Engineering and Physical Sciences Research Council

Enhanced Performance and Productivity via Integration of Multi-scale Modelling

1st August 2023

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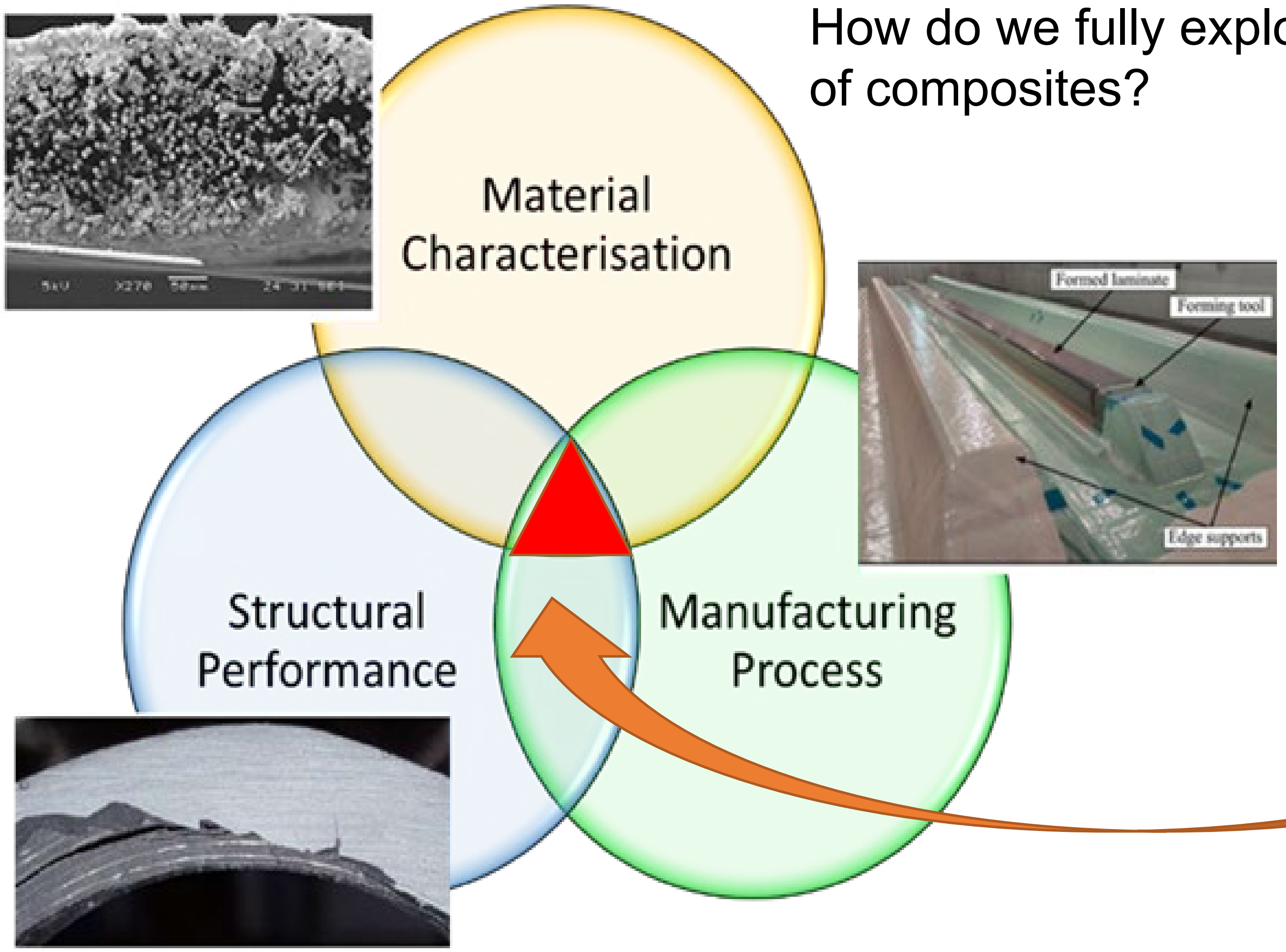
University of Bristol · University of Bath · University of Southampton · University of Exeter

Motivation

How do we fully exploit performance and productivity of composites?



Productivity-driven composite parts requires full integration of materials, manufacturing and structures

Overview

- Part **Formability** – opportunities of non-standard ply angles
- Coupon-level testing – limitations of “Black Metal” approach to certification
- Multiscale modelling: a new pathway to part-level design and certification?

