Computationally efficient FE micromechanical modelling of unidirectional composites under longitudinal loading

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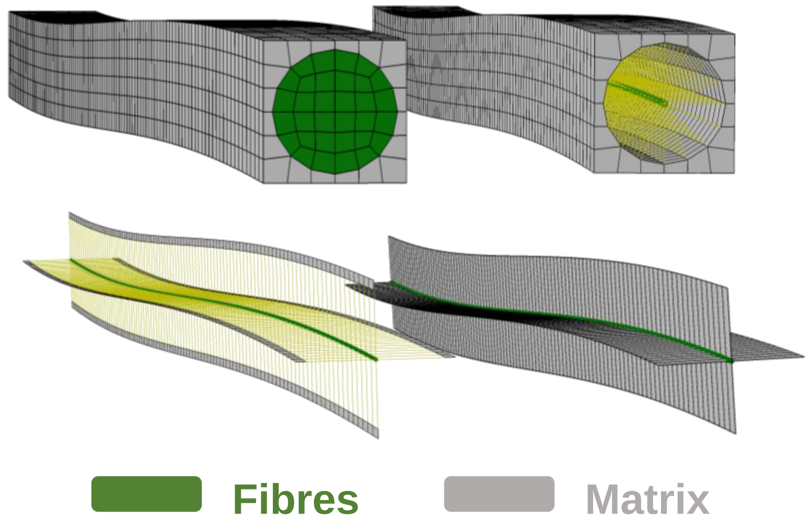

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Next Generation Fibre-Reinforced Composites

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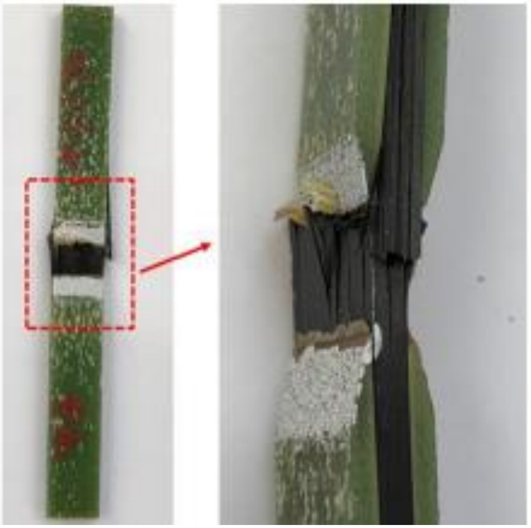
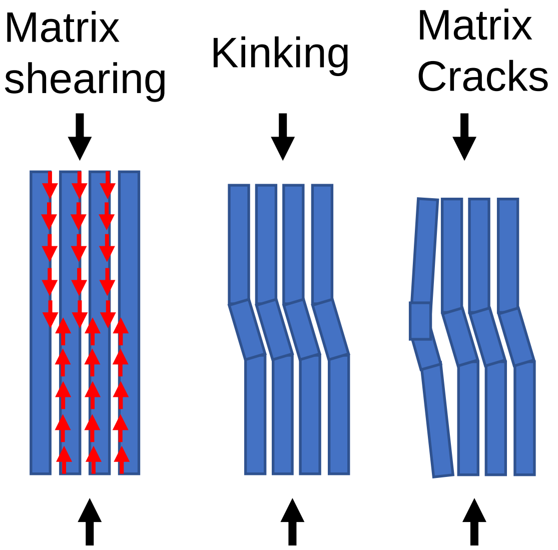
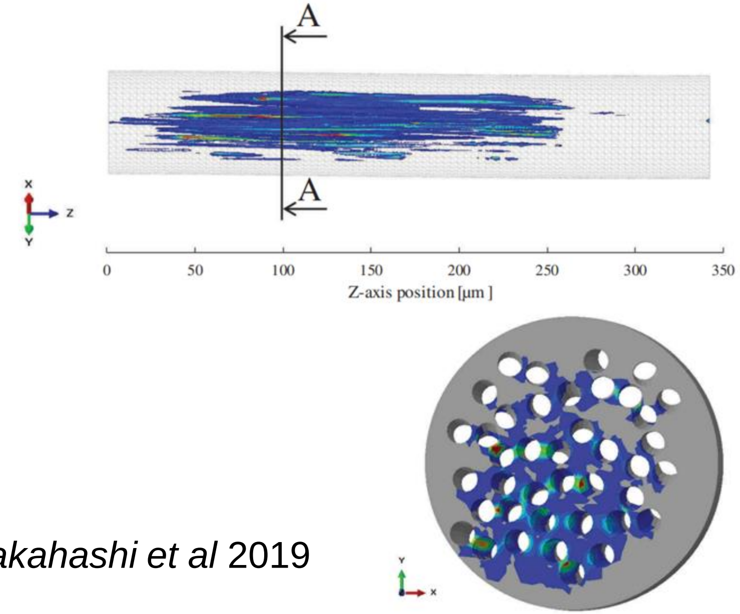
COMPRESSIVE FAILURE OF UD COMPOSITES



Sun et al 2018





Takahashi et al 2019

Composite's compressive strength is dependent on microstructural imperfections: fibre waviness, voids, and notches.

Need to study at microscale level:

- **Local microstructural imperfections guide yielding, fibre kinking, and failure response.**

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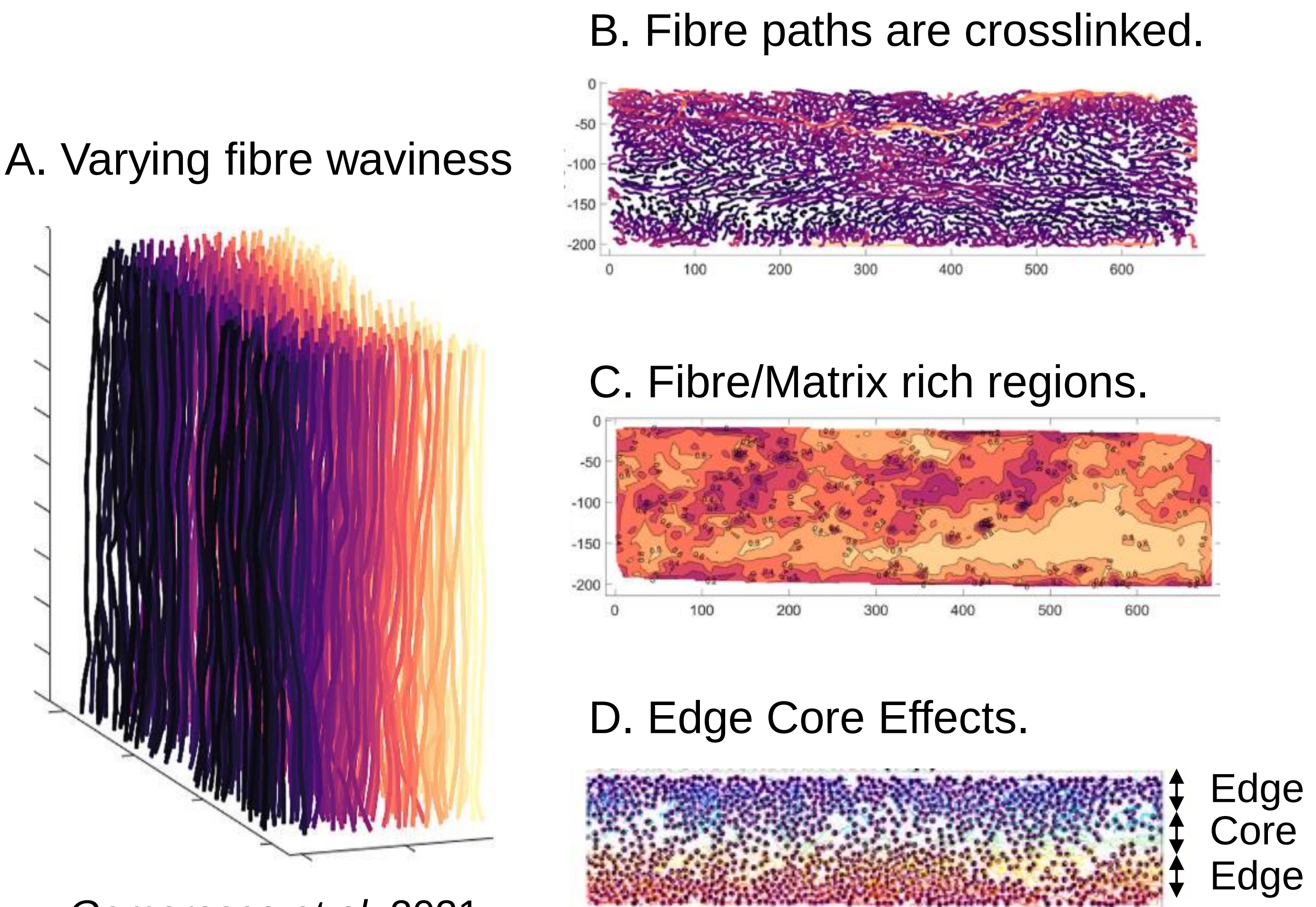
REAL MICROSTRUCTURES – A REPRESENTATIVE VOLUME

A typical microstructure contains the following geometrical imperfections:

An RVE length of **1500 µm** and a cross section of **200 µm** x **200 µm** is required to capture a truly Representative Volume Element (RVE).

This size leads to a volume which contains hundreds of fibres (> 600).

