Bristol Composites Institute Doctoral Research Symposium

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University of Bristol

POSTER BOOKLET

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PLA-HYDROGEL FRACTAL ACOUSTIC COMPOSITE METAMATERIAL FOR SOUND INSULATION

Gianni Comandini, Fabrizio Scarpa, Mahdi Azarpeyvand, Valeska P. Ting

Introduction

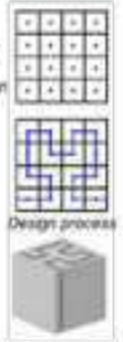
Noise can be a severe threat to human health. The mitigation of this type of pollution is not trivial but essential to improve the collective quality of life. For mechanical, civil, and aerospace engineering applications, one of the common ways to deal with unwanted sound is to exploit the mass law or utilise thick layers of absorbing materials. However, that is not always possible due to weight or space restraints, and new solutions and technologies are needed. Composite metamaterials can be part of the answer. In this work COMSOL Multiphysics simulations and experiments were performed on metamaterials with fractal geometries and hydrogel filters. The results show key features which affect the meta-behaviour of these structures.

Design and Simulations

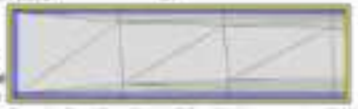
Triangular mesh used

In the model:

- Pressure acoustics for the model in general
- Thermoviscous acoustics in the fractal gap-width
- Boundary layers in the internal parts tortuosity



Design process



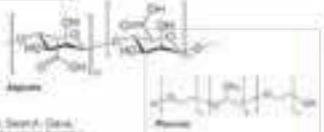
Boundary layers used to mesh the fractal gap width

Comandini, Gianni, Carlos Khodr, V. P. Ting, Mahdi Azarpeyvand, and Fabrizio Scarpa. "Sound absorption in Hilbert fractal and coiled acoustic metamaterials." *Applied Physics Letters* 120, no. 6 (2022): 061902.

Manufacturing Process

Composite Metamaterial:

- Alginate, and Pluronic F127 plus purified water to get the soft gel
- Bath of 100 mmol of calcium chloride at 37°C to set gel
- Drain the hydrogel



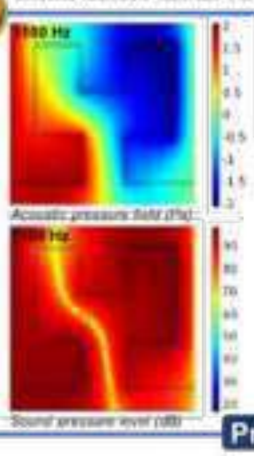
Armstrong, James PK, Madeline Burke, Benjamin M. Carter, Sean A. Davis, and Adam W. Perriman. "3D bioprinting using a templated porous bioink." *Advanced Healthcare Materials* 5, no. 14 (2016): 1724-1730.

Impedance Tube Testing

Impedance Tube:

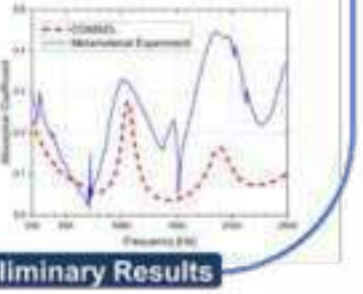
- Three meter impedance tube
- Aluminium and perspex and two inch square section
- Astm E2611-09 standard

Preliminary Results



In the model:

- Trend captured with COMSOL for the AC
- PLA and air have been used in the model as material for the non-composite metamaterial
- Mesh sensitivity study performed



Conclusions

- The COMSOL model of the metamaterial without hydrogel captures broadly the trend in terms of absorption coefficient.
- Even if more tests are needed, the composite Hilbert fractal metamaterial with hydrogel seems to have high values of absorption coefficient in the low frequency range (below 500 Hz), showing interesting properties in terms of energy dissipation.

Future Work

- A poroelastic COMSOL model of the hydrogel inside the metamaterial.
- Understand the physics behind this high energy dissipation in the low frequency range.
- Evaluate how the manufacturing process of the hydrogels influence the acoustic performance

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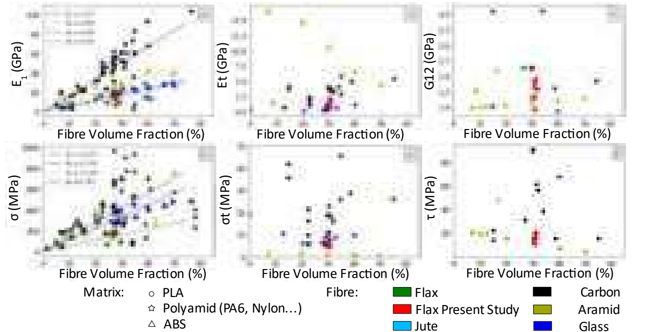
Design strategy for 4D printed flax fibre PLA composite biomimicking humidity triggered actuators

Charles de Kergariou*, Antoine Le Duigou, Adam Perriman, Hind Saidani-Scott, Giuliano Allegri, Sofiane Guessasma, Byung Chul kim, Fabrizio Scarpa
*corresponding author: charles.dekergariou@bristol.ac.uk

Parameters influencing actuation

- ➢ Porosity
- ➢ Mechanical properties
- ➢ Fibre Path
- ➢ Geometry

Comparison literature



1-Porosity

- ✓ Define best strategy for porosity measure

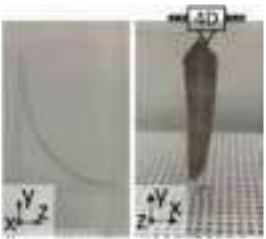
2-Mechanical

- ✓ Influence of humidity on mechanical properties

Paper QR

Paper QR

5-Biomimicking



4-Design Space

- ✓ Greater responsiveness
- ✓ No anticlastic double curvature

3-Model

- ✓ Create model for continuous filament
- ✓ Validation model

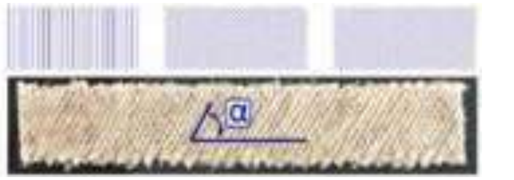
Develop double curvature?

Layers:

Comparison models vs Experiment

Improved actuation?

Layers:



In house model

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The Science Inside

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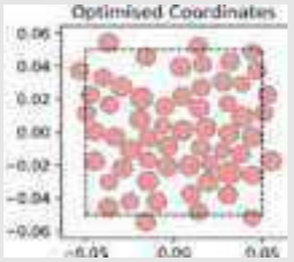
Hierarchical Multiphysics modelling of fibre reinforced composites

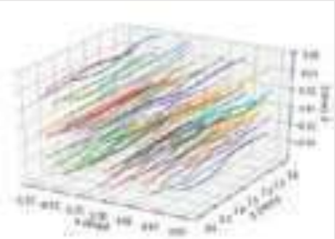
Callum Hill, Jason Yon, Giuliano Allegri, Ian Hamerton, Richard Trask

The electrification of aircraft requires significant improvements in thermal management, weight reduction, energy storage and electrical distribution. The use of multifunctional composites is essential in these endeavours and provides an effective way to eliminate the mass of components by using existing structural elements to perform the same function. In fibre-reinforced composites, the mechanical and physical properties are highly anisotropic – with superior tensile strength, stiffness, thermal and electrical conductivities occurring in the fibre direction rather than in the out-of-plane directions. However, the electrical and thermal behaviours of composites are poorly understood, particularly for complex geometries with different stacking sequences. To more fully understand this behaviour, a multi-physics model has been produced to characterise the directional electrical and thermal conductivity of fibre-reinforced composites.

Microstructural model

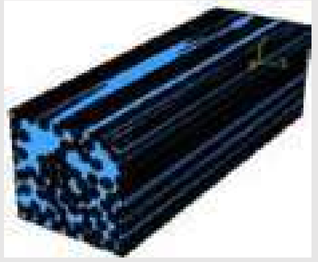


Random fibre distribution created.



Bezier curves plotted and randomly perturbed through control points.

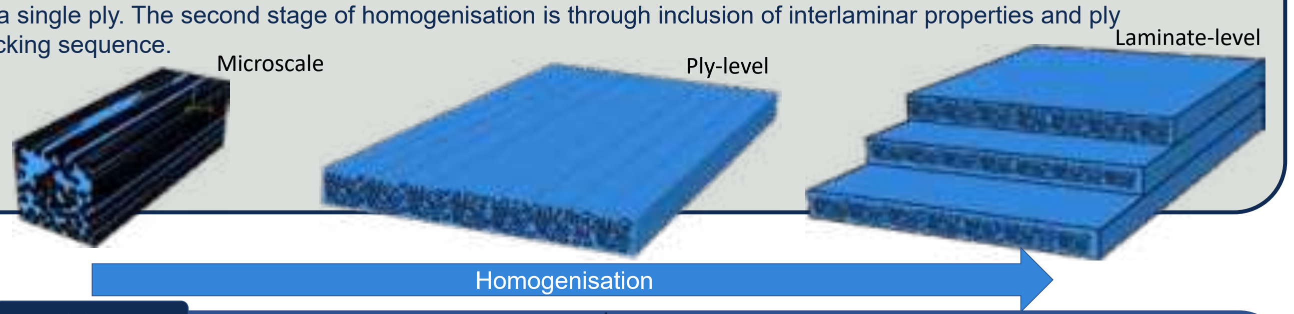
Fibres imported into CAD software.



Geometry exported to Abaqus to produce an RVE.

Homogenisation

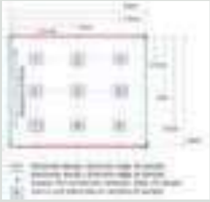
Homogenisation of the microstructural model is essential to be able to simulate the macrostructural behaviour of a composite. This has been achieved through the use of periodic boundary conditions, to give a conductivity tensor for a single ply. The second stage of homogenisation is through inclusion of interlaminar properties and ply stacking sequence.



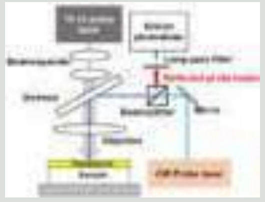
Validation

Electrical

- Assessment of 8552/IM7 Uni-directional laminates with different stacking sequences.
- An electrical conductivity tensor will be derived to validate the computational model.



Schematic of CFRP samples for electrical conductivity testing with each numbered square a contact point where the fibres have been exposed and silver epoxy added [Jones et al.]



Schematic of the nanosecond transient thermoreflectance method of determining the thermal conductivity tensor [Yuan et al.].

Thermal

- Thermal conductivity testing will also be conducted on the laminates.
- This will be carried out using the transient thermoreflectance method in conjunction with the University of Bristol Physics department.
- A thermal conductivity tensor will be derived to validate the computational model.

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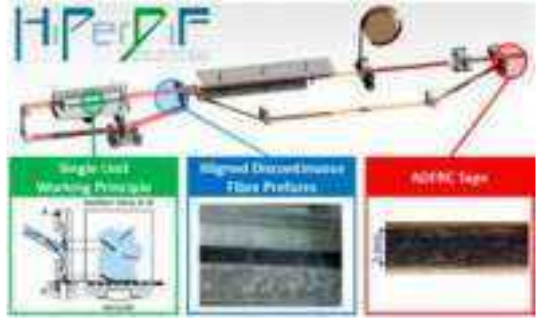
Robust and low temperature repair performance of a vitrimer matrix in aligned discontinuous flax fibre composites

Presenter: Ali Kandemir **Supervisors: M. L. Longana, I. Hamerton, S. J. Eichhorn**

Introduction

This work aims at developing discontinuous natural fibre composites to address the current environmental concerns by delivering sustainable fibre reinforced polymer materials for light-weighting design solutions. The High Performance Discontinuous Fibre (HiPerDiF) method is a high throughput, low environmental impact, water-based manufacturing process to produce high-performance, highly aligned discontinuous fibre composites. It was demonstrated that NFs can be processed into high-performance FRPs with the HiPerDiF method, despite their hydrophilic nature. Following the study on the interfacial properties of potential sustainable matrices with flax fibre in which vitrimer matrix shows better adhesion than standard epoxy matrix, robust and low temperature repair performance of aligned discontinuous 6 mm flax fibre reinforced vitrimers (ADFRV) were investigated.



Materials and Methods

Fibre
EcoTechnilin – Flaxtape

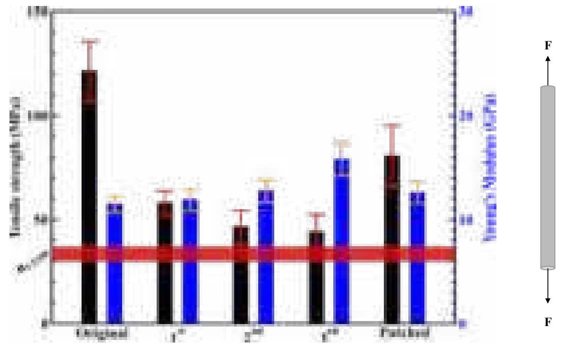
Matrices
Mallinda – VitrimaxT100™

Production
Autoclave cure:
135°C at 1 bar 30 min,
135°C at 6.5 bar 30 min

Lay-up
5×Vitrimer resin film (150-250 gsm)
4×Flax **6mm HiPerDiF preform** (75-85gsm)
Estimated fibre volume ratio = 0.179

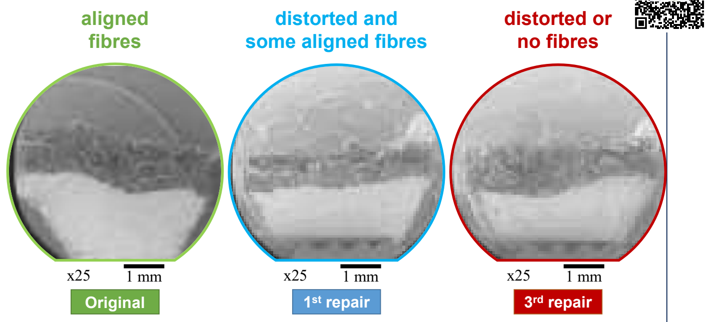
Healing
Compression at 120°C at 100 psi for 5 minutes

Tensile Test



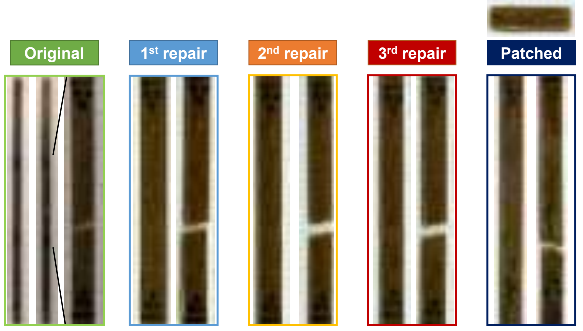
Tensile strength of original, end-to-end repaired & tested, patched ADFRV specimens

SEM Images



Electron Microscopy images of produced, tested, repaired, retested, and patched ADFRV specimens

High resolution scans



Images of produced, tested, repaired, retested, and patched ADFRV specimens

Conclusion

- ADFRV composites showed robust and low temperature repair owing to matrix property.
- End-to-end repair method showed only 50% strength recovery in the first healing cycle.
- Significant performance was observed for the patching repair method after three end-to-end repair cycles.

Future Work

The healing performance of flax vitrimer composites will be investigated using single or double patch method and different healing parameters, such as pressure, time and temperature.

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Acknowledgement

EPSRC Project (EP/P027393/1) and (EP/L016028/1). A.K. acknowledges support from the Turkish Ministry of National Education YLSY grant. The authors thank Ecotechnilin, Fabrizio Scarpa, and Charles de Kergariou for supplying flax-ft fibres. The authors would like to thank Heather Rubin from Mallinda Inc. for providing the vitrimer.

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Life Cycle Framework and Sustainable Design

Will Proud[a], Ian Hamerton[a], Marco Longana[a], Richard Trask[a]

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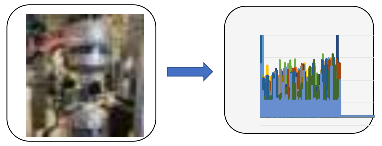
Abstract

This study employs a Multi-Objective Particle Swarm Optimisation (MOPSO) algorithm, incorporating Life Cycle Engineering (LCE), to investigate the performance of nine composite materials (Basalt, Glass and Flax woven fabrics alongside Epoxy, Bio-Epoxy and Elium Thermoplastic infusable matrices). The algorithm is applied to a marine industry structural sub-component. To assess technical performance, analytical sandwich panel design formulae coupled with environmental and economic datasets assessed using Life Cycle Assessment (LCA) and Life Cycle Costing (LCC).

Methodology

Per kg, flax produces 10x less GHG than glass

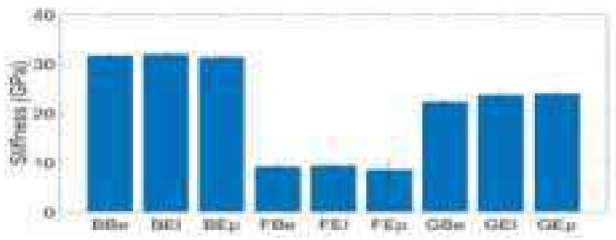
When considering a full life cycle in a marine application, is this still the case?



Database contents

1) Mechanical performance data generated through tensile and shear coupon testing.
2) Economic data (LCC) generated using literature sources
3) Environmental data (LCA) generated using GaBi LCA software with mostly vendor data being implemented

Database generation

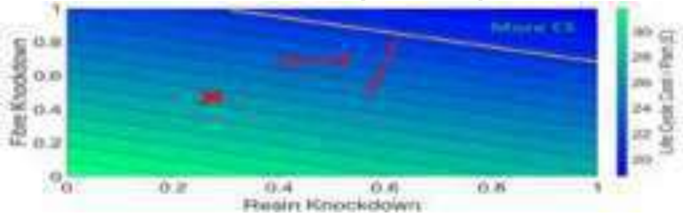


ASTM D3039 Results

- Recycling methods for selected fibres and thermoplastic Elium are cost-ineffective. We are at (**X**) and need to reach **more CE**
- Low economic value of recyclate likely driving low levels of research for non-carbon fibres

Composite	$GWP\ per\ kg\ (CO_2)$	$Initial\ LCC\ per\ kg\ (£)$
Basalt & Elium	5.17	53.90
Glass & Epoxy	7.25	28.15
Flax & Bio-Epoxy	3.25	77.84

Condensed exemplar datapoints



Break-even analysis Thermoplastic Recycling

Optimisation algorithm

Developed MOPSO optimises against up to three (*n*) Objective Functions ($(f_1(x)..f_n(x))$) subject to constraints. Pareto Front diagram of optimised solutions which a designer selects using heuristic methods.

