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PREDICTING THE CONSOLIDATION OF FABRIC-REINFORCED STRUCTURAL POWER COMPOSITES

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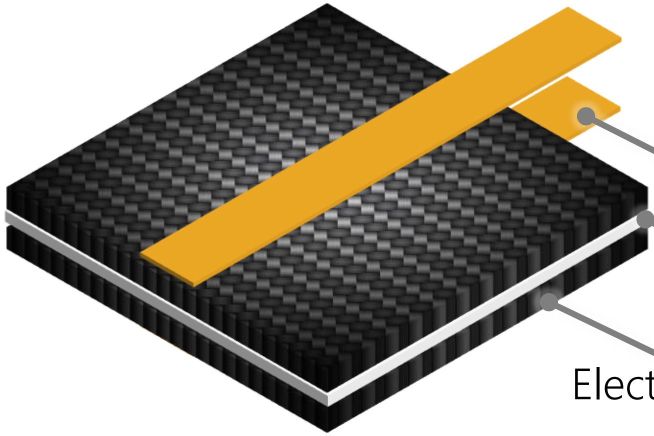
Overview

- Introduction — Why consolidation?
- Experimental — Woven reinforcements and compressibility characterisation.
- Modelling — Mono- and multi-layer reinforcement modelling approach.
- Results — Predictions vs. observations; surface modifications.
- Conclusions — Implications and future work.

Introduction

- Goal of structural power composites (SPCs): achieve competitive energy and power densities while maintaining structural integrity.
- To date, most of the successfully demonstrated SPC devices employ a laminated construction[1,2], combining woven fabric reinforcements (WFR) in a hybrid layup.
- Optimal consolidation of the reinforcements is key for both mechanical and electrochemical performance of SPCs.



[1] Asp LE, Greenhalgh ES. *Structural power composites*. Compos Sci Technol 2014;101:41–61. doi:10.1016/j.compscitech.2014.06.020.
[2] Hudak NS, Schlichting AD, Eisenbeiser K. *Structural Supercapacitors with Enhanced Performance Using Carbon Nanotubes and Polyaniline*. J Electrochem Soc [Internet] 2017;164(4):A691–700. doi:10.1149/2.0721704jes

Motivation for current work

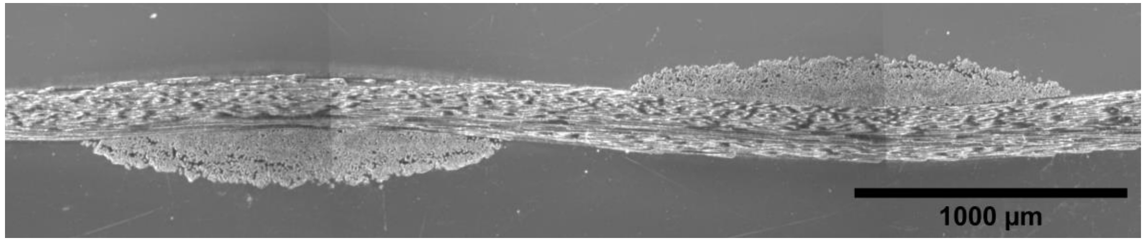
1) • Reinforcement choice and/or surface modifications determine layup consolidation properties[3], and hence, the attainable fibre volume fraction (FVF) and micro-/meso-structures.
   • Expect strong link between structure and SPC properties, as is the case for conventional composites[4].
   • Ability to predict structure and properties will aid selection of reinforcements and processing specifications.

2) • Need for predictive modelling to assist multifunctional device design and optimisation[5].
   • Mechanical and electrochemical FEA relies on realistic geometric models as a starting point[4].
   • Generation of accurate geometric models of WFRCs often involves a process modelling step.

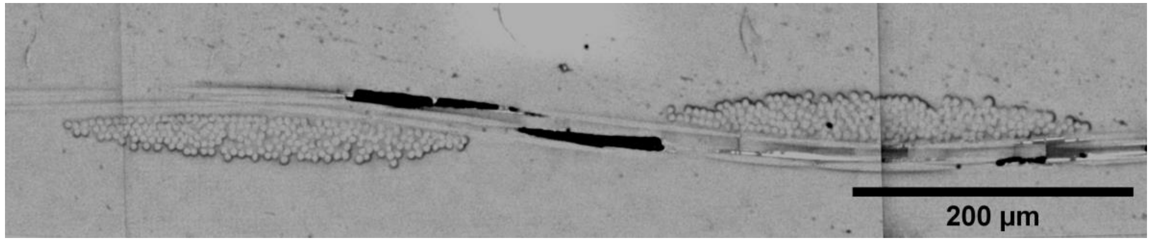
[3] Lomov S V., Gorbatikh L., et al. *Compressibility of carbon woven fabrics with carbon nanotubes/nanofibres grown on the fibres.* Compos Sci Technol 2011;71:315–25. doi:10.1016/j.compscitech.2010.11.024. [4] Gereke T, Döbrich O, Hübner M, Cherif C. *Experimental and computational composite textile reinforcement forming: A review.* Compos Part A Appl Sci Manuf 2013;46:1–10. doi:10.1016/j.compositesa.2012.10.004. [5] Gibson RF. *A review of recent research on mechanics of multifunctional composite materials and structures.* Compos Struct 2010;92(12):2793–810.

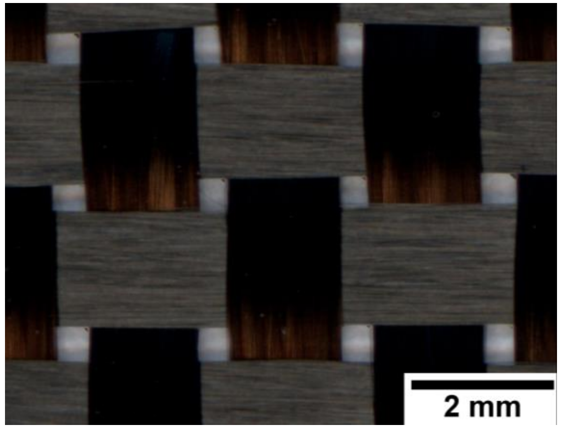
Materials

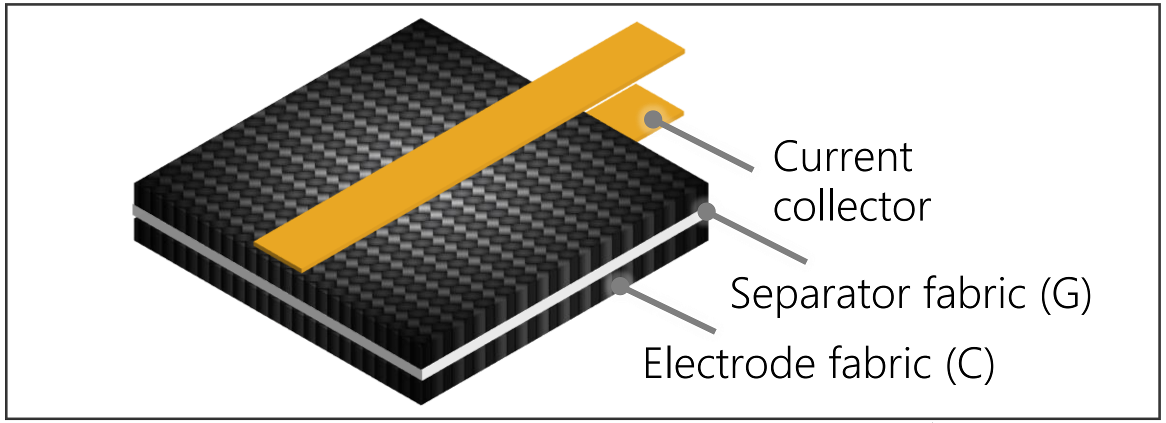
Electrode: Chomarat C-WEAVE™ 200P 3K HS (**C**)

