Microscale modeling of fiber waviness and its effect on the composite properties and damage

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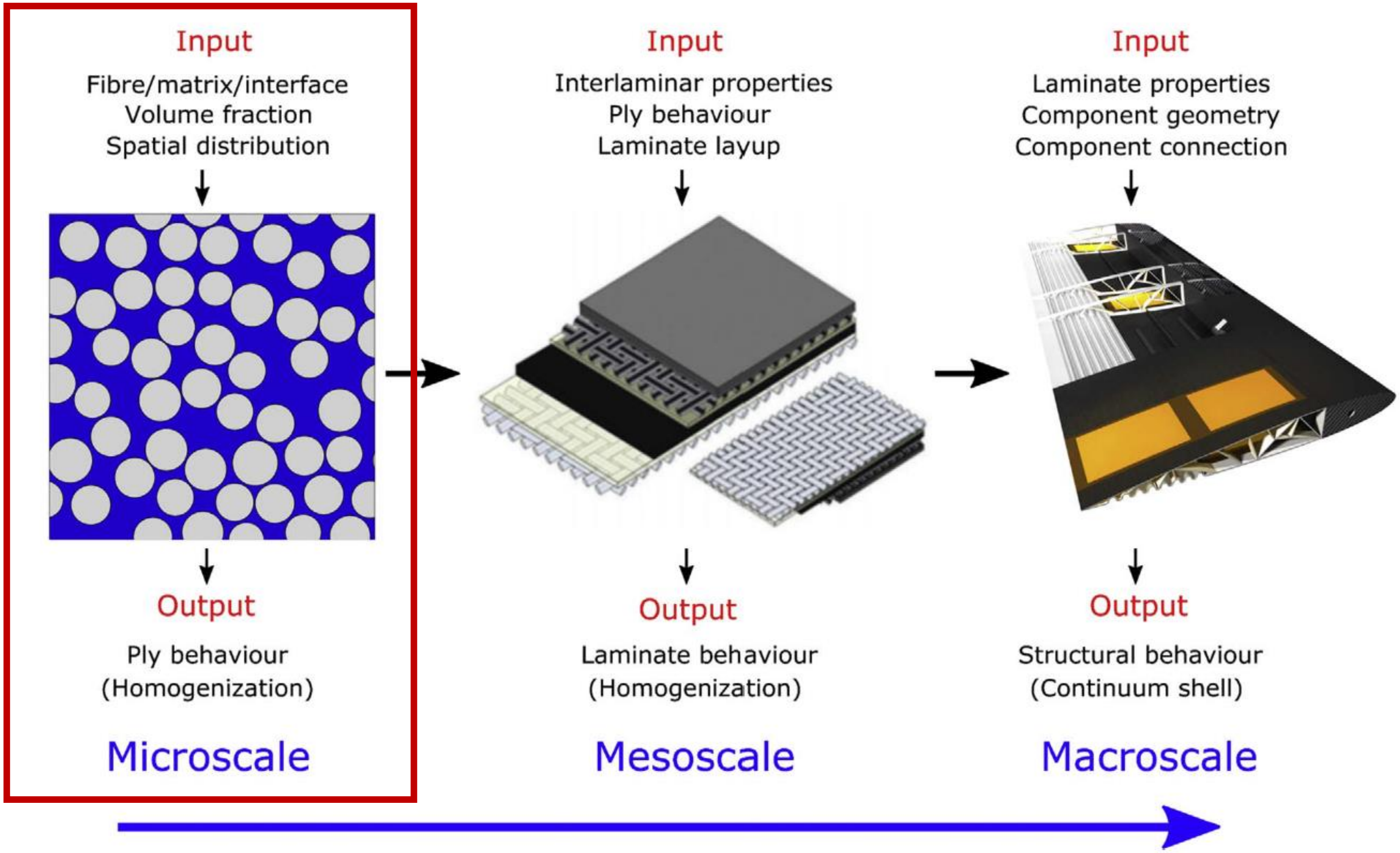
Publications

- G Catalanotti, LF Varandas, AR Melro, **TA Sebaey**, MA Bessa, BG Falzon. Modelling the longitudinal failure of fibre reinforced composites at microscale. MultiScale Continuum Mechanics Modelling of Fibre-Reinforced Polymer, 2021.
- **TA Sebaey**, M Bouhrara, N O'Dowd. Fibre Alignment and Void Assessment in Thermoplastic Carbon Fibre Reinforced Polymers Manufactured by Automated Tape Placement. Polymers 13 (3), 473, 2021
- **T.A. Sebaey**, G. Catalanotti, C.S. Lopes and Noel O'Dowd. Computational micromechanics of the effect of fibre misalignment on the longitudinal compression and shear properties of UD fibre-reinforced plastics. Composite Structures, Vol. 248, No. 112487, 2020.
- **T.A. Sebaey**, G. Catalanotti and Noel O'Dowd. An algorithm for the generation of three-dimensional statistically Representative Volume Elements of unidirectional fibre-reinforced plastics: Focusing on the fibres waviness. Composites Science and Technology, Vol. 183, No. 107793, 2019.
- G. Catalanotti and **T.A. Sebaey**. A microscale integrated approach to measure and model fibre misalignment in fibre-reinforced composites. Composite Structures, Vol. 227, No. 111272, 2019.

Contents

Composite Multiscale Modelling



Tan et al. (2018). *Composites: Part B* 138:206 – 221.

Introduction and Literature

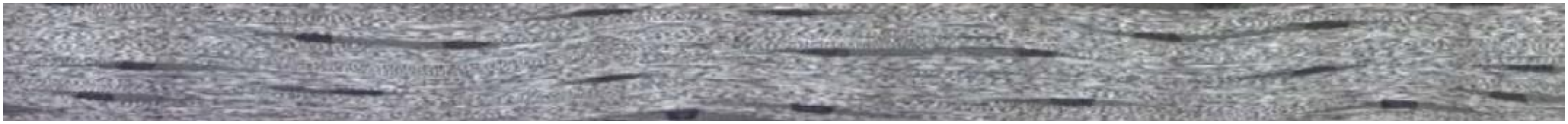
Fibre Misalignment

Fibre misalignment is a fact in laminated composites due to:

- Thermal stresses during curing,
- Manufacturing accuracy.

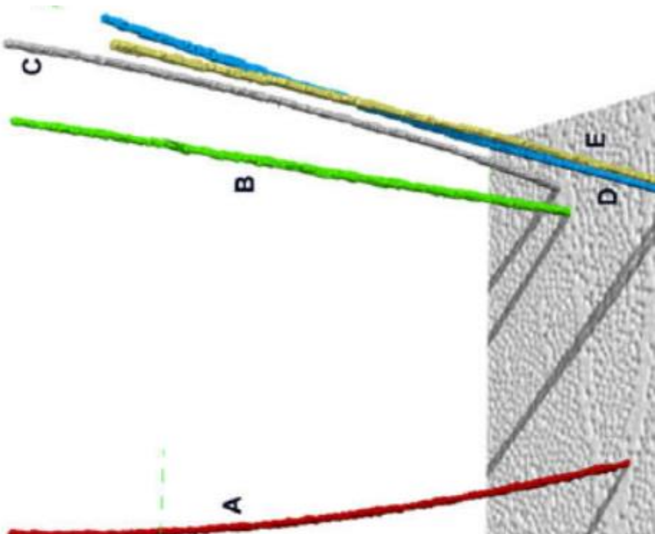
It can be noted on the ply level:

Larranaga-Valsero et al. (2018). *Composites: Part A* 114;225 – 240.