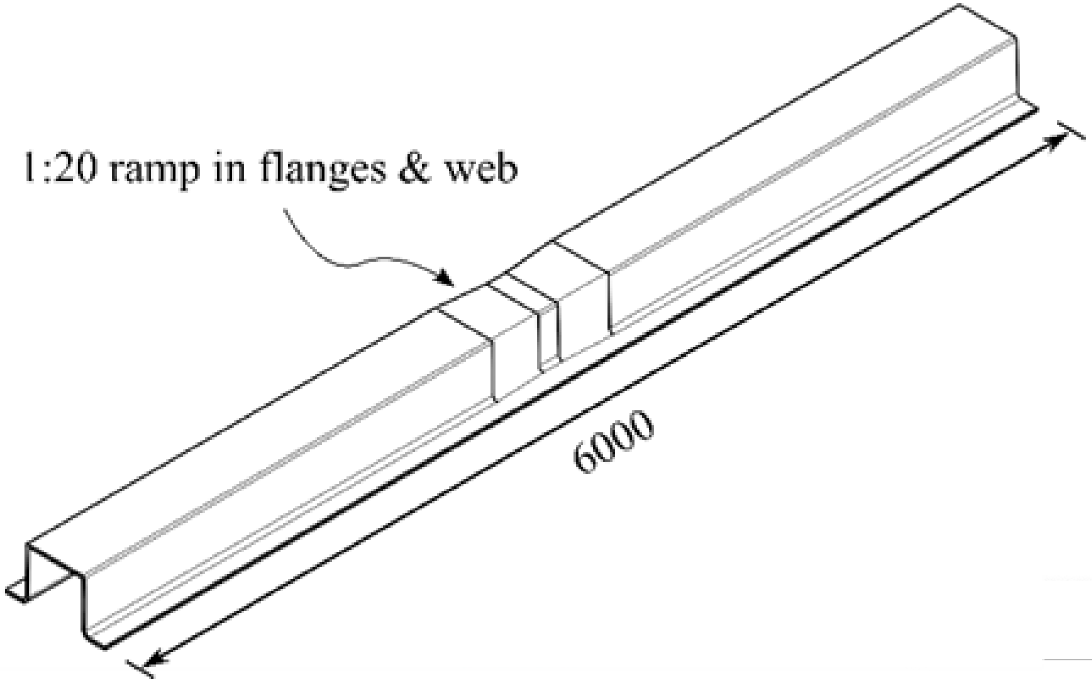
Formability

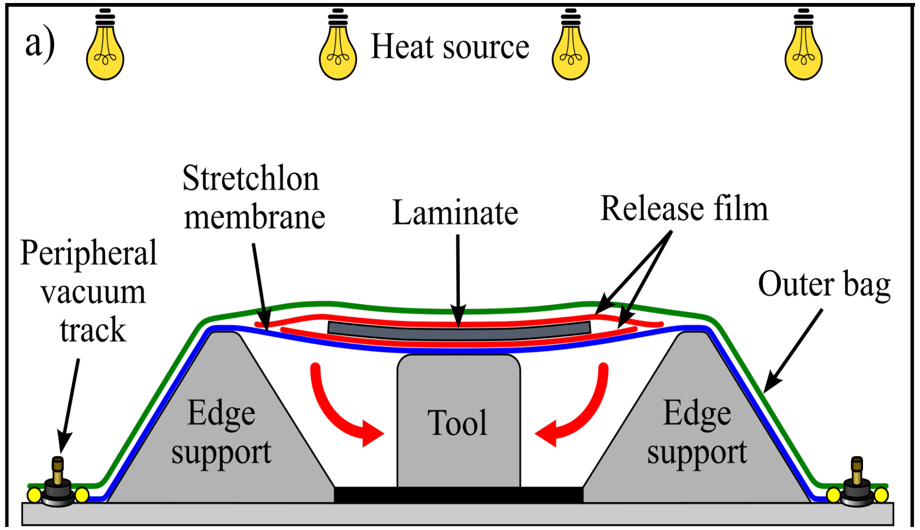
- Forming from flat can increase production rate
- Difficult for complex geometry in long parts
- New laminate design methodologies to improve formability via compatibility index C_{max} [1]
- Investigated length effect in forming of parts with long fibres [2]

1. Johnson et al, Composites Science & Technology, 2019
2. Scarth et al, Composites: Part B, 2023

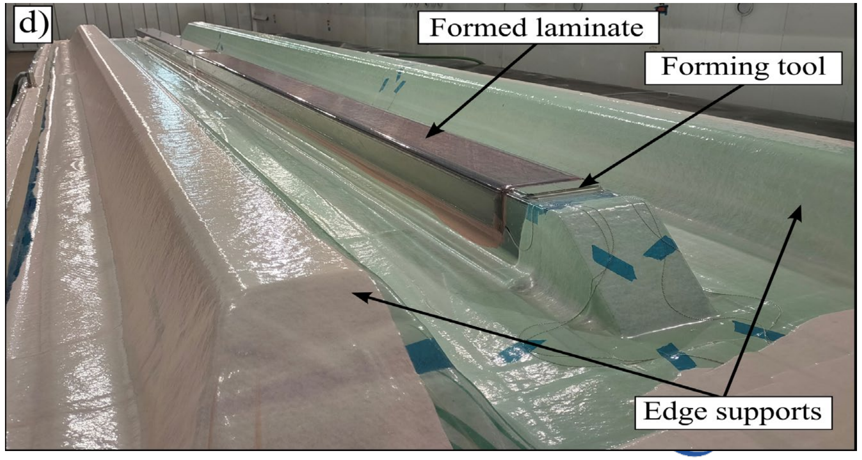
Formability- length effect

- 6m long C-spars with mid-length recess formed at National Composites Centre
- UD pre-preg material
- Three stacking sequences; standard and non-standard ply angles