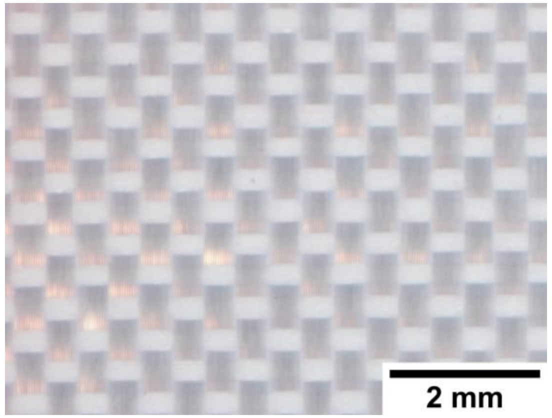


Separator: Gividi Fabrics srl 1086 (**G**)





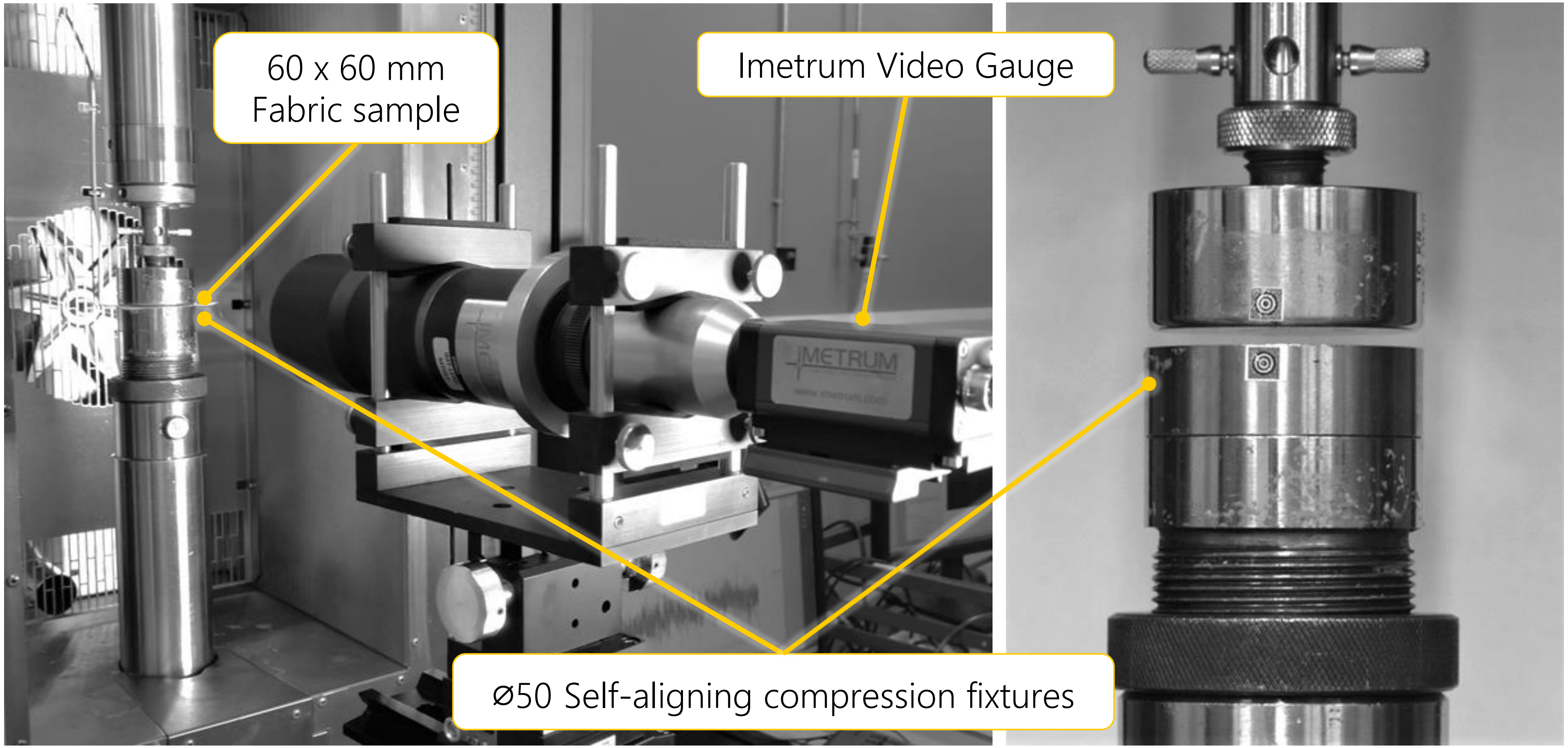




Layups characterised:

Monolayer	C , G
Monolithic multilayer	C_2 , G_2
Hybrid multilayer	CG , CGC

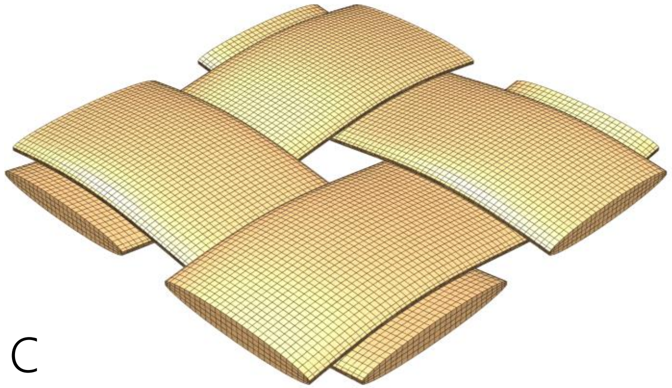
Experimental setup



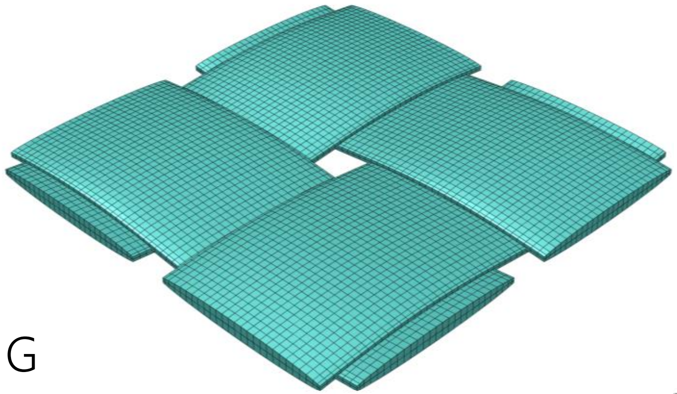
Transverse compression test setup

Modelling methodology

- Each fabric modelled as a meso-scale unit cell (UC).
- Average geometric parameters determined from optical microscopy.
- Yarns idealised as continuous, transversely-isotropic, with homogenised properties.
- Fabric compression response is highly non-linear[6].
- FE sensitivity studies established that the transverse modulus of yarns (E_2) governs this response.