Wilhelmsson and Asp (2018). *Composites: Part A* 107;665 – 674.

and also at the individual fibre level:

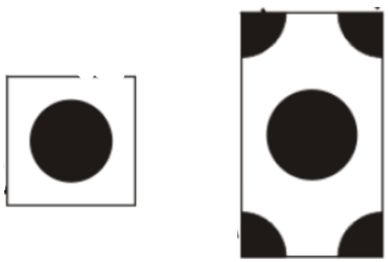


Requena et al. (2009) *Composites: Part A 40;152-163*

Introduction and Literature

2D Modelling

Systematic arrangement



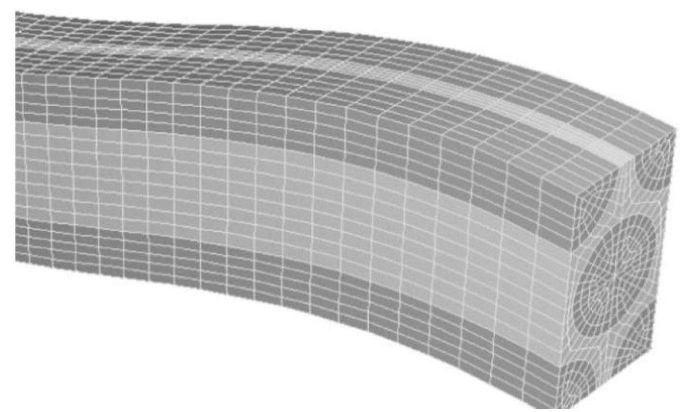
Random arrangement

Interests:

- Fibre arrangement models,
- Materials models,
- Boundary conditions,
- Void effect,
- Resin gaps,
- Etc.

3D Modelling

Yang et al. (2015) *Journal of Reinforced Plastics and Composites* 34;72-83.



Garnich and Karami (2004) *Journal of Composite Materials* 38; 273-292.

Introduction and Literature

Flowchart of the current study:

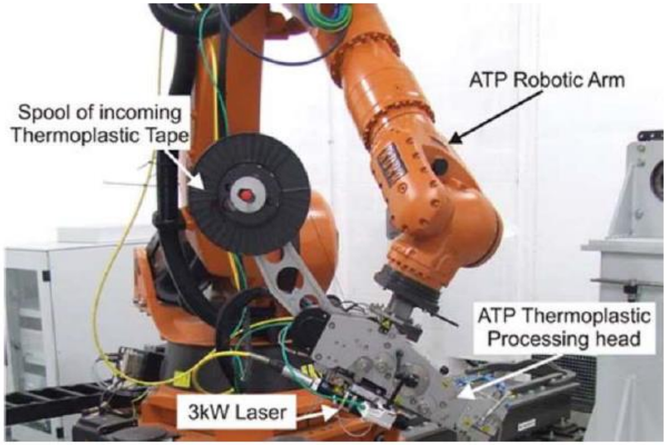
- Measure the fibre misalignments for different materials and manufacturing systems,
- Statistically, represent the measured fibre misalignments
- Geometrically, model the RVEs with fibre misalignments of the same statistical representation as the experimental ones
- Build FE models of the RVEs with misalignments,
- Find out the effect of fibre misalignment on the mechanical characteristics and damage for compression and shear loading

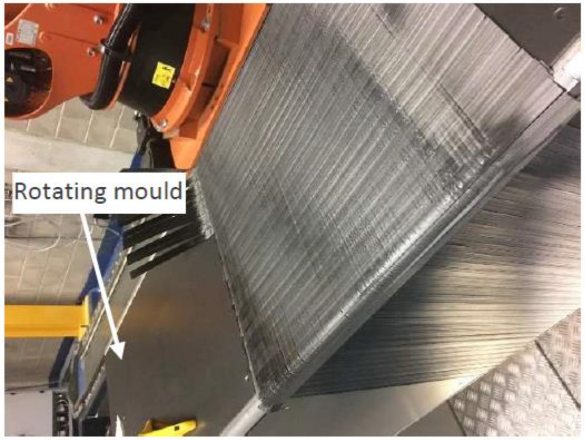
Measuring fibre misalignment

1.2 Specimen Manufacturing

Panel	1	2	3	4	5
Material	IM7/8552	IM7/PEEK	IM7/PEEK_AU*	AS4/PA12	AS4/PA12_AU*
Thickness (mm)	$1.498^{\pm 0.07}$	$1.796^{\pm 0.13}$	$1.582^{\pm 0.36}$	$1.760^{\pm 0.15}$	$1.623^{\pm 0.32}$

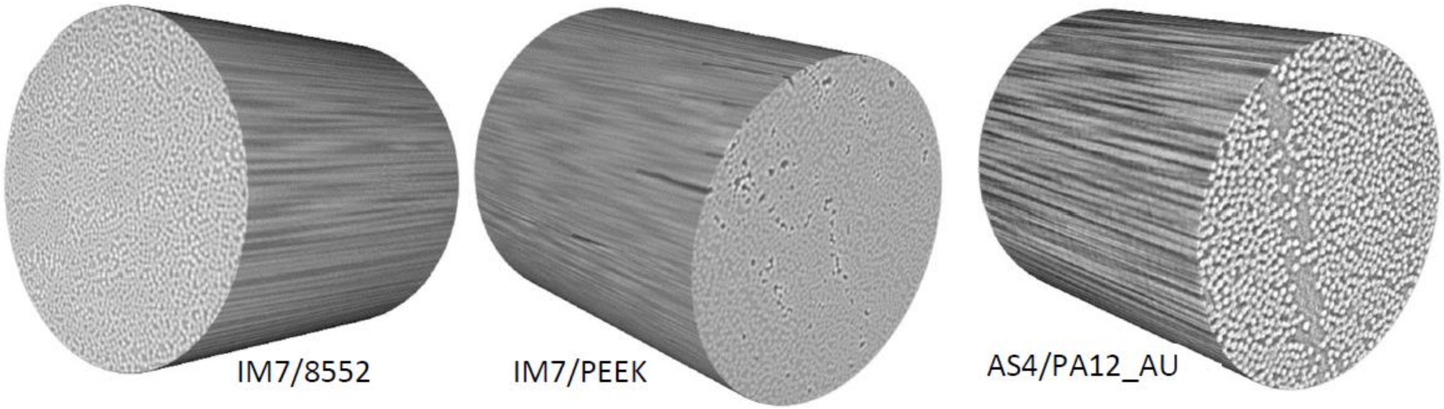
*Materials with autoclave post processing are assigned AU in their code through the whole document.