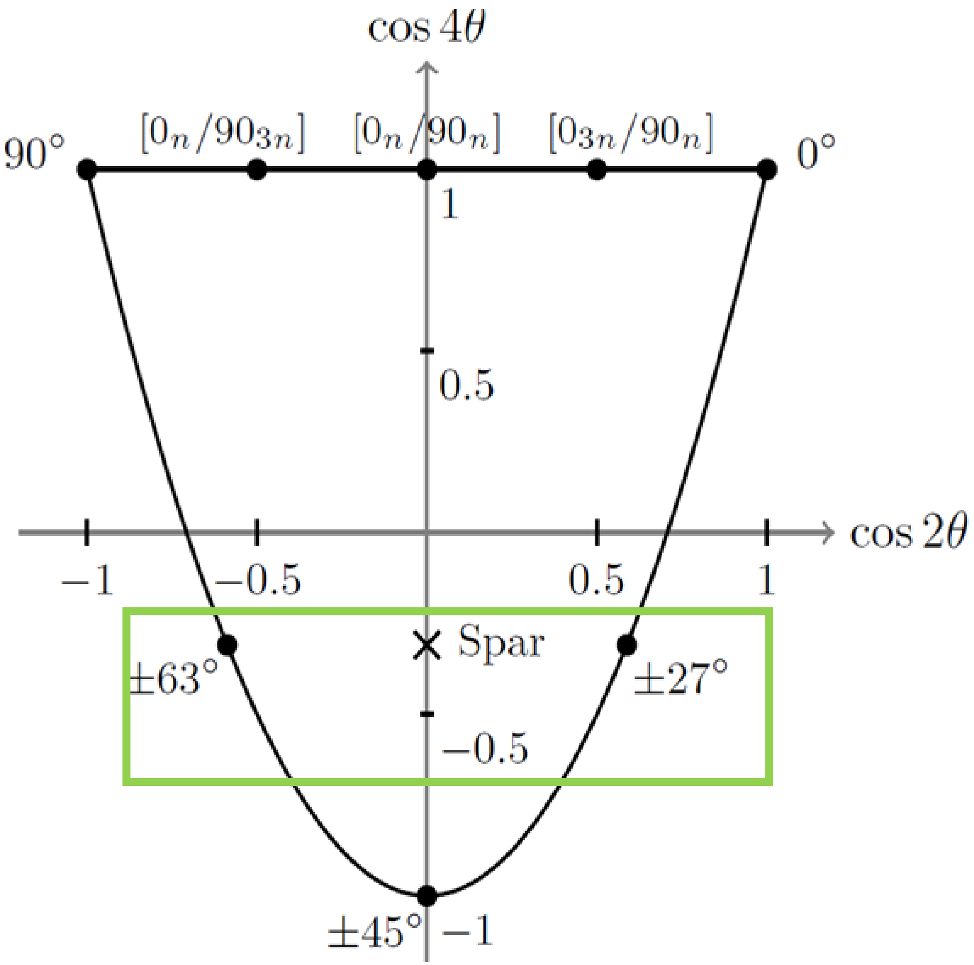


Forming setup



Formed part

Formability – laminate design



- In-plane stiffness is defined by linear combinations of two lamination parameters cos 4θ and cos 2θ
- 50/50 (% ±27°/±63°) has same in-plane stiffness as a standard angle spar laminate – e.g. 17/66/17 (% 0°/±45°/90°)
- Non-Standard angle laminate has reduce fibre length effect – improve formability