C



G

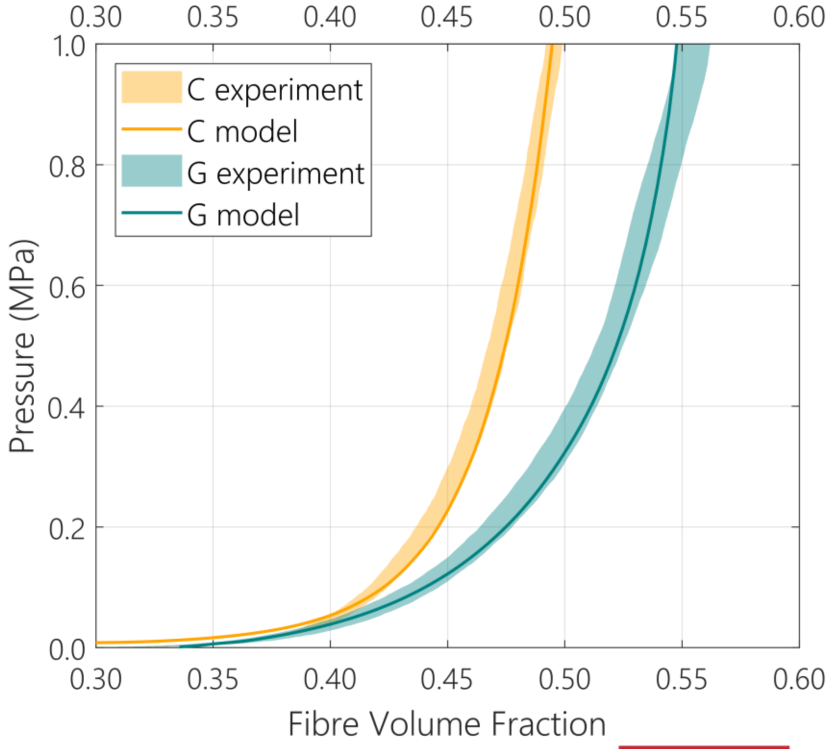
[6] Robitaille F, Gauvin R. *Compaction of textile reinforcements for composites manufacturing. I: Review of experimental results.* Polym Compos 1998;19:198–216. doi:10.1002/pc.10091.

Modelling methodology

- Assumed bi-exponential evolution of E_2 with local FVF($V_{f,l}$): $E_2 = a\,\exp(b\,V_{f,l}) + c\,\exp(d\,V_{f,l})$
- $V_{f,l}$ calculated based on the element volume change, represented by the Jacobian (J):

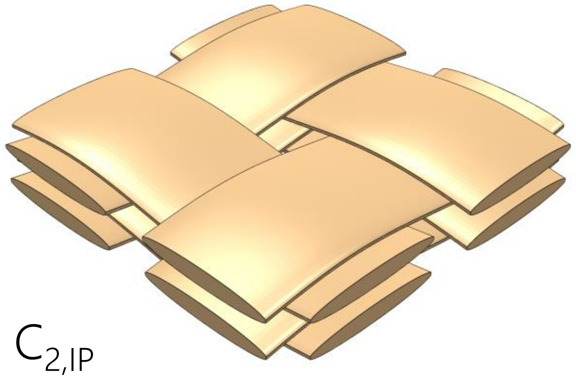
  $V_{f,l} = V_{f,l,0}\,/\,J$ and $J = \det(F)$

  where F is the deformation gradient and $V_{f,l,0}$ is the undisturbed FVF.
- Nonlinearity of E_2 implemented through a user subroutine (VUMAT).
- Monolayer models calibrated against measured compression responses.

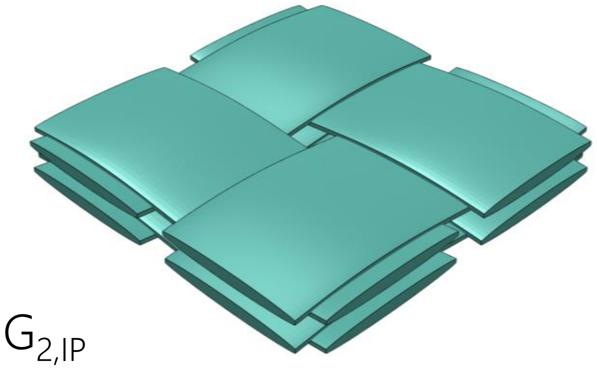


Modelling methodology

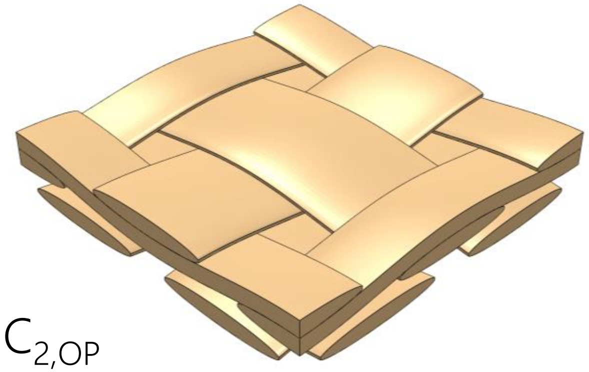
- Inter-ply nesting is a key feature of fabric reinforced composites.
- Range of possible nesting configurations in multilayer fabric stacks, resulting in range of architectures.
- Limiting cases of minimum and maximum nesting of adjacent layers considered:
  - in-phase (IP)
  - 90º out-of-phase (OP)



