University of BRISTOL
Bristol Composites Institute

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Hierarchical and Energy Efficient Composites

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The University of Bristol

- Bristol is a vibrant city with a rich history – once a gateway to the Americas, then a centre of fine Victorian engineering, and finally a hub for high tech industries.
- University of Bristol started as a College in 1876, receiving Royal Charter in 1909
- **Six** faculties: Arts, **Engineering**, Sciences, Biomedical Sci., Health Sci., Social Sci. and Law
- Approximate **30,000** students:
  - 22,000 undergraduates
  - 8,000 post-graduates





Bristol Composites Institute (BCI)

- Established in 2007 as Advanced Composite Centre for Innovation and Science (ACCIS) by Prof. Michael Wisnom
- Granted status as Research Institute in 2017
- Core team of 30 academic staff plus 70 researchers and 150 PhD students
- Over 30 further affiliated academics in Engineering, Science and Medicine
- Focus on collaboration between academia and industry
- More than £25M in current research grant funding

A world leading institute for composites education and research, combining cutting-edge fundamental science with strong industrial links for exploitation and technology transfer.

National Composites Centre (NCC)

NATIONAL COMPOSITES CENTRE

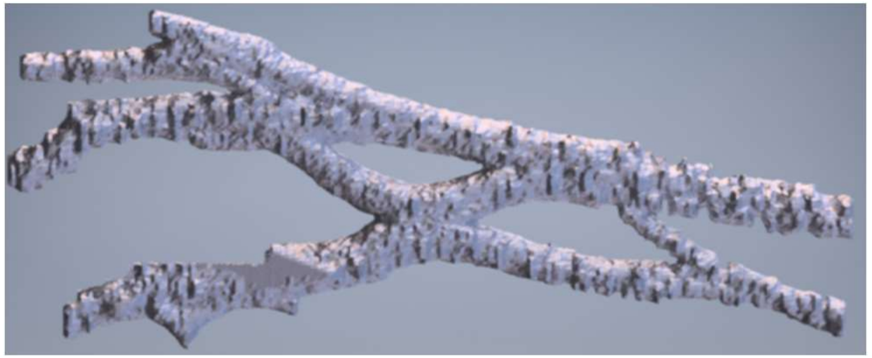
- A University of Bristol owned facility, operated independently, on behalf of its industrial members.
- Mid-TRL research: Translating novel concepts from academia, and de-risking industrial solutions
- Strong cross-sectoral industrial membership
- Non-exclusive list:

TORAY Toray Advanced Composites
BAE SYSTEMS
GKN AEROSPACE
ROLLS ROYCE
aramco
NetworkRail
Baker Hughes
LEONARDO
SPIRIT AEROSYSTEMS

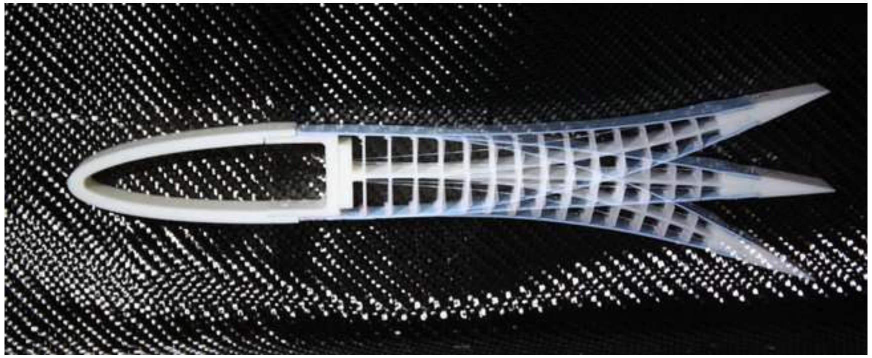
Strong Industry and Academic Partnerships

- Long-running and well-established industry partnerships
  - For example, Rolls-Royce supported UTC, Vestas Wind Systems
- Major academic partnerships
  - Joint EPSRC CIMComp Future Composites Manufacturing Research Hub leaders with Nottingham
  - Programme Grants with Imperial College London, Bath, Exeter, Southampton, Cambridge
  - Dual PhD with TU Dresden, cotutelle agreements with RMIT and TU Delft, collaboration with Texas A&M
  - MOUs with DTU Copenhagen, UBC and others
- Many relationships with smaller companies and SMEs
  - Over 40 companies engaged in BCI research

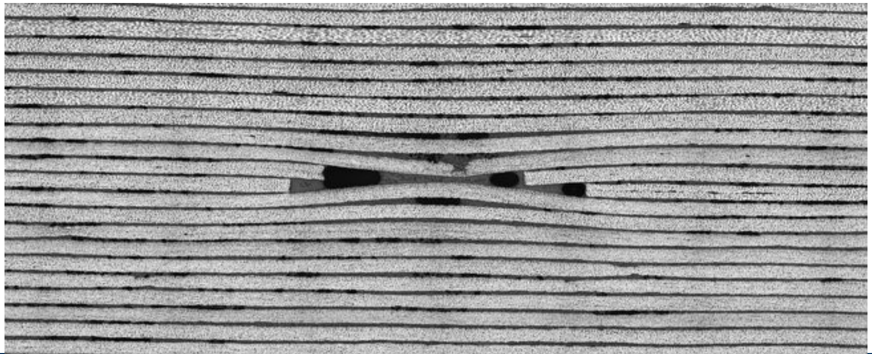
Materials
novel generations of composites with a broad range of multiscale reinforcements, from nanostructures to carbon and natural fibres



Structures
novel numerical methods, novel structural configurations, advanced analysis techniques, multi-functionality and data rich experimentation

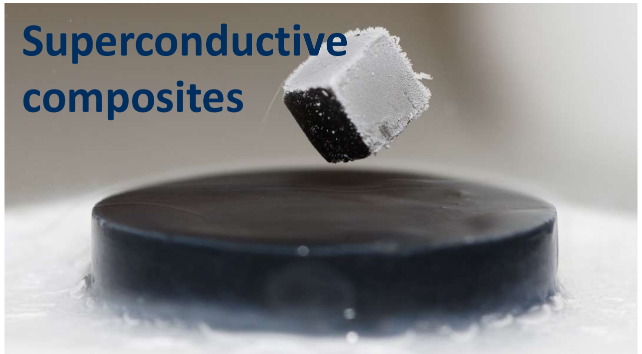


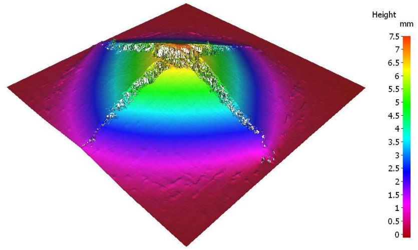
Manufacturing & Design
innovative, science-based, and industrially applicable manufacturing concepts



Multifunctional Composites and Materials

- Smart materials and structures – from fossil to biobased and reclaimed.
- Activities covering structural batteries, materials for energy, biobased load-bearing structures and actuators, hydrogen storage, metamaterials
- Multidisciplinary outlook. Strong push towards sustainability. Interface with SynBio and biomedical
- Close collaboration and alignment with industrial and NCC Core Research Programmes