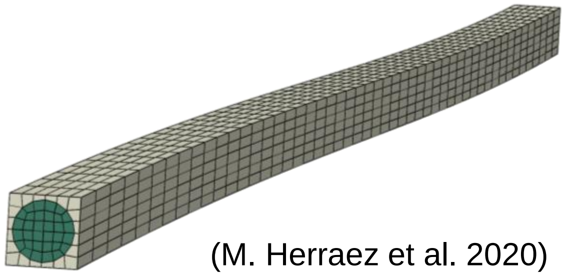


Gomarasca et al. 2021

Modelling compression in UD composites

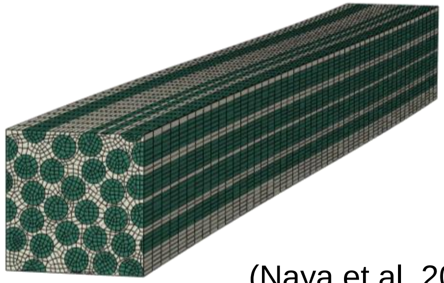
Different FE-model approaches in literature for fibre kinking:

Single-fibre RVE with PBCs



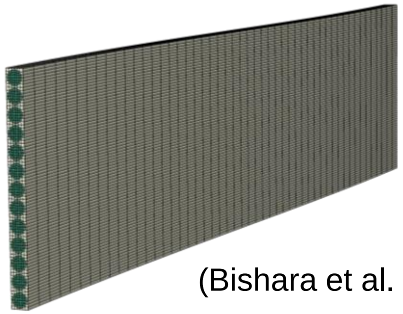
(M. Herraez et al. 2020)

Multi-fibre RVE with PBCs



(Naya et al. 2017)

Single array of fibres RVE without PBCs

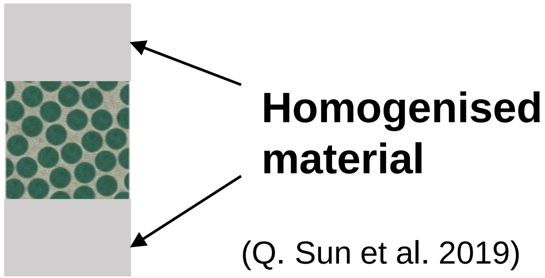


(Bishara et al. 2017)

Multi-fibre RVE from CT scans without PBCs

(Takahashi et al. 2019)

A hybrid micro-macromechanical RVE



(Q. Sun et al. 2019)

However, none of the available models are capable to account the statistical variability needed for a representative microstructure.

Researchers highlight the issue of computational cost using such models.

Outline

Reduce computational cost of micromechanical FE-Models to enable truly representative RVEs (RVEs > 600 fibres)

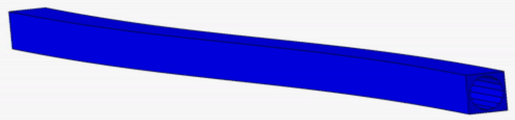
- **Concept**
- **New approach – Shell-Beam models**
- **Application to multifibre scale**
- **Conclusions**

REDUCTION OF COMPLEXITY

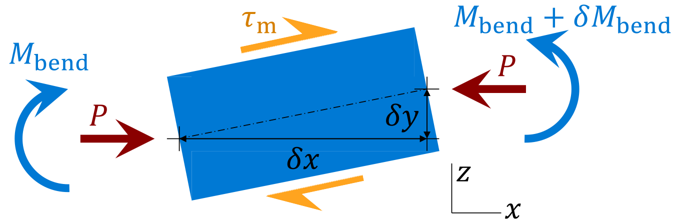
The key mechanisms during fibre kinking are :

Bending stresses acting on the Fibre

Shear stresses experienced by the Matrix



Analytical models correlate with FE-models at single fibre scale confirming these mechanisms (Fleck et al. 1995, Morais and Marques 1997, Pimenta et al. 2009, and others).



(Pimenta et al. 2009)

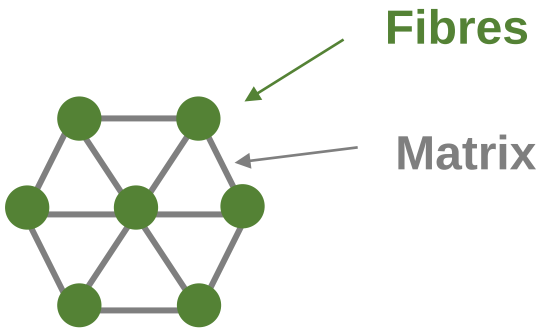
We can reduce the complexity of the FE-models and element dimensionality aiming to improve computational efficiency!

MODELS IN TENSION

Many numerical models in tension employ computationally efficient elements to represent key mechanisms.

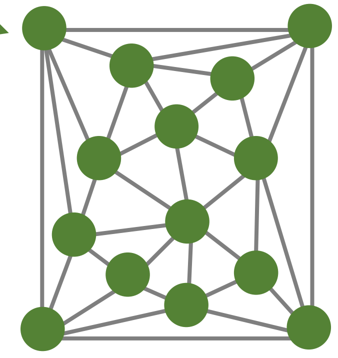
Spring Element Method

Fibres: Longitudinal tensile **springs**
Matrix: Transverse shear **springs**



(Okabe et al. 2005)

(Tavares et al. 2019)

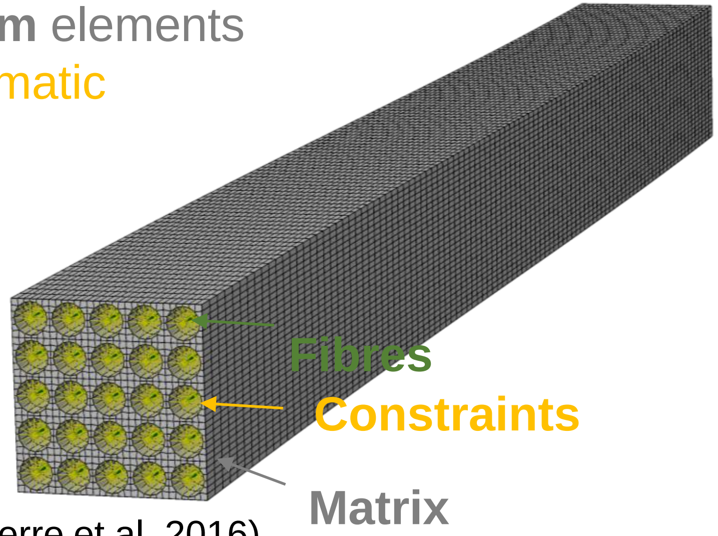


Limitation :

- **Straight fibres in all models**

FE- micromechanical models

Fibres: **Truss** elements
Matrix: **Continuum** elements
Connection: Kinematic constraints



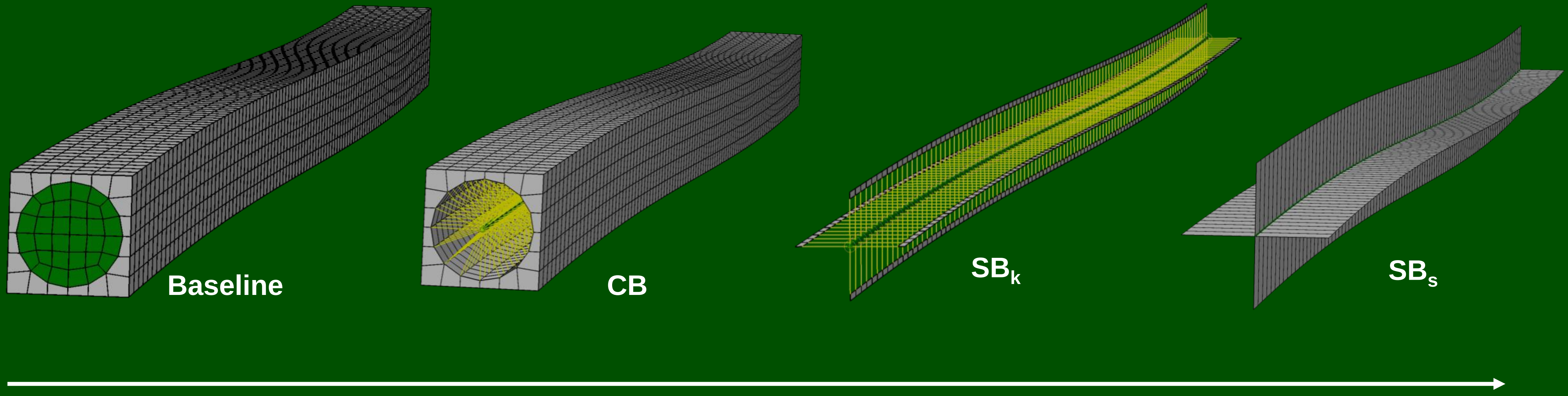
(St-Pierre et al. 2016)

Limitation :

- **Straight fibres**
- **Square packing**

Our Approach at unit cell level

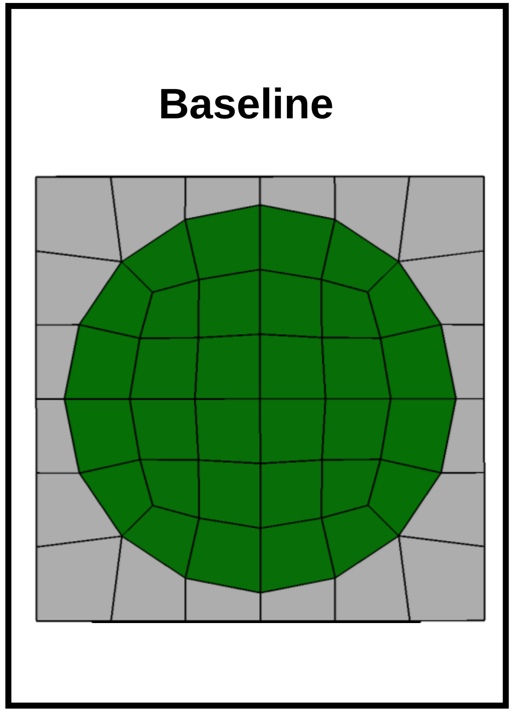
Replace computationally heavy continuum elements with more efficient alternatives !