Pareto Front

Optimised solutions - Glass & Infugreen or Basalt & Epoxy

$[(0/90)_W]_{12-24}$

$$Minimise\ f_1(x) = \frac{Pl^3}{B_1(EI)_{eq}} + \frac{Pl}{B_2(AG)_{eq}}$$

$$Minimise\ f_2(x) = PEI + UEI$$

Subject to:

$$\sigma_f < \sigma_{yf}$$

$$\sigma_f < \frac{3\ E_f^{\frac{1}{3}} E_c^{*\frac{2}{3}}}{(12(3-v_c)^2(1+v_c)^2)^{\frac{1}{3}}}$$

Conclusions

- Basalt & Epoxy or Glass & Bio-Epoxy are the optimised solutions and produced 66% lower emissions than Flax composite over assessed LC
- Glass & Epoxy only optimised solution against cost
- Basalt re-melting presents opportunity for lower LCC

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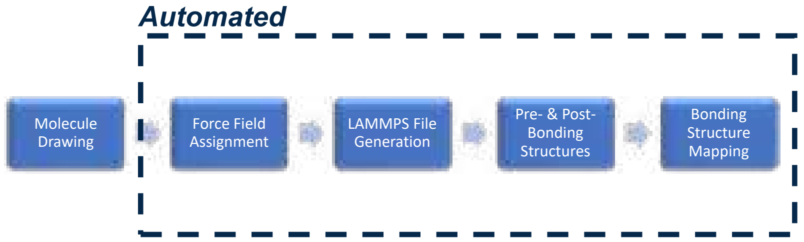
Automating Modelling for Digital Materials Science

Matthew A. Bone, Terence Macquart, Brendan J. Howlin, Ian Hamerton

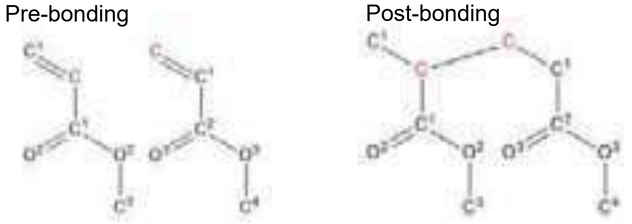
Model Pre-Processing Automation

- Molecular Dynamics (MD) is an atomistic scale computational chemistry technique.
- Discover new polymer matrices by screening virtually, saving lab time and reducing waste.
- Extensive pre-processing is required to parameterise monomers and allow them to bond.
- Using chemical graph theory, we can map atoms in a molecule before and after a reaction has happened.



Automated

Molecule Drawing → Force Field Assignment → LAMMPS File Generation → Pre- & Post-Bonding Structures → Bonding Structure Mapping

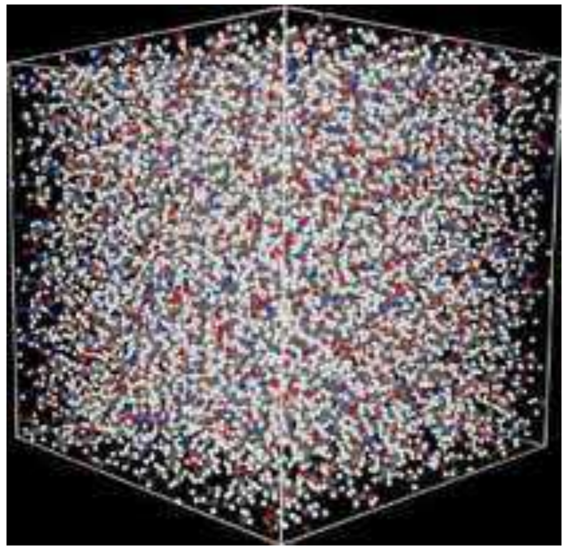


Simulate Challenging Experiments

- Optimising materials for high strain rate impacts is challenging in the laboratory.
- Viscoelastic properties are key to protective coatings on wind turbine and helicopter blades, and aircraft.
- Using MD, it is possible to work backwards from ultra-high strain rates.

Rapid Surrogate Models with AI

- Many MD simulations have a high computational cost e.g. 24 – 36 hrs on supercomputer nodes.
- Using simple neural network surrogate models can eliminate 12 – 24 hrs runtime.
- This makes MD more accessible and enables high throughput materials screening.



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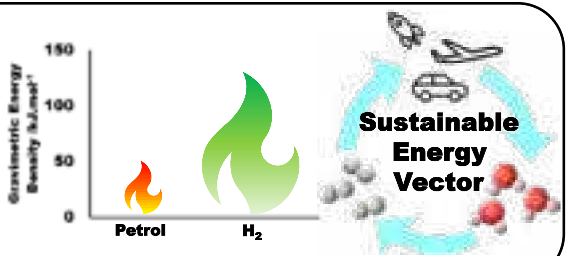
Low-Dimensional Porous Carbon/Sulfur Composites for Hydrogen Storage

Charles D. Brewster†, Lui R. Skytree, Sebastien Rochat, Valeska P. Ting

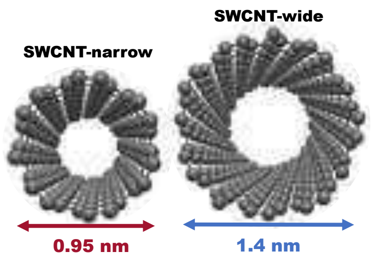
Hydrogen is certain to have a major impact on the future energy landscape. For decades, the promise of a **sustainable, environmentally friendly energy vector** and potential for **cyclic fuel economy** has excited the scientific community. Current technologies for hydrogen storage rely on pressures **up to 100 MPa**, cryogenic conditions (<20 K) or a combination of the two. Sulfur encapsulated within the narrow channels of Single-Walled Carbon Nanotubes (S@SWCNTs) represents a unique **composite material hitherto unexplored for hydrogen storage**. Interactions between sulfur and CNTs modulate the electronic properties of the host, thus offering insight into plausible methods for **improving hydrogen sorption in porous nanocomposites**.



Materials

SWCNTs

- Thermally and chemically stable.
- Good mechanic properties.
- Highly tailorable.
- Cylindrical pore geometry.



Sulfur

- Inexpensive waste material.
- Non-hazardous.
- Boiling point = 445 °C.
- Predicted improved H_2 sorption in SWCNTs [2].

16
32.06
S
Sulfur

Synthesis

- Sulfur incorporated into porous materials via **vapour deposition** [1].
- Emergence of low-frequency Raman shifts from **confined polysulfide** stretching.
- Sulfur content **6-9 wt%** depending on sample.
- Reduction in pore volume following infiltration.

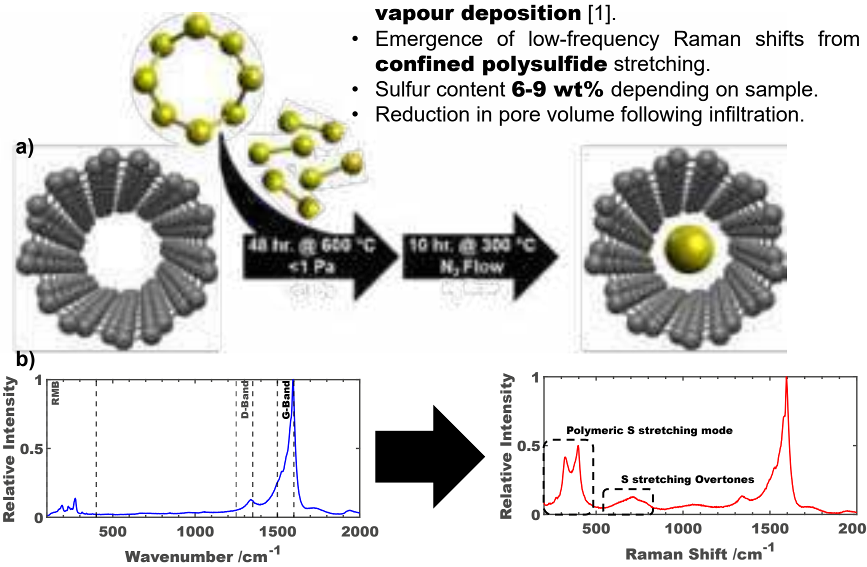


Figure 1 a) Schematic representation for sample preparation. b) 532 nm Raman spectra of SWCNT and S@SWCNT shown above.

H_2 Loading

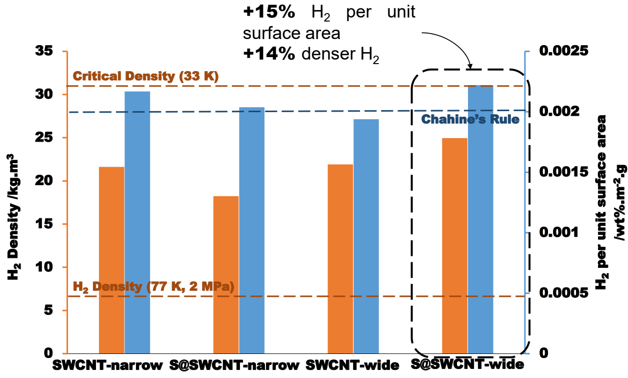


Figure 1 Bar chart showing the volumetric density (left) and H_2 per unit surface area (right) for SWCNT-narrow, S@SWCNT-narrow, SWCNT-wide and S@SWNCT-wide

Conclusion

- We successfully **synthesized sulfur/carbon composites** through vapour deposition in microporous carbons.
- SWCNT/Sulfur composites improve excess H_2 per surface area, through **changes in surface polarity** [2].

Future Work

- Identify the location of hydrogen within the material via **neutron scattering**.
- Determine origin of enhancement through **Raman Spectroscopy**.
- Conduct low-pressure H_2 sorption experiments to determine **enhanced surface packing.**

References

1. Fu, C., et al., *Confined lithium–sulfur reactions in narrow-diameter carbon nanotubes reveal enhanced electrochemical reactivity.* ACS Nano, 2018. **12**(10): p. 9775-9784.
2. Mousavipour, S. and R. Chitsazi, *A theoretical study on the effect of intercalating sulfur atom and doping boron atom on the adsorption of hydrogen molecule on (10, 0) single-walled carbon nanotubes.* Journal of the Iranian Chemical Society, 2010. **7**(2): p. S92-S102.

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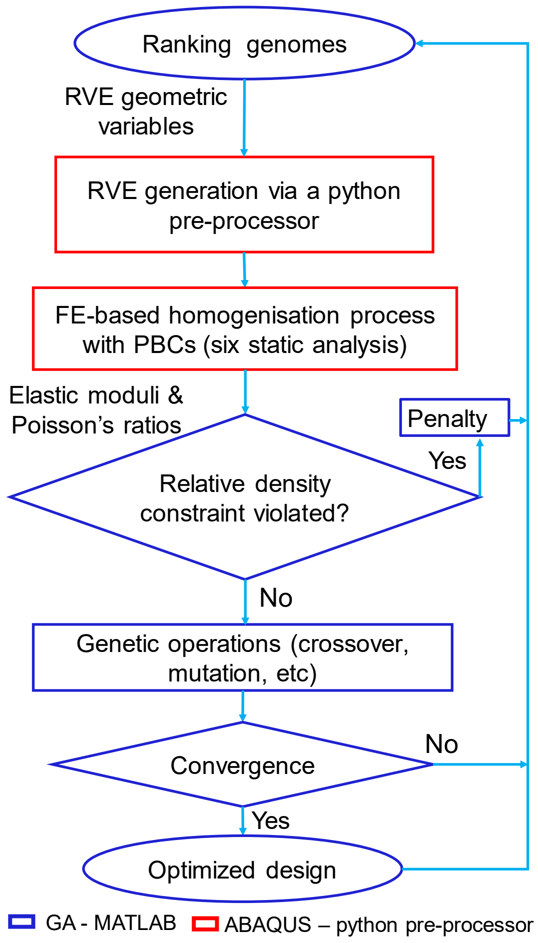
Architecture optimization of 3d-printable lattice structures with an evolutionary-based approach

Athina Kontopoulou, Riccardo Manno, Bing Zhang, Fabrizio Scarpa and Giuliano Allegri

Sandwich panels allow reducing structural weight by replacing traditional monolithic components. Our work aims to develop lattice cores with superior specific mechanical properties for high-performance sandwich panels. The topology and the node connectivity of the lattice unit cell are crucial for the overall performance. Here, we enhance the specific compressive stiffness of lattice cores using size and shape evolutionary optimization via a genetic algorithm (GA). A representative volume element (RVE) of lattice designs is used in finite element (FE) modelling framework which is incorporated with the GA-driven optimisation. Emphasis is given to the manufacturability of these lattice designs, considering layer by layer additive manufacturing constraints in the variables bounds used for the optimization, as well as a relative density constraint.

Computational Approach



Ranking genomes

RVE geometric variables

RVE generation via a python pre-processor

FE-based homogenisation process with PBCs (six static analysis)

Elastic moduli & Poisson's ratios

Relative density constraint violated?

Yes

Penalty

No

Genetic operations (crossover, mutation, etc)

Convergence

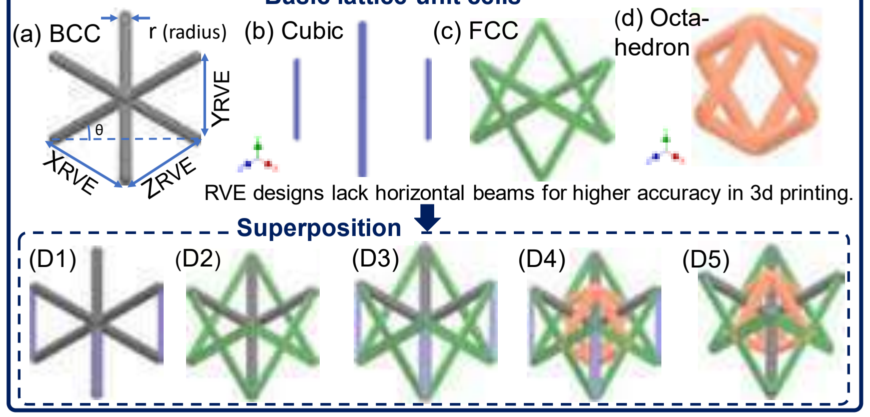
No

Yes

Optimized design

🟦 GA - MATLAB 🟥 ABAQUS – python pre-processor

Designs



RVE designs lack horizontal beams for higher accuracy in 3d printing.

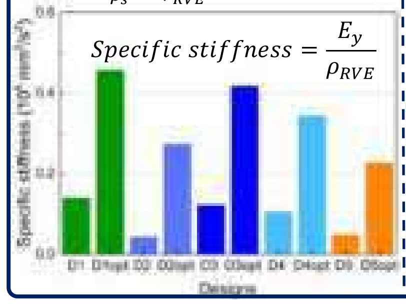
Results of case study

GA geometric continuous variables:

Variables	Lower bound	Upper bound
r(a-d)	0.3 mm	0.7 mm
YRVE	5.0 mm	9.0 mm

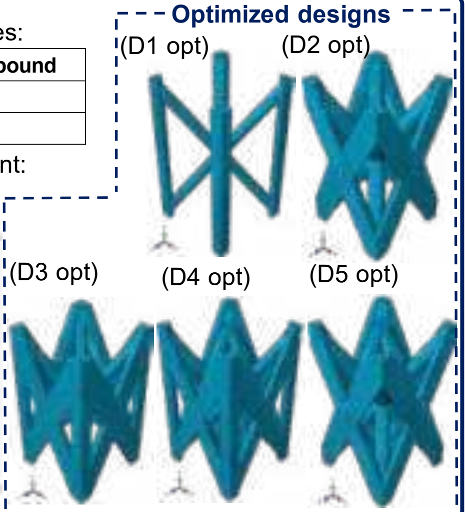
GA relative density (ρ_{rel}) constraint:

$$\rho_{rel} = \frac{\rho^*}{\rho_s} = \frac{V_{lat}}{V_{RVE}} \le 0.3$$



$$Specific\ stiffness = \frac{E_y}{\rho_{RVE}}$$

Optimized designs



Conclusions

- Increased height (YRVE) of the RVE gives a larger specific stiffness.
- Enhanced compressive specific stiffness up to five times in all optimized lattice designs.
- The Cubic (b) and FCC (c) beams of the superimposed designs exhibit higher specific stiffness than BCC (a) and octahedron (d) beams, hence result into greater radius.

Future steps

- Additive manufacturing and mechanical testing of the optimized lattice designs.

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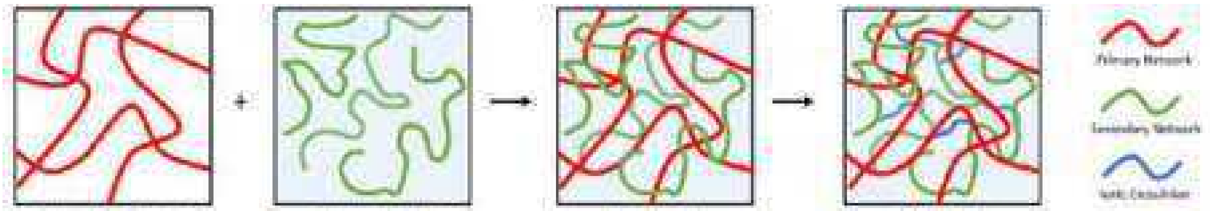
The optimisation of soft composite systems for biomedical applications

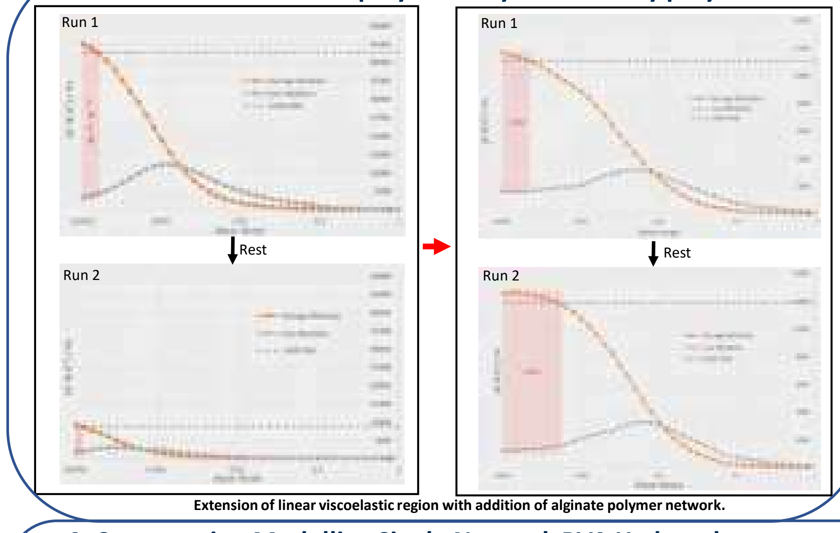
Joe Surmon[1], Sebastien Rochat[2], Kate Robson-Brown[3] , Richard Trask[1]

An investigation into the material properties of semi-IPN crosslinked polymer networks has been carried out. Three material systems have been tuned and optimised for biomedical application. In particular, to withstand the complex and demanding loading environment experienced within a human joint. Material systems were tested under shear stress and their response monitored.