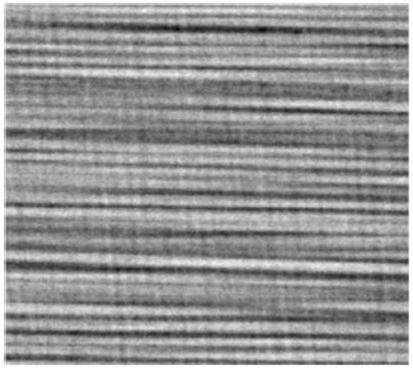


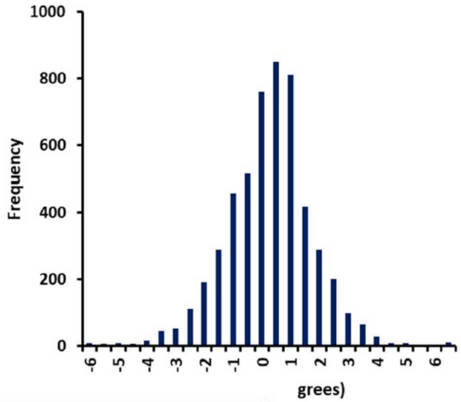


Measuring fibre misalignment

CT scans:



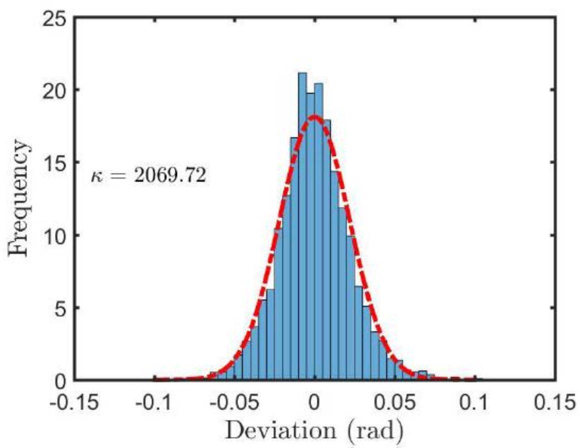




Statistical Representation (Von Mises Distribution):

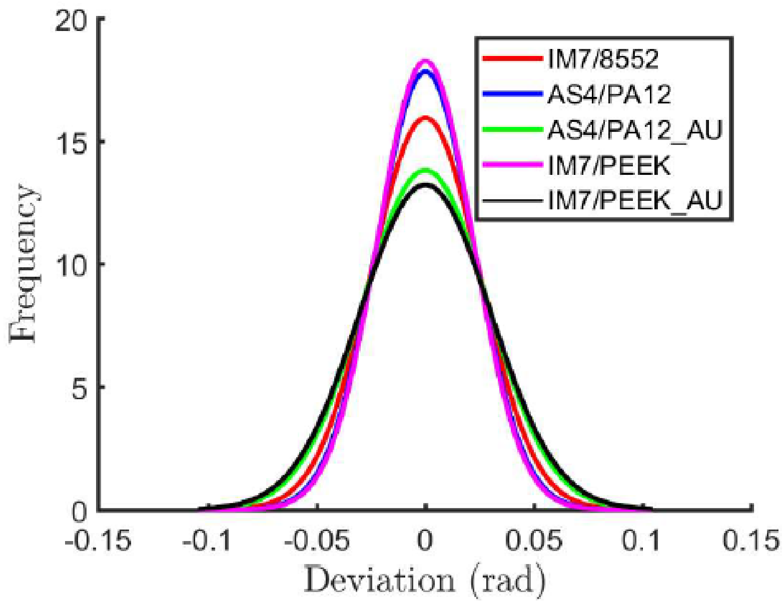
$$P(\alpha, \mu, \kappa) = \frac{1}{2 \cdot \pi \cdot I_0(\kappa)} \cdot e^{(\kappa \cdot \cos \alpha - \mu)}$$

κ tends to ∞ at highly aligned fibres and smaller κ means more misalignments.



Measuring fibre misalignment

Experimental Results



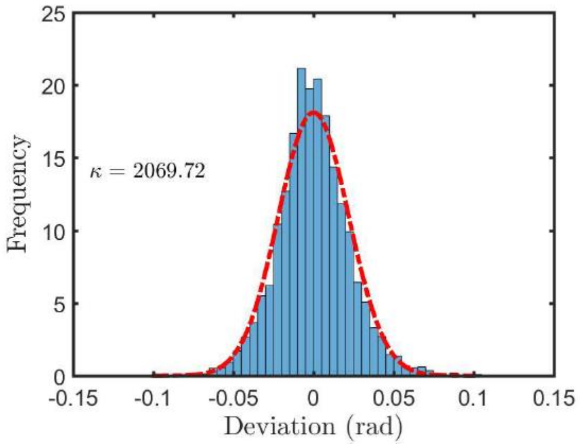
Specimen	Concentration Parameter κ
IM7/8552	1600
AS4/PA12	2000
AS4/PA12_AU	1200
IM7/PEEK	2100
IM7/PEEK_AU	1100

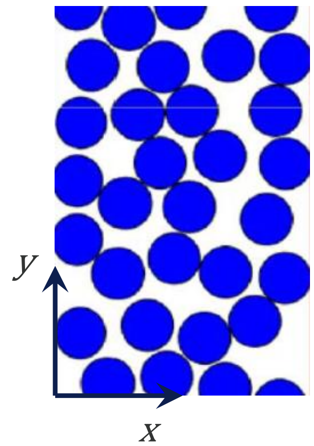
Data generated for 5000 reading per each material

- The thermoplastic materials manufactured by ATP yields the highest values of κ , as an indication of better alignment.
- Melting the cured thermoplastic composites and allow curing at high pressure reduces the void content (as desired), although it increases the fibre misalignment.
- Most of the misalignment data follows $-3 \leq \varphi \leq 3°$.