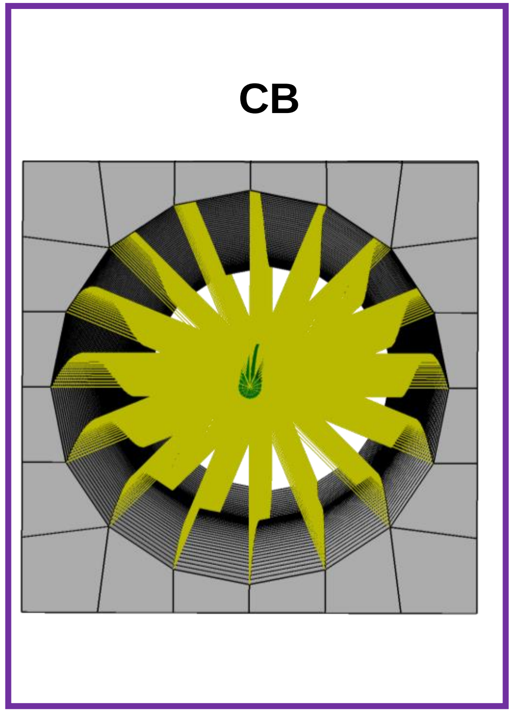
Reduction of the number of DoFs of the FE-model
+
Reduction of the expected simulation time

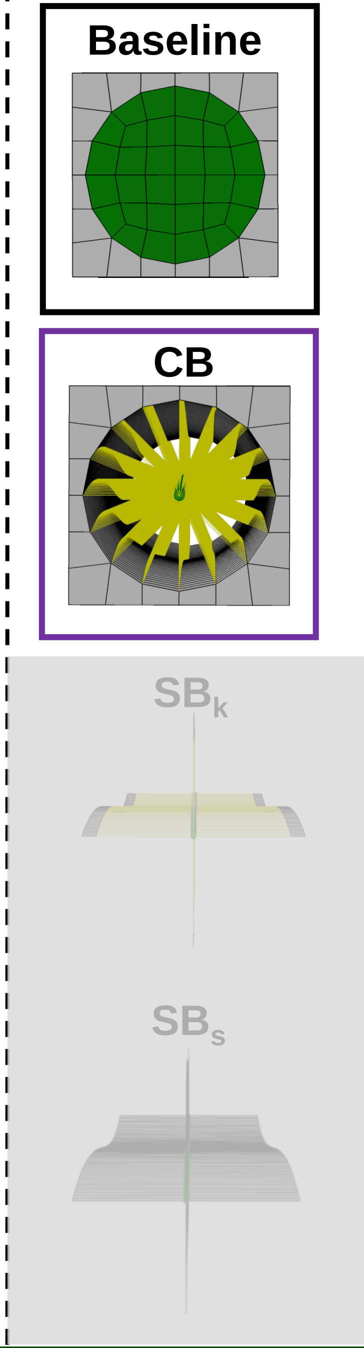
CONTINUUM-BEAM (CB) MODEL

- Fibres → Compression + Bending → Beam Elements



VS





CONTINUUM-BEAM (CB) MODEL

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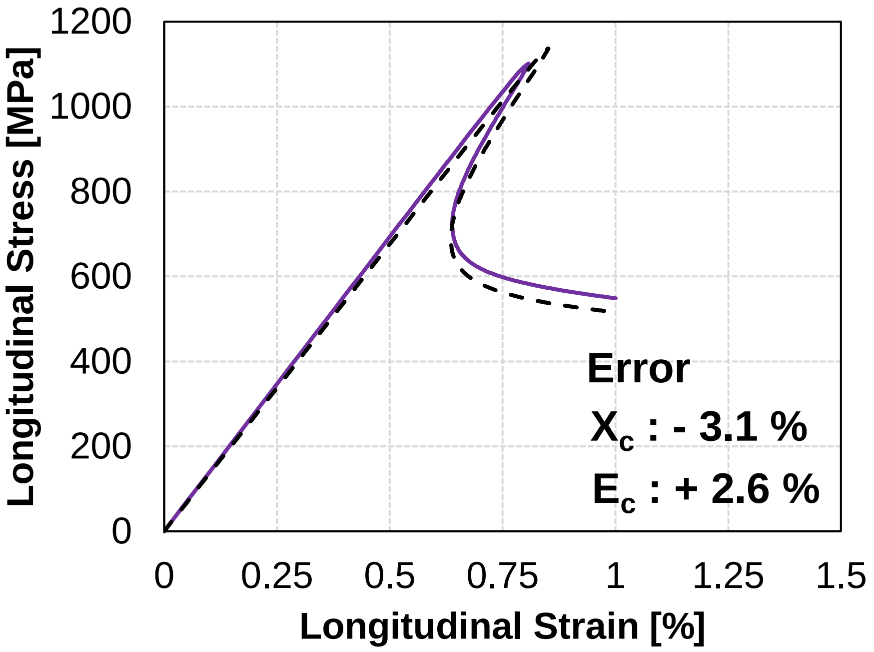
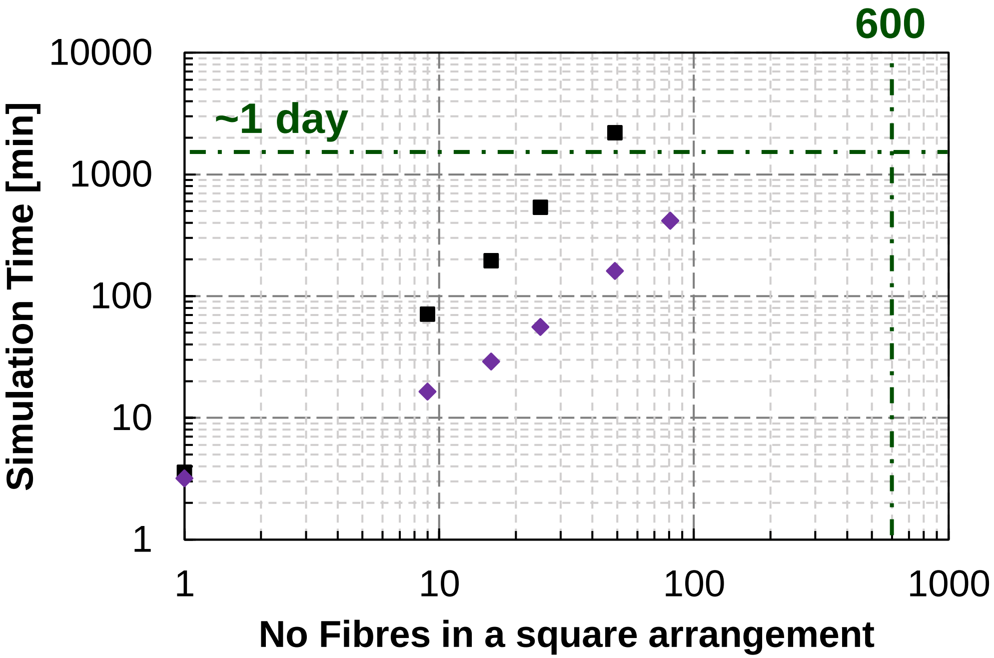
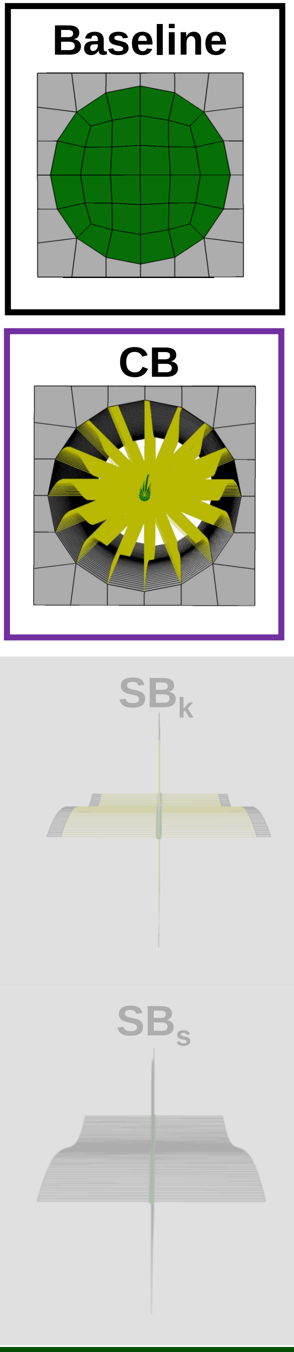




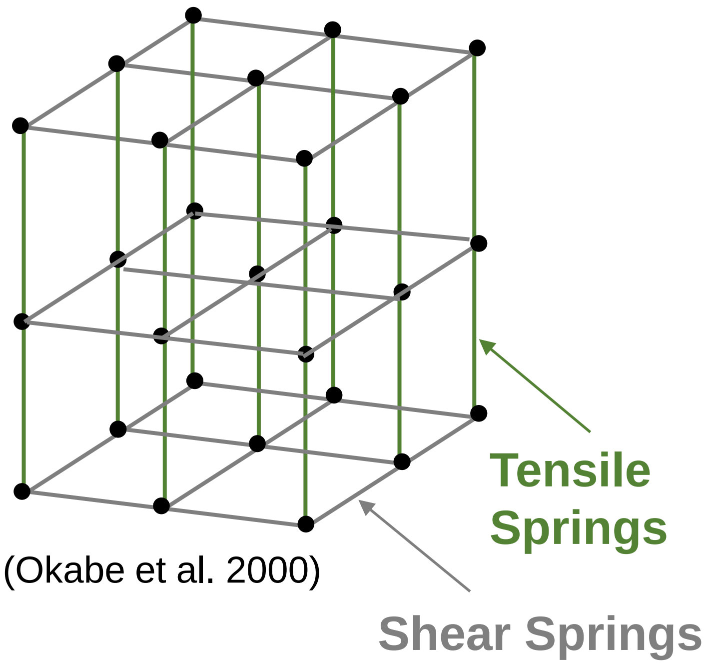


- **92 %** reduction in simulation time.
- **CB Models** cannot reach representative RVE size, i.e., 600 fibres.