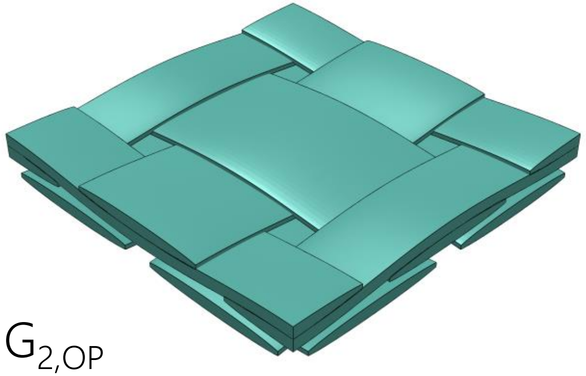
$C_{2,IP}$



$G_{2,IP}$



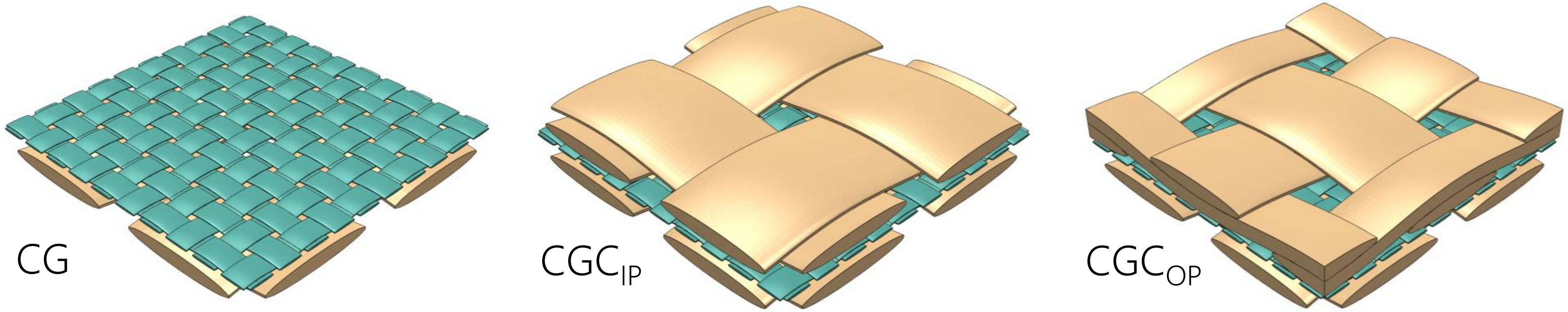
$C_{2,OP}$



$G_{2,OP}$

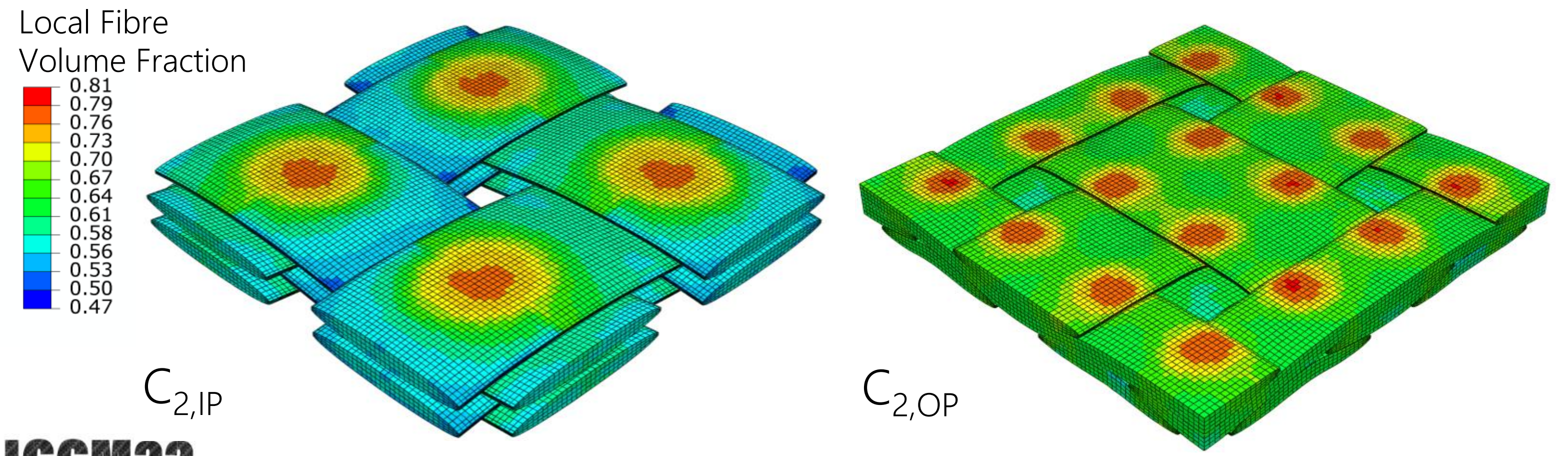
Modelling methodology

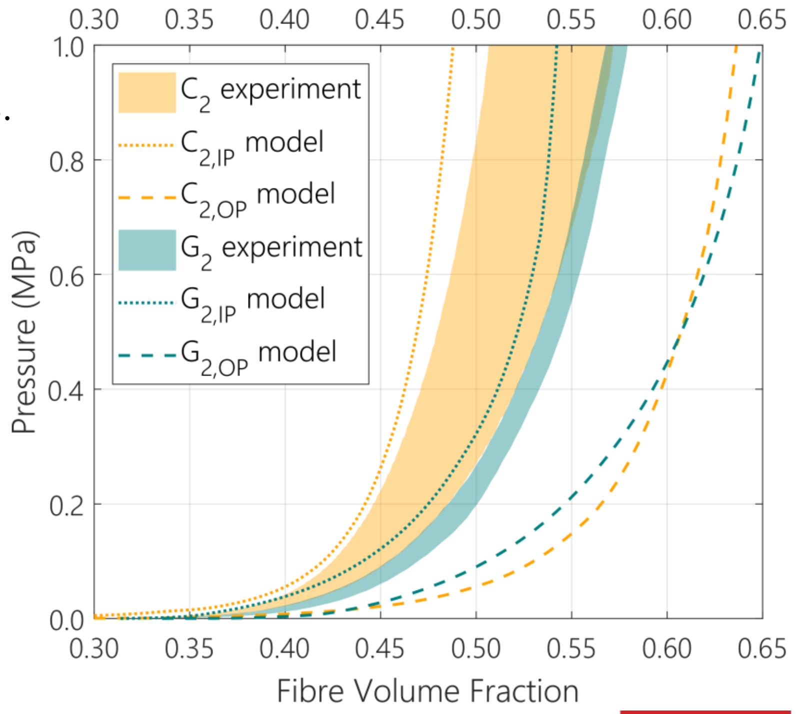
- Dissimilar geometry of C and G requires tessellation of UCs to construct a multilayer hybrid unit cell (hUC).
- To minimise computational domain while preserving periodicity, hUCs constructed using approximate fabric geometric parameters within measurement variability (1σ), resulting in a 1:5 tessellation ratio.
- Limiting cases of nesting considered for CGC (device) stack.



Results

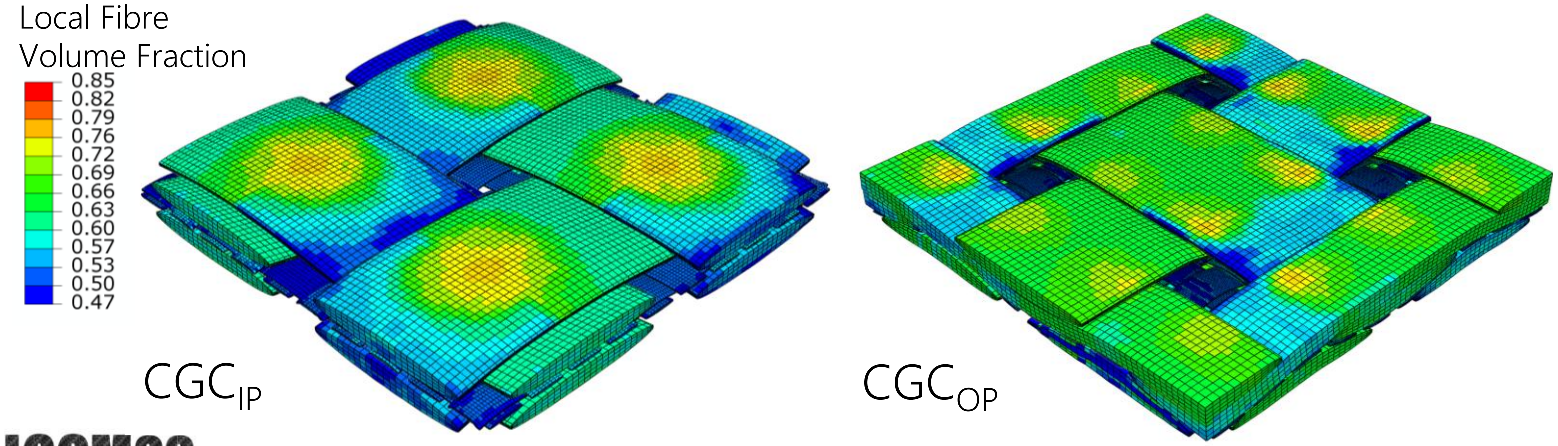
- Monolithic multilayer results indicate OP stacking results in greater structural homogeneity and higher FVF than IP.
- Difference between IP and OP model compaction responses greater than experimentally measured range, indicating only moderate nesting achieved in practice. Process variability, ply misalignment and shear as possible causes.