Modelling fibre misalignment

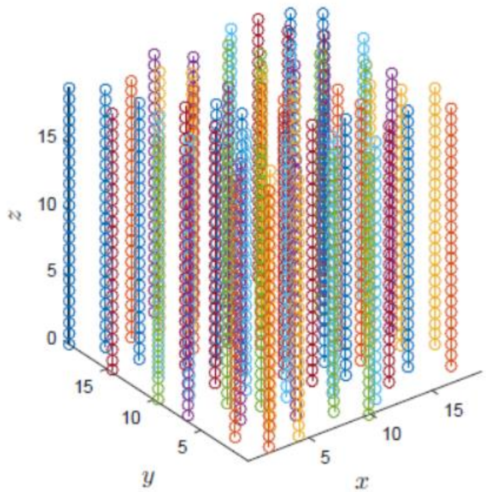
Inputs

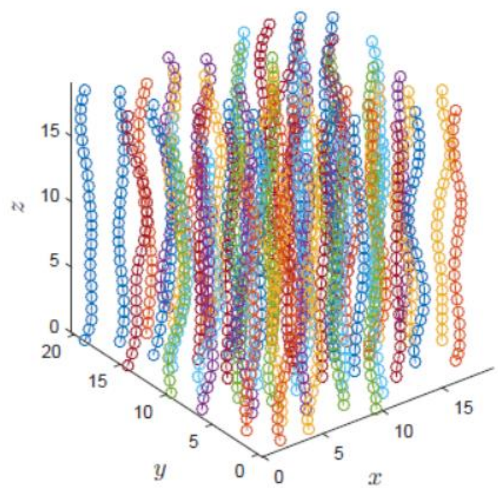




Catalanotti (2016*) Composite Structures 138:84-95,*

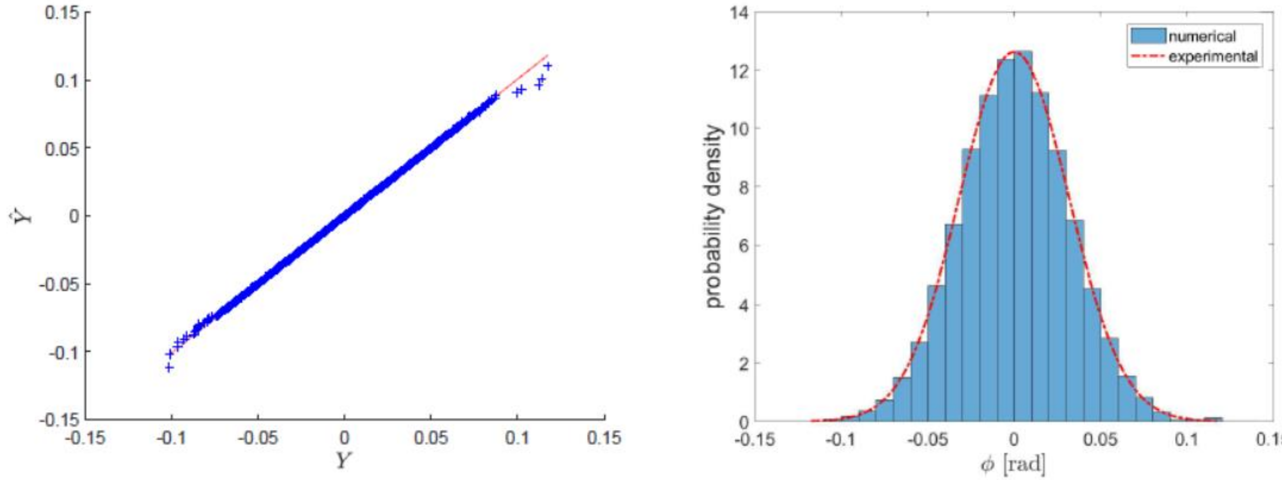
Extrusion of the centres of individual fibres in z-direction and random perturbation





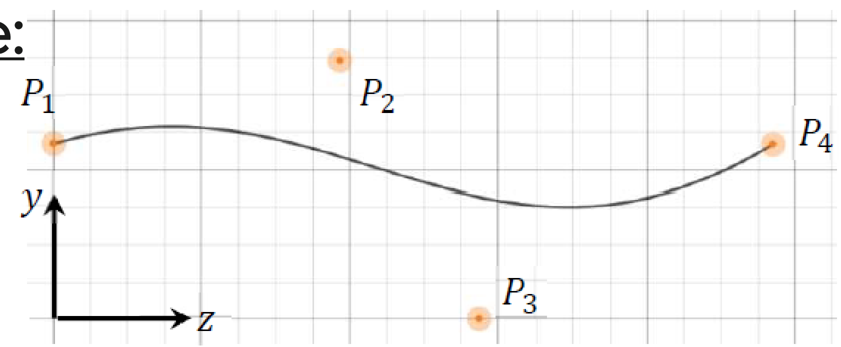
Modelling fibre misalignment

Optimize the position of the control points to fit the experimer



(a) Q-Q plot. (b) pdf of the distributions.

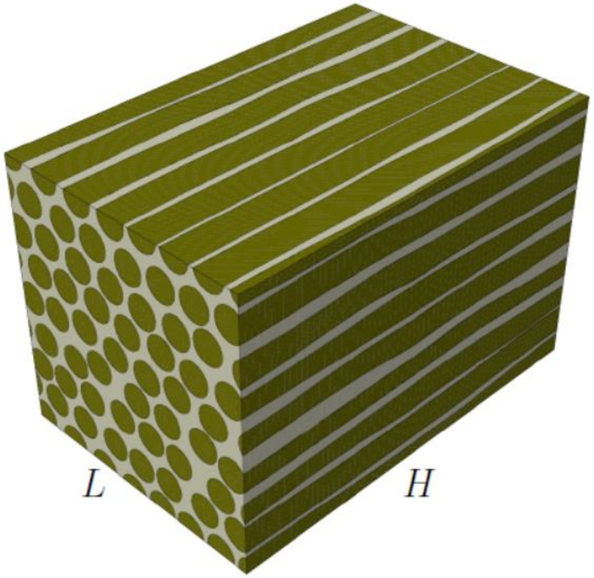
Model each fibre as a Bezier Curve:



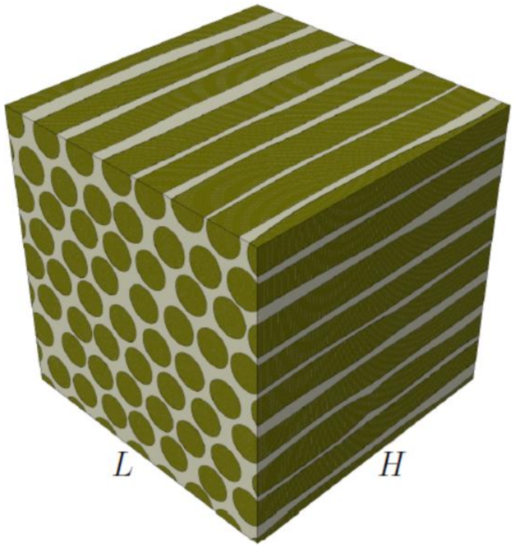
$$B(t) = \sum_{i=1}^{n} \frac{n!}{i! \cdot (n-i)!} \cdot (1-t)^{n-i} \cdot t^i \cdot P_i$$

Modelling fibre misalignment

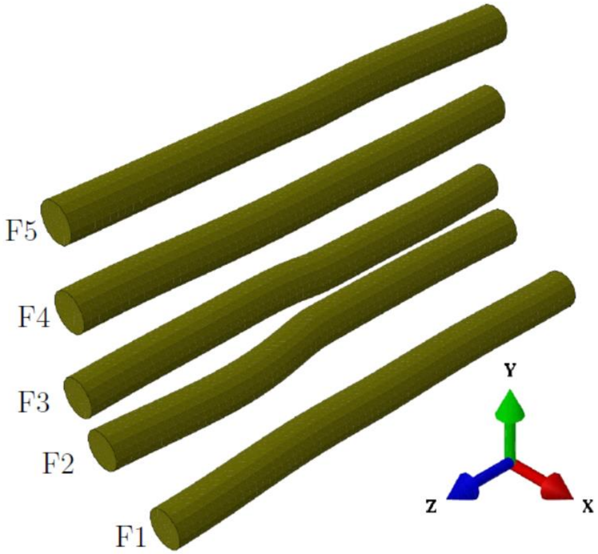
Construct the RVE



IM7/8552 ($\kappa = 1600$)



IM7/PEEK ($\kappa = 2100$)



- The method works for any input data of the RVE size and/or characteristics (fibre volume fraction, fibre diameter, misalignment concentration parameter, etc.)
- Similar to the experimental observations, each individual fibre has its own misalignment. The criteria is the concentration parameter of the whole RVE.