1. Schematic representation of composite polymer system



3. Effect of addition of polyelectrolyte secondary polymer



Extension of linear viscoelastic region with addition of alginate polymer network.

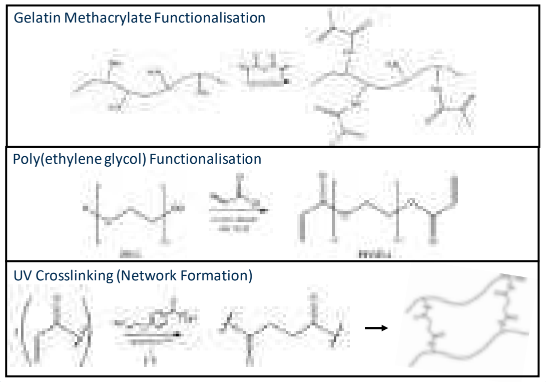
2. Polymer Composite Definition

Primary Network

1. Gelatin methacrylate
2. Poly(ethylene glycol) diacrylate
3. Poly(vinyl alcohol)

Secondary Network
Alginic acid

Ionic Crosslinker
Ca^{+2}

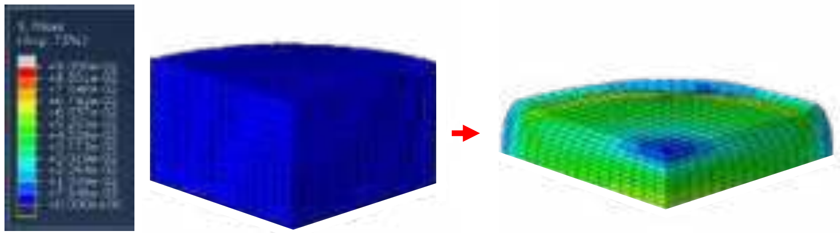


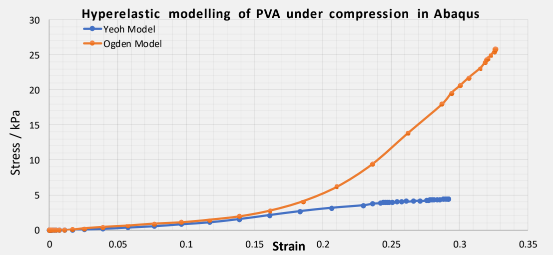
Gelatin Methacrylate Functionalisation

Poly(ethylene glycol) Functionalisation

UV Crosslinking (Network Formation)

4. Compression Modelling Single Network PVA Hydrogel





Conclusion

- A range of material systems have been tested and optimised to determine their suitability for *in-vivo* application
- Complementary modelling has been constructed to supplement the experimental data

Future Work

- Full (DIC) compressive and shear testing to determine complete material properties
- Incorporation of nano material additives such as: hydroxyapatite and ‘spring-like’ proteins.

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1. Bristol Composites Institute, University of Bristol, Bristol, BS8 1TR
2. School of Chemistry, University of Bristol, Bristol, BS8 1TH
3. Department of Anthropology and Archaeology, University of Bristol, Bristol, BS8 1TH

1. Nichol, J. W., Koshy, S. T., Bae, H., Hwang, C. M., Yamanlar, S., & Khademhosseini, A. (2010)., *Biomaterials*, *31*(21), 5536–5544.

2. Browning, M. B., Wilems, T., Hahn, M., & Cosgriff-Hernandez, E. (2011)., *Journal of Biomedical Materials Research Part A*, *98A*(2), 268–273.

3. *What’s Behind the Amazing Accuracy of Joint Replacement Surgery?* (2018). Cleveland Clinic. https://health.clevelandclinic.org/whats-behind-the-amazing-accuracy-of-joint-replacement-surgery/

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Sustainable Green concrete with recycled carbon fibre

Meiran Abdo, Eleni Toumpanaki, Andrea Diambra, Valeska Ting, Fabrizio Scarpa, Adam Perriman, Gianni Comandini

Aims: For mitigating the potential environmental pollution of waste carbon fibre, the present study investigates the feasibility of collaborative use of these recycled materials in construction filed, as well as the effect of chopped recycled carbon fibre addition to the concrete mechanical properties after 7 days of curing. For this purpose, several specimens with different volumes (0%, 0.01%, 0.02%, 0.03%,0.04%, and 0.06%) of carbon fibre were examined to show the effect of recycled carbon fibre on the specimens' mechanical properties (compressive strength and splitting tensile strength).

Materials: A recycled carbon fibre length = 6 mm with [Tensile Strength MPa = 3530, Density(kg.m-3) = 1760, and E (GPa)=230], coarse aggregate a crushed stone average size of 3-6 mm , and an Ordinary Portland Cement.

Results

1. Testing

For analyses simplicity, all specimens in this study were tested in accordance with ASTM C39 and ASTM C496 standards for compressive strength and split tensile strength, respectively see Fig1. The Instron 600DX machine was used for testing all samples , while a Zeiss Microscopy were used to obtain a visual images.

Figure 1: A) compressive strength. B) split tensile strength Test

2. Fracture Patterns : Four major fracture patterns have been identified for the compressive strength test of the cylinder concrete at age 7 days. All four fracture patterns were reported based on ASTM C39 standard In Fig 2.

Figure 2: Figure 6 Fracture Pattern types.

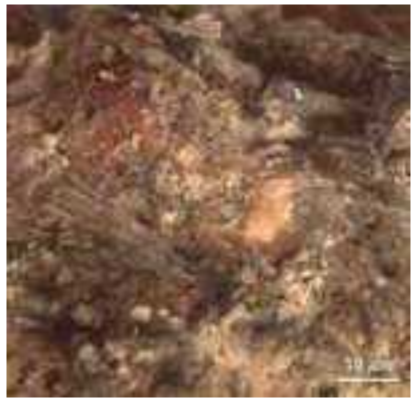

Figure 3: Microstructural analysis showing carbon fibre distribution.

3.Microscopy: The microscopy in Figure.3 shows an equally distributed recycled carbon-fibre in concrete matrix; however, an evidence of fibre balling and clumping were reported due to the difficulty of carbon fibre to disperse using a hand mixing concrete method.

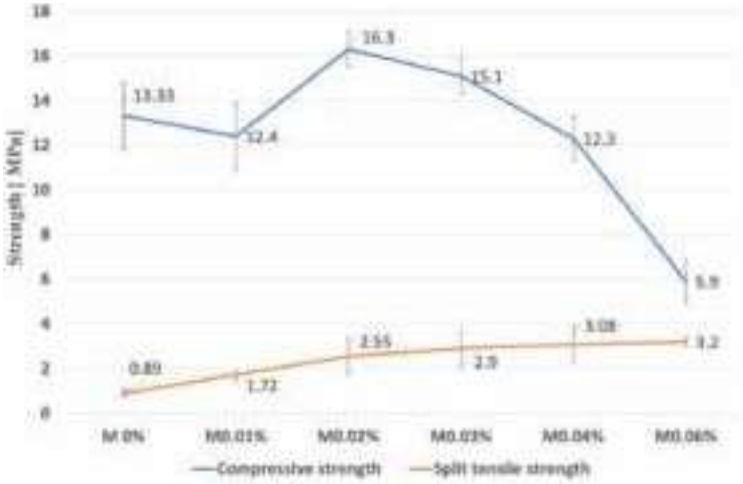

Figure 4: Relationship between compressive and Split Tensile Strength.

Conclusions :

The results in Fig.4 shows that amount the addition of recycled carbon fibre improves the compressive strength of concrete to a certain range, while The addition of recycled carbon fibre in the mixture improves the split tensile strength significantly.

Further developments:

- Introducing a Fibre reinforced polymer composites materials as aggregate replacement.
- Studying the long-term mechanical performance of FRPcrete for structural applications considering different variables.

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TMD and carbon nanocomposites for room temperature superconductivity.

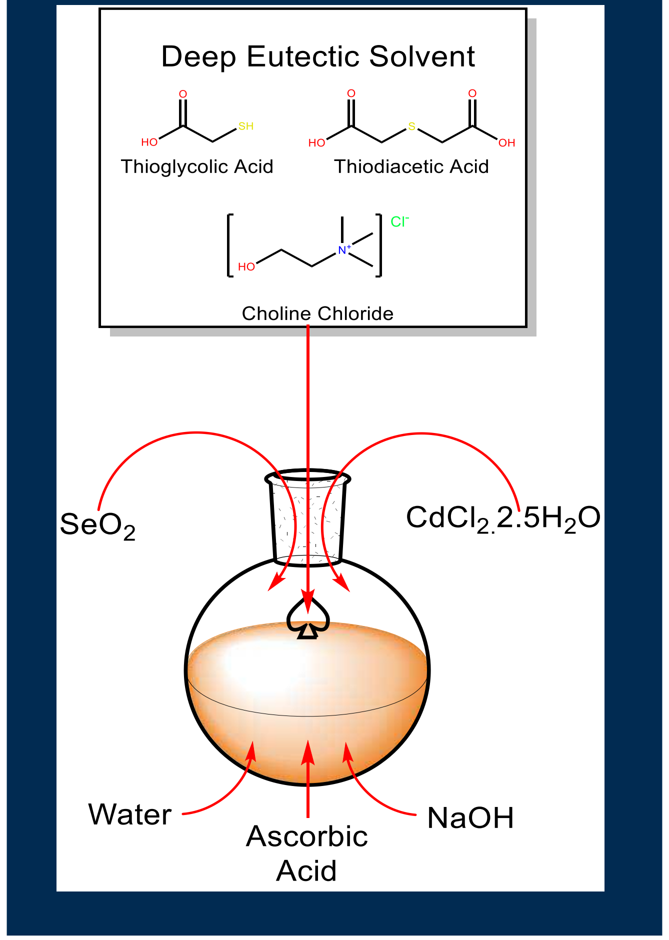
Rikesh Patel, Prof Simon Hall, Prof Steve Eichhorn, Dr Chris Bell

Superconductors are materials that, below a critical temperature, exhibit 0 DC resistance and expel an applied magnetic field from within itself. Often, the critical temperature is reached through cryogenic cooling. However, a mechanism of superconductivity, known as excitonic superconductivity, has been hypothesised to allow for room temperature superconductivity, through the compositing of transition metal dichalcogenides and carbon. No excitonic superconductor has yet been realised. This project aims to take the existing theory and make it a reality.

Aims:

- → To synthesise a range of transition metal dichalcogenide nanoparticles in a controllable and reliable way.
- → To encompass these nanoparticles in a carbon shell.
- → Measure for room temperature superconductivity.

Synthesis of CdSe Nanoparticles



The resulting mixture from the synthesis to the left is refluxed at 100 °C.

The time spent refluxing determines the size of the resulting nanoparticles as can be seen from the picture on the right.

Next Steps

- → To synthesise other TMD Nanoparticles
- → To create a carbon shell
- → To determine superconductivity through SQUID Measurements

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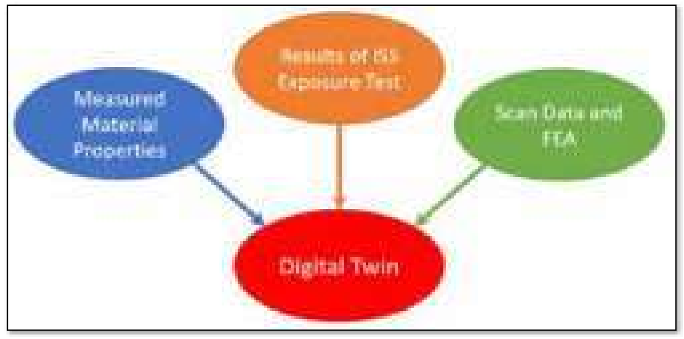
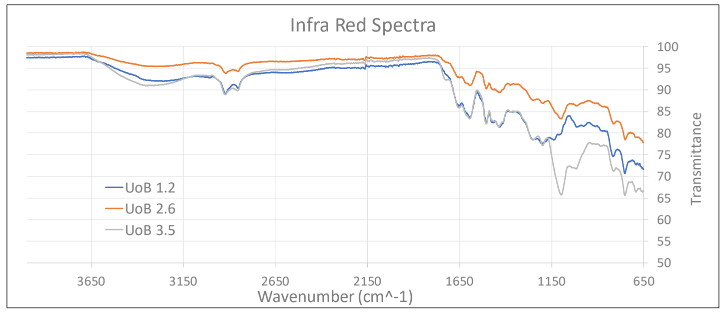
Digital Engineering of Space Composites

George Worden, Ian Bond, Kate Robson-Brown & Ian Hamerton

Problem and Aims

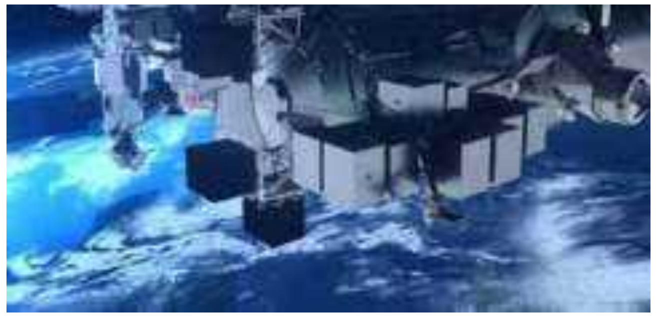
- The environment in low Earth orbit (LEO) is very hostile to materials, due to atomic oxygen, micrometeoroids, radiation and other factors.
- Testing materials in space is incredibly costly and time-consuming
- The creation of a "Digital twin" of material components in LEO would provide a method to predict degradation and therefore lifespan.
- A novel benzoxazine based polymer was developed to be resistant to the LEO environment with the addition of POSS nanoparticles.





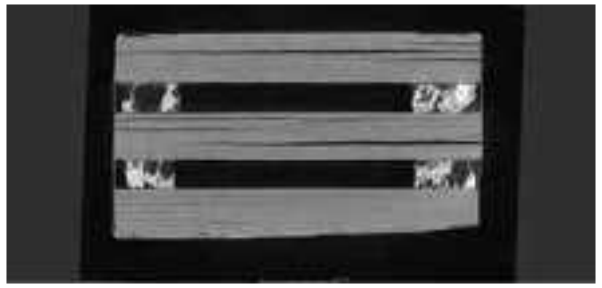
Summer 2021

- Over Summer 2021 a number of techniques were used to begin characterisation of a three composite laminates manufactured with the novel benzoxazine and varying quantities of POSS.
- Optical microscopy was used to produce high-resolution images and roughness measures of the sample surface.
- FTIR was used to characterise the chemical bonds/composition at the surface of the samples.
- DSC was used to characterise the thermal properties
- Surface properties are particularly important as that is the area that will be attacked by AO in LEO.



ISS Mission

- A number of samples of the original material will be sent to the ISS and exposed to space from the Bartolomeo platform.
- After 6 months of exposure they will be returned to Earth and the exposure data used to validate the model.



Current Work

- Development of an improved material composition to alleviate some of the issues of the first.
- Manufacture of large laminates that can be used for a wide range of mechanical/thermal tests.
- Creation of a framework for the digital twin, using CT scan data

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This was carried out with additional support from Mayra Rivera Lopez, Joseph Gargiuli, Yusuf Mahadik, and the BCI lab support team.

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Investigation of porous composite materials for hydrogen storage

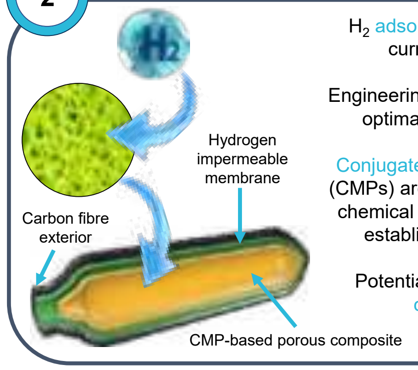
John Worth[a][b], Prof C. F. J. Faul[a] & Prof V. P. Ting[b]

[a] School of Chemistry, University of Bristol, Bristol, BS8 1TS, UK
[b] Department of Mechanical Engineering, University of Bristol, Bristol, BS8 1TR, UK

1 Hydrogen (H_2) for renewable energy storage

✓ Clean combustion	✗ Highly flammable
$2H_2 + O_2 \rightarrow 2H_2O$	✗ Highly compressed (70 MPa)
✓ Globally abundant	✗ High mechanically performing containment materials needed
✓ High gravimetric energy density	✗ Current storage technology is costly

2 Conjugated microporous polymers



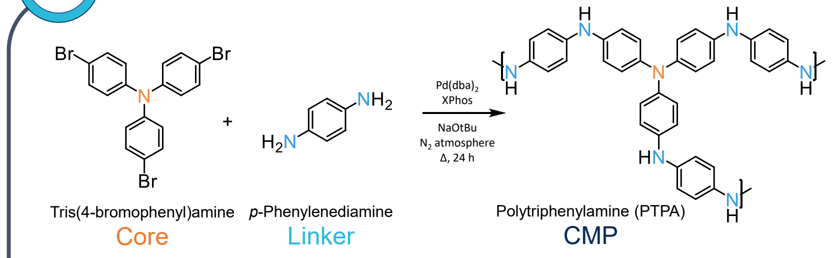
H_2 adsorption in pores combats current storage issues

Engineering micropores (< 2 nm) for optimal H_2 storage capacity[1]

Conjugated microporous polymers (CMPs) are promising owing to their chemical and thermal stability and established synthetic routes

Potential for incorporation into composite tanks

3 Material synthesis and optimisation



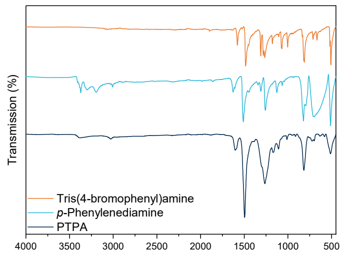
Buchwald–Hartwig cross-coupling amination reactions used to create porous CMPs[2]

Reaction conditions changed to create material with different properties

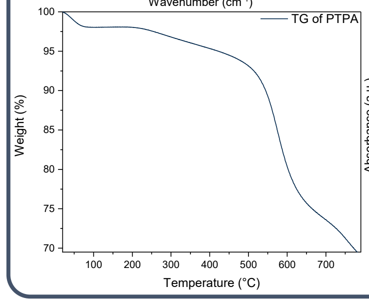
Sample №	Core:Linker	Solvent	Ionic salt
PTPA-1	1.00:1.50	Toluene	-
PTPA-2	1.00:1.50	Tetrahydrofuran	Sodium fluoride
PTPA-3	1.85:1.00	Tetrahydrofuran	Sodium fluoride
PTPA-4	1.95:1.00	Tetrahydrofuran	Sodium fluoride