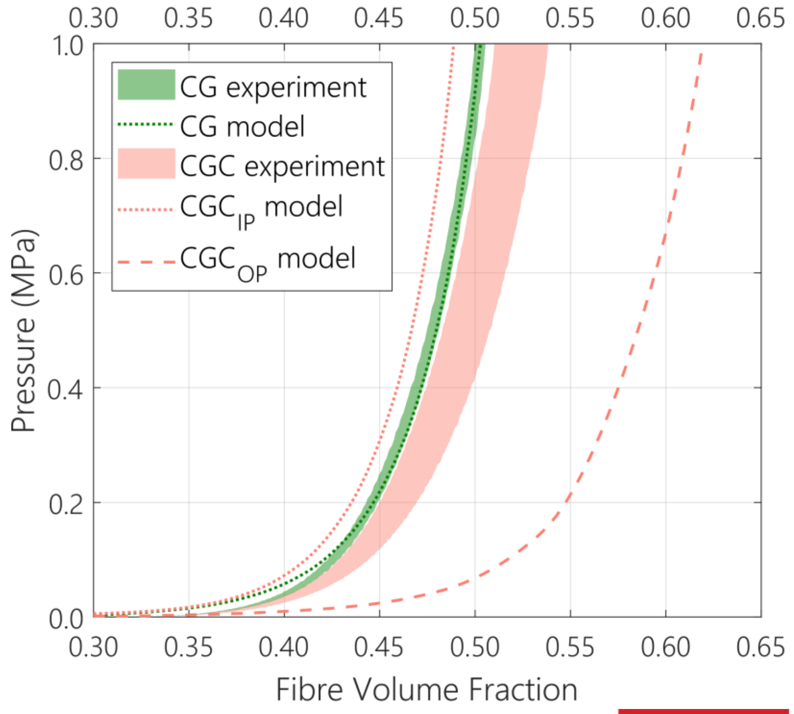




Results

- IP vs. OP CGC hybrid model results suggest C-C nesting may still be transmitted through separator fabric G.
- In practice, experimental consolidation range displays only moderate inter-ply nesting.





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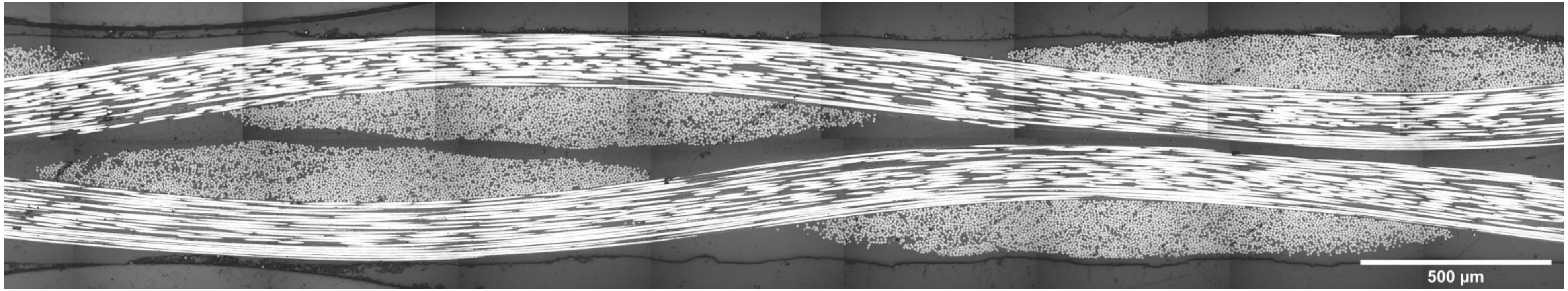

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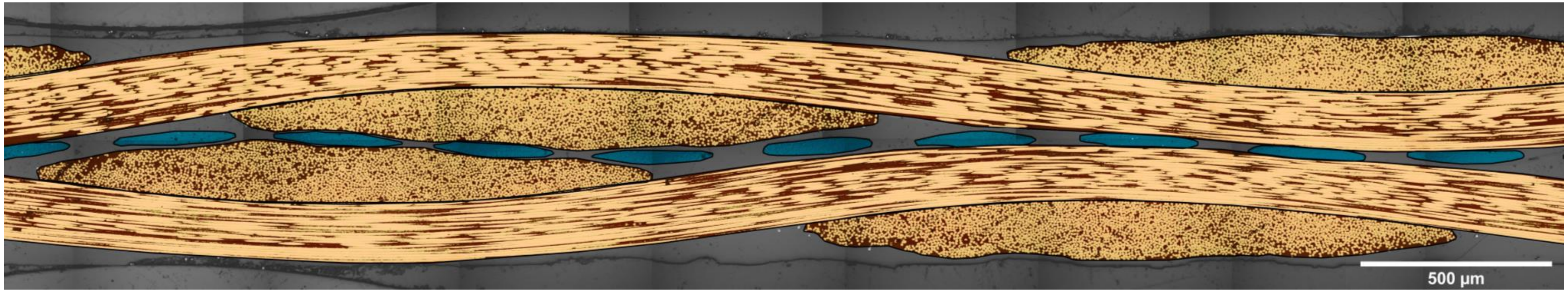