SHELL-BEAM (SB) MODEL

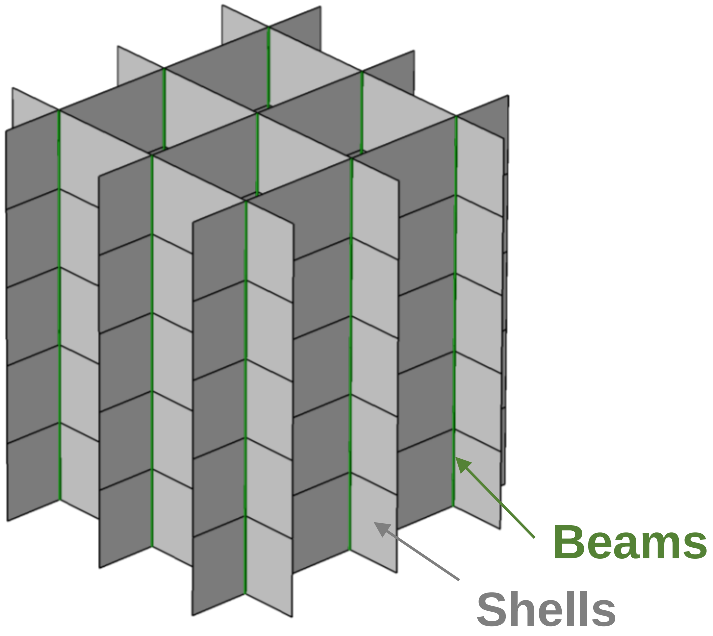
Shells can replace continuum elements and experience shear.

Spring Element Method

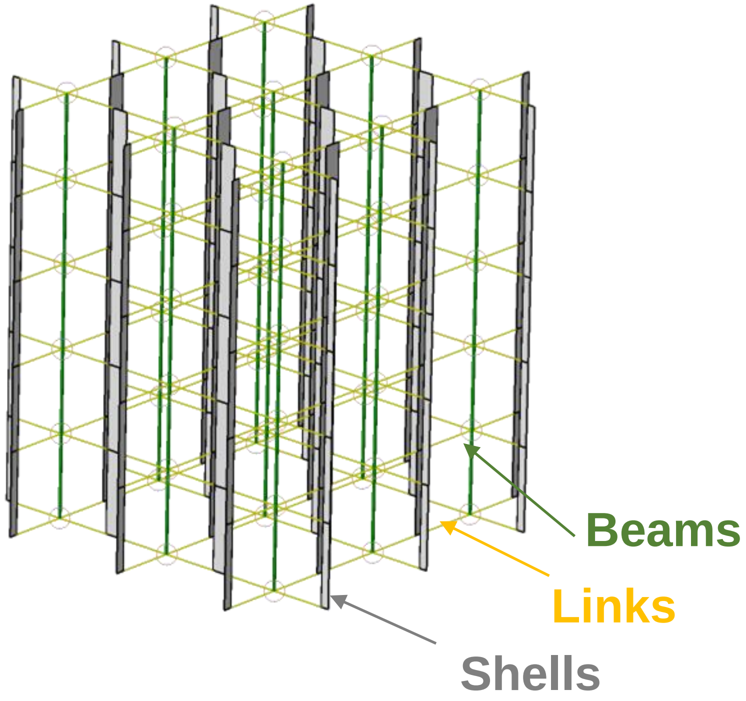


(Okabe et al. 2000)

SB_s



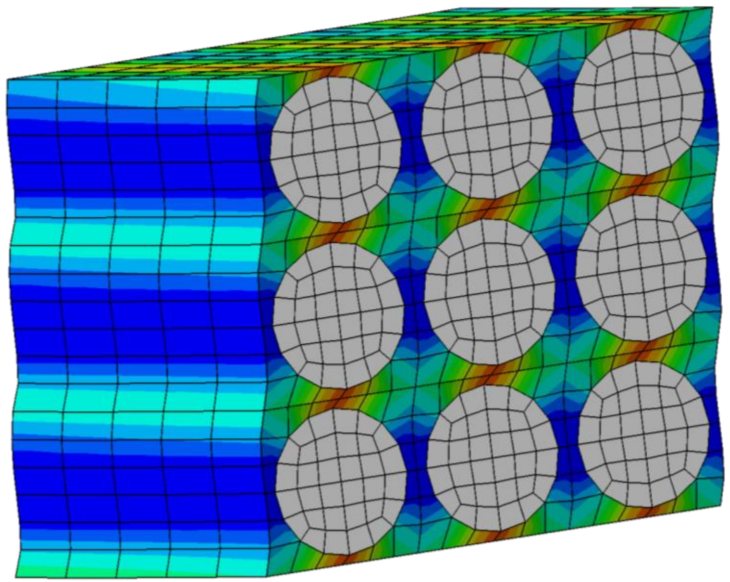
SB_k



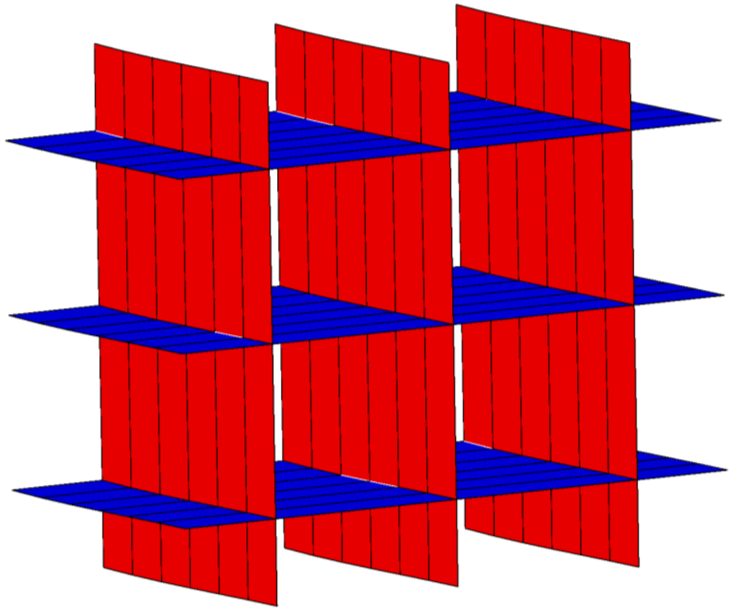
Shell-beam (SB) model

Main challenge when using shells: account for the non uniform stress and strain distribution of the 3D volume.