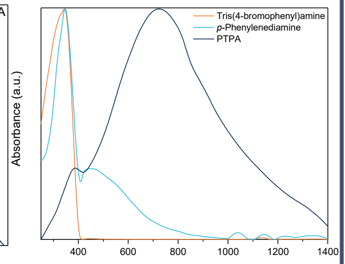
Bristol–Xi'an Jiaotong (BXJ) optimisation of Hansen Solubility Parameters (HSPs) to extend growth of CMP networks[3]

4 Material characterisation

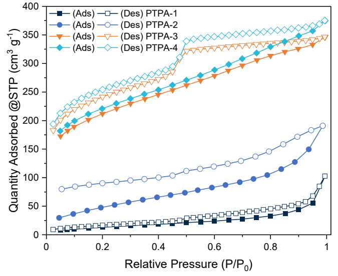


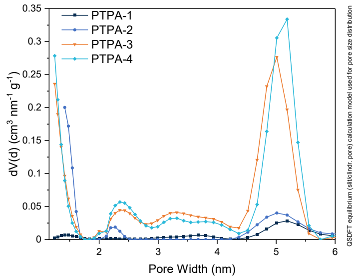
Wavenumber (cm^{-1})	Assignment
1178	Aromatic C-Br stretching
3299 & 3196	$-NH_2$ stretching
1623	$-NH_2$ deformation
3382	-NH-
1604 & 1496	Benzoid & quinoid rings
818	Aromatic C-H

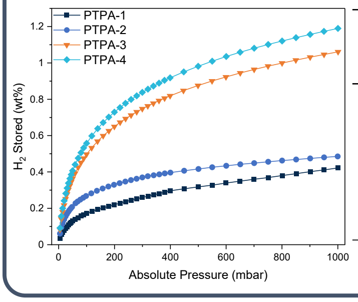




5 Gas sorption analysis







Sample №	Surface area (m^2 g^{-1})[a]	Pore volume (cm^3 g^{-1})[b]	Micropore volume (cm^3 g^{-1})[c]	H_2 Stored (wt%)
PTPA-1	53	0.16	-	0.4
PTPA-2	187	0.30	-	0.5
PTPA-3	760	0.54	0.16	1.1
PTPA-4	795	0.58	0.19	1.2

[a] Calculated from N_2 isotherm with BET equation [b] Calculated from N_2 isotherm at $P/P_0 = 0.95$ [c] Calculated using the t-Plot method with P/P_0 range 0.2–0.5 and the generalised Halsey thickness equation

6 Conclusions

- Series of CMPs synthesised and characterised
- Synthetic modifications resulted in tuning of surface area, pore size distribution & pore volume
- Increased H_2 storage performance

7 Future work

- Further optimisation of CMPs for H_2 storage
- Improve processibility via composite formation
- Mechanical testing of and characterisation of composite
- Gas sorption analysis of composite material

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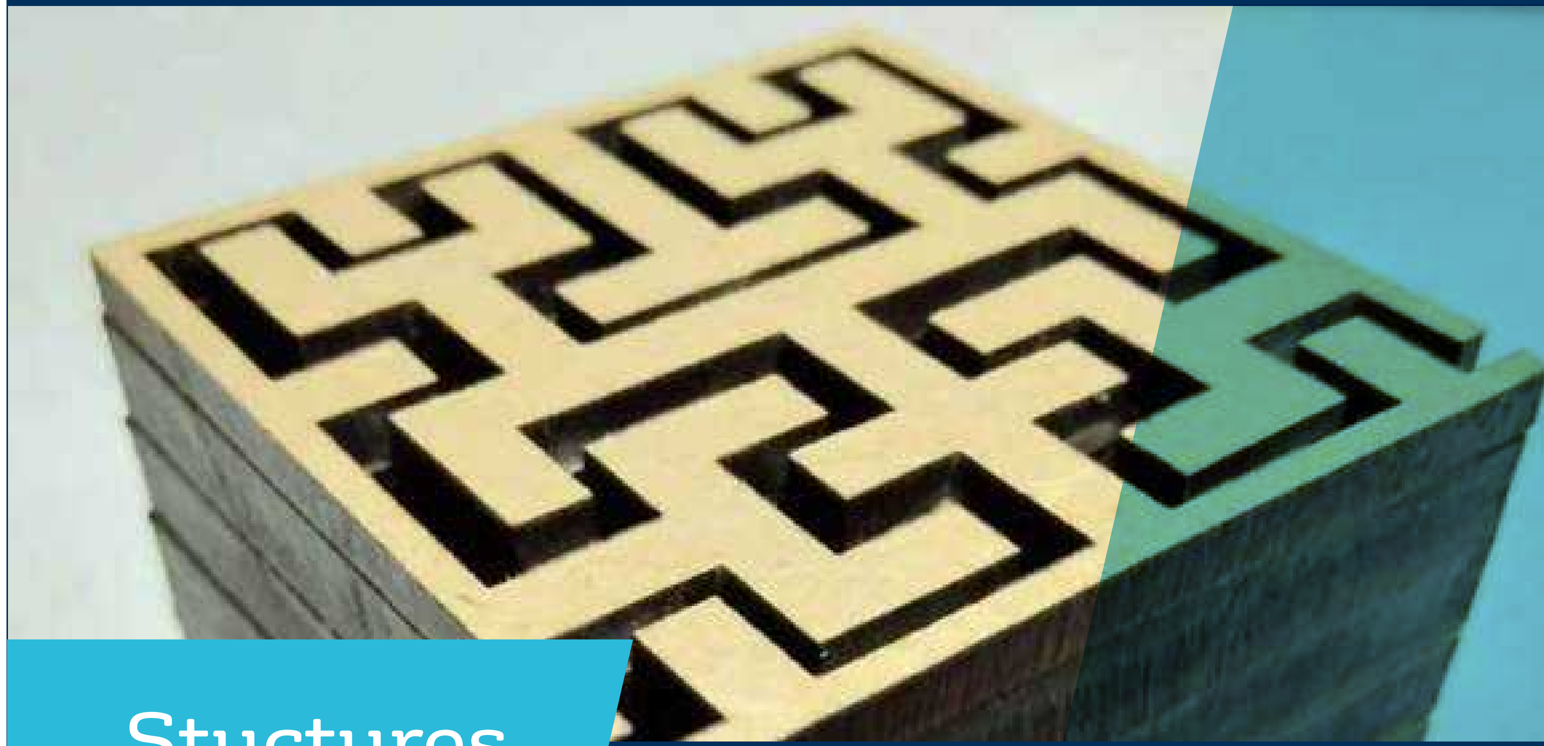
3. J. Chen, T. Qiu, W. Yan, C.F.J. Faul, Exploiting Hansen solubility parameters to tune porosity and function in conjugated microporous polymers, J. Mater. Chem. A. 8 (2020) 22657–22665.



Stuctures

Photo credit: MDF Acoustic Metamaterial_Gianni Comandini

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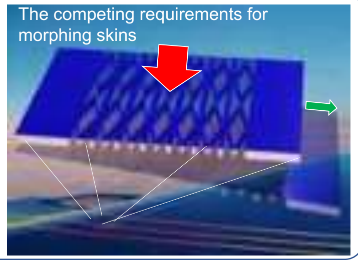
3D printed GATOR morphing skins

Rafael Heeb, Michael Dicker, Fabrizio Scarpa, Benjamin K. S. Woods

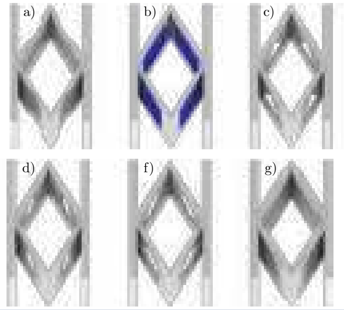
Morphing aircraft are one promising solution to reducing the aviation industry's greenhouse gas emissions in aircraft more aerodynamically efficient. GATOR morphing skins seek to solve the fundamental design tradeoff of needing low in-plane stiffness to reduce actuation energy but high out-of-plane stiffness to resist aerodynamic loads. This is achieved by taking advantage of multi-material additive manufacturing methods and thermoplastic elastomers of different stiffnesses, allowing strategic placement of stiffness and compliance, taking advantage of geometric anisotropy and design scaling laws.


The competing requirements for morphing skins

Geometrically Anisotropic ThermOplastic Rubber morphing skin design principles

Thermoplastic Elastomers

which can be printed into complex geometries.

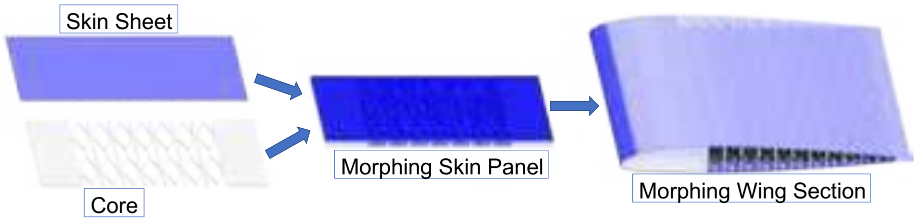


Multi-Material 3D Printing

of different stiffness materials in a single component to locally tailor stiff and flexible features.

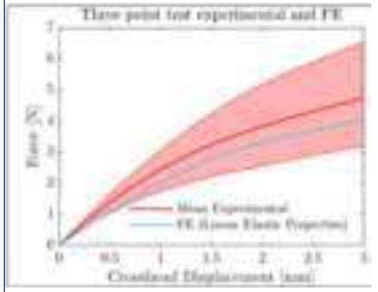
Exploiting Geometric and Structural Scaling Laws

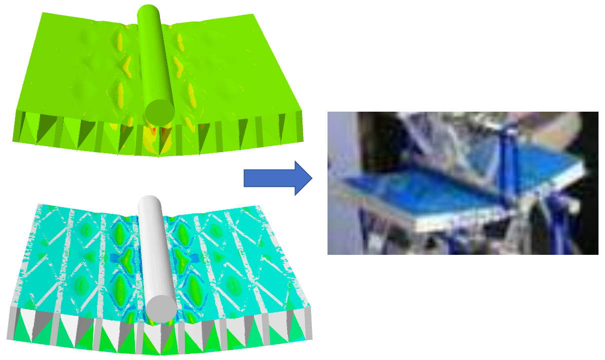
to help decouple morphing design constraints.



Experimental and FEA analysis of the hyperelastic GATOR sandwich panels

Flexural

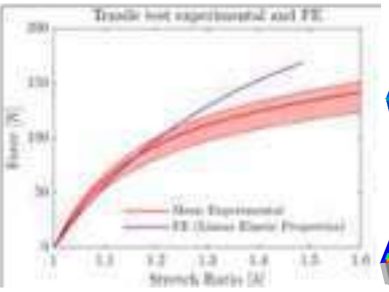


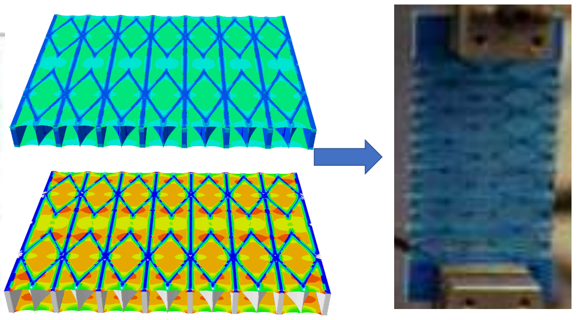


- Experimental data shows that the flexible skin can resist some compressive loads despite the low stiffness.
- A linear behaviour is observed at low out-of-plane displacements before buckling.
- The FEA model using 2D and 3D elements for the skin and core respectively closely matches the experimental data.

Tensile

- Linear elastic material properties can be used to model the in-plane properties at low stretch ratios.
- The periodic arrangement of cells causes high biaxial strains which results in a softening effect at very large stretch ratios.





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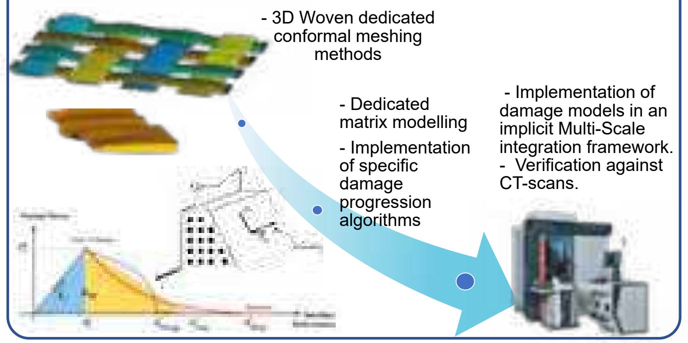
Advanced High-Fidelity Modelling of Woven Composites

Ruggero Filippone, Bassam Elsaied, Adam Thompson, Peter Foster, Stephen Hallett.

This research aims to develop state-of-the-art modelling capabilities for meso-scale damage modelling in woven textile composites. In particular, 3D woven composites debonding is one of the key damage mechanisms that have been extensively observed via experimental test studies. In the absence of debonding models, Matrix cracks can progress directly from matrix to yarn materials, resulting in a premature prediction of failure. Consequently, it is essential to include this damage mode in simulation for accurate predictions of the ultimate failure strength.
Here, a dedicated meshing framework is proposed to include reliable debonding failure detection in the meso-scale models of textile composites. In this first stage of research, a dedicated model has been implemented to generate a structured mesh of woven composites. It can automatically generate the geometry of the *RUC* (Representative Unite Cell) of a tessellated woven fabric embedded into the matrix, generating a tailored structured mesh for both of yarns and matrix. Furthermore, the cohesive elements are generated into the interfaces region to investigate how the stress/strain state in these regions generate the debonding defect, leading to an anticipated failure.

Objectives



- 3D Woven dedicated conformal meshing methods

- Dedicated matrix modelling

- Implementation of specific damage progression algorithms

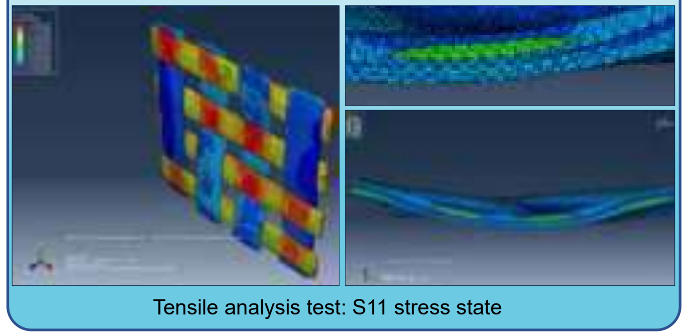
- Implementation of damage models in an implicit Multi-Scale integration framework.

- Verification against CT-scans.

FEA

Preliminary finite element analysis has been used to test the consistency of the mesh. To date, the results achieved show:

- Reduced number of elements needed to achieve an high fidelity model.
- Reduced computational load and time to run complex structures.
- Detailed stress gradient in the interface region.


Tensile analysis test: S11 stress state

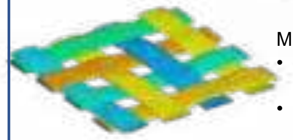
Meshing Algorithm

Integration of the specific mesh algorithm with SimTex Software

From SimTex:
- Generation of Fabric Textile geometry data as CSV list of yarn cross sections.
- Importing CSV geometry data of tessellated woven fabric.
- Inflected yarns CSV file is generated with high level of precision,

Geometry building Algorithm:
- Generation of surfaces and volumes

- Boolean operation defines 3 different volumes:
  - Fabric yarns
  - Matrix
  - Interface layer

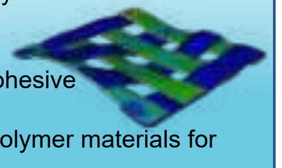


Mesh and *inp* file generation to start the FEA:
- An API was developed to generates a tailored mesh of each volume.
- Material properties and coordinates system for each element are generated.

Overview and Future Works

The algorithm generates a high-fidelity model of Woven Composites, offering a reliable method to implement cohesive elements. This paves the way to investigate the debonding failure in these composites.
Furthermore, the structured mesh showed promising results in the FEA benchmark, stating as a potential enhancement in the multiscale analysis framework.

Next steps:
- FEA of woven composites with cohesive elements.
- Enhancing of damage model of polymer materials for the matrix.



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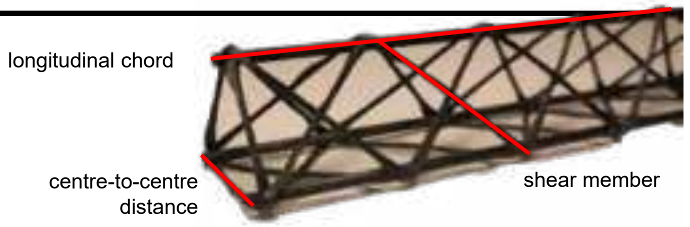
WrapToR Truss Stiffened Skin Panels for Aerospace Applications

Chris Grace, Prof Michael Wisnom, Dr Terence Macquart, Dr Mark Schenk, Dr Benjamin Woods

The Wrapped Tow Reinforced (WrapToR) truss concept has been shown capable of producing low cost, consistent truss beam structures with a rapid and simple fabrication process[1,2]. This project aims to characterise and optimise the application of the WrapToR truss concept as a reinforcement member for structural panels, to demonstrate that such stiffened skin panels can improve the mechanical performance of aerospace vehicles for a low mass budget.

Technology

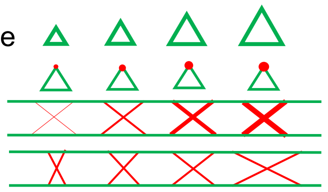
A WrapToR truss uses an adapted filament winding method to lay down continuous carbon fibre as shear members. Reduces assembly of individual parts and allows use of continuous carbon fibre.

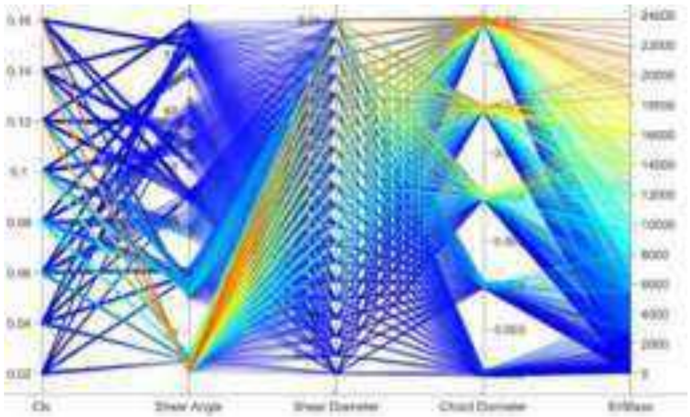


Modelling and Analysis

Numerical design space exploration of truss design variables to identify trends, and their effect on mechanical performance.