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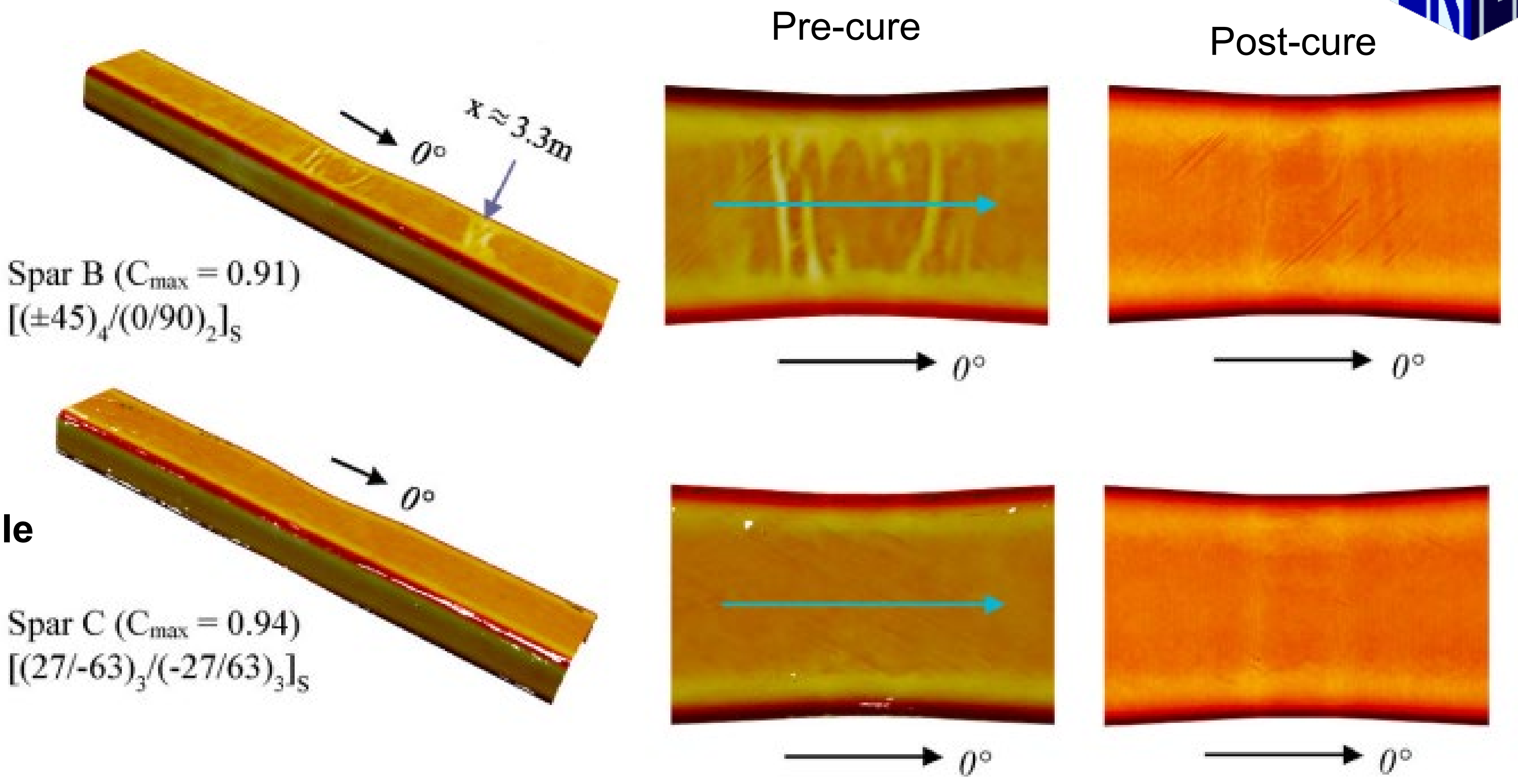
Post forming - surface scans

Standard Angle Laminate

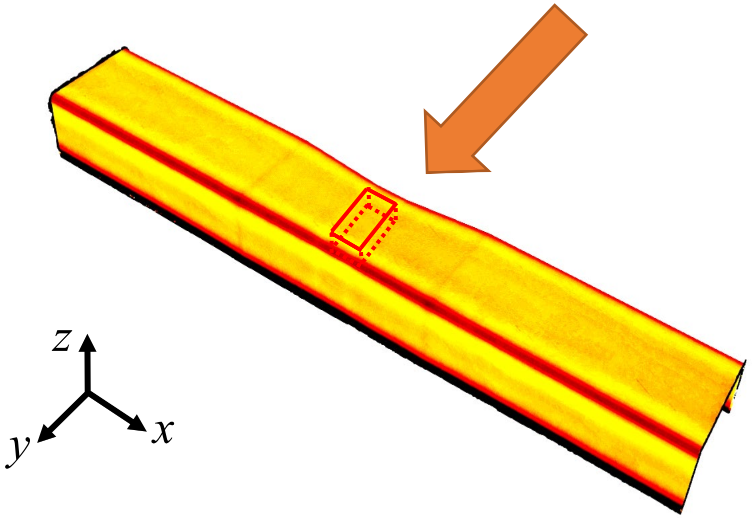
Non-standard Angle Laminate



- Standard angle laminate (6m long 0° fibres) has transverse wrinkles
- Non-standard angles (0.6m long 27° fibres does not