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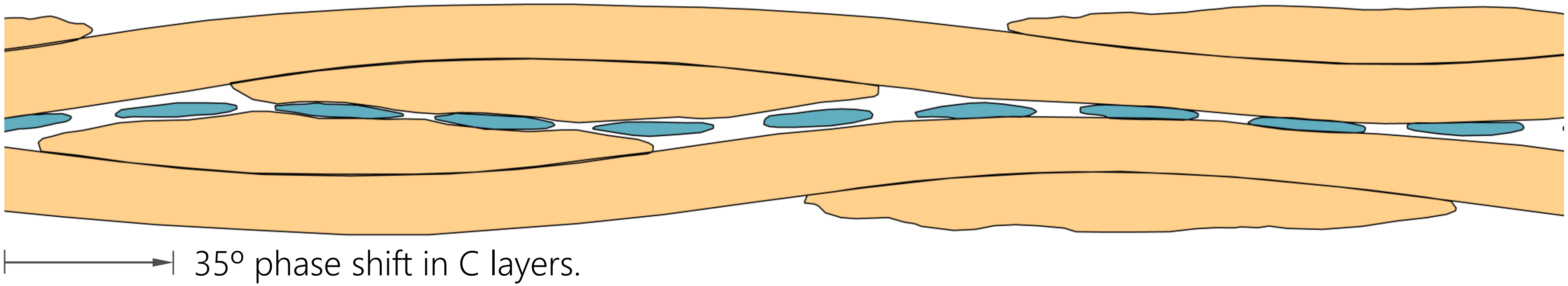
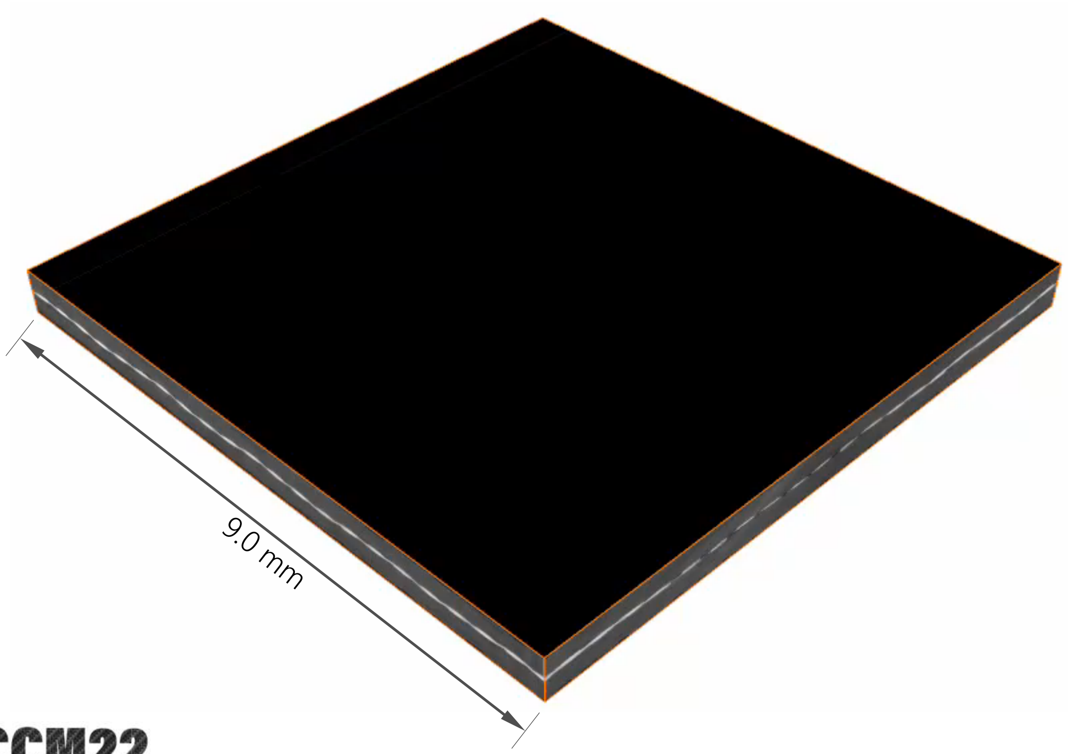
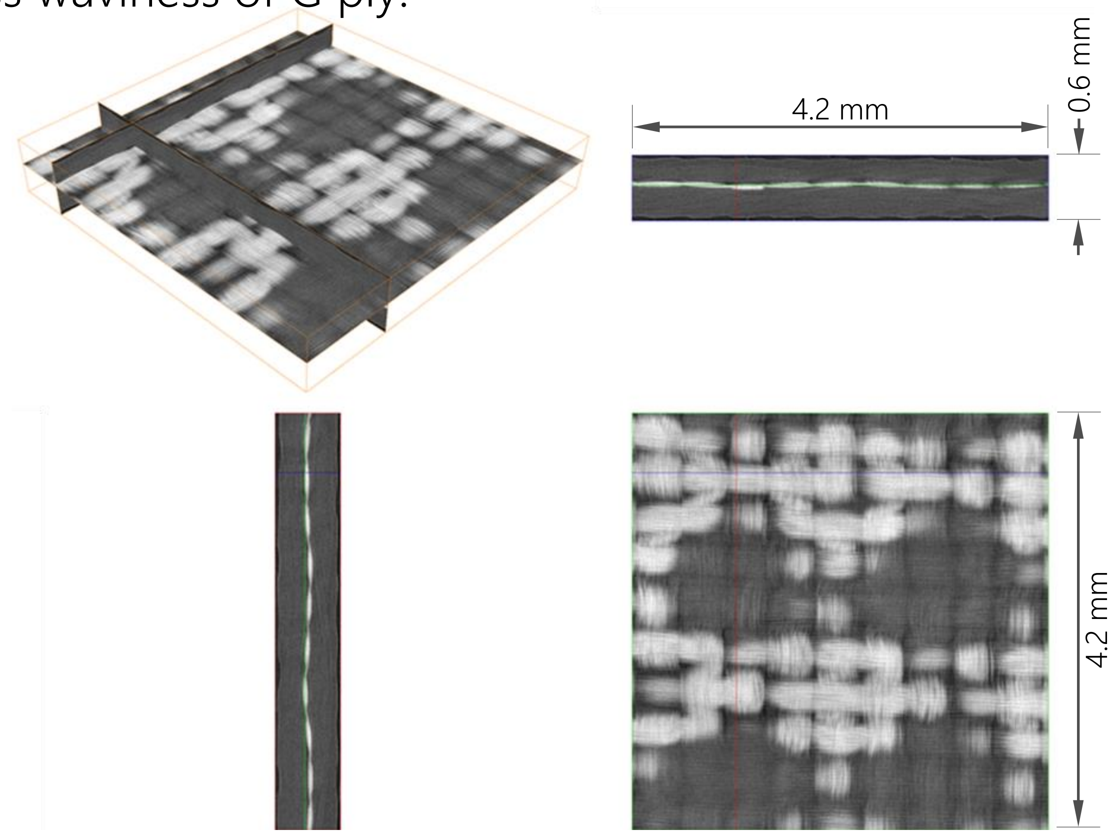


35° phase shift in C layers.

Results

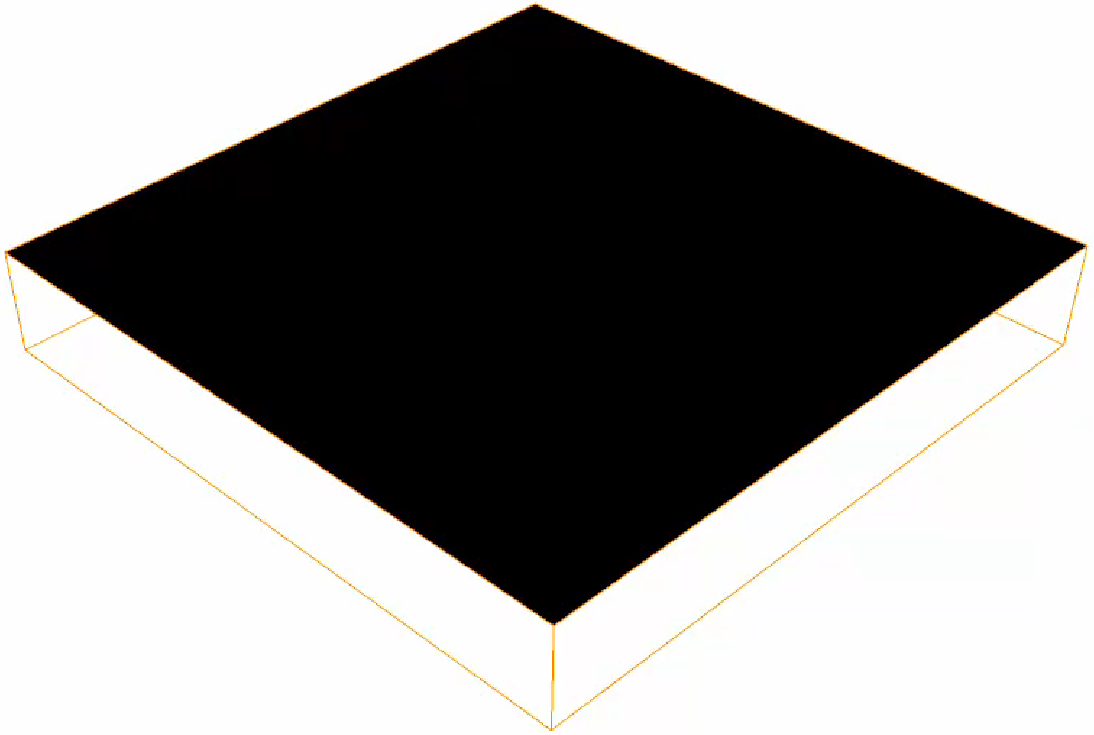
- X-ray µCT: C-C nesting evidenced by through-thickness waviness of G ply.