Modelling fibre misalignment

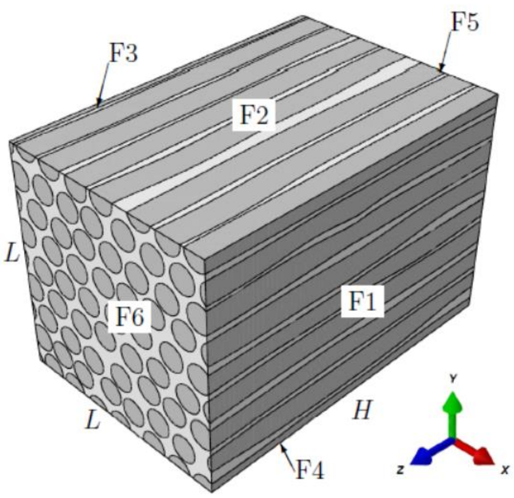
Finite Element Modelling

- Fibres were modelled using C3D8R 8-node linear brick reduced integration elements with hourglass control.
- Due to the complex geometry of the matrix including wavy (non-standard) holes to fit the fibres, the same element type could not be guaranteed.
- To that end, C3D4 4-node linear tetrahedron elements are used to model the matrix material.
- Boundary Conditions:

Longitudinal compression: $u_z^{F5} = \delta_{LC}$, $u_z^{F6} = -\delta_{LC}$ and $u_x^{F6} = u_y^{F5} = 0.0$.

Longitudinal shear: $u_z^{F2} = \delta_{LS}$, $u_z^{F4} = -\delta_{LS}$, and $u_y^{F4} = u_y^{F2} = 0.0$.

Transverse shear: $u_y^{F1} = u_x^{F4} = \delta_{TS}$ and $u_x^{F2} = u_y^{F3} = -\delta_{TS}$



Modelling fibre misalignment

Material Models

- Only **IM7/8552** is considered for the initial stage.
- **Fibres** were modelled as linear elastic orthotropic constitutive behaviour.
- **Matrix** is modelled as concrete damage plasticity model included in Abaqus.
- Fibre-matrix **interface** is modelled using the cohesive surfaces included in Abaqus.

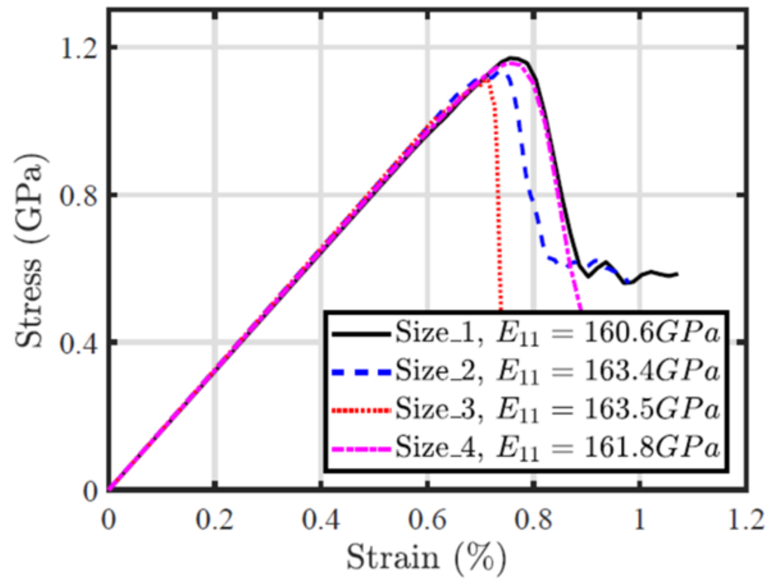
Fiber properties [36, 37]:
Diameter 5.2 = μm; $\rho = 1.78$ g/cm^3; $E_{11} = 276.0$ GPa; $E_{22} = E_{33} = 15.0$ GPa; $\nu_{12} = 0.2$; $G_{12} = G_{13} = 15.0$ GPa; $G_{23} = 7.0$ GPa
Matrix properties [39, 40]:
$\rho = 1.26$ g/cm^3; $E_m = 5.07$ GPa; $\nu_m = 0.35$; $\sigma_m^{t0} = 121$ MPa; $G_m^t = 90$ J/m^2; $\sigma_m^{C0} = 176$ MPa; $\sigma_m^{CU} = 180$ MPa
Interface properties [18, 37, 41]:
$\sigma_c^0 = 50$ MPa; $\tau_c^0 = 70$ MPa; $\eta_{BK} = 1.45$; $\mu_c = 0.52$ $G_{IC} = 2$ J/m^2; $G_{IIC} = G_{IIIC} = 6$ J/m^2

Modelling fibre misalignment

Sensitivity to RVE size and mesh

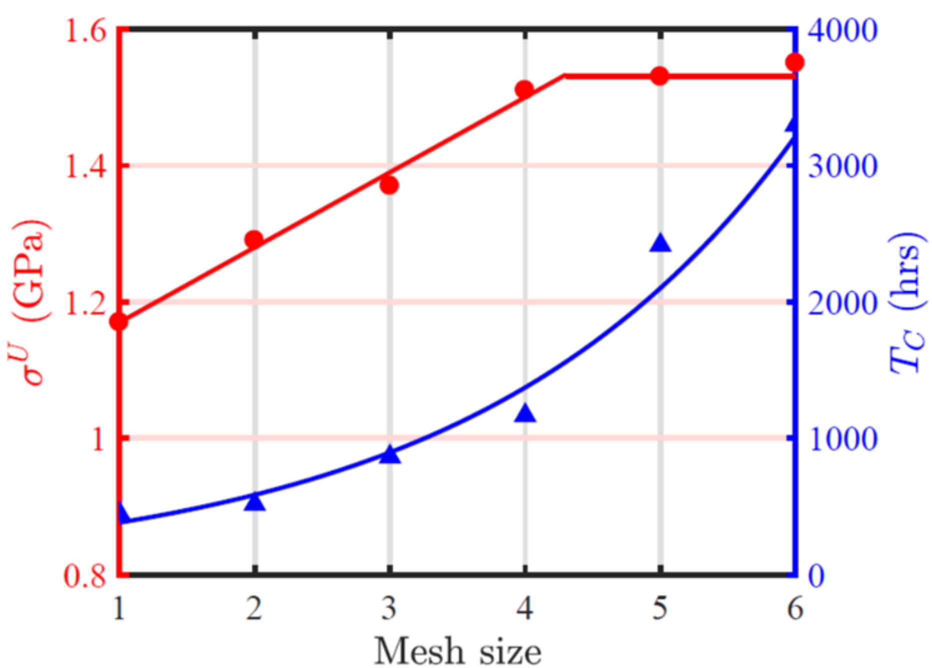
RVE size

Size	L (μm)	H (μm)	# of elements
Size_1	43.845	43.845	479163
Size_2	43.845	87.691	960293
Size_3	43.845	131.548	1126898
Size_4	75.942	75.942	2523780



Mesh size

Mesh	# of Elements
1	479163
2	997962
3	1437978
4	2734645
5	4630976
6	8929419



Size_1 and Mesh 4 are selected to continue the current analysis.