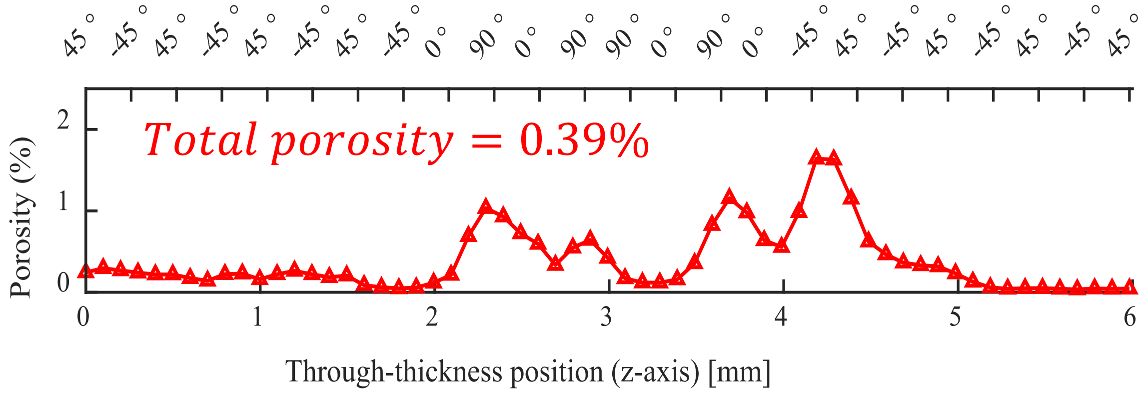
Post-cure X-Ray CT

- Porosity in recess – centre of web

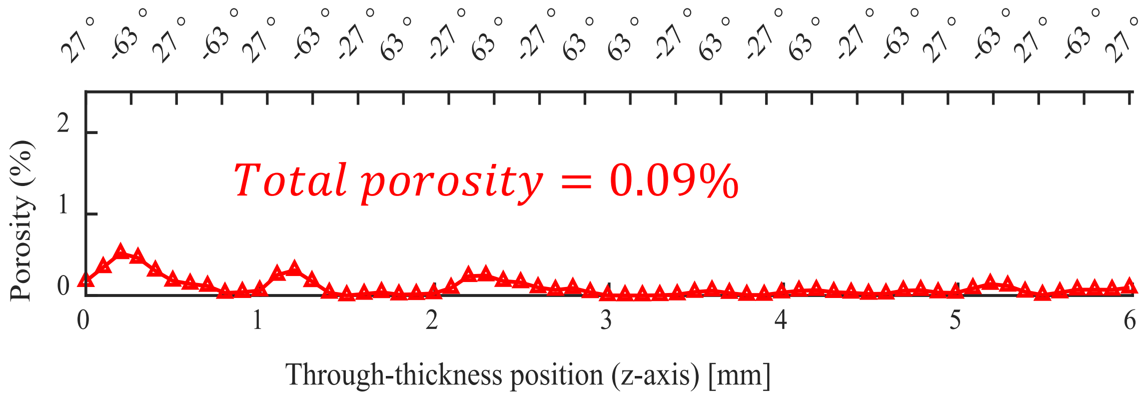


- Standard Angle laminate has 1-2% porosity in 0° plies
- Significantly lower porosity in Non-Standard Angle Laminate

Standard Angle Laminate



Non-Standard Angle Laminate



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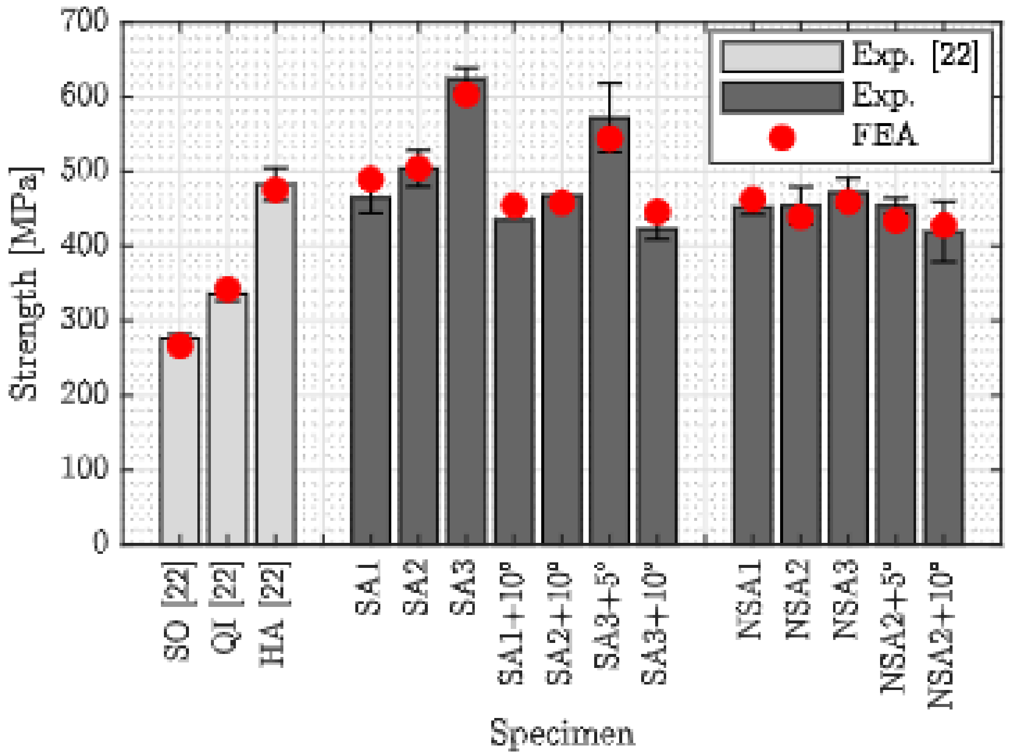
- **Coupon-level testing** – limitations of “Black Metal” approach to certification
- Multiscale modelling - a new pathway to part-level design and certification?