- centre-to-centre distance
- chord Diameter
- shear Diameter
- shear Angle

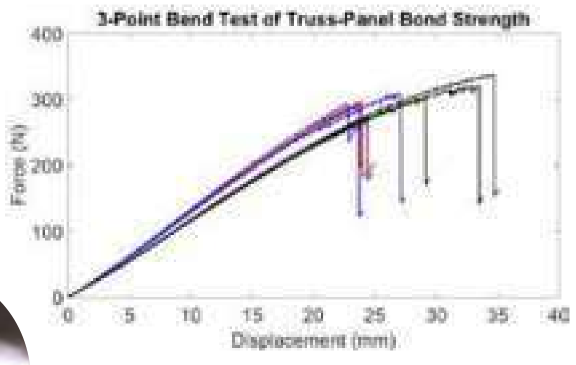




Parallel coordinate plot showing 1500 different configurations. Each axis shows one variable, with the right being performance metric. A line is drawn for each combination of variables and colour represents best (red) to worst (blue) performance

Experiments

Adapting fabrication process from truss beam to stiffener, and comparing different curing methods on truss-panel bonding.



Experimental results for 3 curing methods:
Blue – hanging rotation
Red – single sided compression
Black – double sided compression

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1. Woods, BKS., Berry, BO, and Stavnychyi, VB, “Continuous wound composite truss structures,” US Patent Application No. US20130291709 A1, May 1, 2013.

2. Hunt, CJ, Wisnom, MR, and Woods, BKS, “WrapToR composite truss structures: Improved process and structural efficiency,” Composite Structures, 2019, Vol. 230, p., 111467.

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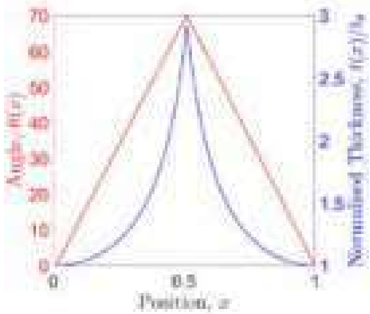
Embedded Stiffening Grids in Laminated Plates and Shells

Calum J. McInnes, Alberto Pirrera, Byung Chul Kim, Rainer M.J. Groh

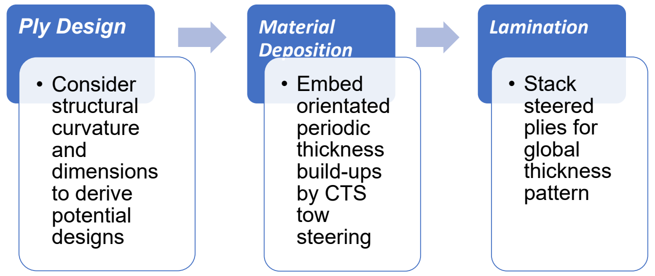
Lightweight structures have been identified as a key enabling technology for next-generation air and spacecraft. In traditional structural design, machined or bonded grid-stiffened structures give significant performance benefits to aerospace vehicles by allowing directionally tailorable stiffness and strength. With the development of new composites manufacturing capabilities, such as Continuous Tow Shearing (CTS) it is envisioned that the process-inherent nonlinear material orientation-thickness coupling can be exploited in a novel design methodology for highly efficient laminated structures.

Continuous Tow Shearing

- Continuous Tow Shearing (CTS) process shears material along periodic curvilinear paths
- Material volume conservation dictates out-of-plane thickness increase



Embedded Grid Design

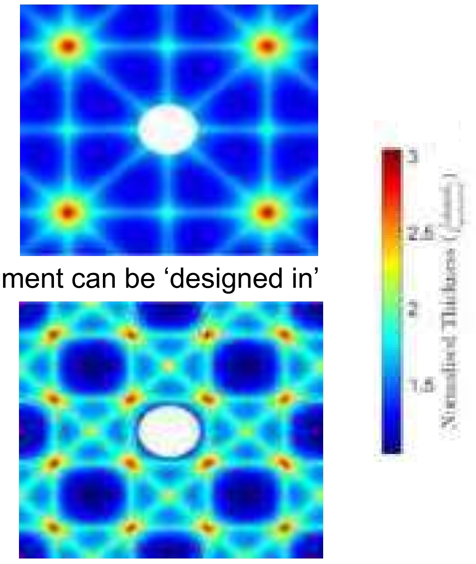


Ply Design
- Consider structural curvature and dimensions to derive potential designs

Material Deposition
- Embed orientated periodic thickness build-ups by CTS tow steering

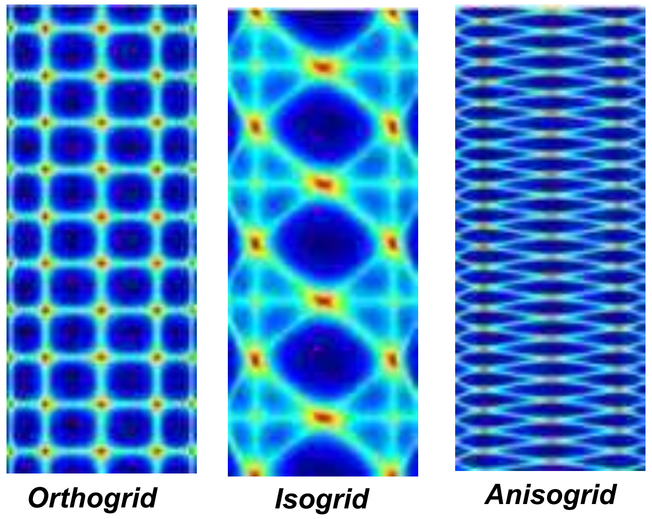
Lamination
- Stack steered plies for global thickness pattern

Geometric Feature Masking



- Holes placement can be ‘designed in’

Tailorable Monocoque Structures



- Grids can be embedded during manufacture

Conclusions

- Significant design potential to be unlocked
- Physical features of selected manufacturing process can be exploited in structural design
- Rich solution space available for exploration

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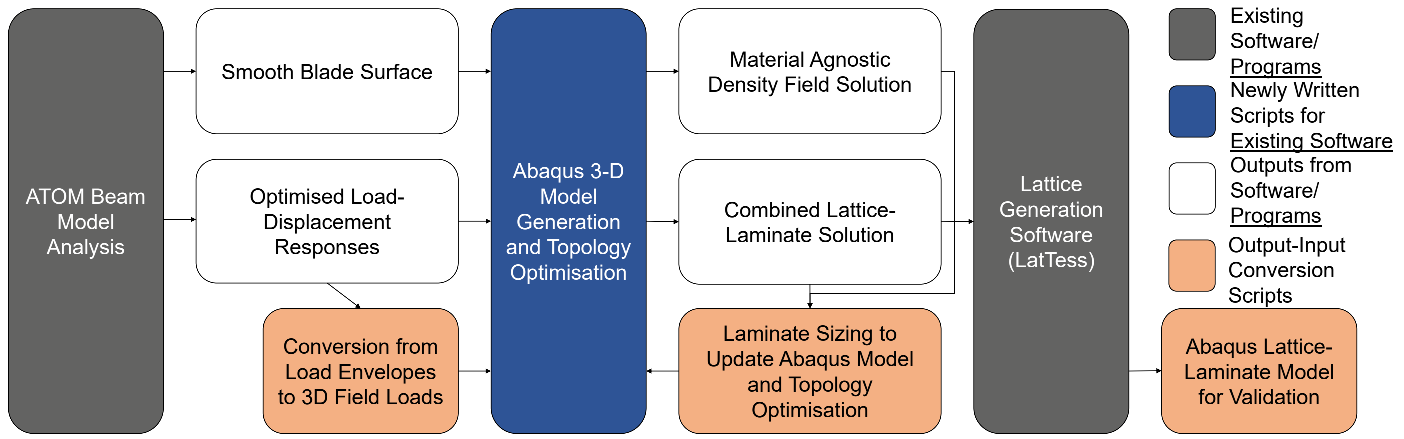
Structural Design of Wind Turbine Blades with an Additively Manufactured Graded Lattice Core using Topology Optimisation

Alex Moss, Dr Ajit Panesar, Dr Terence Macquart, Dr Alberto Pirrera, Dr Peter Greaves, Dr Mark Forrest

Conventional wind turbine blade manufacture relies on large, expensive moulds. Instead, using additive manufacturing to print the internal structure of blades, upon which it would be possible to lay composite plies, could significantly reduce manufacturing costs and, as one could "3D print" topologically optimal designs, improve structural efficiency. Topology optimisation generally integrates well with additive manufacturing, however there are two main challenges associated with the adoption of topology optimisation in wind blade design: (i) the aeroelastic response of blades; (ii) the use of multiple materials in the design of the composite laminates as well as the printed structure. To address these challenges, a new multi-step design and optimisation framework is proposed, relying on the combination of three software.

Design Methodology



ATOM Beam Model Analysis

Smooth Blade Surface

Optimised Load-Displacement Responses

Conversion from Load Envelopes to 3D Field Loads

Abaqus 3-D Model Generation and Topology Optimisation

Material Agnostic Density Field Solution

Combined Lattice-Laminate Solution

Laminate Sizing to Update Abaqus Model and Topology Optimisation

Lattice Generation Software (LatTess)

Abaqus Lattice-Laminate Model for Validation

■ Existing Software/ Programs

■ Newly Written Scripts for Existing Software

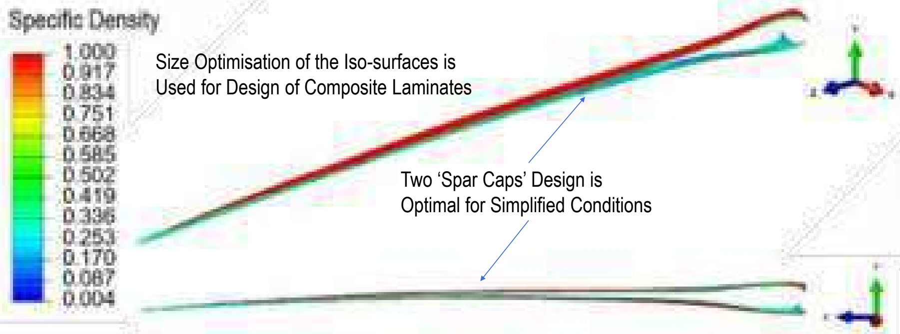
□ Outputs from Software/ Programs

■ Output-Input Conversion Scripts

Firstly, a conventional aero-servo-elastic model is used to evaluate blade loads and displacements. Next, a topology optimisation software is used to optimise the blade laminates and core structure. Third, a lattice generator is used to convert the topologically optimised "grey" design into an equivalent cellular design that can be printed using additive manufacturing.

Initial Topology Optimisation Results

Idealised Wind Blade Design

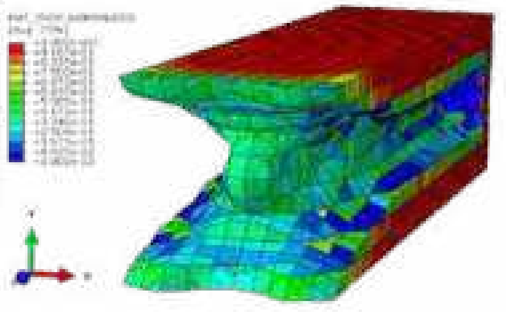


This image shows an isometric and side view of the initial topology optimisation solution for the blade, using a minimum compliance objective function and a volume constraint of 12.5%. A penalisation factor of 1 was used to simplify the optimisation and produce a "grey" design which smoothly transitions the specific density between solid and "void".

Testing Abaqus' Optimisation Capabilities

The full blade optimisation requires many constraints and load cases, so it is important to test Abaqus' ability to find solutions and identify best practice when such conditions are imposed.

The solution below had two load cases applied in the X and Y direction respectively and was able to find a minimal volume solution for the target displacements.



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Compliant fairing for folding wingtips on commercial airliners

Student: Nuhaadh Mahid **Supervisors: Dr Benjamin Woods, Dr Mark Schenk, Dr Branislav Titurus**

1. Folding wingtips – why?

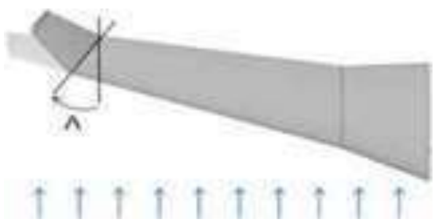
- Increase wingspan while fitting within current airport gate sizes
- Alleviate gust load to minimize structural penalty of increased span

But why?

- To minimize fuel costs and emissions

1a. Minimize gust load – how?

High flare angle (Λ), low torsional stiffness and damping of the hinge, along with low wingtip mass has been shown to alleviate gust load [1]



Schematic of a starboard wing with a flared wingtip [1].

2. A morphing fairing – why?

- To protect the hinge from debris, particularly during take-off and landing
- To avoid the excessive vortices generated by an exposed hinge which is not aligned with the flow

Wing-tunnel model of a folding wingtip with flared hinge [2].

4. Conclusions

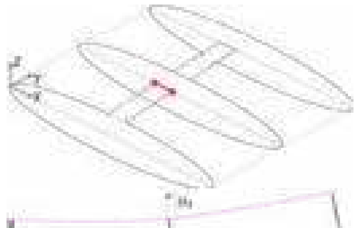
A compliant fairing using stiffness-tailored sandwich panel with cellular core and elastomeric skin has potential to achieve:

- Robust cross-section shape for aerodynamic surface
- Reduced folding stiffness

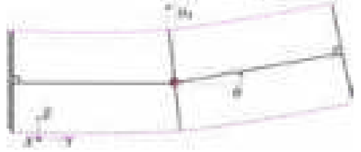
3. Compliant fairing: challenges and solutions

High strain across the hinge due to folding

- ➢ Minimize strain via pivoted ribs to redistribute the strain over a longer length of skin



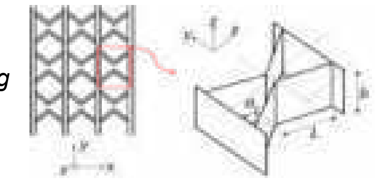
Isometric view of the pivoted inner-rib design. Folding hinge and the hinge of the rib are co-located.



Rear view with folding angle (θ) and rib rotation angle (μ).

Distortion of cross-section due to:

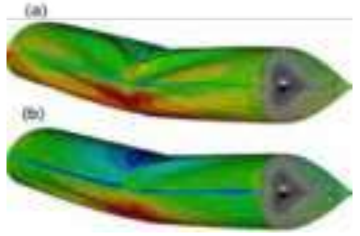
- Bending of skin under pressure load
  - ➢ High out-of-plane stiffness via sandwich panel with fibre-reinforced elastomeric facesheets away from mid-plane
- Poisson's ratio effects along the hinge
  - ➢ Near-zero Poisson's ratio via anisotropic cellular core and fibre-reinforced elastomeric facesheet [3]



Ribs make the core stiff along y-axis and bending of chevron walls gives flexibility along x-axis.

Wrinkling on the skin as wingtip folds

- ➢ Spatially varying stiffness, using curvilinear fibres on the facesheet along with varying rib direction in the core



Finite element simulation of (a) a highly wrinkled skin, and (b) a skin with reduced wrinkling.

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[1] A Castrichini, "Parametric Assessment of a Folding Wing-Tip Device for Aircraft Loads Alleviation," PhD Thesis, University of Bristol, 2017

[2] RCM Cheung, D Rezgui, JE Cooper, and T Wilson, "Testing of a Hinged Wingtip Device for Gust Loads Alleviation," Journal of Aircraft, vol. 55(5), 2018

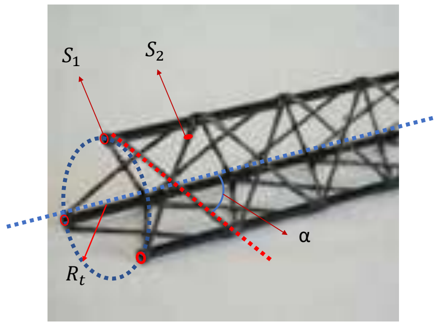
[3] EA Bubert, BKS Woods, K Lee, CS Kothera, and NM Wereley, "Design and Fabrication of a Passive 1D Morphing Aircraft Skin," Journal of Intelligent Material Systems and Structures, vol. 21(17), 2010

Manufacturing and Design

Trusstruder: Continuous Manufacture of Wrapped Tow Reinforced Truss Beams

Francescogiuseppe Morabito, Dr Terence Macquart, Dr Mark Schenk, Dr Alberto Pirrera and Dr Benjamin Woods

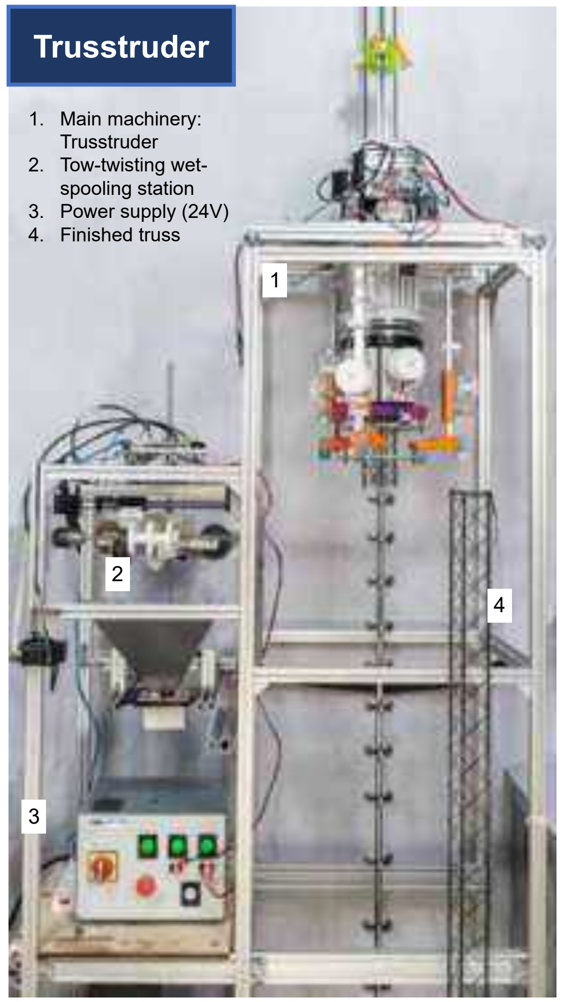
Recent developments in ultra-efficient composite truss structures have shown very high levels of achievable structural efficiency through the combination of truss geometries, composite material properties, and scalable manufacturing processes. Filament winding-based approaches such as the WrapToR process allow for simpler machine design; on the other hand, it is limited to batch production of truss beams with limited lengths. We present a new machine concept to overcome this limitation: the Trusstruder. This concept uses a coaxial winding head to wrap multiple pre-wetted tows in opposite directions around continuously extruded longitudinal members to achieve a fully wound truss structure in one passage, avoiding the need for the reciprocating motion of conventional winding machines. Trading process and geometry versatility for standardisation and production rate, this new machine concept moves towards high throughput, continuous production of WrapToR truss beams.