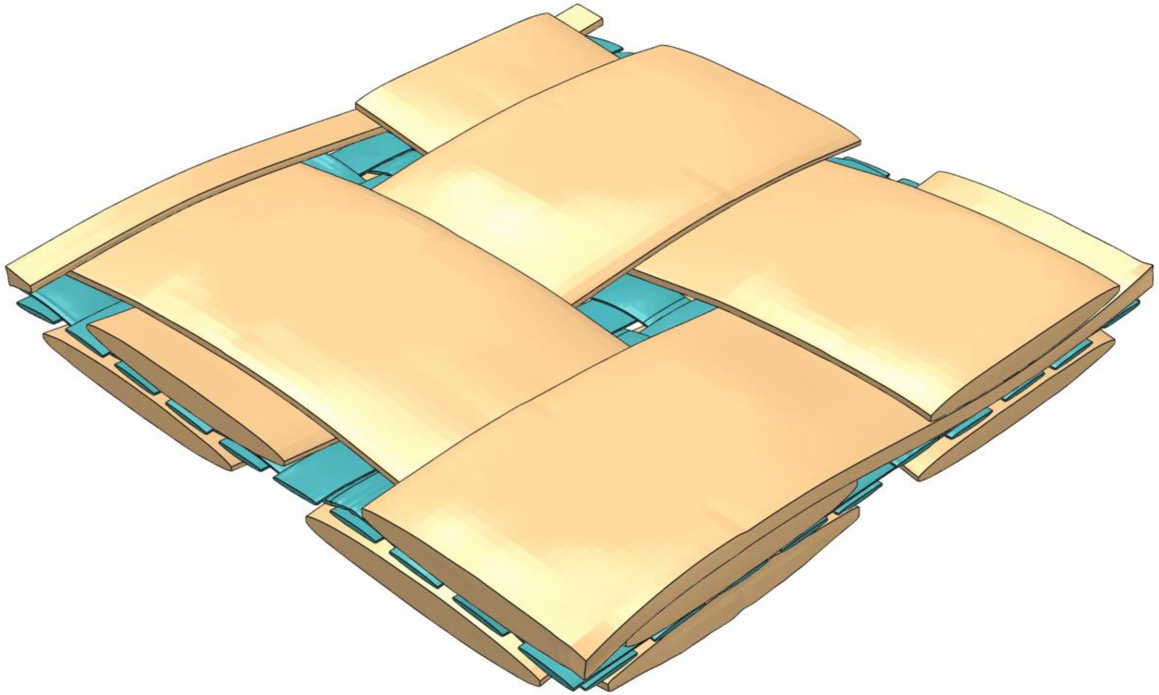




Results

- Through-thickness waviness features observed in X-ray μCT captured in 35° phase shift model.





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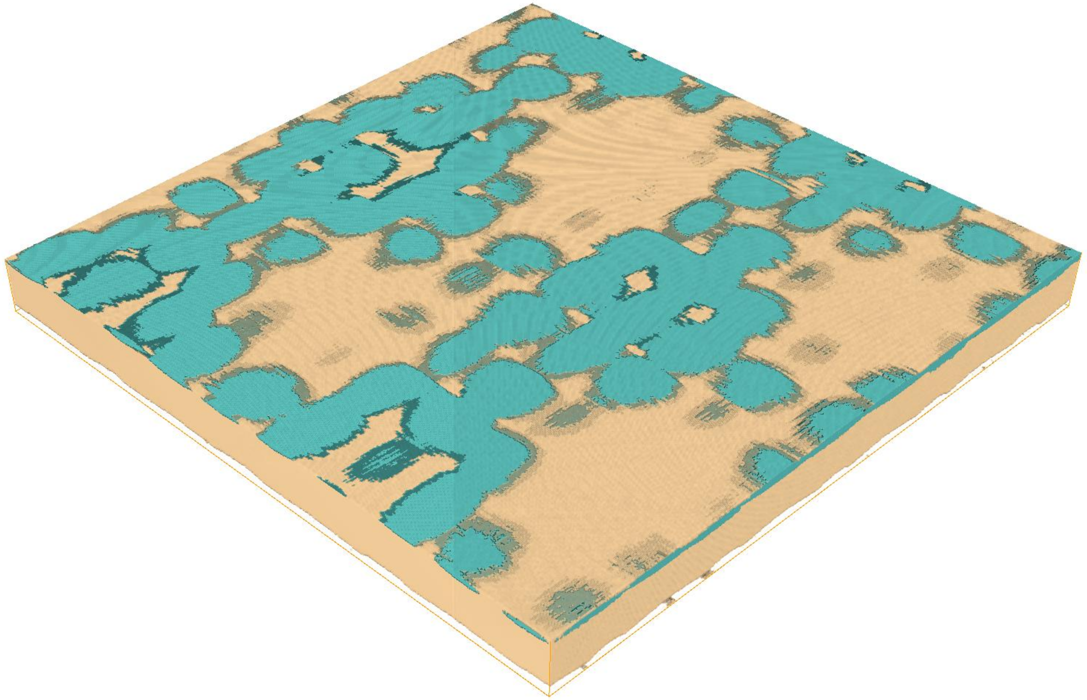
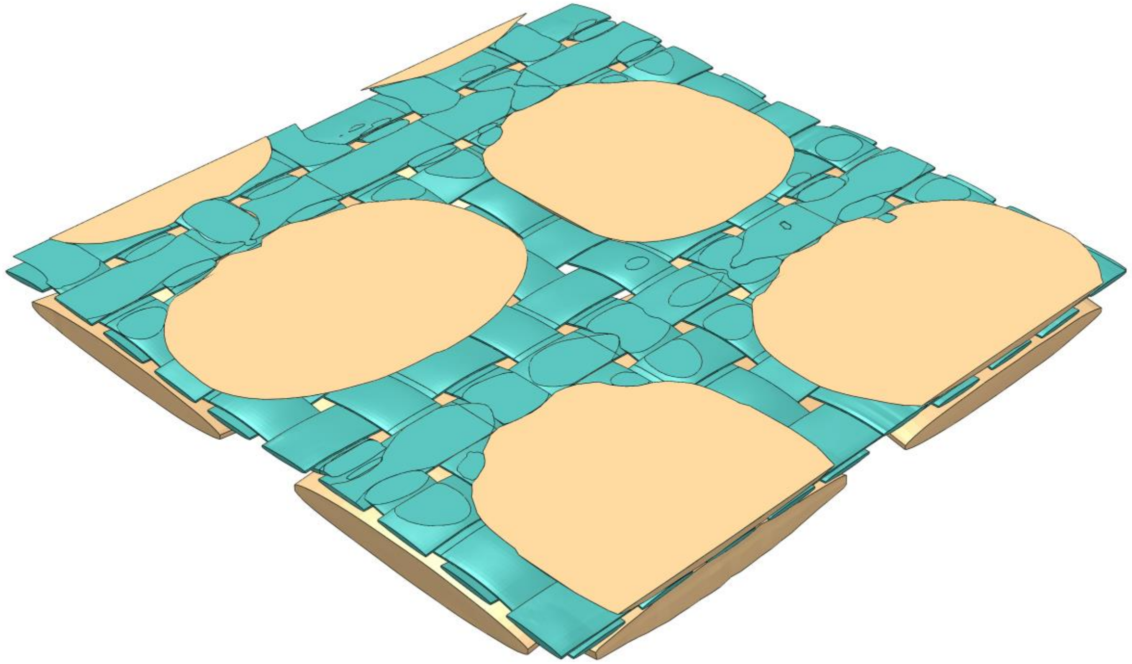
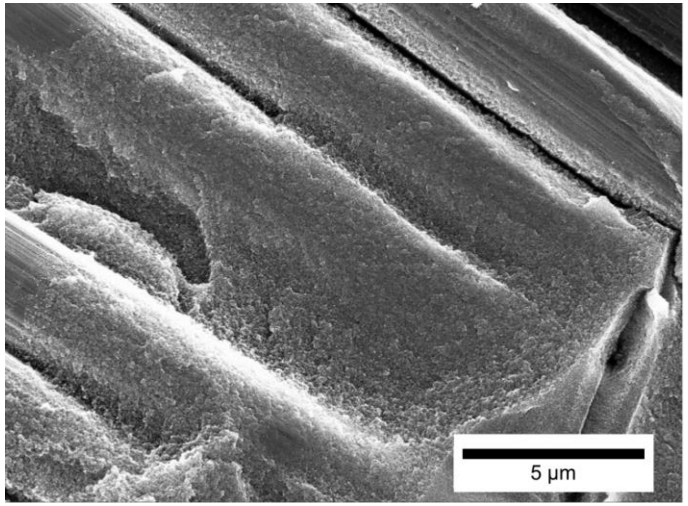
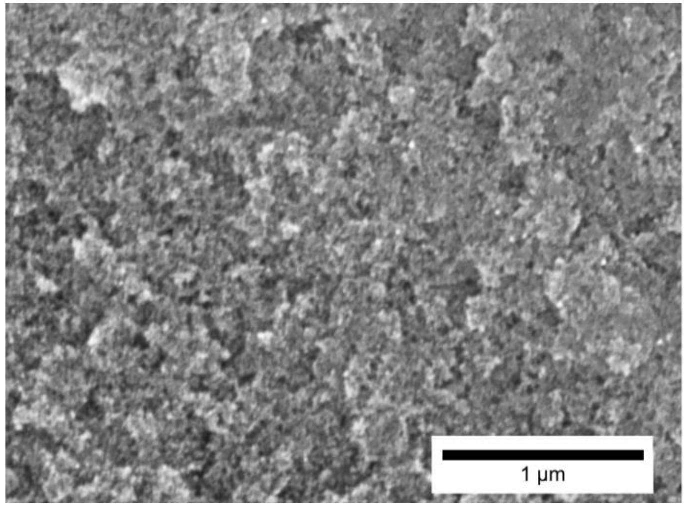