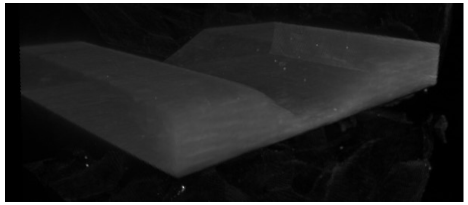




Fracture, impact and mechanical properties

Sustainable materials

(Xiao S *et al.*, 2021. Lightweight, strong, moldable wood via cell wall engineering as a sustainable structural material. *Science* 374, 6566)

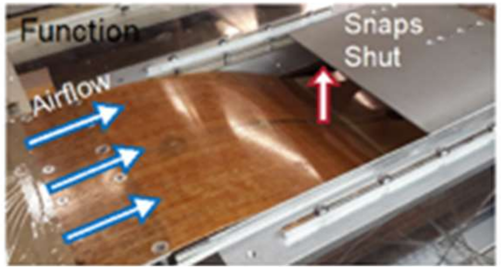


Xray CT image of CFRP for space use

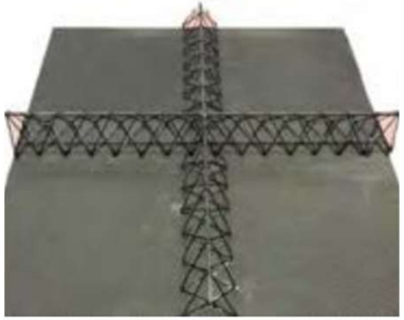
Extreme temperatures and environments

Structures

- Advanced modelling capability including micro, meso and macro scale, drape and 3D woven composites, fatigue.
- Wind Blade Research Hub
- CerTest: Certification for Design: Reshaping the testing pyramid
- Hierarchical structures
- Lightweight design and optimization
- Biomechanics and biomimetics
- Digital twins

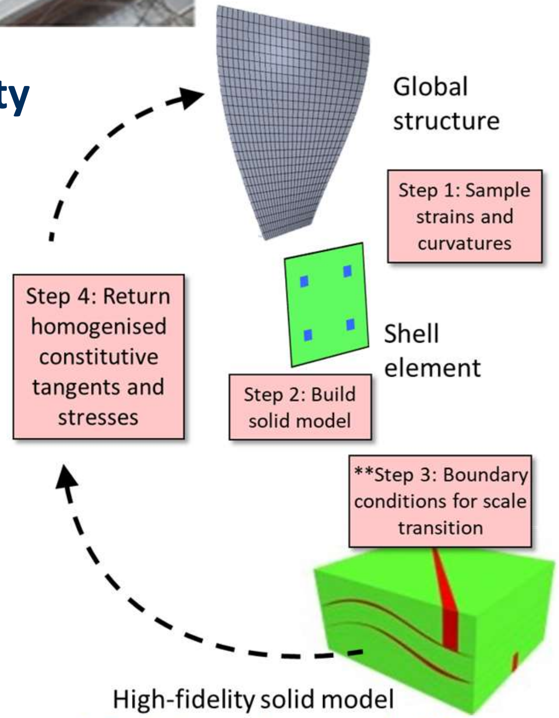


Multistability



Truss structures

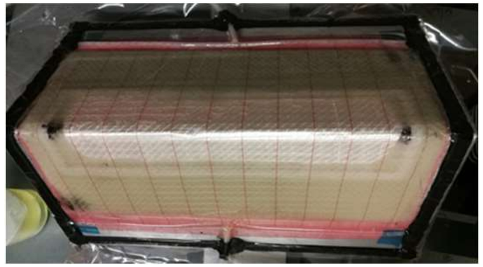
Morphing technologies



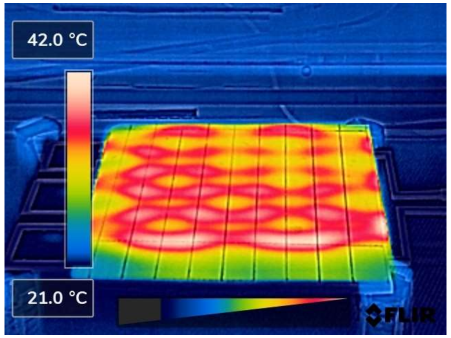
Multi-scale modelling

Manufacturing and Design

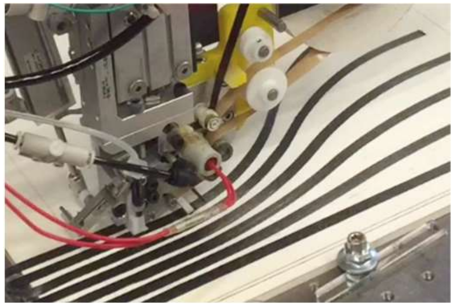
- Disruptive novel technologies such HiPerDiF, layer by layer curing, steered preforms for forming of complex shapes
- Cure by electromagnetic induction for locality and energy efficiency
- Real time active process control
- Digitalisation by numerical models for process improvement, data processing through machine learning, autonomous testing, AI based process optimisation



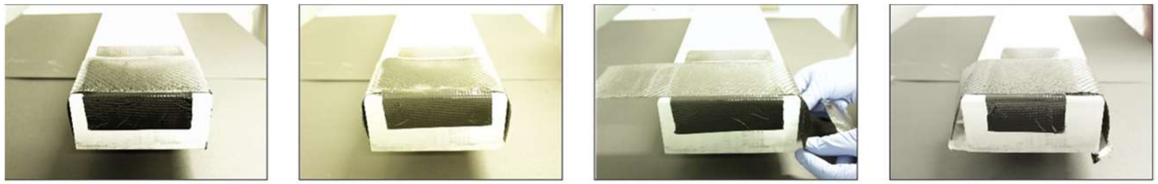
Multi-matrix continuously reinforced composites