The current Trusstruder can produce WrapToR truss beams (figure above) with geometrical properties described in the table below.

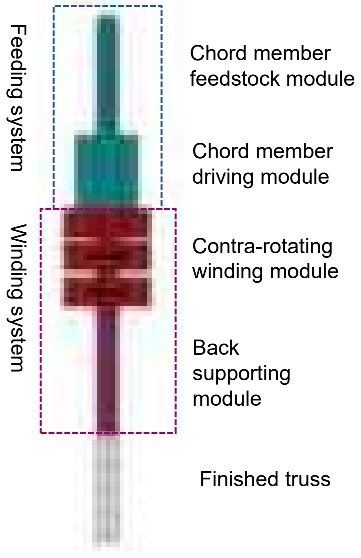
	Property	Symbol. [unit]	Value / Range
R_t	Truss radius	R_t [mm]	40
α	Shear web angle	deg [-]	[15, 60]
S_1 - Chord member	R external	R_{ext} [mm]	6
	R internal	R_{int} [mm]	n.a.
S_2 – Shear web member	Web radius (6K to 48K)	R_{web}[mm]	[0.8, 1.25]


Contra-rotating module in operation



Trusstruder

1. Main machinery: Trusstruder
2. Tow-twisting wet-spooling station
3. Power supply (24V)
4. Finished truss



Trusstruder's modules schematic


WrapToR truss beam testing

[1] C J. Hunt, F. Morabito, C. Grace, Y. Zhao, and B.K.S. Woods, “A review of composite lattice structures,” *Compos. Struct.*, vol. 284, p. 115120, 2022, doi:10.1016/j.compstruct.2021.115120.
[2] B.K.S. Woods, I. Hill, and M. I. Friswell, “Ultra-efficient wound composite truss structures,” *Compos. Part A Appl. Sci. Manuf.*, vol. 90, pp. 111–124, Nov. 2016, doi:10.1016/j.compositesa.2016.06.022.

Infusion of integrated structures with semi-cured elements

Michael O'Leary

Industrial Supervisors: Jon Price, Turlough McMahon. Academic Supervisors: James Kratz, Dmitry Ivanov.

Introduction:

Post cure joining operations and complex preform integration prior to resin infusion processes are two challenges facing manufactures as they can lead to delays in production and additional process verification. A multistage cure process is seen as having the potential to alleviate both issues. In this PhD project, a simple structure containing elements which were semi-cured prior to a final infusion and curing has been created for the purpose of investigating the effect of integrating these semi cured elements within composite structures and the subsequent effect on interfacial properties. Feasibility study results indicate that the addition of a semi-cured element slightly lowers the interfacial mode 1 fracture toughness. The research will develop over the coming years to close the performance gap and reduce manufacturing risk.

Manufacture & Testing

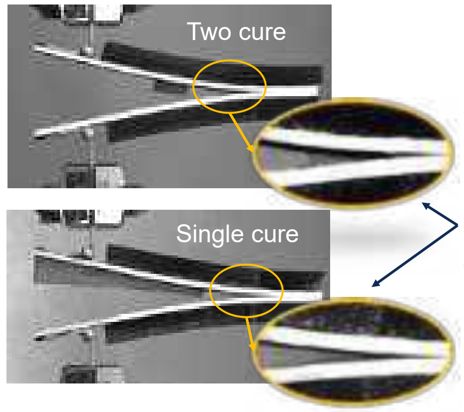
Two stage infusion & oven cure process:

- 1st cure @ 140°C for X min (semi cure) cure achieving DoC's from 0.2-0.9
- 2nd cure @ 180°C for 150 min (final cure) cure achieves T_g ~ 165C and DoC ~ 1

Comparative panel:

- Single infusion & cure @ 180 for 150 min

DCB specimens machined from panels and tested.



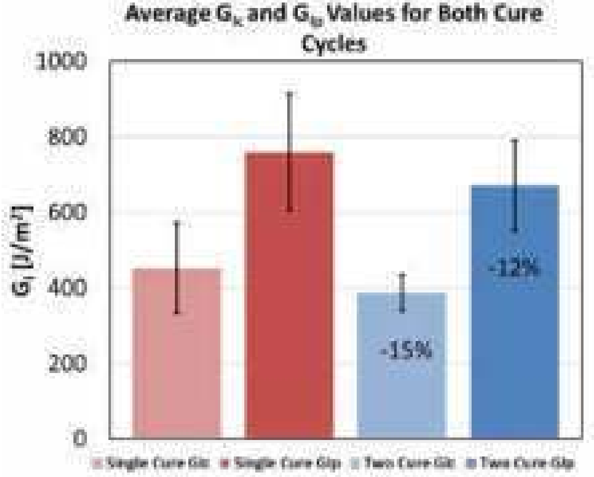
Regardless of specimen manufacturing method fibre bridging was witnessed during DCB testing

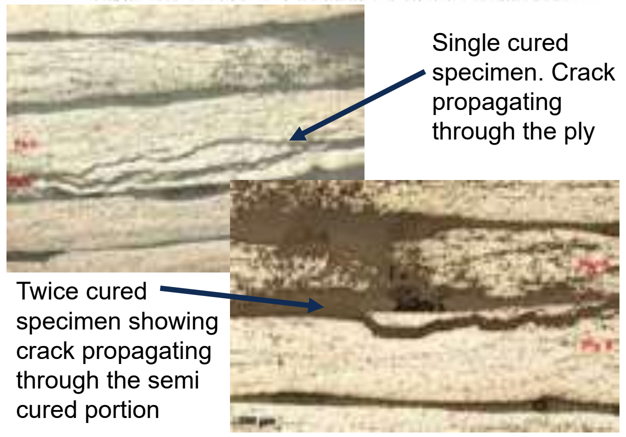
Future Work:

1. Evaluation of remaining DoC's to determine optimal DoC for real world manufacturing conditions
2. Exploration of the effect of cure path on neat resin properties.
3. Process modelling to optimize the manufacturing window

Initial Results

15% reduction in $\mathbf{G_{ic}}$ and **12%** reduction in $\mathbf{G_{ip}}$ experienced in panels undergoing two cure process with initial DoC of ~0.7 in the semi-cured element





Single cured specimen. Crack propagating through the ply

Twice cured specimen showing crack propagating through the semi cured portion

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Advanced Continuous Tow Shearing

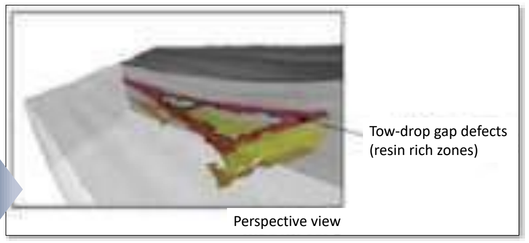
Michelle Rautmann, Edwin Rosario Gabriel, Dmitry Ivanov and Byung Chul Eric Kim

Common AFP **layup defects**, such as fibre buckling or stretching, or tow drops or overlaps result in considerable **reduction of the structural performance** of a composite. For 1D angle variation layups, the **C**ontinuous **T**ow **S**hearing **(CTS)** process eliminates tow gaps and overlaps by utilising in-plane shear deformation. However, laying up on a complex 3D surface is to date challenging, as triangular gaps with fibre discontinuities and resin rich areas are induced that lead to high stress concentration and areas of failure initiation.

A novel concept of a **T**ow **Wi**dth **C**ontrol **(TWiC)** mechanism enables the adjustment of the tow width on the fly, which allows for eliminating tow drops and resin pocket defects whilst maintaining a constant fibre volume fraction. The TWiC device allows for the production of **defect-free 3-Dimensional composite lay-ups,** and achievement of **ultra-high structural efficiency.**

3-Dimensional layups – AFP limitations

AFP induced triangular shaped gaps on 3-dimensional surface. [1]



X-ray computed tomography of specimens. [2]

Geometry induced defects:
Resin rich areas and fibre discontinuities
High stress concentration
Areas of failure initiation

22.1% strength reduction for 0% gap-covered test specimens
10.8% strength reduction for 100% gap-covered test specimens (overlapping tows)
8.6% strength reduction using staggering method of gaps
[3]

Schematic of layup over a conical surface: AFP layup with tow drops, i.e., resin pockets.

Advanced Continuous Tow Shearing (ACTS) with Tow Width Control (TWiC)

Advantages

- On-the-fly control of the tow width
- Constant fibre volume fraction
- Production of complex shaped 3-Dimensional structures without tow gaps and overlaps
- No fibre discontinuities and resin rich areas (hot spots for damage initiation)

'Defect-free' TWiC layup.

CTS/TWiC layup.

Defect-free 3D fibre steering

- ➡ **Significantly expand the design space**
- ➡ **Achieve ultrahigh structural efficiency**

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[1] https://www.youtube.com/watch?v=xK4gMDduHgA

[2] Test specimens with induced tow drops, resulting in triangular shaped resin rich areas for un-notched and notched tensile tests by Falco et al..

[3] O. Falcó, J.A. Mayugo, C.S. Lopes, N. Gascons, J. Costa, Variable-stiffness composite panels: Defect tolerance under in-plane tensile loading, Composites Part A, 63, 2014, pp. 21-31 (doi: 10.1016/j.compositesa.2014.03.022).

This work was funded by the EPSRC project "Advanced Continuous Tow Shearing in 3D (ACTS3D): Advanced fibre placement technology for manufacturing defect-free complex 3D composite structures" (EP/R023247/1) and the EPSRC Centre for Doctoral Training (CDT) (EP/L016028/1).

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Influence of matrix ductility on the delamination bridging behaviour of z-pins

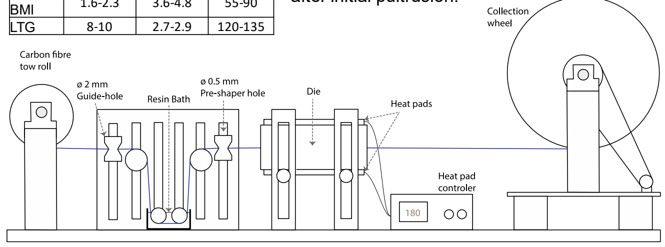
E. Santana de Vega, G. Allegri, B. Zhang, I. Hamerton and S. R. Hallett

Z-pinning is an effective method for embedding through-thickness reinforcement in composite laminates. Z-pins are typically manufactured employing carbon fibres combined with a bismaleimide (BMI) resin. The toughness improvement they provide decreases dramatically as the delamination mode ratio of Mode I to Mode II decreases, due to the inherent brittleness of this material combination. In this study, novel carbon-fibre Z-pin rod-stocks were successfully manufactured considering alternative matrix formulations to BMI. A ductile epoxy resin exhibited the most promising performance, showing extensive bending deformation and pin fibrillation. Z-pins based on this resin exhibited superior apparent delamination toughness throughout the full mode-mixity range.

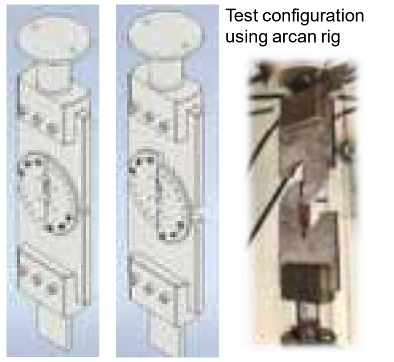
Z-pin Manufacturing

Resin	Ultimate Elongation	Flexural Modulus	Ultimate Strength
Unit	*%*	*GPa*	*MPa*
BMI	1.6-2.3	3.6-4.8	55-90
LTG	8-10	2.7-2.9	120-135

Pultrusion of unidirectional carbon fibre within a thermosetting resin matrix. Notice a post-cure step is necessary after initial pultrusion.

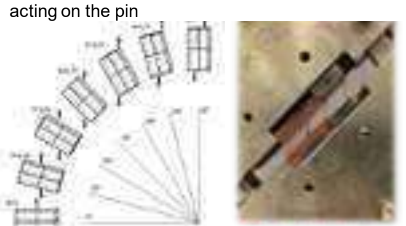


Test Procedure

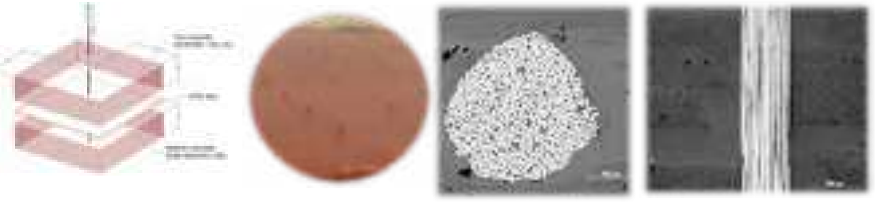


Test configuration using arcan rig

Rotation of arcan rig allows testing at 15° intervals, encapsulating the full range of load mode mixities acting on the pin

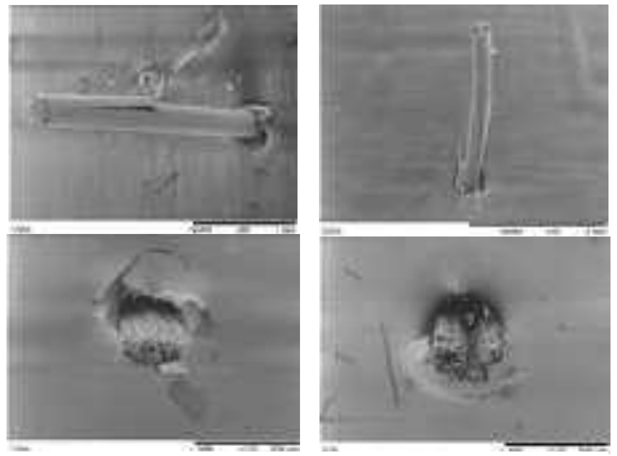


Coupon Preparation

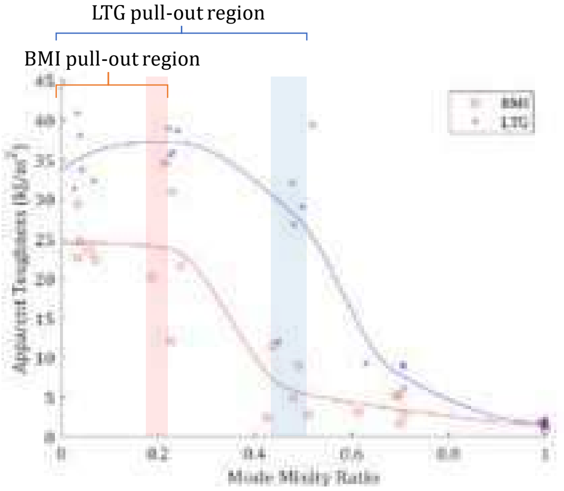


Test coupon configuration (left). Micrographs showing the microstructural features of manufactured Z-pins within a E-glass/epoxy laminate after the insertion and curing (right).

Test Results



SEM images of failed z-pins after single pin bridging tests at transition regions. Top images show pin pull-out at a mode-mixity of 0.2 of BMI (left) and LTG (Right) pins. Bottom images show pin rupture at a mode mixity of 0.5 of BMI (left) and LTG (right) pins.



Apparent delamination toughness of the BMI and LTG pins throughout the full load mode-mixity range, normalised for an aerial density of 0.2%.

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Development of an accessible prosthetic socket system

K. Alarcón, B.C. Kim, A. Dickinson, E. Seminati

Research aim

Develop an accessible transtibial (below knee) prosthetic socket via a systematic design methodology and generation of affordable bespoke composite structures.

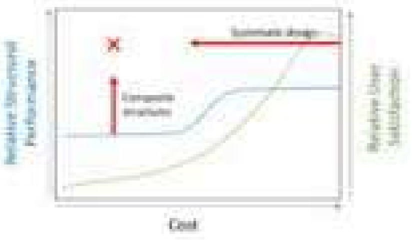


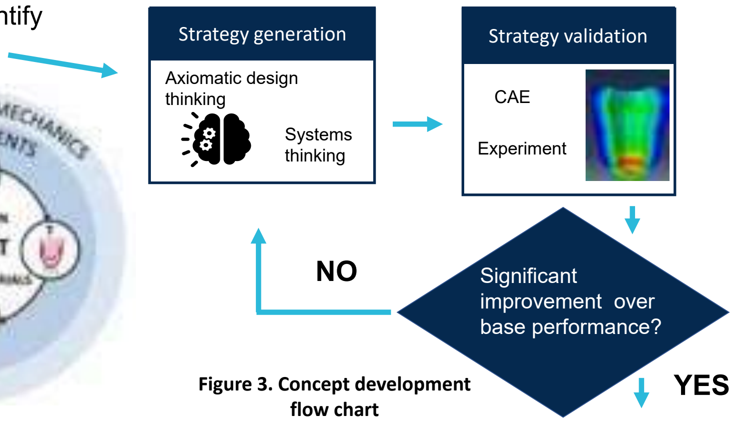
Figure 1. Current socket design envelope with relation to cost, structural performance and user satisfaction

Systematic design methodology

1.Evaluate socket interface system and user feedback to identify control points

Figure 2. Primary factors affecting the stump-socket interface [1]

2. Develop a system control strategy



Strategy generation

Axiomatic design thinking

Systems thinking

Strategy validation

CAE

Experiment

Significant improvement over base performance?

NO

YES

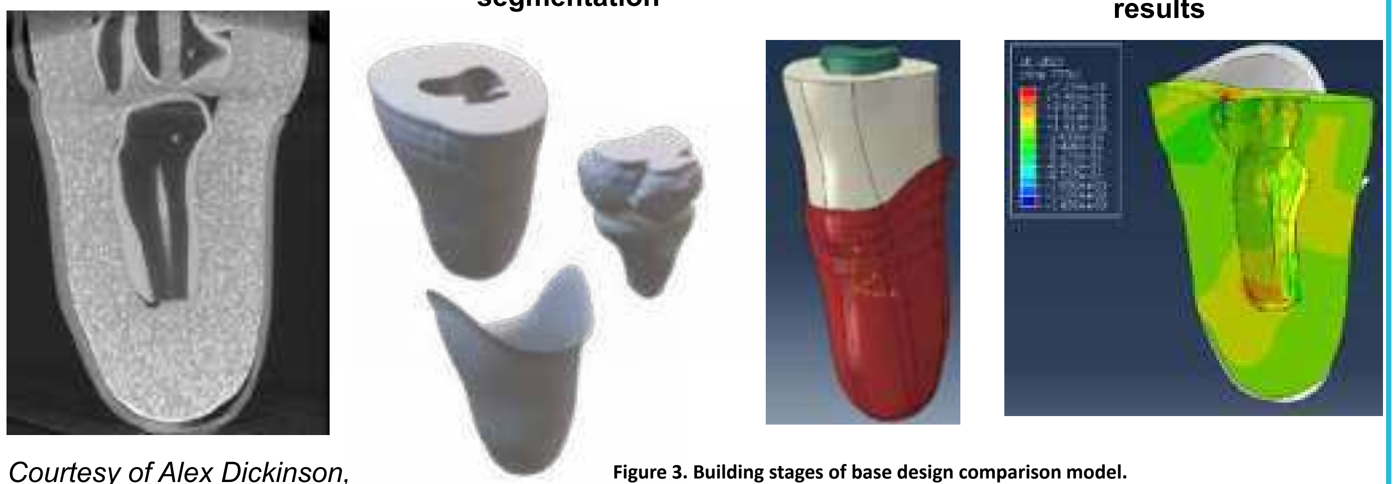
Figure 3. Concept development flow chart

Implement in design!

