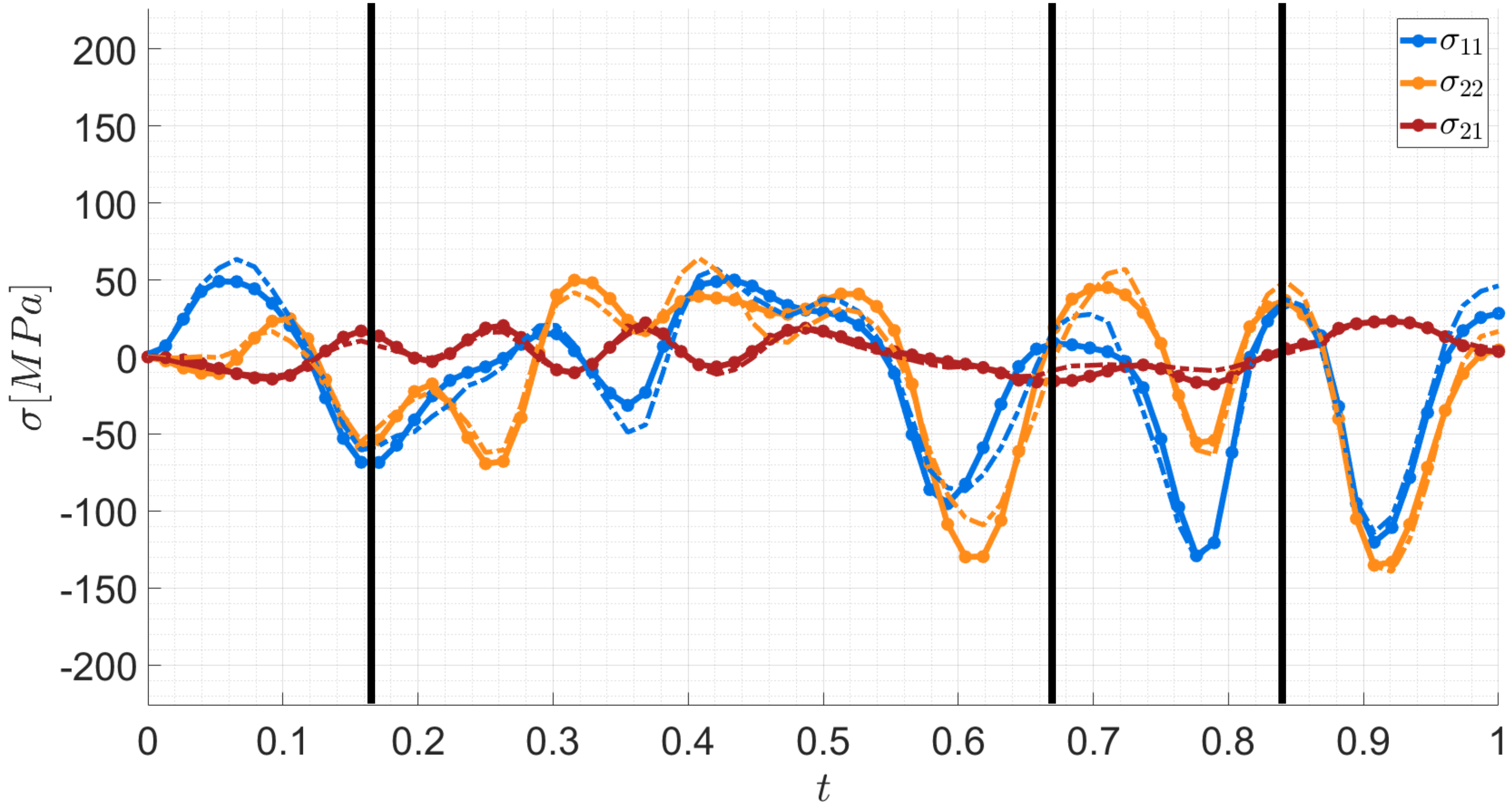
Learned Behaviour





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Summary & Future Work

- A methodology for training surrogate models for RVEs is tested on a micro-scale composite material RVE with matrix damage and interface debonding

- The proposed method is able to reconstruct general-shape strain-stress curves under damaged conditions.

Future Work

Implementation in Abaqus

3D RVE

Geometrical Parameters(Volume Fraction, Fibre Diameter,…)

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Thank you for your attention

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