Optimised induction coils and process control



Continuous Tow Shearing



Formable multi-functional energy storage devices

Next Generation Fibre-Reinforced Composites

A full scale redesign for compression

NextCOMP takes inspiration from the hierarchical structure of natural materials

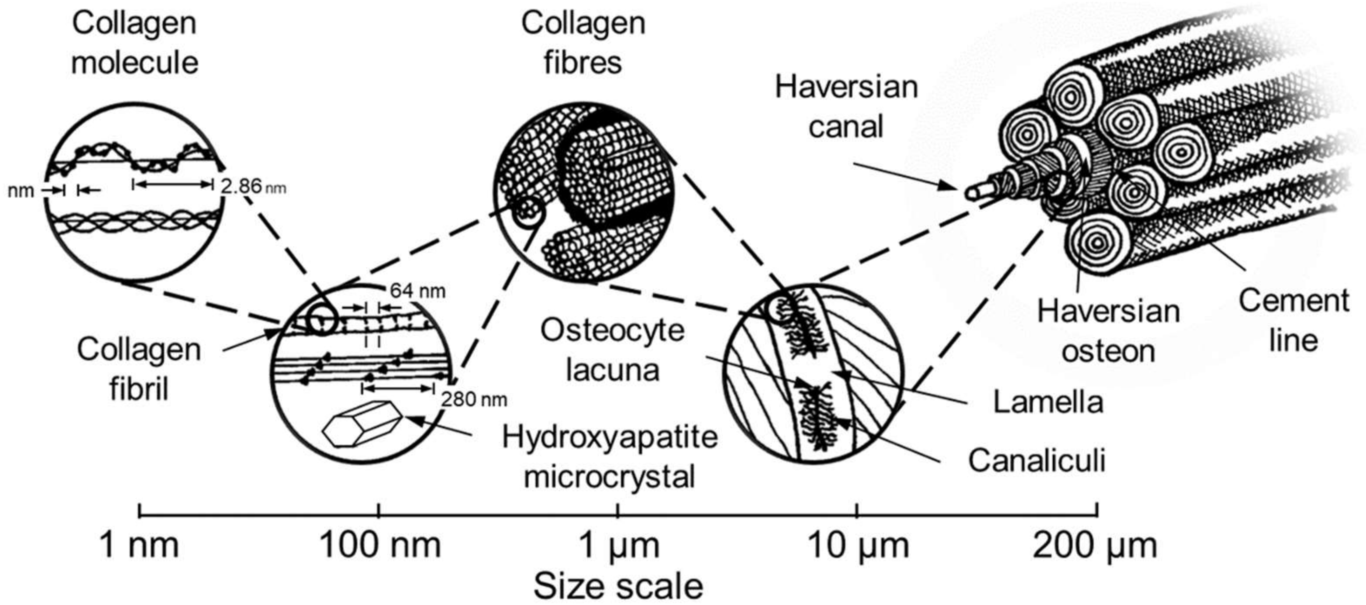
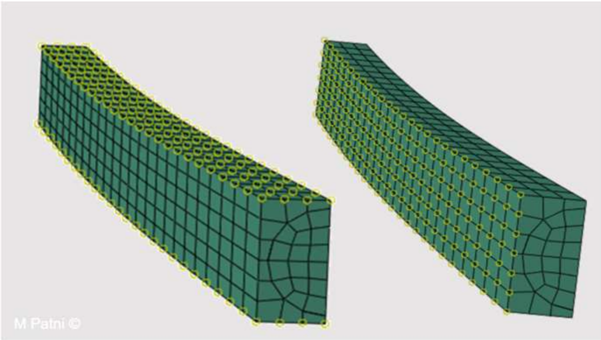
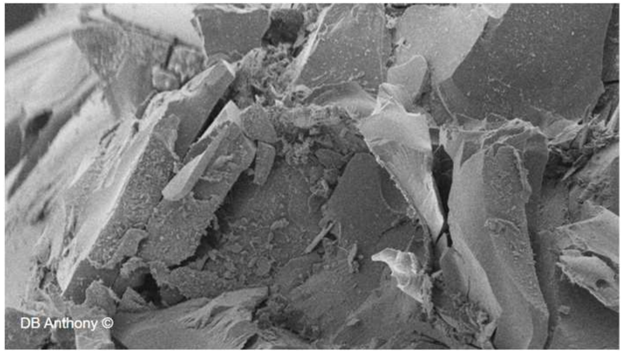


Illustration of the structure of human compact bone, a biological, hierarchical composite. Adapted from R. Lakes, "Materials with structural hierarchy," Nature, vol. 361, no. 6412, pp. 511–515, Feb. 1993, doi: 10.1038/361511a0.