Coupon testing: Open Hole Tension

Standard Angle laminate: 50/40/10 (0/±45/90)

Non-Standard Angle laminate: 60/40 (±10/±57)

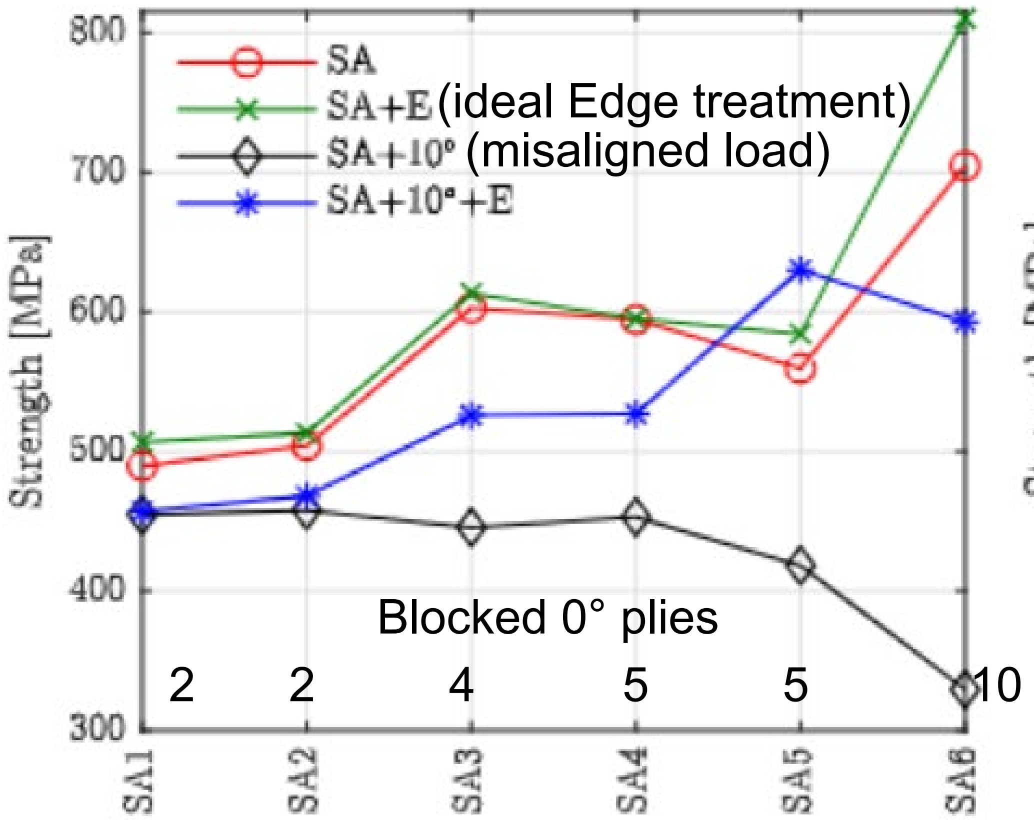
} Equivalent in-plane stiffness (skin laminate)



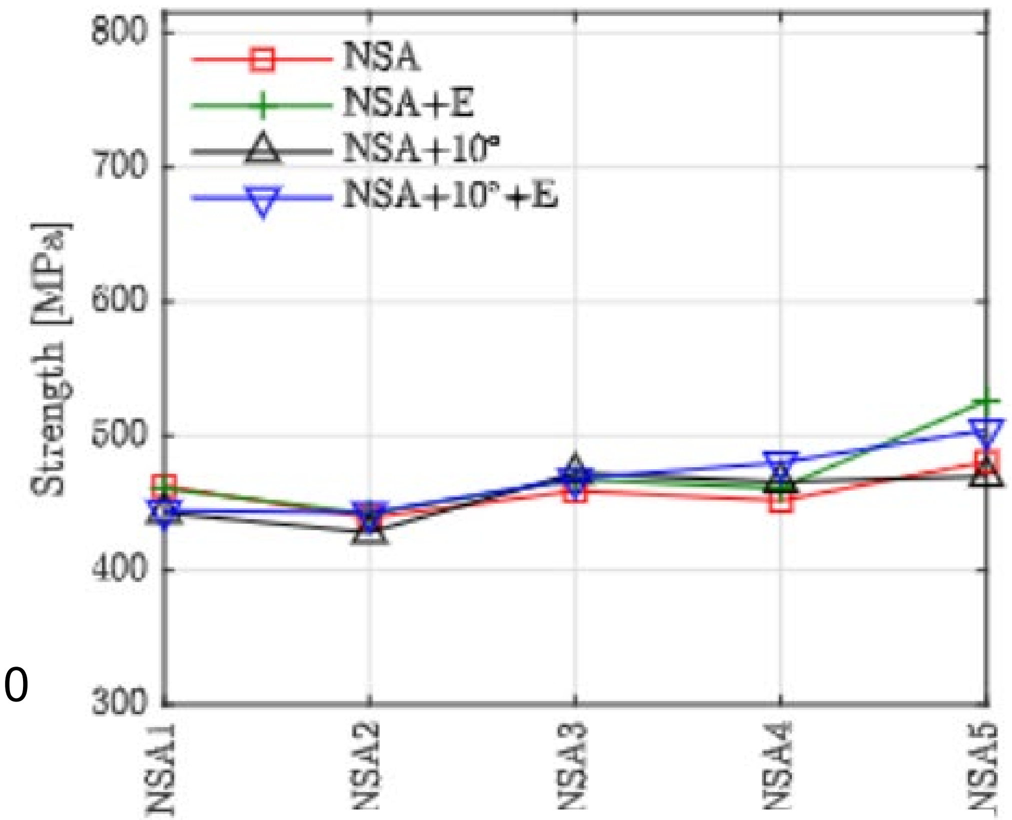
- [22] = Falco et al., Compos Struct, 2018.
- SA1; SA2 two blocked 0° plies
- SA3; four blocked 0° plies
- +10° = tension applied with 10° misalignment

