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.
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.
Materials

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

Separator: Gividi Fabrics srl 1086 (G)

Layups characterised:

<table>
<thead>
<tr>
<th>Layup</th>
<th>Fabric Combination</th>
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</thead>
<tbody>
<tr>
<td>Monolayer</td>
<td>C, G</td>
</tr>
<tr>
<td>Monolithic multilayer</td>
<td>C₂, G₂</td>
</tr>
<tr>
<td>Hybrid multilayer</td>
<td>CG, CGC</td>
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</tbody>
</table>

Current collector
Separator fabric (G)
Electrode fabric (C)
Experimental setup

Transverse compression test setup

60 x 60 mm Fabric sample

Imetrum Video Gauge

Ø50 Self-aligning compression fixtures
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.
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)
  - 90° out-of-phase (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.

![Graph showing local fibre volume fraction and pressure vs. fibre volume fraction for CGC_{IP} and CGC_{OP} models.](image)
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• In practice, experimental consolidation range displays only moderate inter-ply nesting. Findings supported by optical microscopy:

  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.
Results

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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.
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