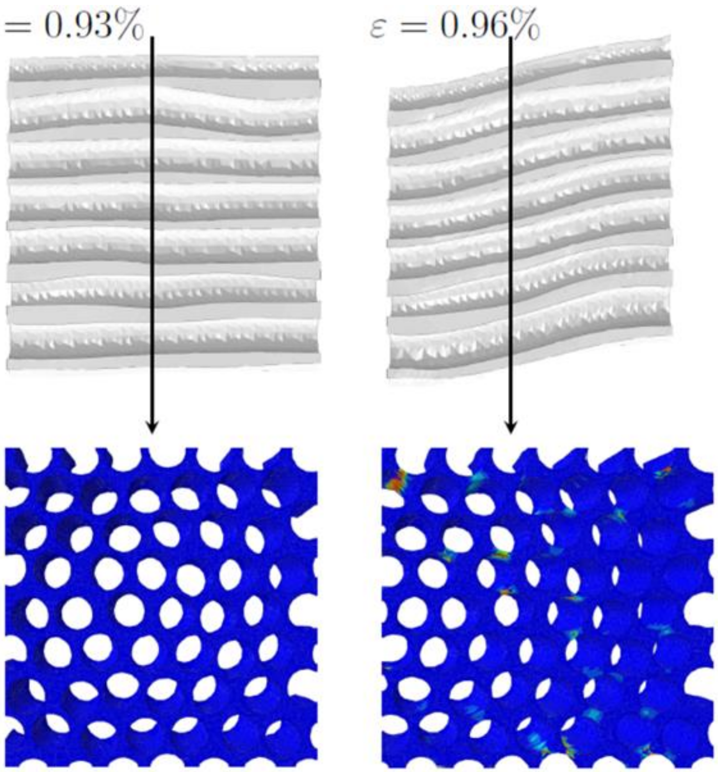
Misalignment effect on

Longitudinal Compression

κ	∞	5000	2400	2000	1600	1200	800
$1/\kappa\ 10^{-4}$	0	2	4.17	5	6.25	8.3	12.5

Misalignments Increased

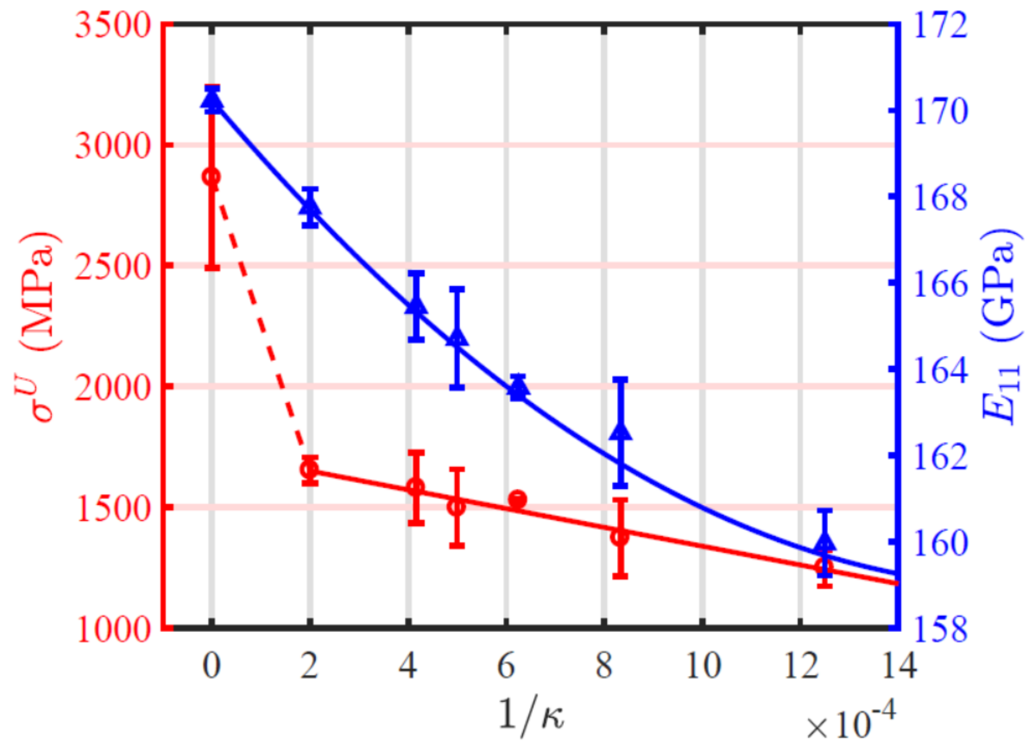
Misalignment does not show any effect over the damage. All the RVEs failed by kinking that promote matrix plasticity and damage, as a standard compression failure mode, which is in agreement with the published data.



Misalignment effect on

Longitudinal Compression

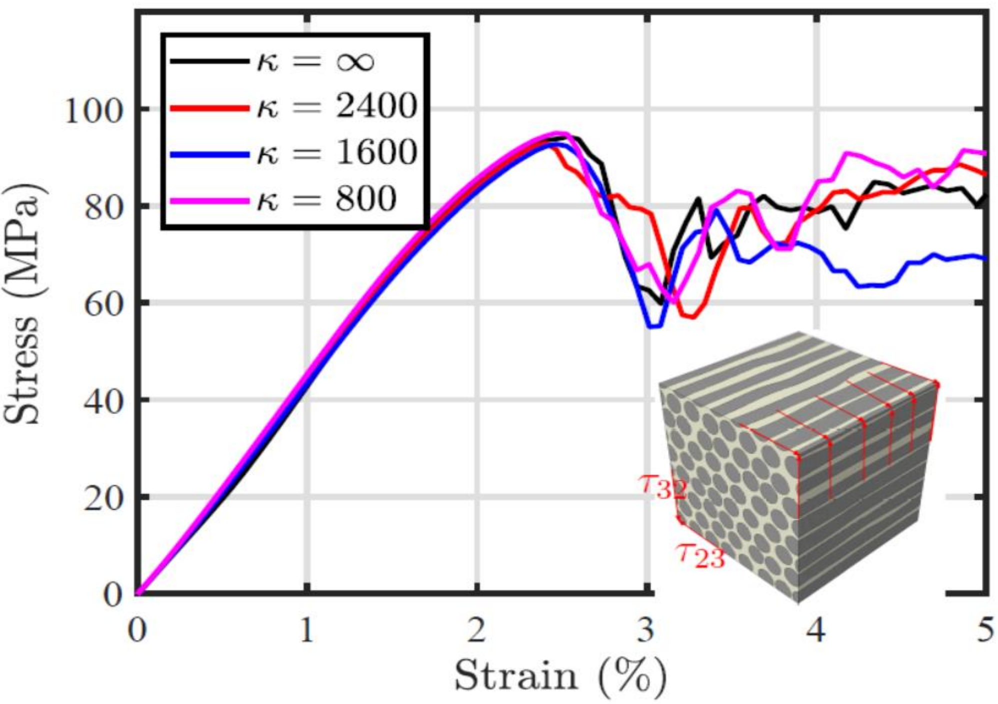
- Both strength and stiffness are affected negatively by increasing the misalignments.
- A great drop in the strength was recorded with any small value of misalignment.
- Predictions are in agreement with the experimentally measured values for the IM7/8552 carbon/epoxy composites. ($X^C = 1690$ MPa and $E_{11} = 165$ GPa)