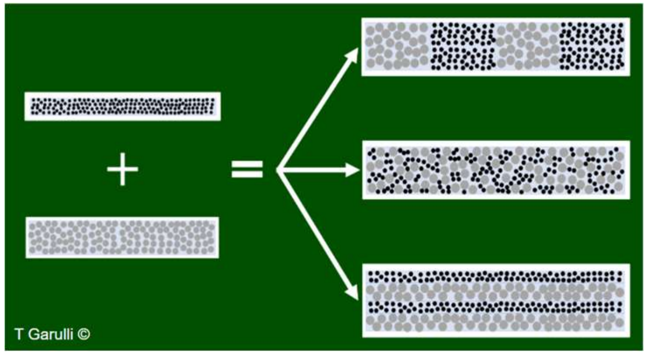
Hierarchical Composites



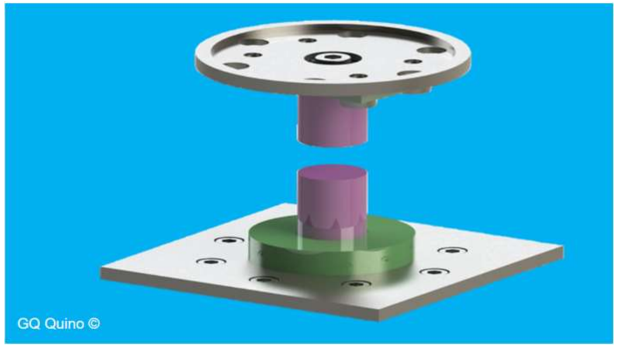
Mechanistic modelling



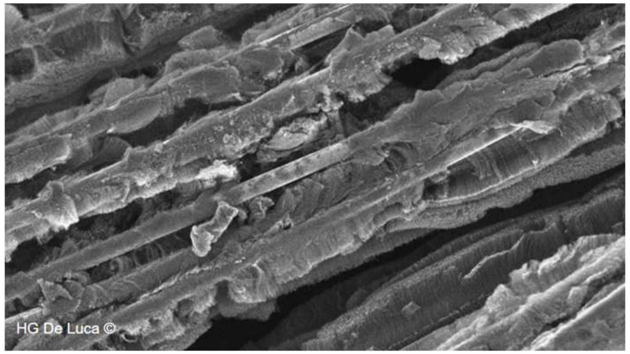
Resin systems



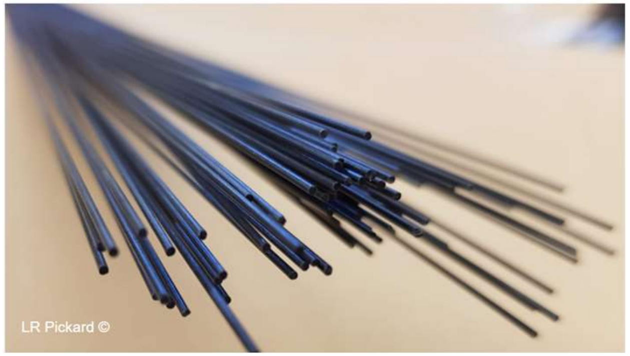
Ply level systems



In-Situ mechanistic studies

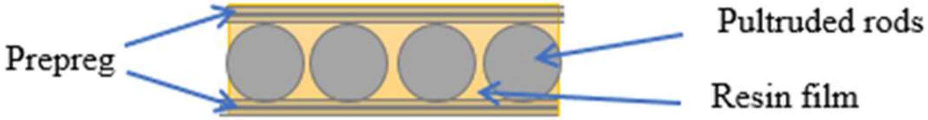


Fibre platforms

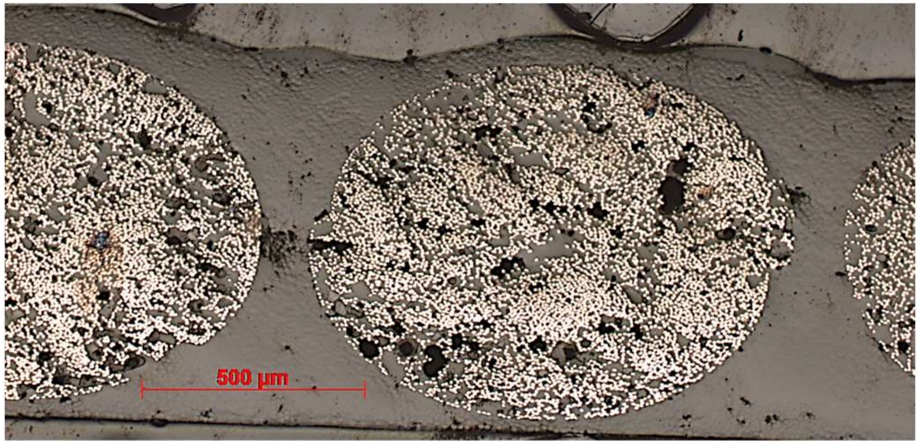


Bundle systems

Geometry: Thick plies



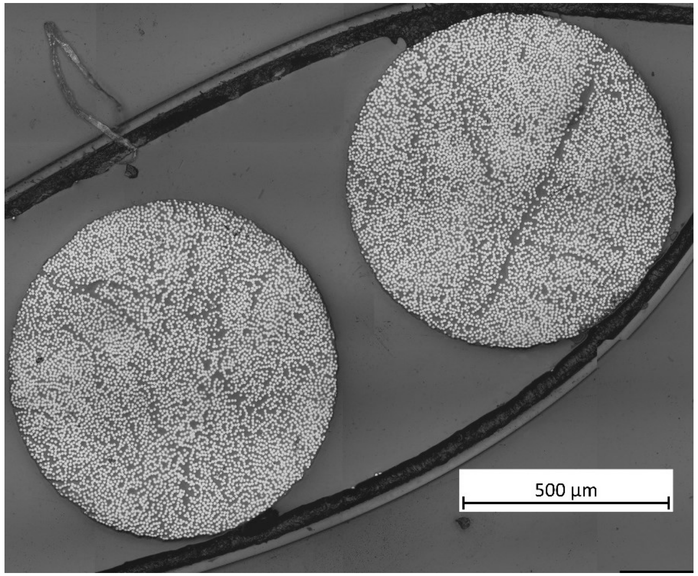
Prepreg sandwich geometry. Based on Clarke 1998



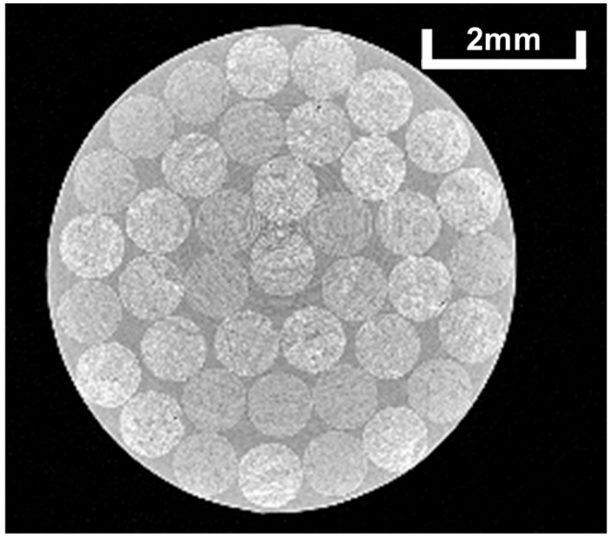
Microscope image showing commercially supplied carbon fibre-epoxy pultruded rods between layers of Hexcel 913 E-glass prepreg. Skyflex K51 resin film used between rods.

- Initial “prepreg sandwich” thick plies laid up by hand
- Low V_f rods distort in autoclave
- Higher V_f rods for next stage
- Human-robot collaborative manufacturing method developed, improves:
  - Manufacturing speed
  - Reproducibility
  - Rod alignment
  - Human ergonomics

Geometry: Structural Member



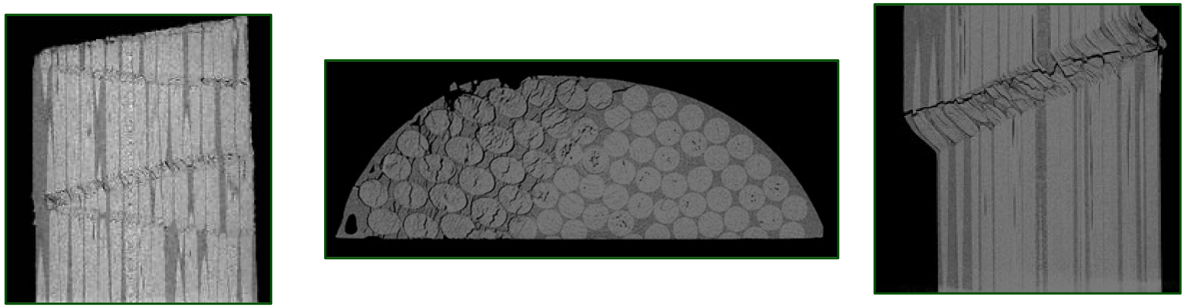
Cross section of two commercially supplied carbon fibre-epoxy rods pultruded rods taken using Zeiss microscope 20x lens



- Various cross-sections possible
- Manufactured by vacuum infusion or resin injection
- Hierarchical- fibres within rods within struts
- Plan to use overbraided rods
    - Suppress kink-band formation
- Dual matrix option

Top: slice from XCT reconstruction showing cross section of strut made from pultruded rods. Bottom: image showing cured strut in laboratory.

Overwinding and Overbraiding



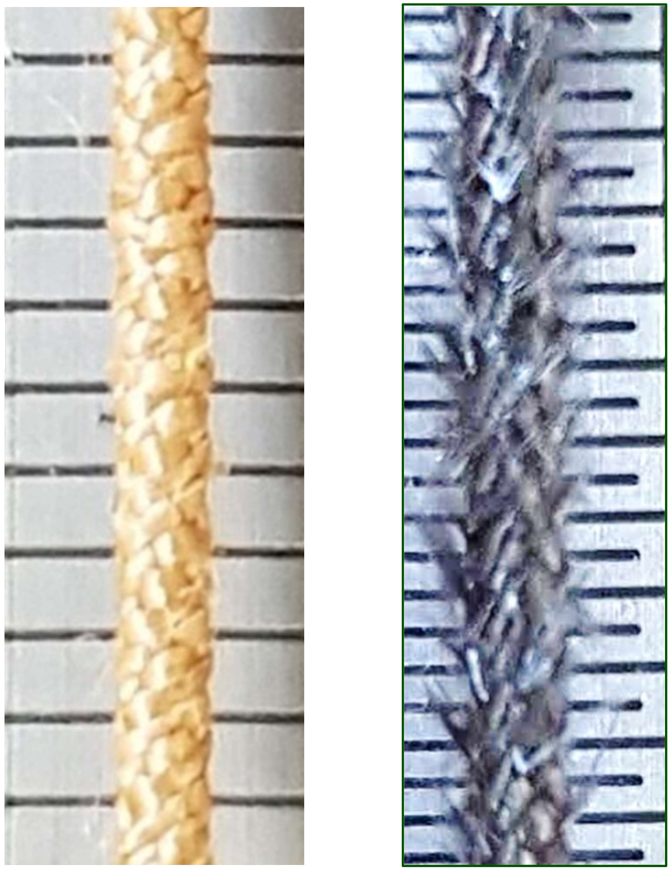
Samples from Potter et al 2000,CT scans L R Pickard. Following compression after impact tests. Overwound strut (left) exhibited greater compressive strength than without overwind (centre, right)