Strategy validation model

The purpose of this 'base' model is for socket **design comparison**. It is based on the analogue model by Rankin et al.[2] at Southampton, which aimed to investigate internal strains (injury indicators) from different socket designs. This model is being developed to test each design strategy generated, this will include structural elements and novel features of the socket. The preliminary results show the strain build up near the distal end of the tibia. The aim of the design strategy is be to minimise this build up in any loading scenario.

CT-Scan → **Model segmentation** → **FEA Assembly** → **Preliminary results**



Courtesy of Alex Dickinson, Southampton University

Figure 3. Building stages of base design comparison model. Preliminary study shows the placing of the socket onto the amputated limb.

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References

[1] Paternó L. et al., IEEE Transaction on Biomedical Engineering, 2018
[2] Rankin K. et al., Materials, 2020

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Investigating the scale up of the HiPerDiF process through manufacturing & testing

Chantal Lewis[1*], Rhys Tapper[2], Mark Harriman[2], Marco Longana[1], Carwyn Ward[1] and Ian Hamerton[1]
[1]Bristol Composites Institute, University of Bristol *Chantal.Lewis@Bristol.ac.uk
[2]Solvay Materials

Research aims:

- Produce aligned discontinuous fibre feedstock using HiPerDiF 3G with optimized fibre and process parameters
- Determine a suitable manufacturing and testing process for HiPerDiF 3G samples
- Compare performance of HiPerDiF 3G composite with UD continuous composites through mechanical testing
- Investigate the microstructure of HiPerDiF 3G composites

Method:

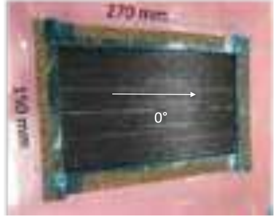
1

Rendered image of the HiPerDiF 3G machine

2 Impregnated roll

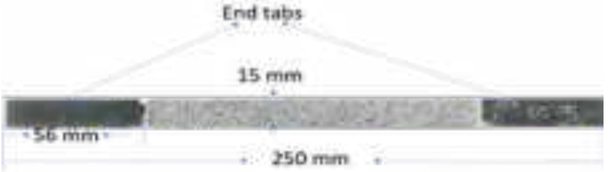
- CYCOM® 977-2 resin
- 30mm width, 25m length

3 Test panel manufacture



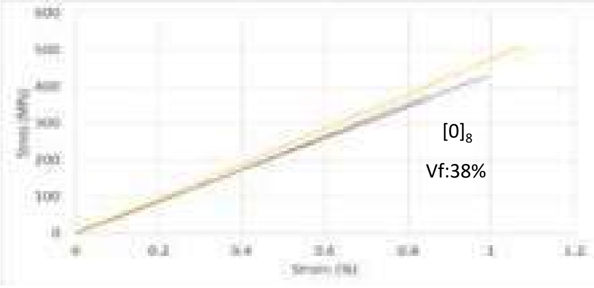
- Manual layup
- Autoclave cure

4 Mechanical testing



- ASTM D3039/3039M
- Strain measured by Digital Image Correlation

Initial results:



Representative stress-strain curve of HiPerDiF 3G composites

Mechanical properties of HiPerDiF-3G composites compared against UD-continuous samples normalised to 65% fibre volume fraction

Conclusions:

- Successful manufacture of large laminates with minimum gaps and overlaps to maintain specimen quality
- Stress strain curve show linear elastic tensile behaviour and brittle failure similar to continuous fibre composites
- Modulus of 78 GPa, strength of 751 MPa and failure strain of 0.97% comparatively low which indicates low level of alignment

Next steps:

- Optimise machine settings to improve tape quality
- Continue with further characterisation of HiPerDiF-3G composites
- Further investigation on strength properties of HiPerDiF-3G composites
- Investigate microstructure using image analysis techniques

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HiPerDiF High Performance Discontinuous Fibre

Supported by SOLVAY

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Intelligent composites forming: simulations for faster, higher quality manufacture

Siyuan Chen, Adam Thompson, Tim Dodwell (Exeter University), Stephen Hallett and Jonathan Belnoue

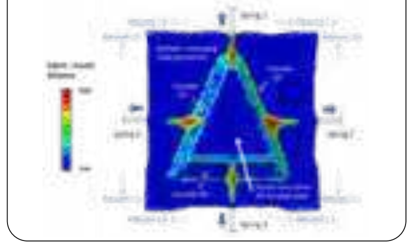
Composites are becoming increasingly important for light-weight solutions in the transport and energy sectors. In the field of composites manufacture, resin transform moulding (RTM) is a cheaper alternative to traditional manufacturing method. Before resin infusion, the fabric is to be formed into shape, however, the quality of forming is a highly sensitive to wrinkles and bridging. These defects must be eliminated by optimising the forming parameters such as pressure, tensile forces or the geometry of the tooling. Simulation is a good way to understand and achieve this process. Current BCI's forming process simulation tool can make high quality predictions but have long run times. On the other hand, we need large batches of simulations to find the forming conditions that minimize defects.

The project aims at exploring a new framework for the efficient optimisation of the processing conditions in the dry fibre forming process. This is achieved by building a Gaussian Process (GP) emulator that is trained from finite element (FE) simulation data. Longer term, a fully autonomous forming rig that allows defect mitigation by automatic adaptation of the process based on in-situ measurements and predictions from the GP will be built.


Forming rig
Forming Process Simulator
Gaussian process emulator
Sequential design
Fast Prediction & Optimisation

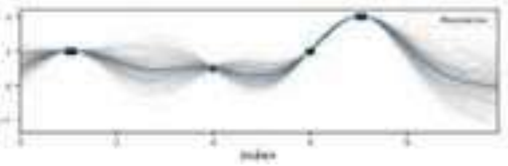
FE simulations

- Industrial inspired mould geometry.
- Double-diaphragm forming
- Springs connected to fabric on each side to provide tensile forces. The springs stiffness and position can be varied through Python scripting facilitating the study of the effect of different process conditions.

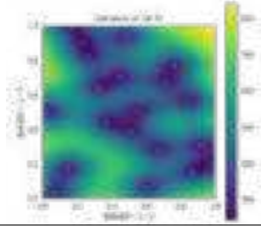


Gaussian Process (GP) emulator

- A **machine learning method**.
- Allows almost **immediate** prediction.
- Only needs a few data points to make accurate predictions.
- Also provides **uncertainty quantification.**
- An example of a 2-dimensional GP variance (reflects the uncertainty predicted by GP) for the forming case described in the "FE simulations" box is given on the right hand-side of the present section.

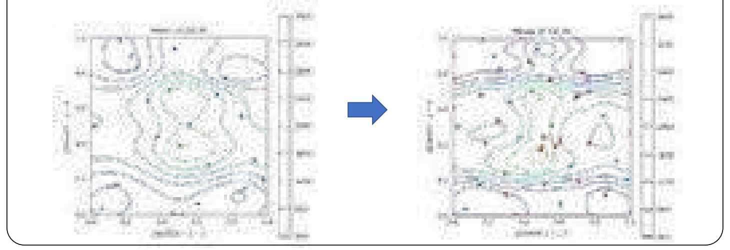


- **Inputs**: Positions of springs 1 & 3, and 2 & 4 respectively. The spring positions are coupled by pairs.
- **Output**: Sum of the distances between the fabric nodes and the mould surface (characterises defect severity).
- **Initial training batch**: 20 data points generated by Latin hypercubic sampling.
- Each point refers to a FE result.



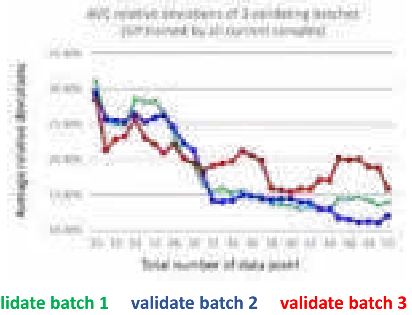
Sequential design (SD)

Iterative addition of supplementary data points (in red on the figure on the right), to improve model predictive capabilities.



Validation of the GP

- Three validation batches of 10 data points each.
- Sequential design significantly improves the GP's predictive capabilities.



Long-term ambition:

- A fully autonomous forming rig that allows zero-defect forming of dry textiles will be built.
- This will be made possible by "on the fly" adaptation of the manufacturing conditions based on in-situ sensing and real-time optimisation using the GP presented here.

Acknowledgement: this project is funded by the China Scholarship Council, the University of Bristol and the EPSRC via the CoSEM CDT.

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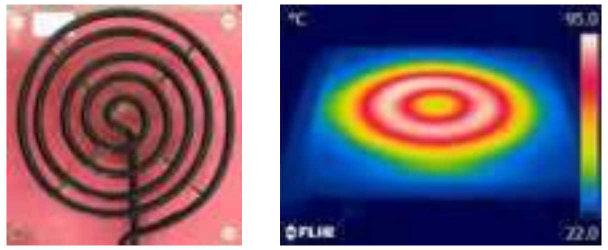
Modelling inductive heating for optimised composite processing

James Uzzell, Dmitry Ivanov, Laura Pickard and Ian Hamerton

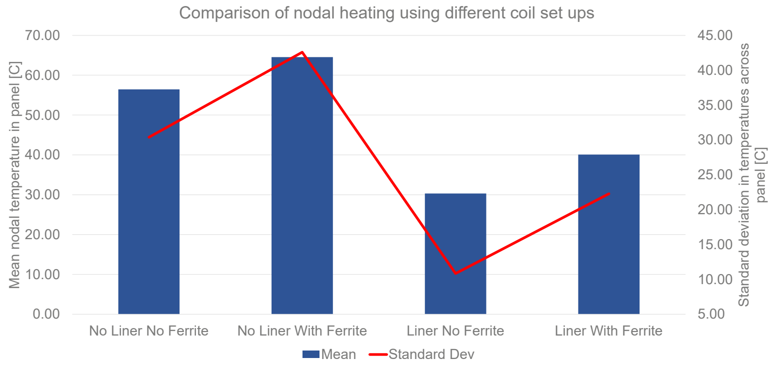
An iterative design process has been used to optimise the design of an inductive coil to improve the efficiency and in-plane uniformity of induction heating for carbon fibre reinforced composites.

Heating via induction is highly energy efficient due to the direct volumetric heating produced in the conductive regions of the specimen. Standard pancake induction coils used for metallic processing produce nonuniform, ring shaped, heating patterns. To account for this, a new coil geometry has been designed for the inductive heating of composites to directly account for their lower electrical and thermal conductivity compared to metals. Numerical modelling has been used to model Joule heating and thermal propagation. Ferritic flux concentrators and a metallic liner were modelled to understand their effect on both the in plane uniformity and heating efficiency. It is hypothesized that the use of ferritic flux concentrators along with a metallic liner attached to the coil will improve the in plane uniformity and heating efficiency in finite element models.

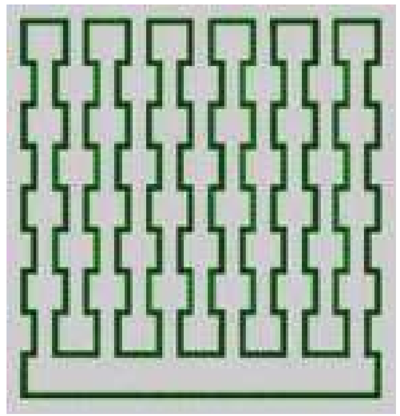
In all models, the addition of the ferritic flux concentrator significantly increased the heating efficiency however this impacted the uniformity of the heating. Conversely, the metallic liner improved the uniformity at the cost of efficiency. In-plane uniformity has been regarded as the most important factor in judging a successful induction coil so a design involving a coil and liner set up has been proposed.



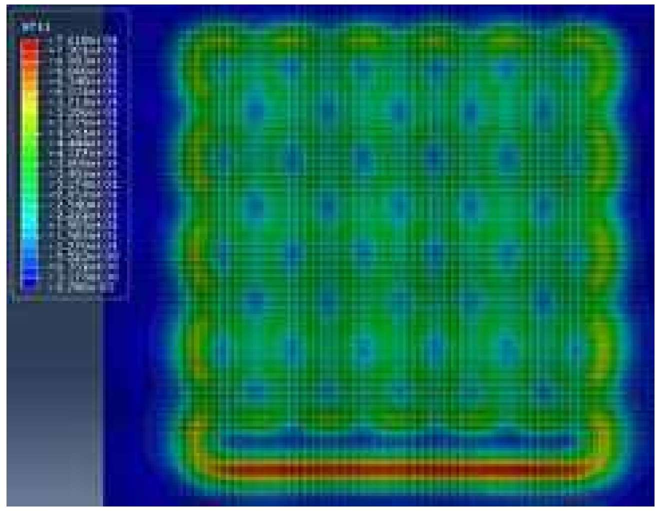
Above: (Left) Photograph showing standard pancake coil design used for metallic processing. (Right) Thermal image showing the ring shaped heating pattern produced using the pancake coil.



Above: Comparison of average nodal temperature and standard deviation across a QI panel heated using coils with differing set ups.
Ferrite impact: Average temperature of the panel increased by 10 degrees with standard deviation also increasing by 15 degrees on average.
Metallic liner impact: Average temperature decreased by 25 degrees with standard deviation also decreasing by 20 degrees.



Above: Complex coil geometry involving square cells in a 6x4 design. An iterative process was used to compare the individual cell size and shape as well as the total number of cells and their layout.
Below: Thermal results for a QI panel heated using the coil geometry shown above along with a metallic liner.



The optimised coil geometry uses a wide coil geometry along with a metallic liner, shown to help widen the flux path. This has been found to be superior to the conventional pancake coil in terms of in plane uniformity when heating composites due to their lower thermal and electrical conductivity.

The future of this work is to validate these modelling results before manufacturing a coil capable of composite processing in application such as rapid cure and in-situ repair.

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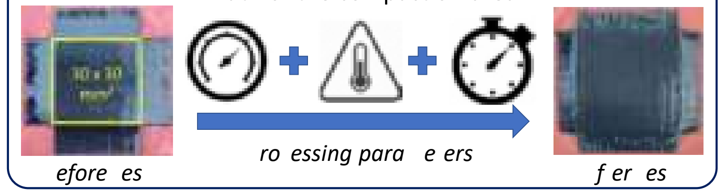
Influence of AFP processing parameters on the consolidation of out-of-autoclave prepreg

Axel Wowogno, Iryna Tretiak, Stephen R. Hallett and James Kratz

Autoclave curing, one of the commonly used manufacturing processes for composites, creates a bottleneck in the production workflow despite its effectiveness for part consolidation. This reveals the need for a novel curing technology that would remove the need for an additional curing step after the material deposition. Making use of the Automated Fibre Placement (AFP) process, an online out-of-autoclave (OOA) Layer-By-Layer (LBL) consolidation approach has been developed for component creation [1]. In order to fully comprehend the impact of the main process parameters, this study aims to assess the selected material's behaviour.

Study's goal

Analyse the material behaviour, by exposing prepared samples to various pressure magnitudes, temperatures and pressure application times, and by monitoring the thickness and the width of the compaction area.



Before tests — *Processing parameters* — *After tests*

Materials and Methods

Material : OOA Prepreg - Carbon Fibre / Epoxy (IM7/M56)

HexTow® IM7 Carbon Fiber + HexPly® M56

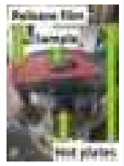
Method : Compaction test, using custom made heating plates, mounted onto a universal Instron testing machine.

***Step 1** : Low T° & varying pressure / **Step 2** : High T° & fixed pressure*

Procedures

Laminate preparation : Cruciform layup of unidirectional 30 x 50 x 0.25 mm plies. 2mm thick samples were made (8 plies).

Test setup : Unrestrained and on release film, the samples were centered on the heating plates (same temperature for top and bottom for each test).

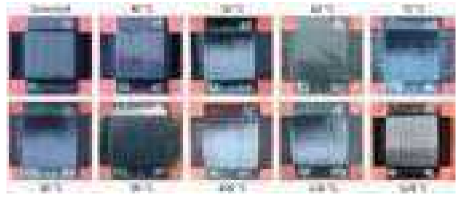


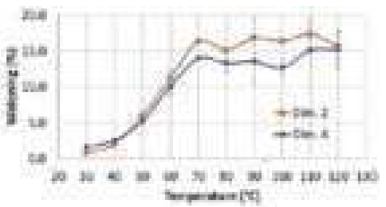
Program 1 : Ramp – Dwell method
This method executes a fast application of load followed by long creep intervals, while incrementally covering a range of pressures commonly seen in the AFP conditions. Test temperatures vary from 30 to 120 °C (with 10°C increments), with a fixed length of time (20 min). This allows to assess the temperature's effect.

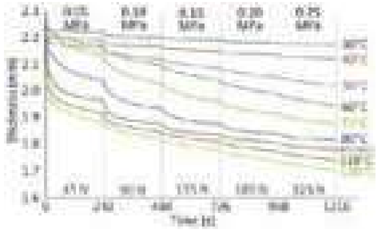
Program 2 : Hold method
This method is performed with a fixed pressure (chosen from previous results), for short amounts of time (1, 2.5, 5, 10s), at test temperatures varying from 120 to 210°C (30°C increments). This allows to assess both time & temperature's effects.

Results – Program 1

Figures below show how the compaction area expands with temperature, that its widening stagnates after 70°C and that the samples' thickness didn't greatly vary after application of 0.1MPa. This makes them the minimum compaction values.