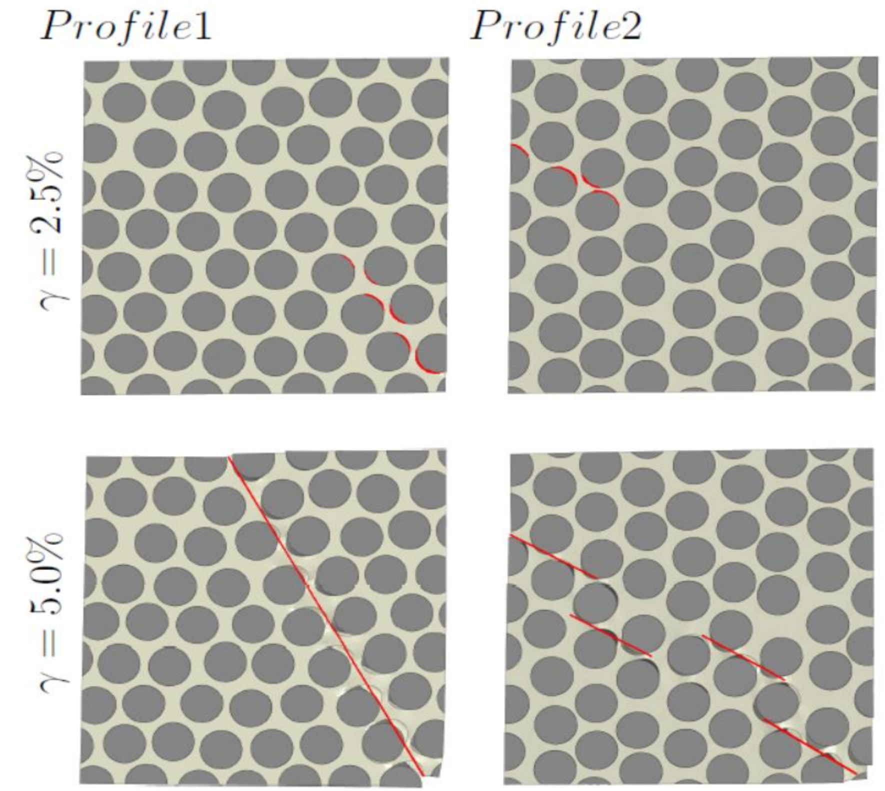


Misalignment effect on

Transverse Shear

- No effect was recorded for the misalignment on the strength, the stiffness, and the failure profile.
- Failure is governed by de-bonding between the fibres and the matrix with different profiles.

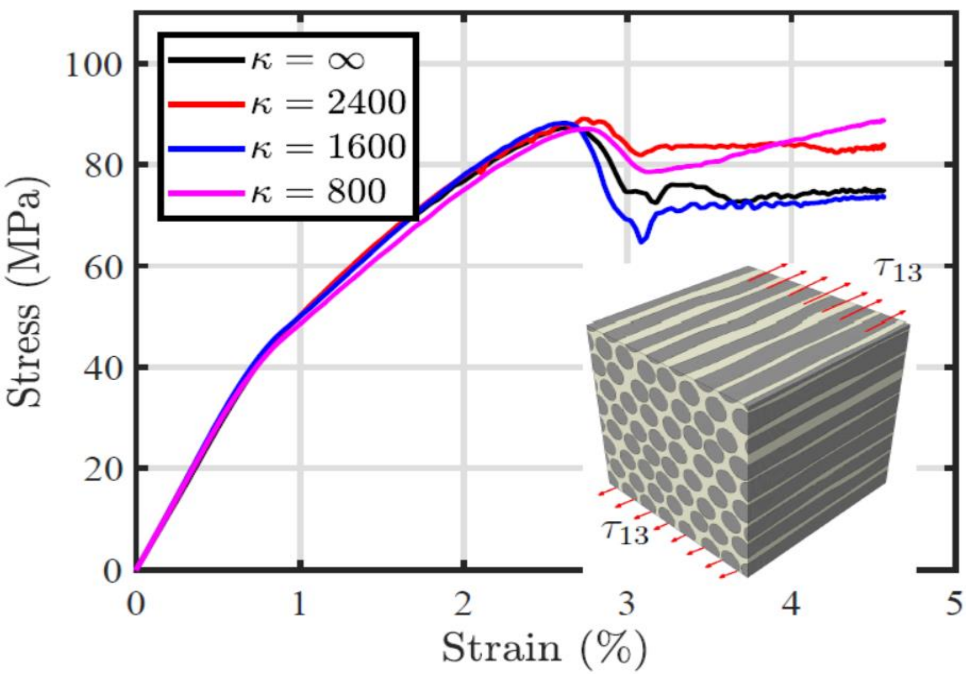


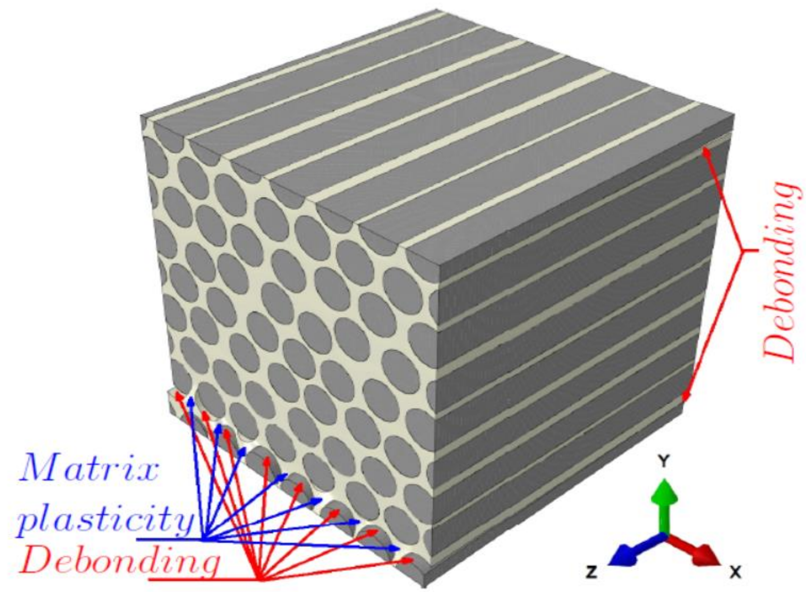


Misalignment effect on

Longitudinal Shear

- No effect was recorded for the misalignment on the strength, the stiffness, and the failure profile.
- Failure initiated by de-bonding between the fibres and the matrix that promoted matrix plasticity and damage.





Property	$\kappa = 800$	$\kappa = 1600$	$\kappa = 2400$	$\kappa = \infty$
$\tau_{13}^U = \tau_{12}^U$ (MPa)	$87.0^{\pm 2.5}$	$89.6^{\pm 3.2}$	$90.4^{\pm 1.3}$	$88.9^{\pm 2.6}$
$G_{13} = G_{12}$ (GPa)	$5.43^{\pm 0.15}$	$5.43^{\pm 0.03}$	$5.43^{\pm 0.04}$	$5.37^{\pm 0.14}$

Summary and Conclusions

- This work presents a method to consider the fibre misalignment in micromechanical modelling of composites. The method starts from the experimental characterization and proceeds by statistical analysis, geometrical modelling and Finite Element analysis.
- The method works for any material with misalignment addressed by the von Mises distribution parameter.
- The damage configurations predicted from the current analysis were identical to those found in the literature.