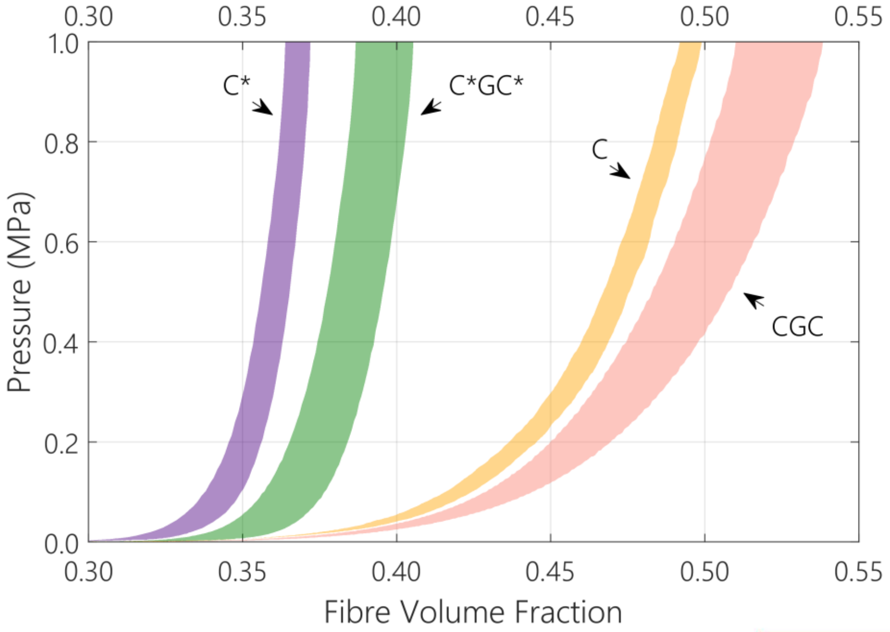


Results

- Fibre surface modifications often pursued as means to increase electrode surface area, e.g. carbon aerogel (CAG).
- CAG-modified carbon fibre fabric (C*) and associated device layup (C*GC*) display a marked decrease in compressibility in transverse compaction tests.

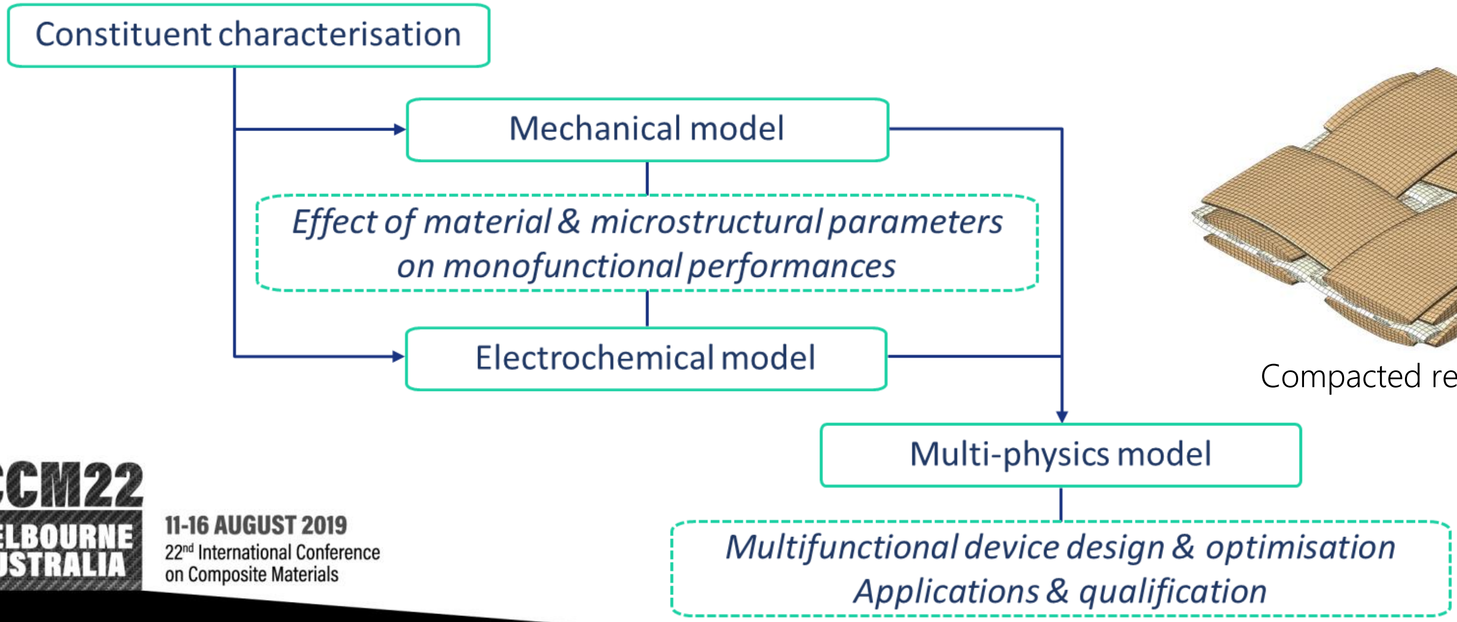


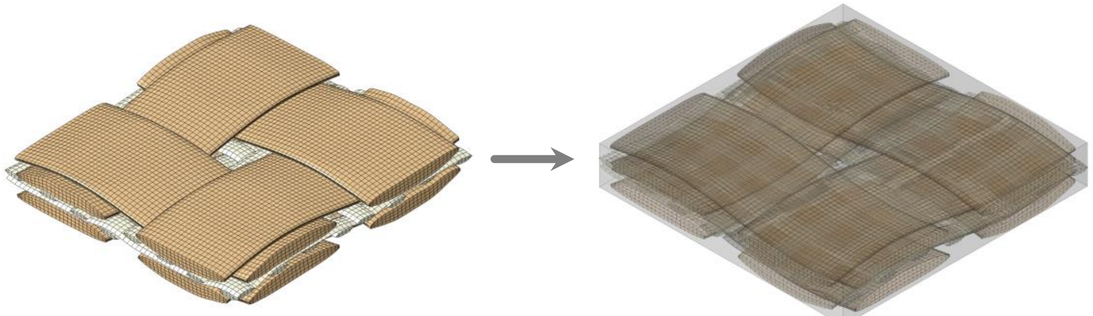




Conclusions

- Procedure for generation of meso-FE models of WFR SPCs established.
- Attainable FVF in SPCs dependent on selection of reinforcements and/or presence of surface modifications; additional limitations due to layup process and ply variability.
- 3D models of device meso-architecture to be used in further mechanical and electrochemical FEA.





Compacted reinforcements

Multifunctional laminate

Imperial College London

AIRBUS

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