*Chuaqui et al, Composites B, 2021

Virtual coupon testing



Standard Angle laminates



Non-Standard Angle laminates

Chuaqui et al, Composites B, 2021

- Shear load (misaligned tension) reduces strength by up to 60%
- Up to 50% recovery with numerical (ideal) edge treatment – edge failure prevented
- Non-standard angles less optimal but insensitive to misalignment and edge treatment

Overview

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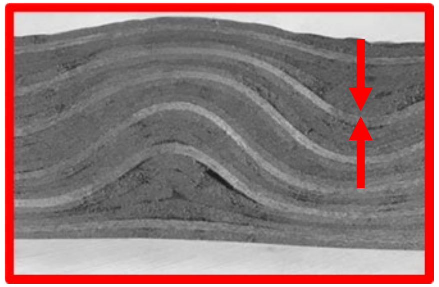
- **Multiscale modelling** - a new pathway to part-level design and certification?

Multiscale modelling

Motivation

- Coupon tests represent failure without any local/global interaction ("Black Metal" approach)
- Defects and failure of composite laminates can modelled at scale of layers and interlayers (**meso-scale, of order 10 μm**)
- How do we link this scale with structural performance of parts (**macro-scale,** of order 1m)?
- We are creating two approaches to Multiscale Modelling



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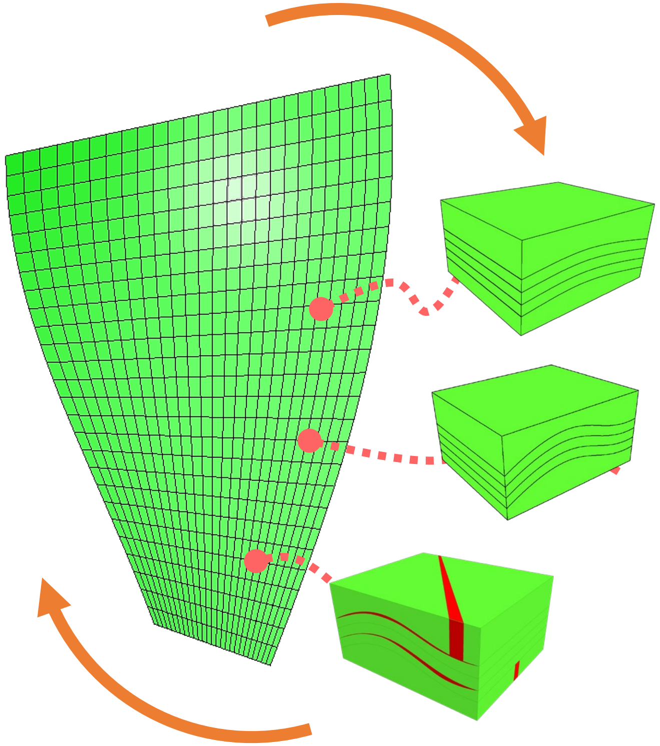
Multi-scale modelling
1. Framework for shell elements

Scale transition:
Second-order homogenisation

Downscaling:
Apply shell strains to the RVEs

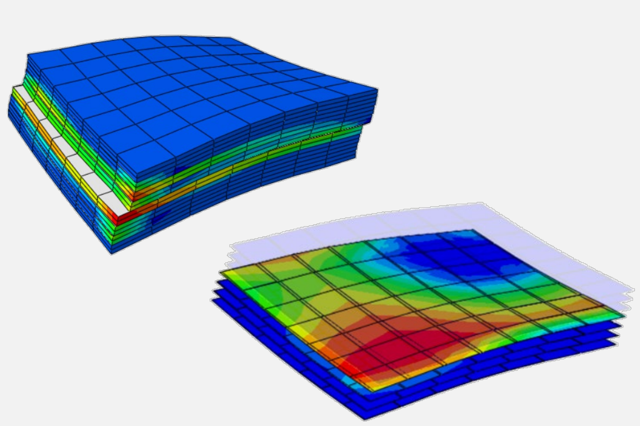
Upscaling:
Homogenise shell resultants and ABD + shear matrices



Macromodel: Shell elements

Mesomodel: Hi-fi solid RVE model
- Manufacturing defects
- Complex geometric features
- Progressive damage events