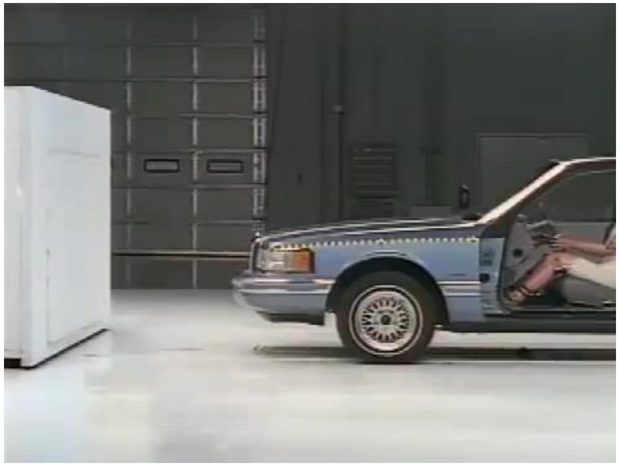
Summary and Conclusions

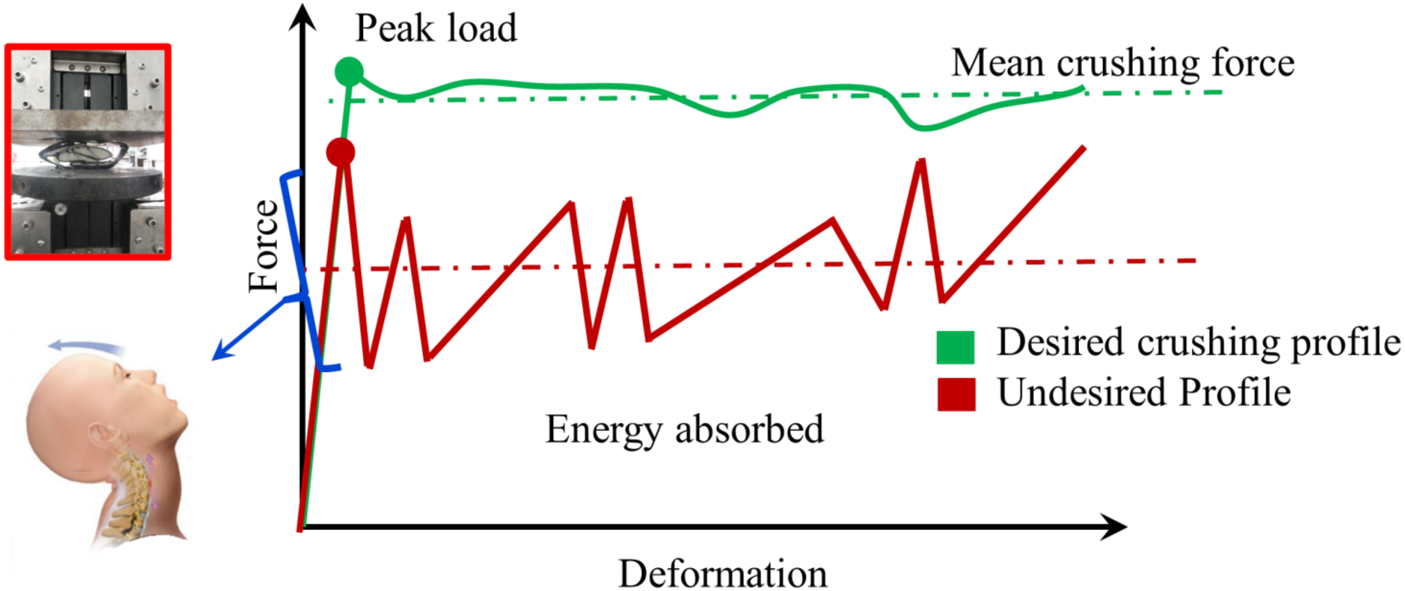
- Unlike our initial fear, the material constants and the strength coefficients are comparable to the experimental data with the maximum deviation of 10% in stiffness and 6% in strength.

- With these results, the periodic boundary conditions seem to have less effect on the accuracy in 3D modelling, compared to the 2D modelling of composite RVEs, which is an indication that the volume of the material in our RVE is representative to the actual material.

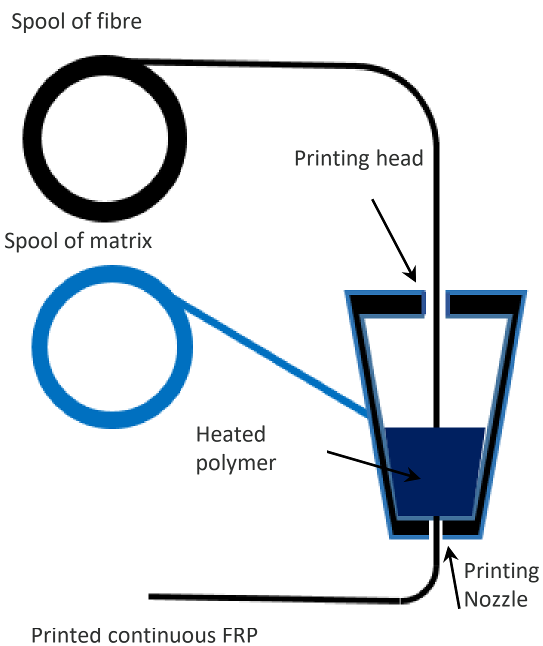
- Further investigations are still needed to confirm these findings under different loading conditions.

- Automotive Structures Crushing

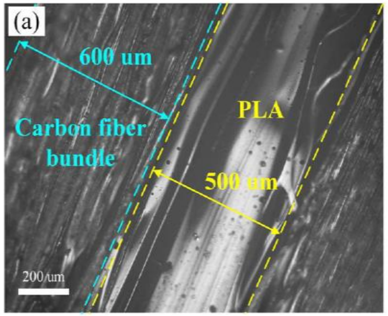




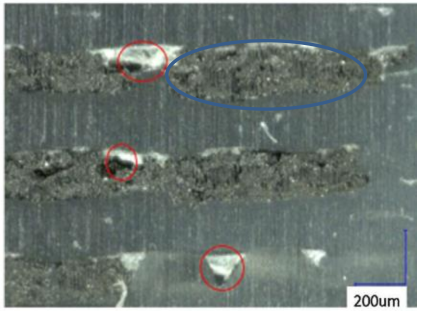
3D printing of continuous FRP composites



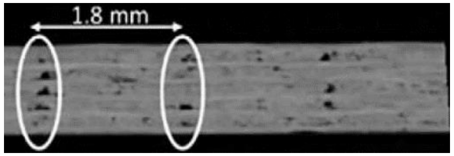
(a) Schematic sketch



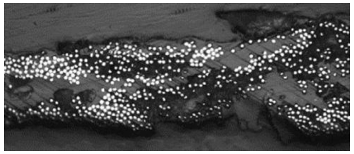
(b) Thick FRP and pure polymer plies (Li et al. 2016)



(d) oval fibre bundle, thick matrix layer and voids (Dickson et al. 2017)



(c) voids between filaments (Goh et al. 2018)



(e) low fibre volume fraction (Justo et al. 2018)

Figure 2. *Basic features of printing continuous fibre-reinforced plastics using FDM.*

Thanks

Any Questions