- Can we apply this in a hierarchical manner?
    - Overbraid individual rods
    - Short lay length required
    - Constrain kink band formation at rod level

Herzog microbraider with 8 tows PBO 273dtex overbraiding pultruded rod.

Overbraiding

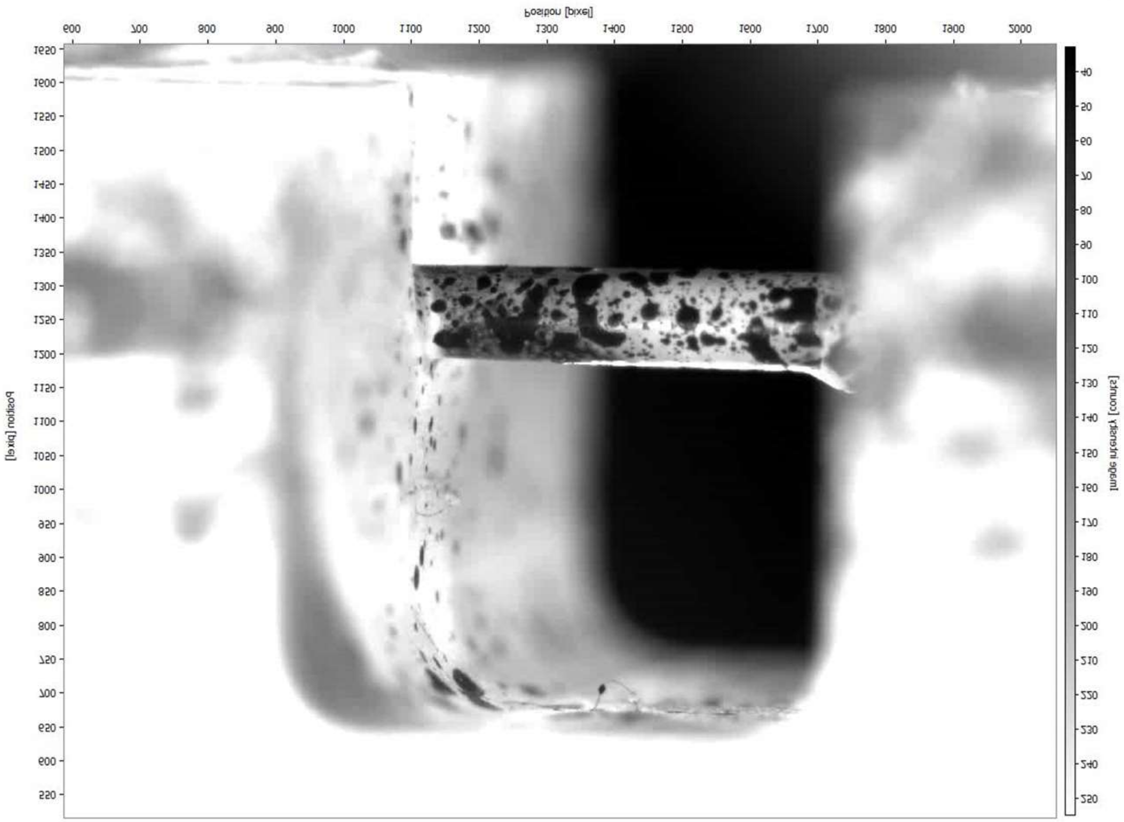
- PBO and aramid conform well to rod
  - Lay length of ~1.5mm achievable
- Carbon breakage at shorter lay lengths
  - 'Fuzzy' overbraid
- Modelling suggests adding shear support to matrix region around rod will deliver improved compressive performance
  - The best results have shear support in a larger matrix area around the rod
- Broken 'fuzzy' carbon overbraid:
  - Shear support in wider matrix area



Rods overbraided with Zylon (left) and Carbon

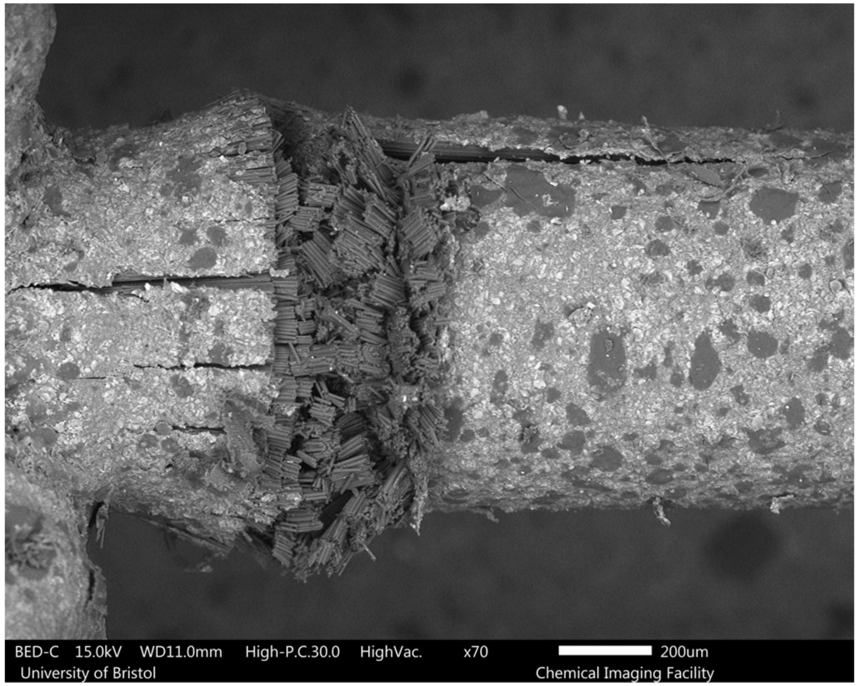
L. R. Pickard, G. Allegri, and M. R. Wisnom, "Manufacturing Advances for Pultruded Rod Based Structural Members and Thick Ply Systems," in *20th European Conference on Composite Materials, ECCM20.*, 2022