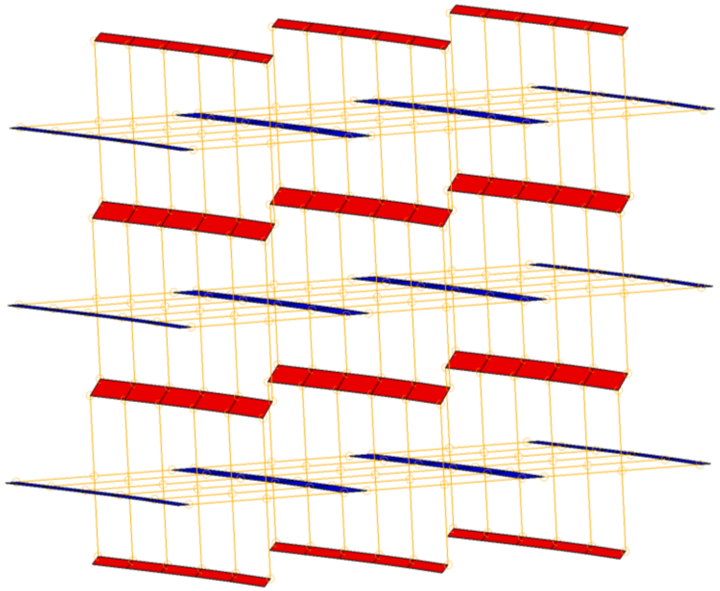
Baseline



SB_s



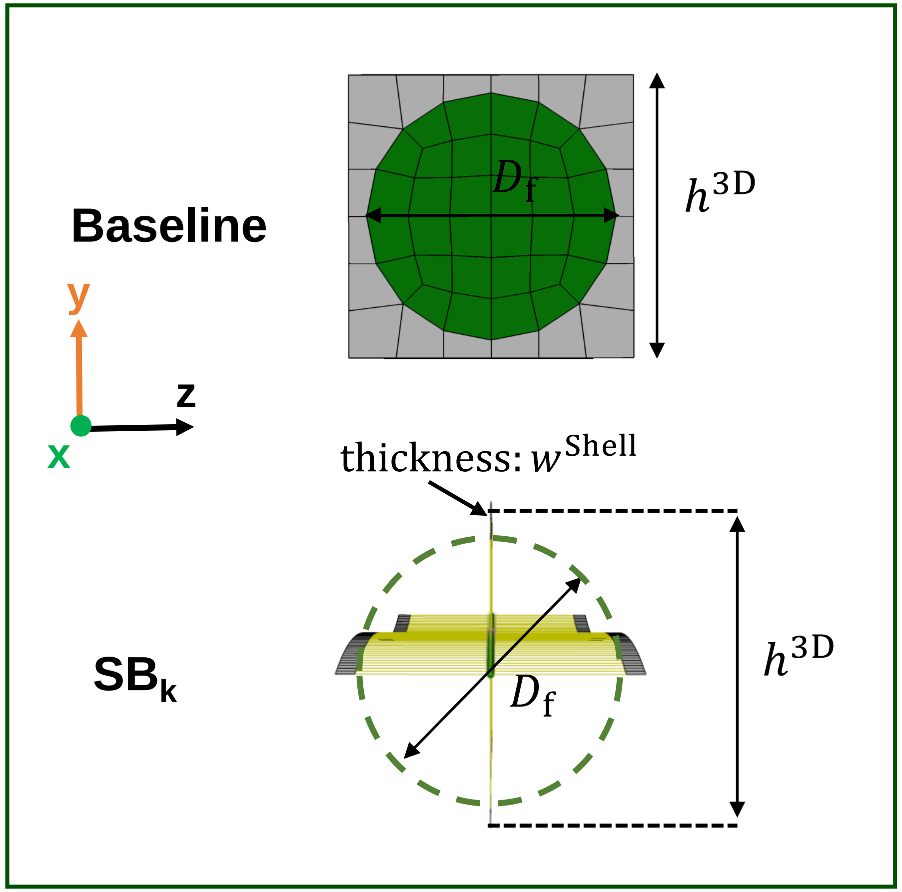
SB_k



Shell-beam (SB_K) model

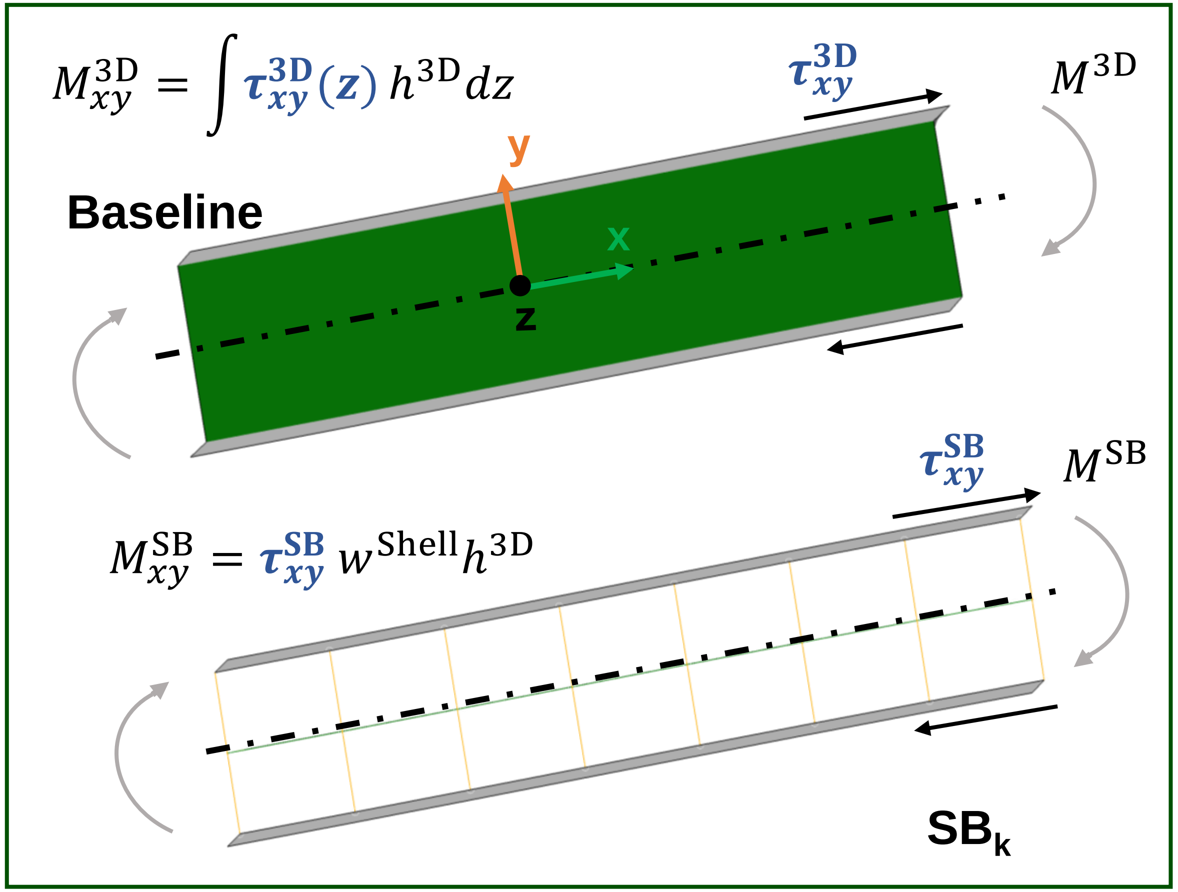
We can ensure equivalent fibre-kinking by calibrating the shear stresses of the matrix assuming equilibrium of moments at the edges of the RVE

Fibre volume fraction



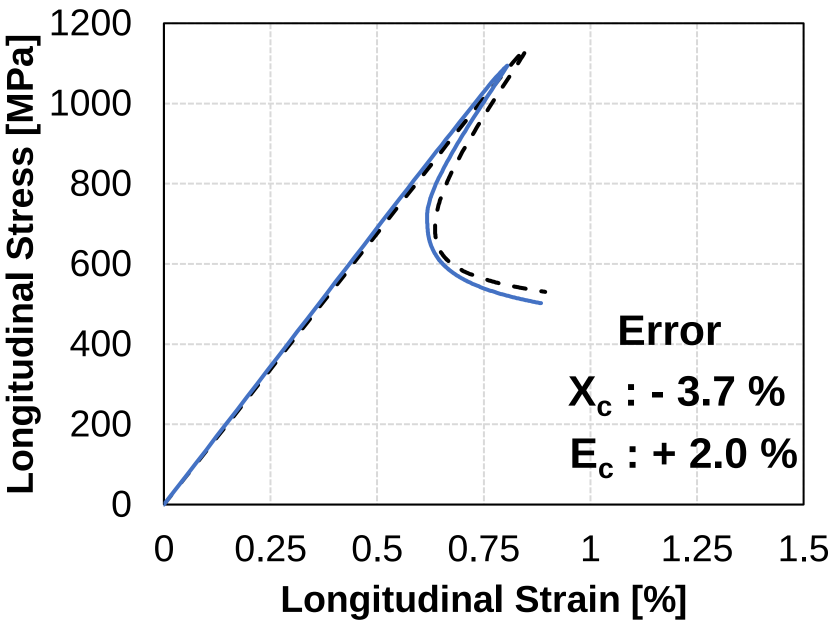
Calibration of stresses :

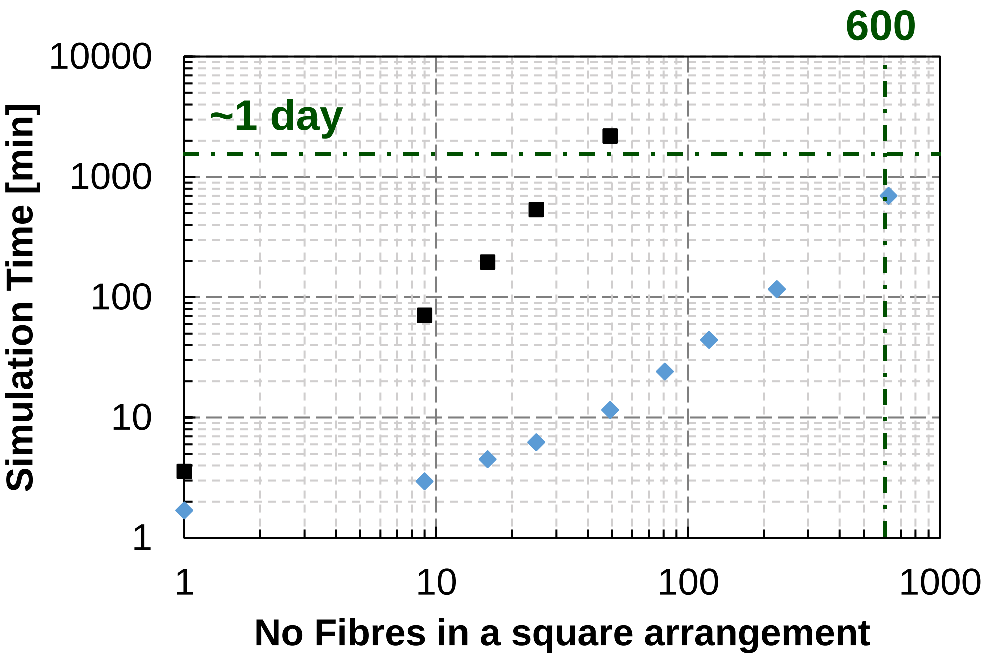
$$M^{3D} = M^{SB}$$

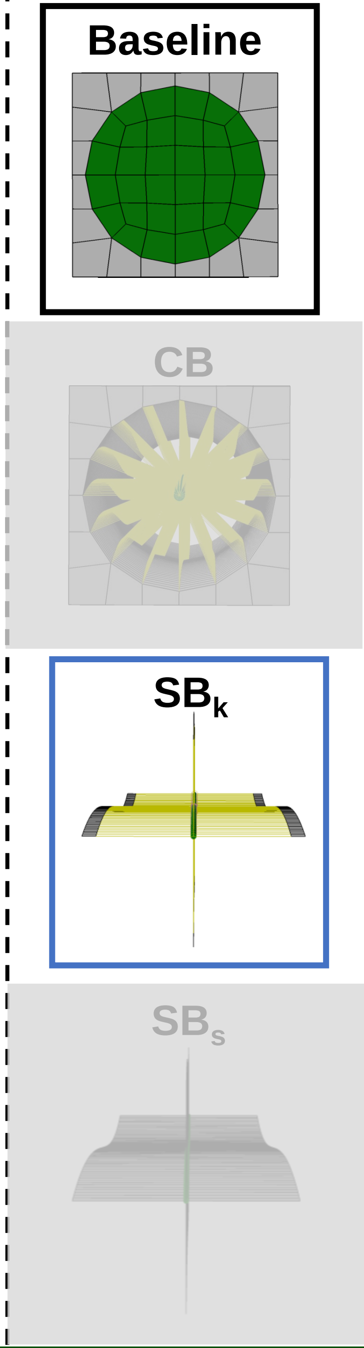


SHELL-BEAM (SB_K) MODEL

- Matrix → Shear → Shell elements







- **SB_k** Model vs **Baseline** model:
  - ✓ Great predictive power (< 4% error).
  - ✓ Great improvement in efficiency (~ 99.5 % reduction).
  - ✓ Target RVE size (< 11 hours)