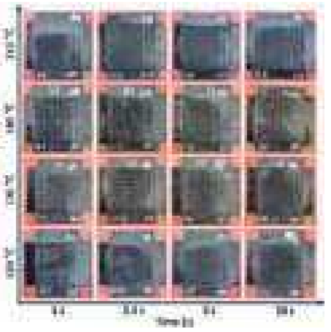






Results – Program 2

From previous results, 0.1 MPa was here chosen as fixed pressure value. Figures show the compaction area's evolution, its widening rate (2.3% per 10°C). Thickness analysis reveals a noticeable springback.



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PhD project:
Layer by Layer manufacturing of complex composites

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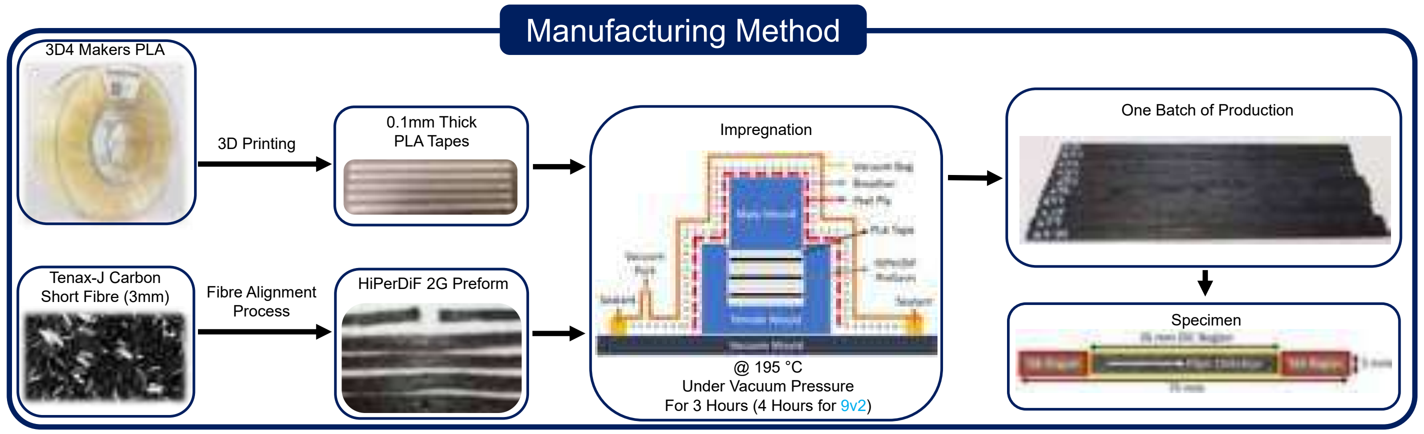
Effect of processing conditions on the elongation behaviour of PLA/Carbon fibre HiPerDiF tapes

Burak Ogun Yavuz, Ian Hamerton, Marco L. Longana and Jonathan P.-H. Belnoue

Aim: Material characterisation for forming simulations of aligned discontinuous fibre thermoplastic (HiPerDiF) prepreg

Manufacturing Method



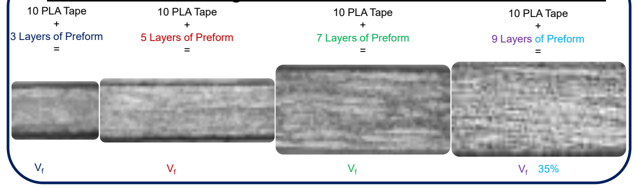
3D4 Makers PLA → 3D Printing → 0.1mm Thick PLA Tapes →

Tenax-J Carbon Short Fibre (3mm) → Fibre Alignment Process → HiPerDiF 2G Preform →

Impregnation
@ 195 °C
Under Vacuum Pressure
For 3 Hours (4 Hours for 9v2)
→ One Batch of Production → Specimen

Effect of Fibre Volume Fraction

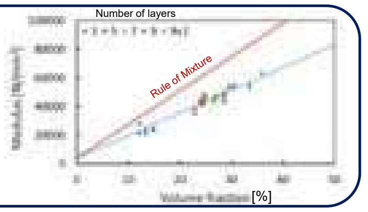
Cross-section images of different fibre volume fractions



10 PLA Tape + 3 Layers of Preform =	10 PLA Tape + 5 Layers of Preform =	10 PLA Tape + 7 Layers of Preform =	10 PLA Tape + 9 Layers of Preform =
V_f	V_f	V_f	V_f 35%

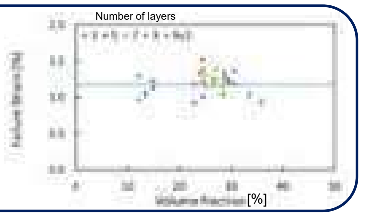
Stiffness

- Fibre volume fractions calculated by thermogravimetric analysis (TGA)
- Deviation from rule of mixture
  Due to:
  - Fibre misalignment
  - Lack of sizing for fibre-matrix bonding



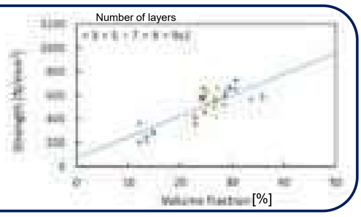
Failure Strain

- 1.19 % average strain to failure
- Not affected by fibre volume fraction
- Distribution around average value caused by manufacturing variability



Strength

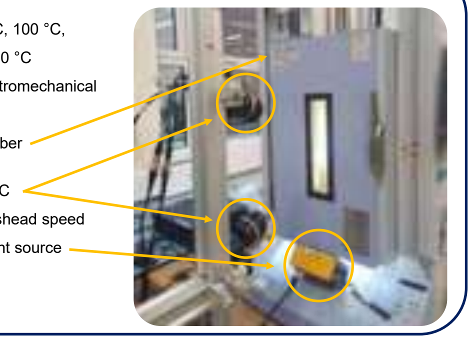
- The trend is dependent from fibre volume fraction
- Distribution around trendline caused by manufacturing variability



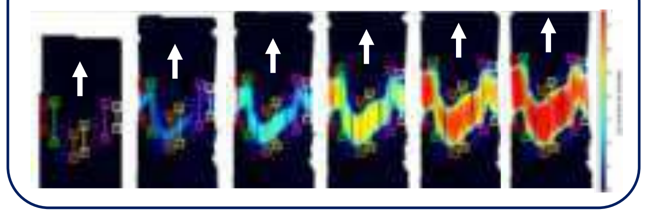
Tensile Characterisation under Processing Conditions

Test setup

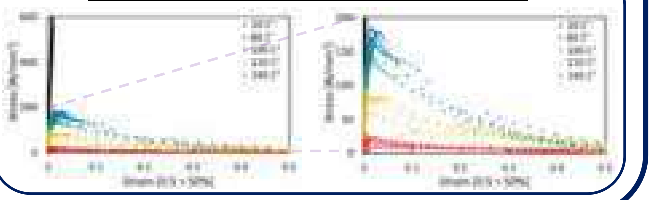
- @ 20 °C, 80 °C, 100 °C, 120 °C, and 140 °C
- Shimadzu electromechanical test machine
- Thermal Chamber
- 10 kN load-cell
- 5MP Stereo DIC
- 1mm/min crosshead speed
- Strong LED light source



Digital extensometer within necking region



Tensile behaviour temperature dependency



Future work: → Transverse and shear behaviour temperature dependency → Implementing material behaviour into forming simulations → Forming defect free parts experimentally

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This study is supported by the EPSRC through the CoSEM CDT and a scholarship (started by Atatürk) from the Republic of Türkiye Ministry of National Education

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The most influential uncertainties in thermoset curing

Adam Fisher, Arthur Levy, James Kratz

Sensitivity to input parameters

Key results
- Influence on cure time was dominated by a few cure kinetics parameters and dwell temperature
- Influence on temperature overshoot was dominated by activation energy and dwell temperature
- Sensitivity was greatest with the low conductivity tool and higher heat transfer coefficient

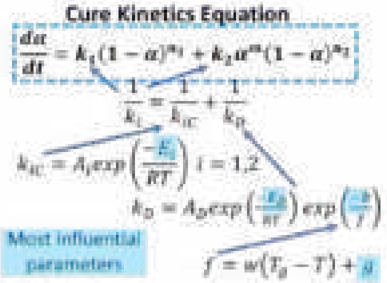
Set up
- Processing parameters: dwell temperature, heat transfer coefficient, tool thickness, fibre volume fraction, initial degree of cure
- All cure kinetics parameters were considered
- 5% coefficient of variation in all parameters
- Cure time defined as time to reach 90% degree of cure through the thickness
- Temperature overshoot defined as largest positive difference to dwell temperature across the thickness

Reduced Sensitivity (Influence metric)

Parameter standard deviation

$$\frac{\sigma}{\theta(\mu)}\left|\frac{d\theta}{d\mu}\right| \times 100\%$$

Considered output　　Parameter mean



$$\frac{d\alpha}{dt} = k_1(1-\alpha)^{n_1} + k_2\alpha^{m}(1-\alpha)^{n_2}$$

$$\frac{1}{k_i} = \frac{1}{k_{ic}} + \frac{1}{k_D}$$

$$k_{ic} = A_i exp\left(\frac{-E_i}{RT}\right) \quad i = 1,2$$

$$k_D = A_D exp\left(\frac{-E_D}{RT}\right) exp\left(\frac{-b}{f}\right)$$

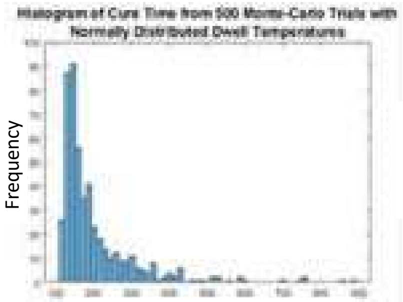
$$f = w(T_g - T) + g$$

Cure time and temperature overshoot are sensitive to uncertainty in the processing environment and cure kinetics parameters

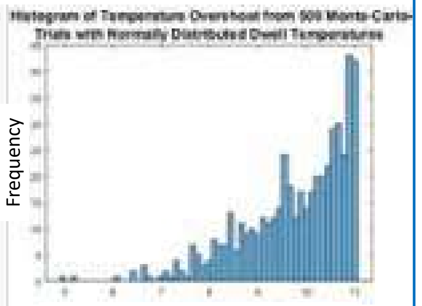
Influence of input uncertainty

Key results
- Normally distributed inputs caused
  - Leftward skewed cure time distributions
  - Rightward skewed temperature overshoot distributions
- Deterministic methods are liable to overpredict cure times and underpredict temperature overshoots

Set up
- 500-trial Monte Carlo simulations showed output distributions due to the input uncertainties
- 4 cure kinetics parameters and 3 processing conditions were treated as normal random variables with 5% coefficient of variation



Cure Time [minutes]

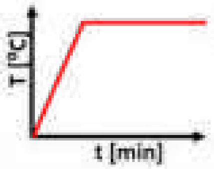


Temperature Overshoot [^{o}C]

Deterministic assumptions lead to **excessive cure times and temperature overshoots** in the majority of cases

Finite Element Model

Cure Cycle
1. 2^{o}Cmin^{-1} ramp from 20^{o}C to 180^{o}C
2. Hold at 180^{o}C until cured



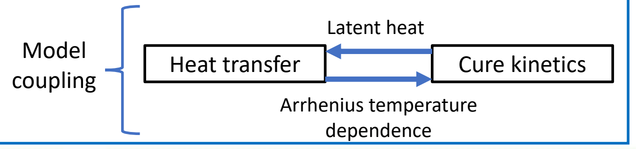
Convective boundary condition

Heat transfer coefficients representative of industrial oven and autoclave data

Thermoset Laminate
HexPly M21 – 20mm

Tool
Invar & composite – mean: 10mm

Convective boundary condition


Model coupling

Heat transfer
Latent heat
Cure kinetics
Arrhenius temperature dependence

1D model coupling **heat transfer** and **cure kinetics**

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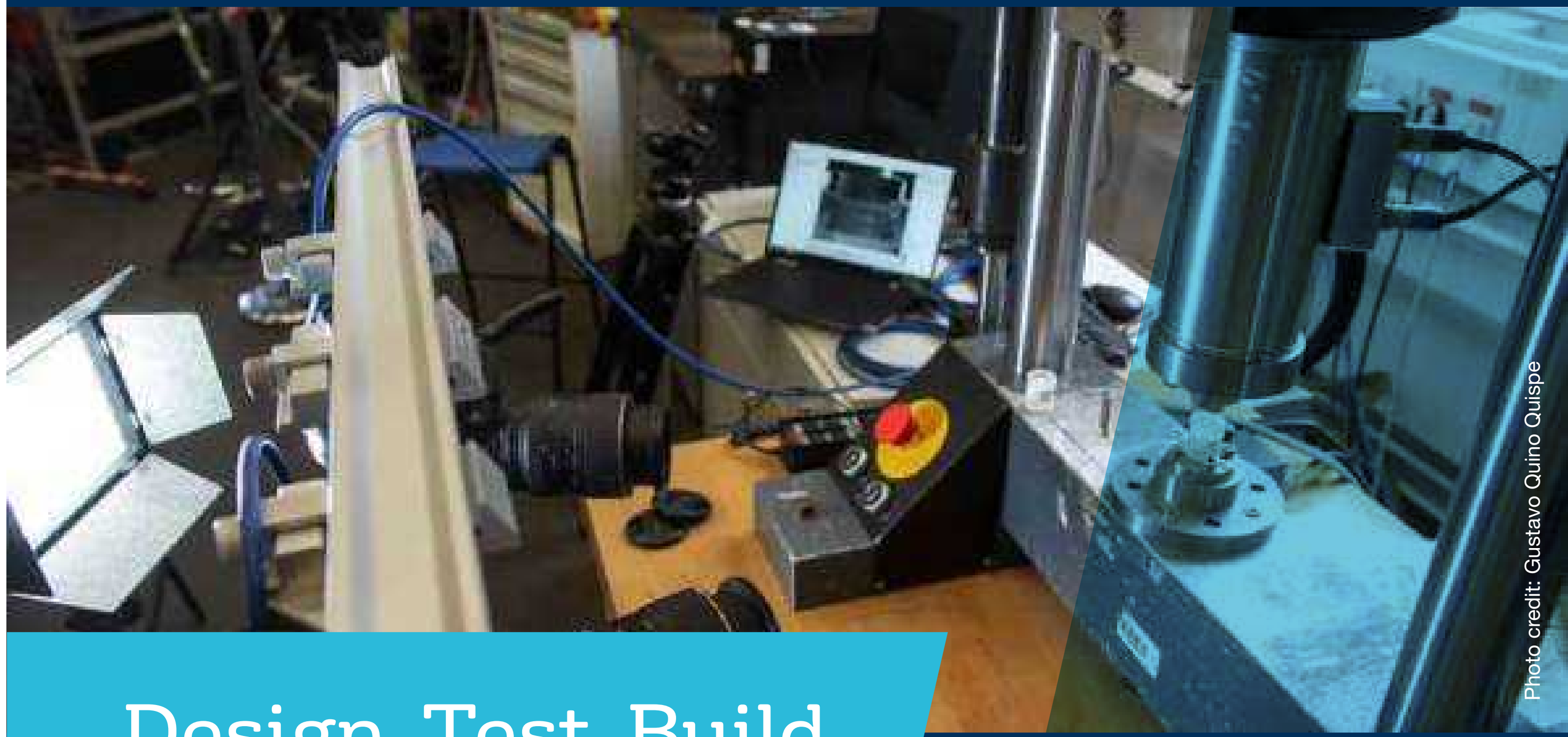
Photo credit: Gustavo Quino Quispe

Design, Test, Build

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CDT21 - Design, Build & Test - Group Project

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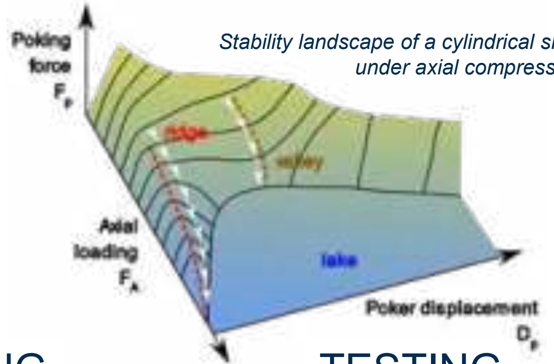
Buckling failure is a key consideration in the design of thin-walled cylindrical composite shells, particularly within industrial applications such as rocket fuselages where light-weighting is vital. Axially-compressed thin-walled cylinders are highly sensitive to imperfections and as such, developing accurate predictions for the critical buckling load is difficult. Current estimates, such as deterministic approaches, are conservative and do not allow for the full load-carrying capabilities of composite structures to be utilised. The present work implements a methodology that enables the non-destructive evaluation of the critical buckling load of an axially-compressed cylindrical shell.

METHOD

By increasing the axial load and measuring the resistance to a lateral probing force, the critical buckling load can be non-destructively extrapolated using the stability landscape.



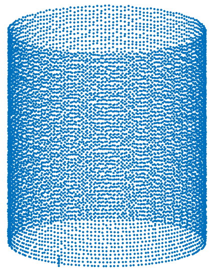
Stability landscape of a cylindrical shell under axial compression

MANUFACTURE

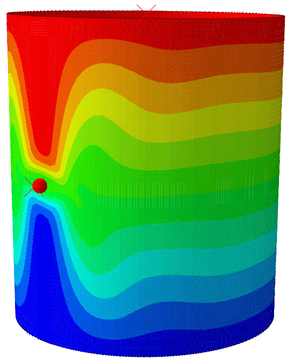
- Two composite cylinders, r = 100 mm, l = 200 mm
- Layup: $[\pm 60,0]_{2s}$ with ThinPreg 402
- Manufactured with vacuum bagging and autoclave curing
- End-potted to ensure clamped boundary conditions

MODELLING

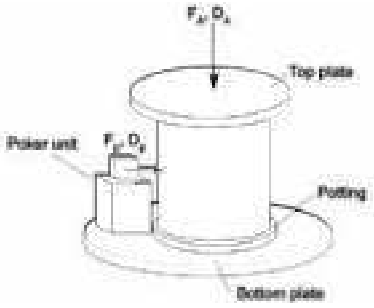
- Perfect cylinder model used to define initial experimental parameters
- Imperfection signature of manufactured cylinder captured with 3D-scan



- Computational model used to predict stability landscape for comparison with experiment

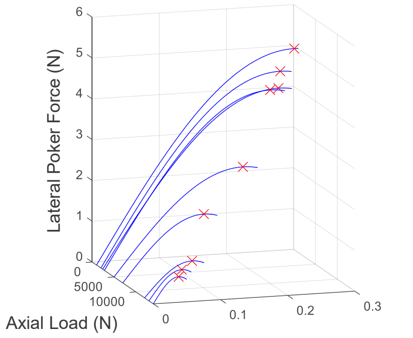


TESTING



Test procedure:

- Axially compressed and stop
- Laterally poked
- F_p, D_p recorded for each F_A to plot the stability landscape



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