Pultruded Rod Testing



Video showing gauge section failure

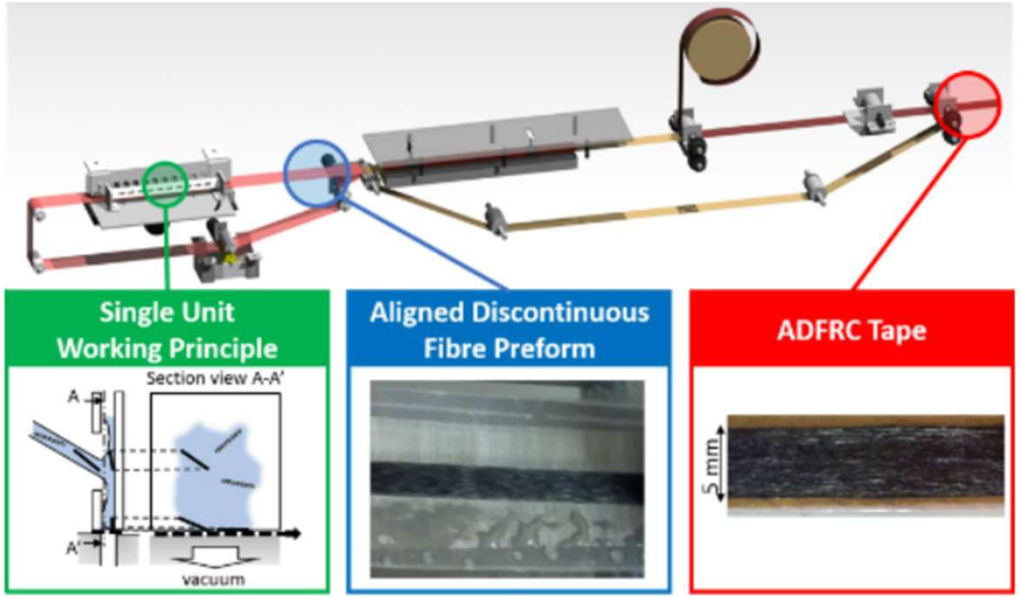
G. Quino, P. Robinson, and R. S. Trask, “Design of a bending experiment for mechanical characterisation of pultruded rods under compression,” in *20th European Conference on Composite Materials, ECCM20, 2022*



SEM image showing failure surface of rod. Image courtesy Ian Lee, NextCOMP CDT student

Sustainability

- Testing underway with natural materials
- PhD student- Understand and characterize performance of natural materials in hierarchical structure
- Henry Royce Internship- natural structural materials for extreme environments
- PhD student- Characterise performance of aligned discontinuous fibre composites under compression with a view to utilization in hierarchical composites
- Discontinuous fibre from HiPerDiF process, can be reclaimed material

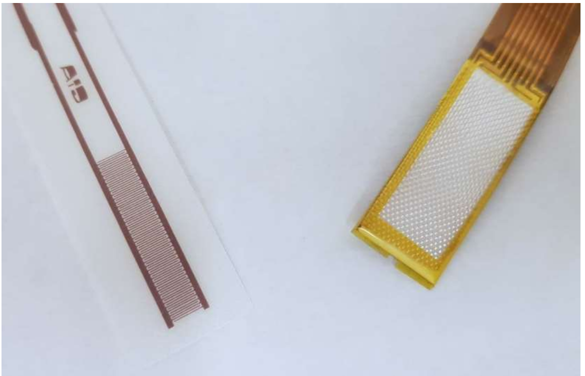


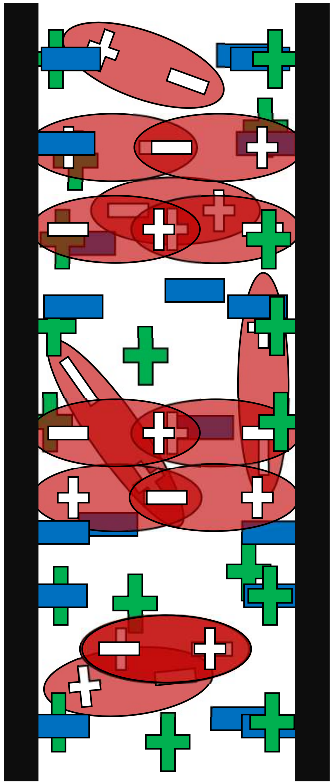
High Performance Discontinuous Fibre

https://www.bristol.ac.uk/composites/research/hiperdif/

Energy Efficient Cure: Active Process Control

- Recommended cure cycles are conservative
- Track degree of cure with dielectric sensors
- Electrodes in contact with resin
  - Embedded or in tool
- Apply alternating current
- Charged species move accordingly
  - Response varies with frequency of oscillation
  - Degree of cure, viscosity etc can be tracked
    - Model required for chosen resin

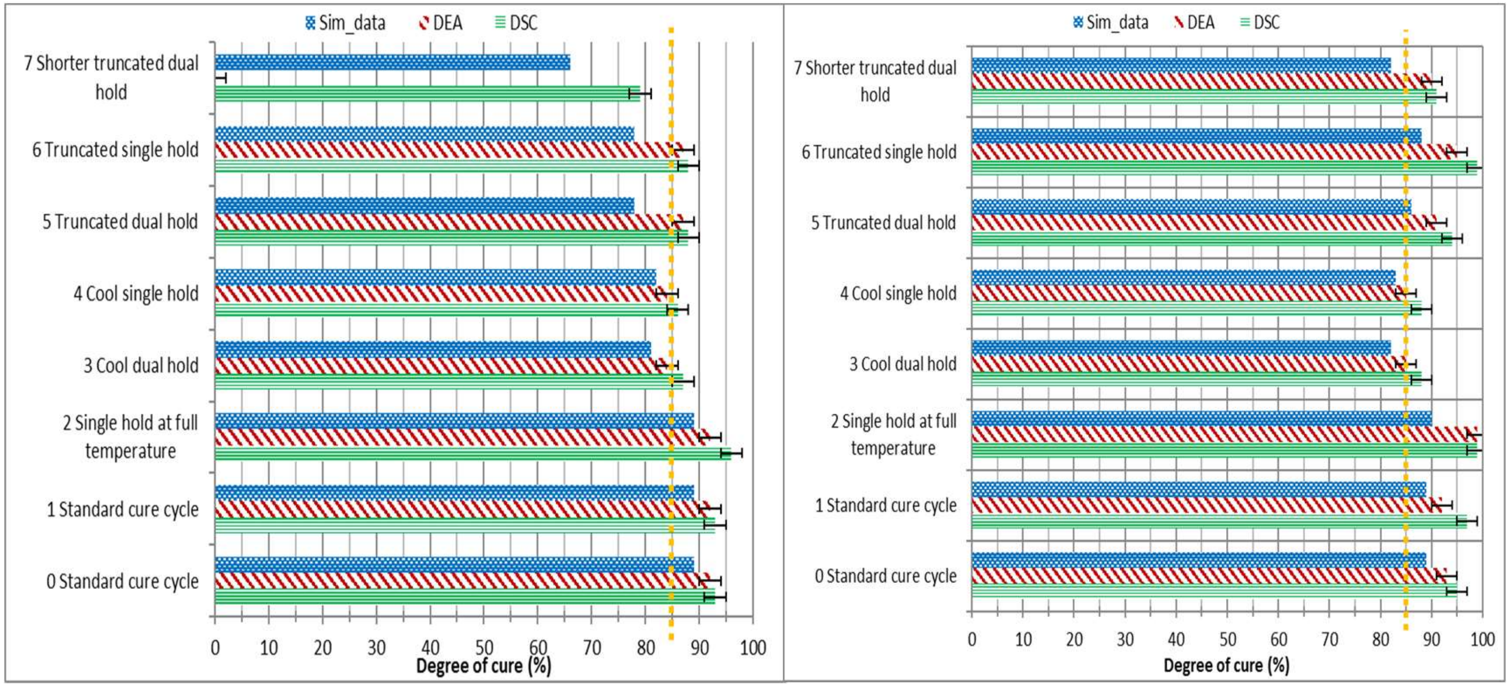




Autoclave integration

- Instrumented autoclave at National Composites Centre
- Sensor output used as input to autoclave control, e.g.
  - Change pressure at set resin viscosity
  - Change temperature at set T_g
  - Turn off when required degree of cure reached
- Verified by comparison to DSC and simulation