SHELL-BEAM (SB_S) MODEL

Apart from:

1. **Calibration of shell thickness**

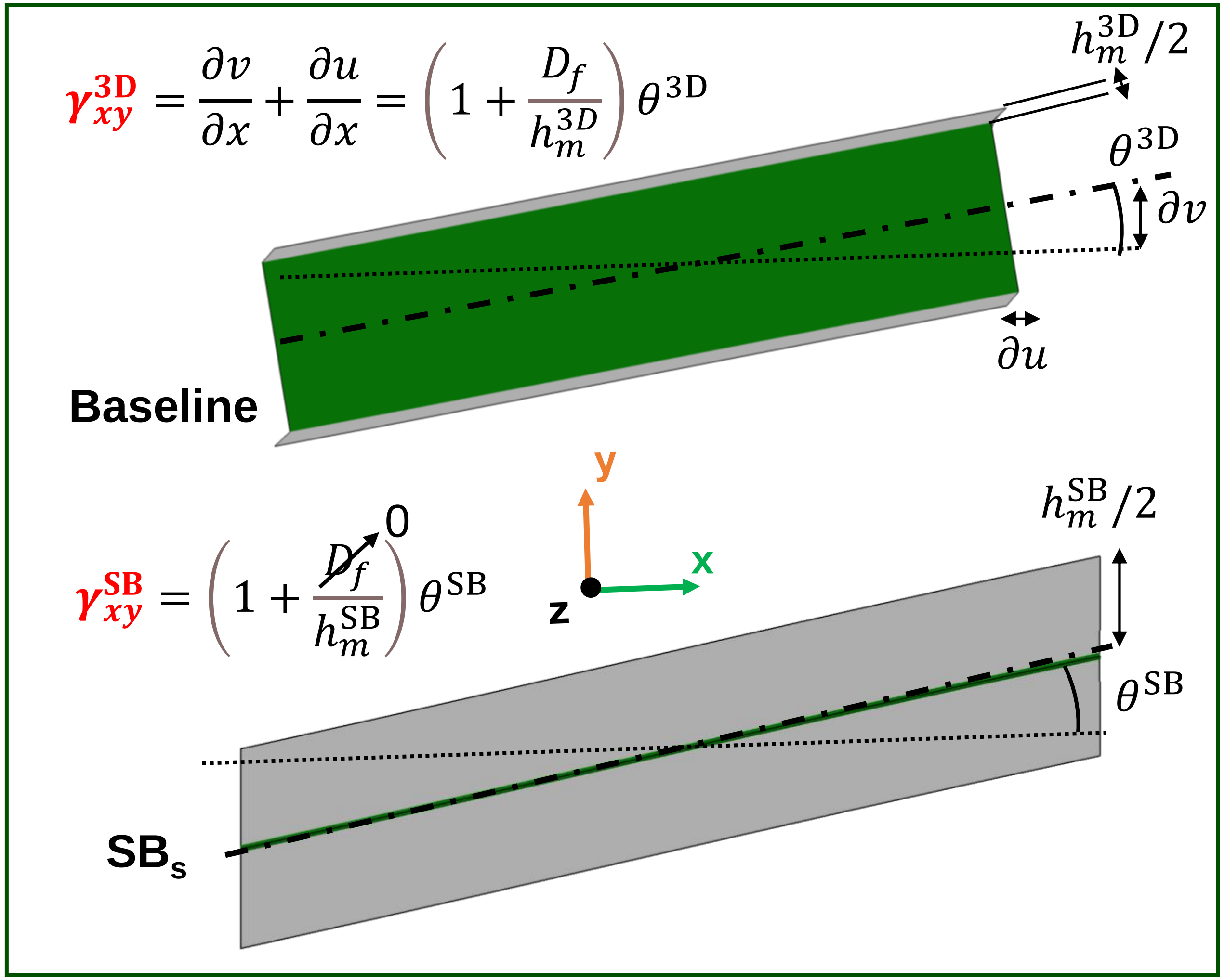
2. **Calibration shear stresses (equilibrium of moments)**

Fibres need to behave the same way as in baseline case.

Compatibility of rotations ensures the fibres kink in the same way as the baseline model.