Example RVE modes



Inter + intralaminar damage progression

A.K.W. Hii, B. El Said, ***A kinematically consistent second-order computational homogenisation framework for thick shell models***, Computer Methods in Applied Mechanics and Engineering, Volume 398, 2022

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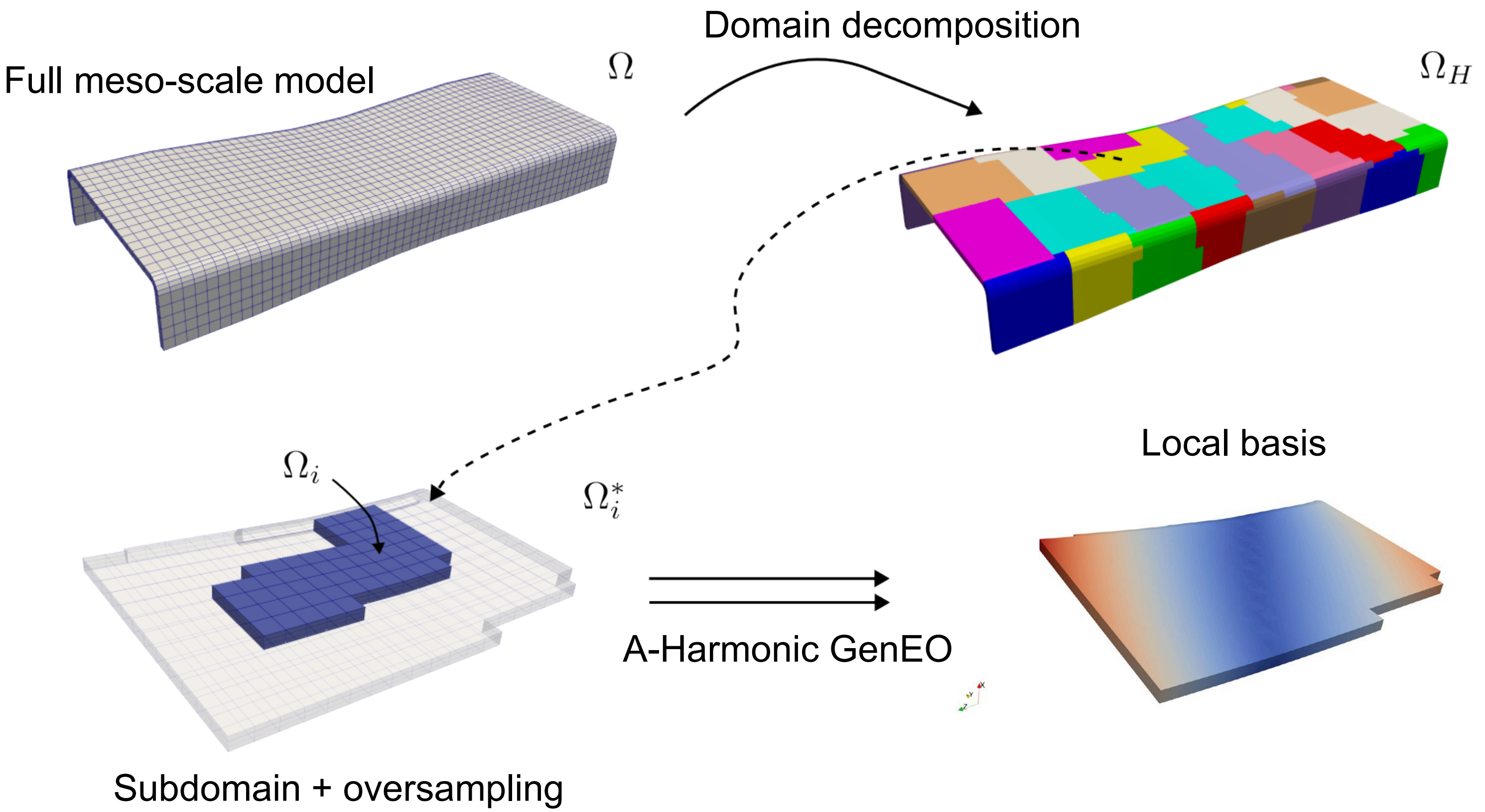
Multiscale modelling
2. Spectral Generalized FEM



- **Partition of Unity** operator stitch subdomains
- **Oversampling** ease accuracy of coarse solution at interfaces
- Very **efficient and parallelized method** for nonlinear large scale problem
- **No scale separation**: various imperfection type / size / shape

Bénézech, J, et al. Scalable multiscale-spectral GFEM with an application to composite aero-structures, 2023, submitted to JCP https://doi.org/10.48550/arXiv.2211.13893

Conclusions

- The **great challenge**: produce radically new high-performance products with reduced time to market
- Fundamental significance of **manufacturing process** on **material characterisation** and **structural performance**
- Alignment and length of **fibres**, and **matrix** constitution within the final product is critical
- The **current Building Block** approach, underpinned by coupon testing, does not fully exploit design opportunities nor is it representative of in-situ strength
- New statistical methods must be created to design, model and test at the component level, safely accounting for **uncertainty** and exploiting new design opportunities including manufacturability.