Dielectric Analysis (DEA) vs DSC and simulation



Thin end

Simulation in blue, DEA in red, DSC in green

Thick end

- Simulation is based on thermocouple data during cures
- DSC measurement of degree of cure for comparison

Stepped wedge test part

- Minimum 85% degree of cure required throughout, IM7/8552 prepreg

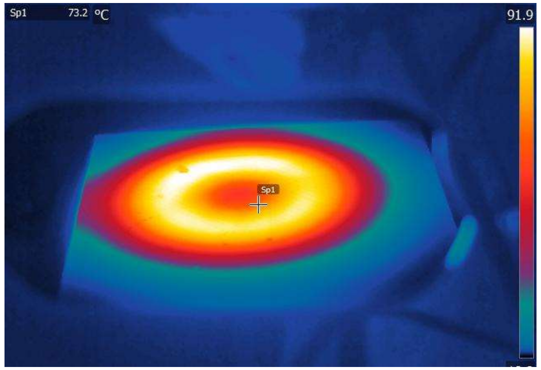
Cure cycle	kWh used	Cost (£)	CO_2e (kg)
Standard	180	26	95
One hold	184	26	96
Cool	164	24	86
Cool 1 hold	156	23	82
Sensor controlled	129	19	67
Sensor controlled 1 hold	110	16	58

- Just under 40% reduction in energy use
- Emissions reduction equivalent of driving a standard petrol car 100 miles
- https://www.carbontrust.com/media/18223/ctl153_conversion_factors.pdf

Pickard 2019

Energy Efficient Cure: Electromagnetic Induction

- Traditional cure by thermal conduction must heat air and tooling
- Lag between outer surface and centre
- Cure by EM induction is volumetric- heats the part directly
- Carbon Fibre is sufficiently conductive
- Susceptors can be added to non conductive panels



- Traditional coils result in non-uniform heating

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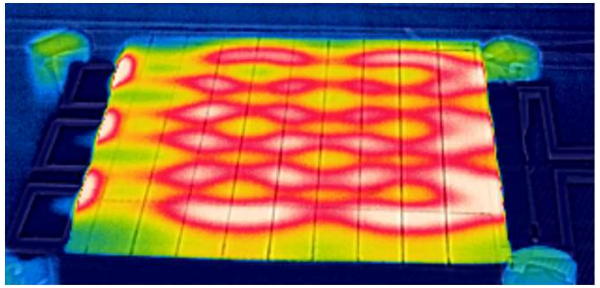
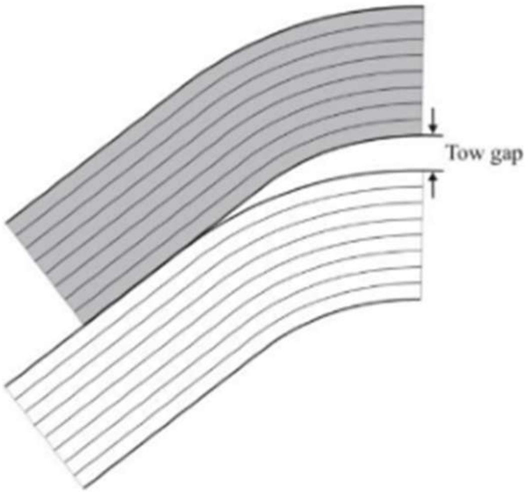


- PhD student -coil modelling and design: improved uniformity
- PhD student- machine learning based active process control of induction curing

J. Uzzell, D. Ivanov, L. R. Pickard, and I. Hamerton, "Parametric modelling tool for inductive processing of conventional and functionalised preforms," in *on Manufacturing of Advanced Composites*, 2022,

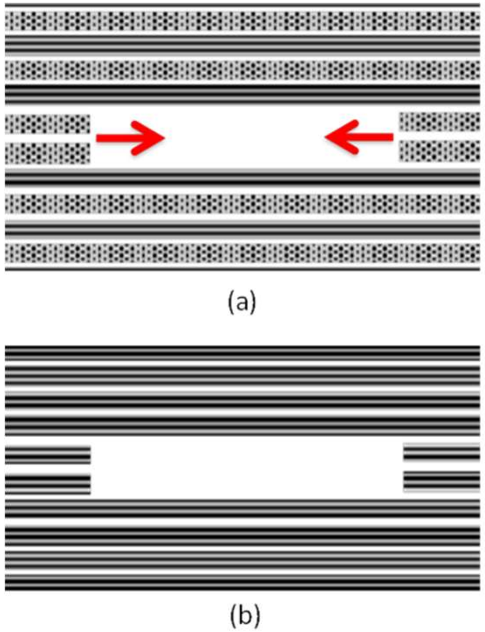
Tracking Features Through Cure

- Reduce waste by understanding defect/feature evolution

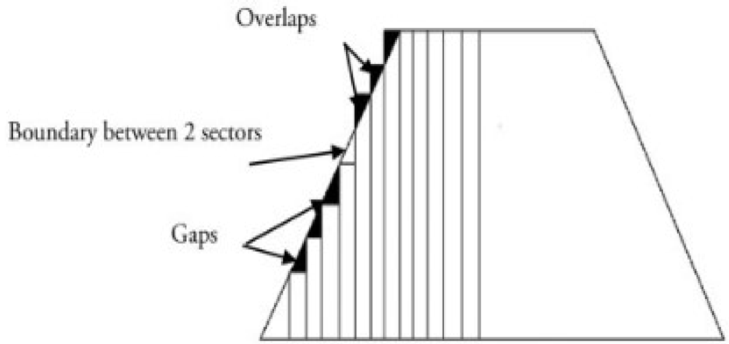


A. T. Rhead, T. J. Dodwell, and R. Butler, "THE EFFECT OF TOW GAPS ON COMPRESSION AFTER IMPACT STRENGTH OF AFP LAMINATES," in *Proceedings of the 15th European Conference on Composite Materials*, 2012.