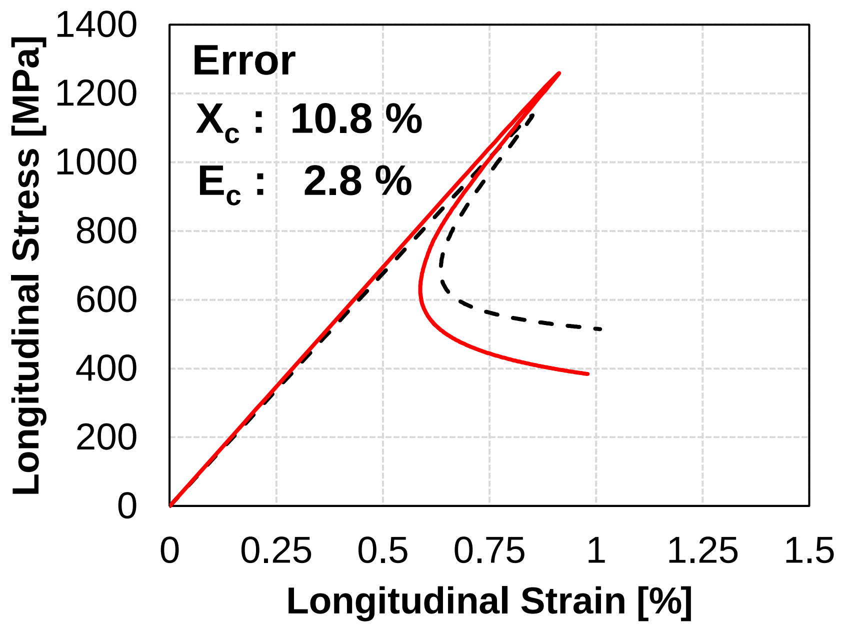
Calibration of strains

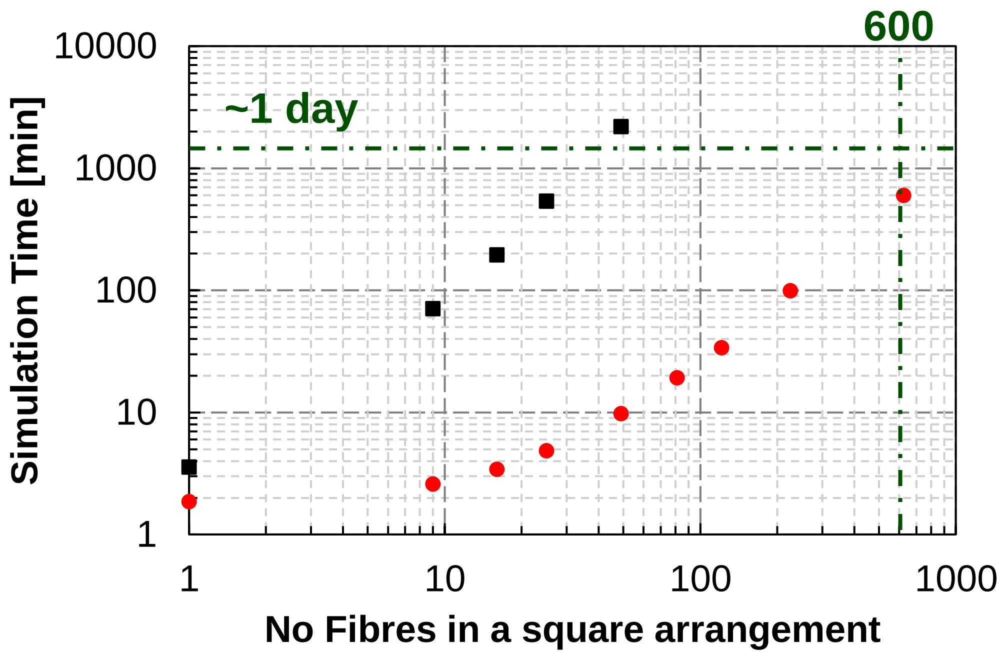
$$\theta^{3D} = \theta^{SB}$$

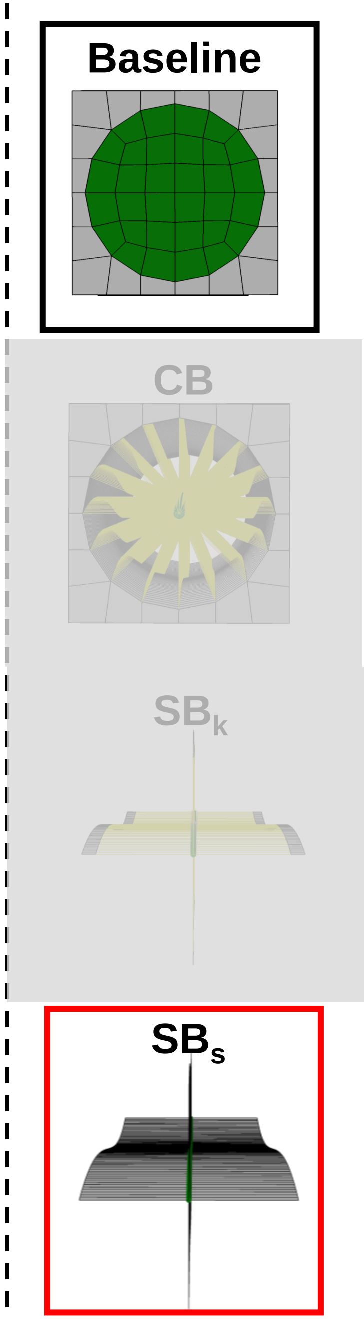


SHELL-BEAM (SB_S) MODEL

- Matrix + Fibres → Remove kinematic constraints → Merged nodes







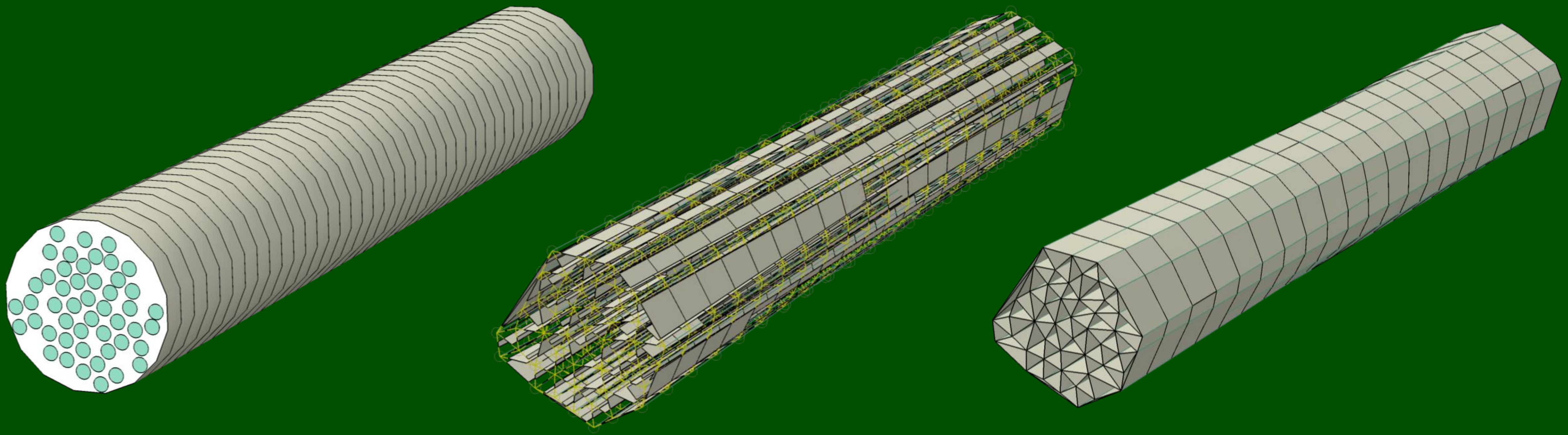
- **SB_s Model** vs **Baseline** model:
  - ✓ Good predictive power (< 11% error).
  - ✓ Great improvement in efficiency (~ 99.6 % reduction).
  - ✓ Target RVE size (< 10 hours)

* Fibre data from: *Emerson et al.* 2017

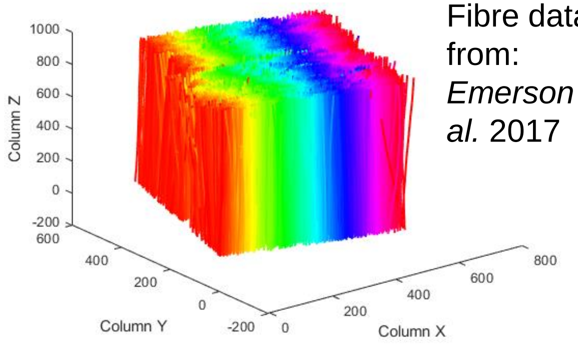
Application on real microstructures

Assessment of computational cost on real microstructures from CT images*

Baseline SB_K SB_s

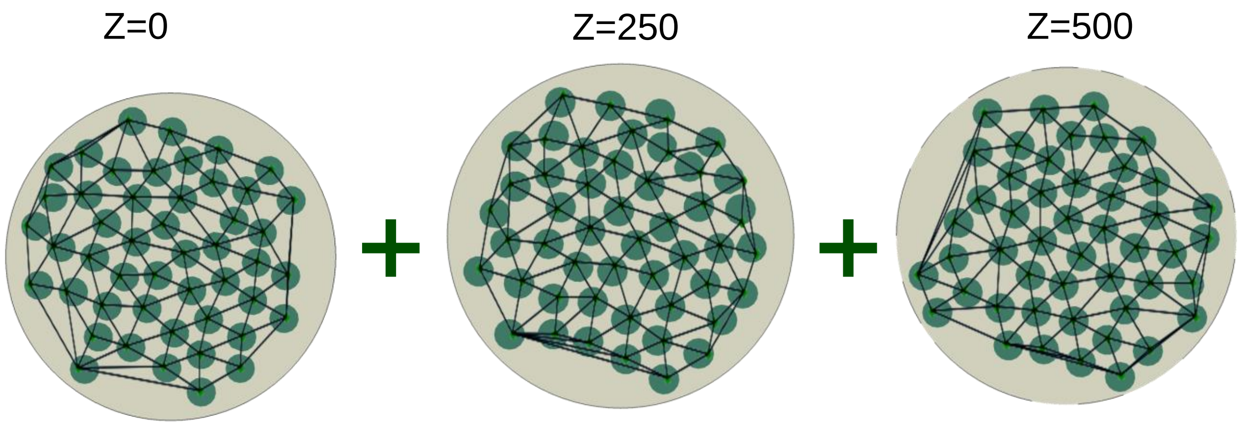


REAL MICROSTRUCTURES

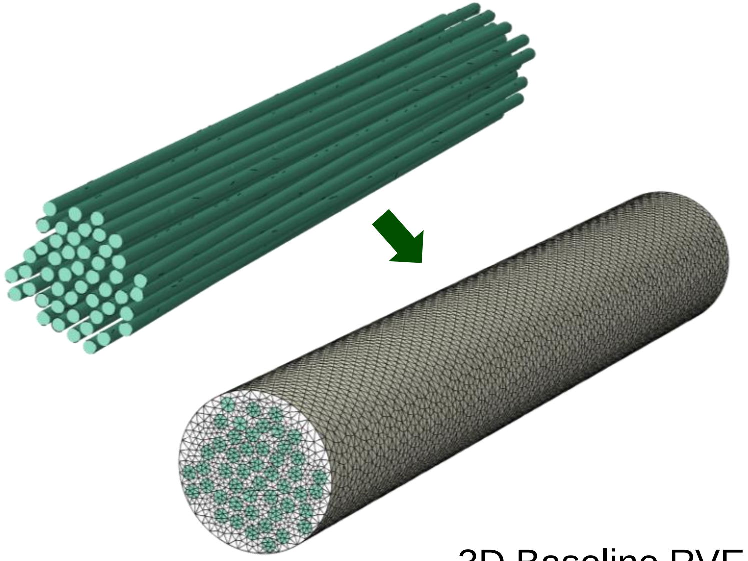


Fibre data from: *Emerson et al.* 2017

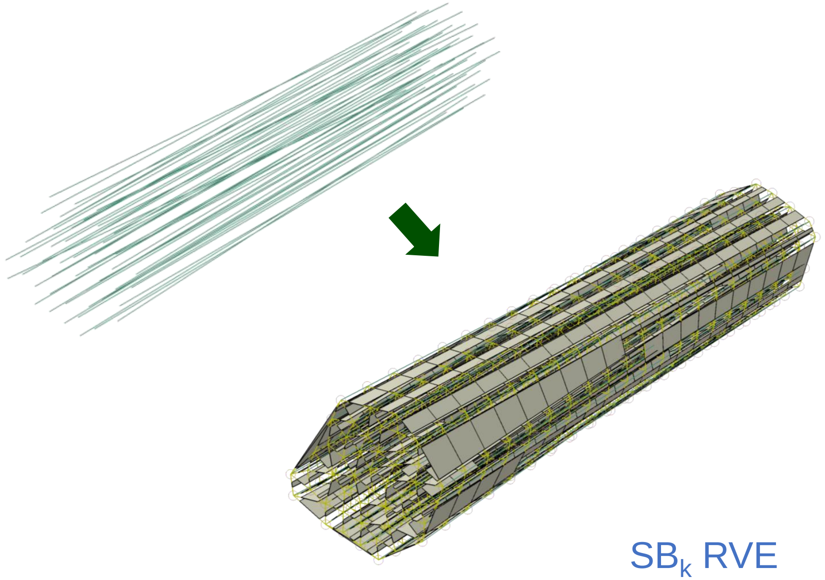
Real fibre paths



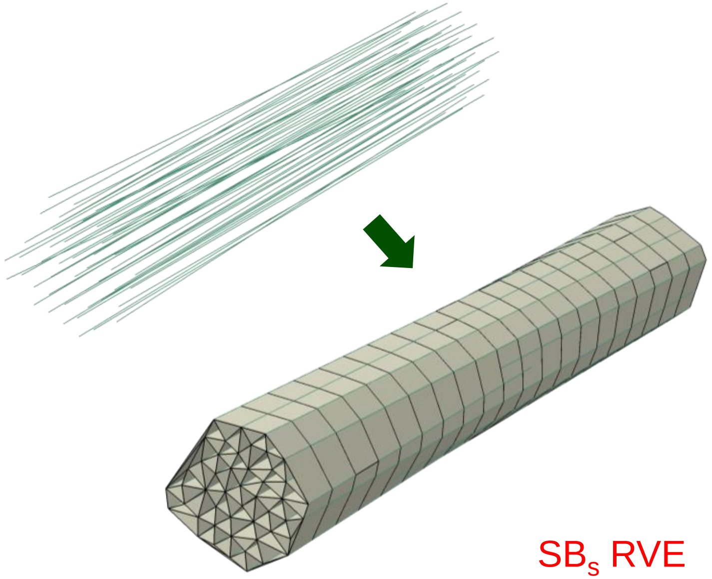
3D SB RVE: Connect parallel Delaunay Triangulation networks to represent the real fibre paths.



3D Baseline RVE

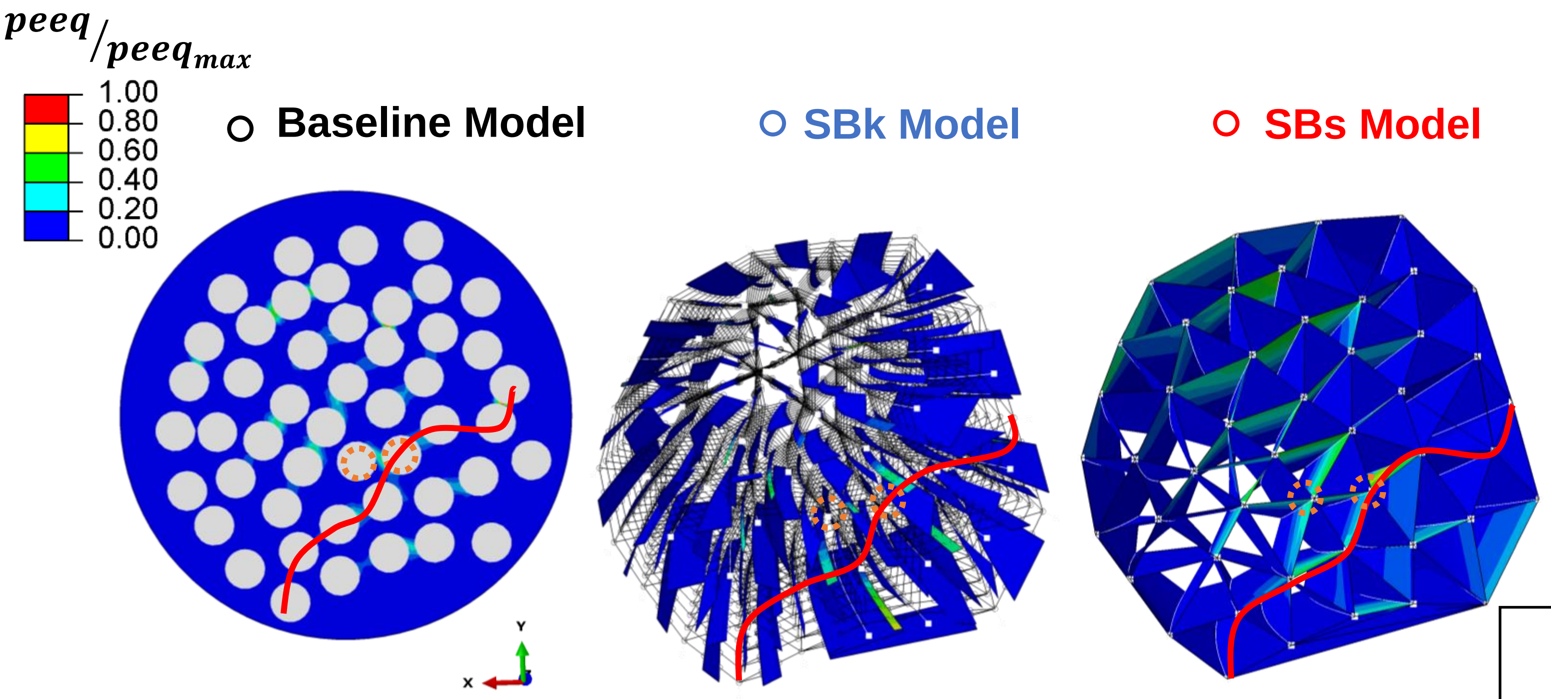


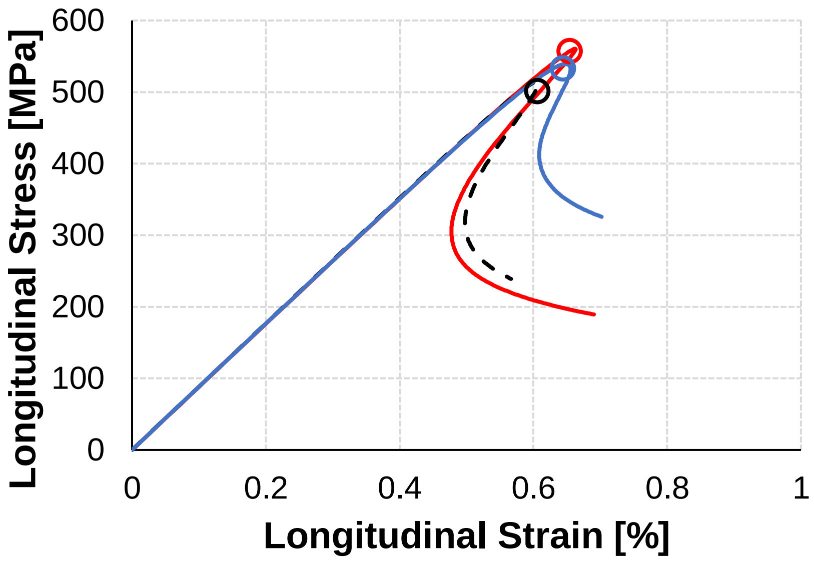
SB_k RVE



SB_s RVE

REAL MICROSTRUCTURES – COMPUTATIONAL COST





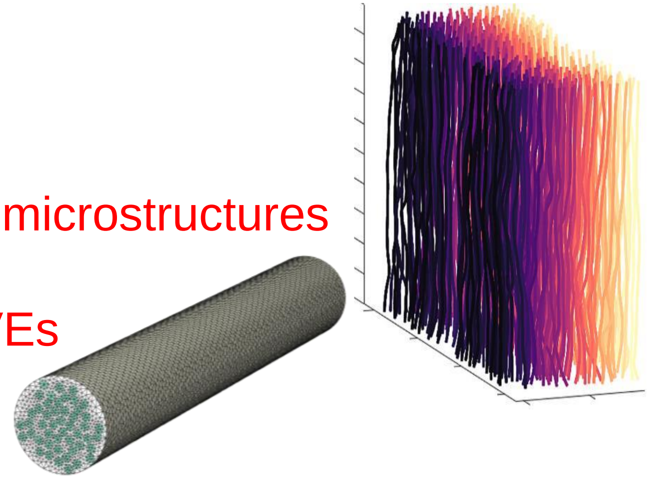
	Stiffness (% error)	Strength (% error)	Simulation time (% reduction)
Baseline	**-**	**-**	**113 hours (-)**
SB_k	- 0.3 %	+ 6.4 %	**~ 3 min (99.997 %)**
SB_s	- 0.4 %	+ 8.9 %	**~ 2 min (99.999 %)**

- Maximum plastic shear strains in the matrix occur in similar locations in the RVE.

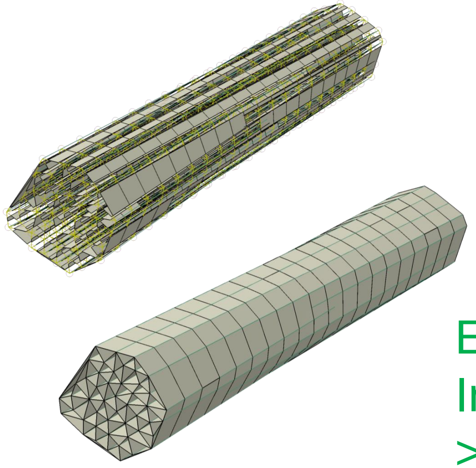
CONCLUSIONS & SUMMARY

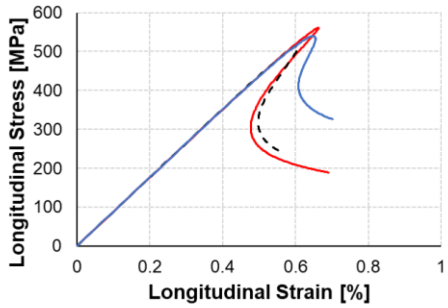
Challenges

1. Computational cost
2. Creation of truly real microstructures
3. Not large enough RVEs



Proposed SB Models





Error in strength: < **9 % (SB)**
Improvement in simulation time: >**99.99 %**

Applications

- What are the key features trigger fibre kinking (e.g., fibre misalignment or fibre waviness)?
- Which parameter dictates failure (e.g., fibre misalignment or voids/cracks)?
- How can we improve compressive strength?

- Expand to longitudinal tension.
- Expand to short-fibre composites.

Next Generation
Fibre-Reinforced Composites

https://nextcomp.ac.uk

I would like to acknowledge funding which supported this work from the UK Research and Innovation - EPSRC Programme Grant; Next Generation Fibre-Reinforced Composites: A Full Scale Redesign for Compression (EP/T011653/1)

A collaboration between Imperial College London and University of Bristol

Imperial College London

University of Bristol

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