(a)



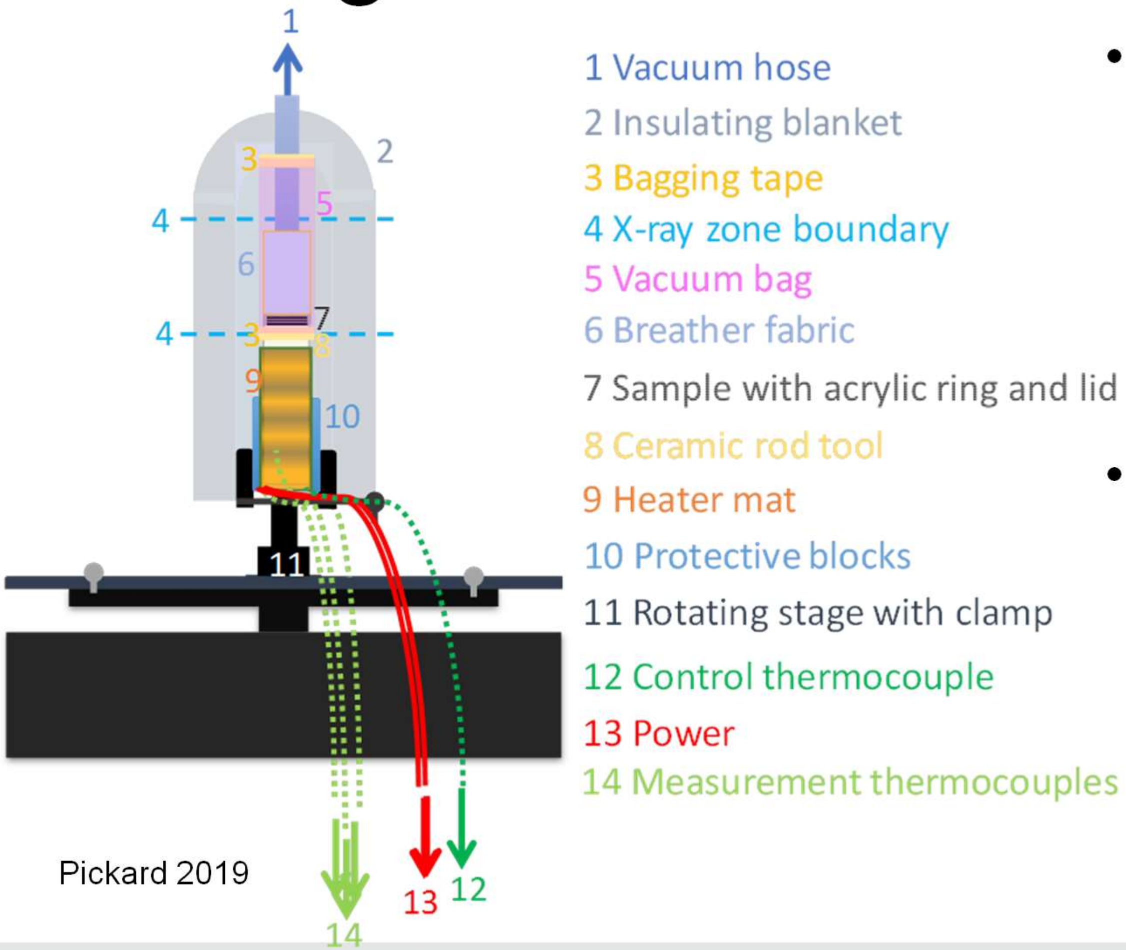
Pickard 2019



Y. M. Elsherbini and S. V Hoa, "Experimental and numerical investigation of the effect of gaps on fatigue behavior of unidirectional carbon/epoxy automated fiber placement laminates," *J. Compos. Mater.*, vol. 51, no. 6, pp. 759–772, 2017.

(b)

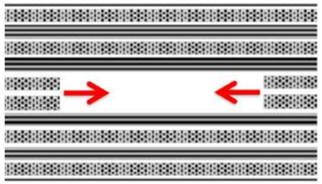
Tracking Features Through Cure



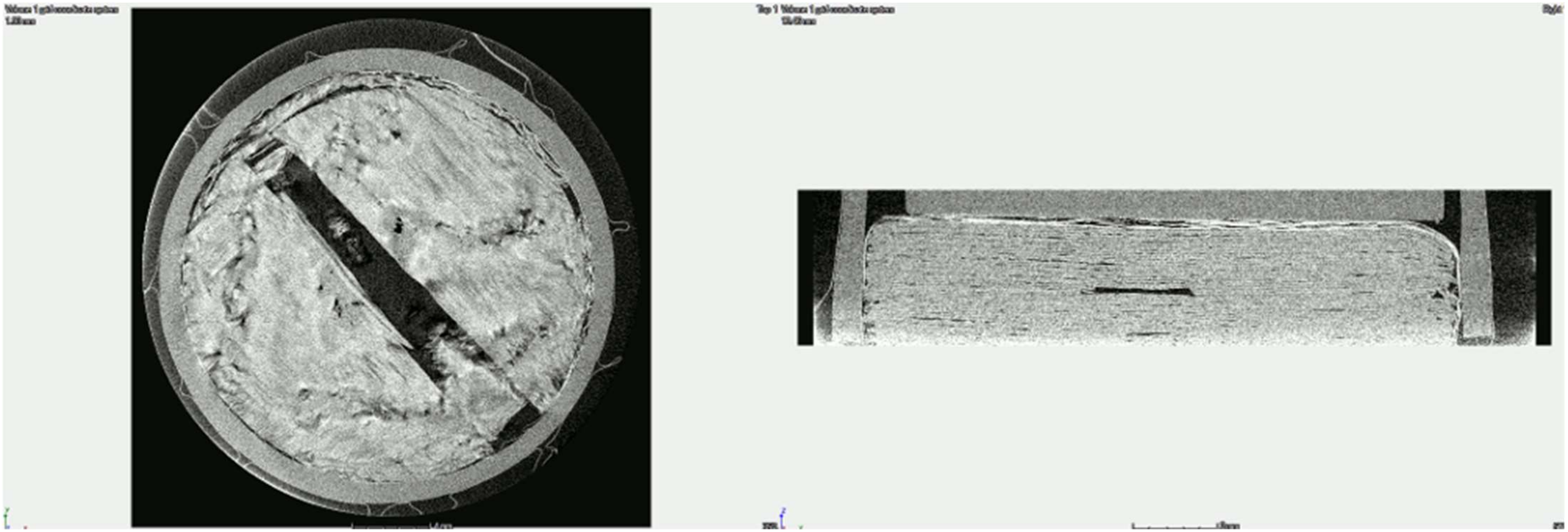
Pickard 2019

- In-Situ Micro-XCT during cure
  - Nikon XTH-320
  - Bespoke heating rig
  - 7 minute scans. 1600 projections, 250ms
- AFP type features:
  - (a) Tow gap parallel to fibre direction, fibres can move into gap.
  - (b) Ply drop between end of one tape and start of next, cut perpendicular to fibre direction.

Animation of Tow Gap

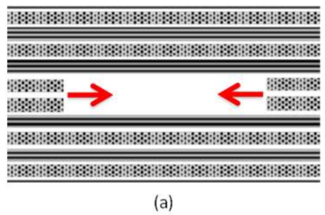


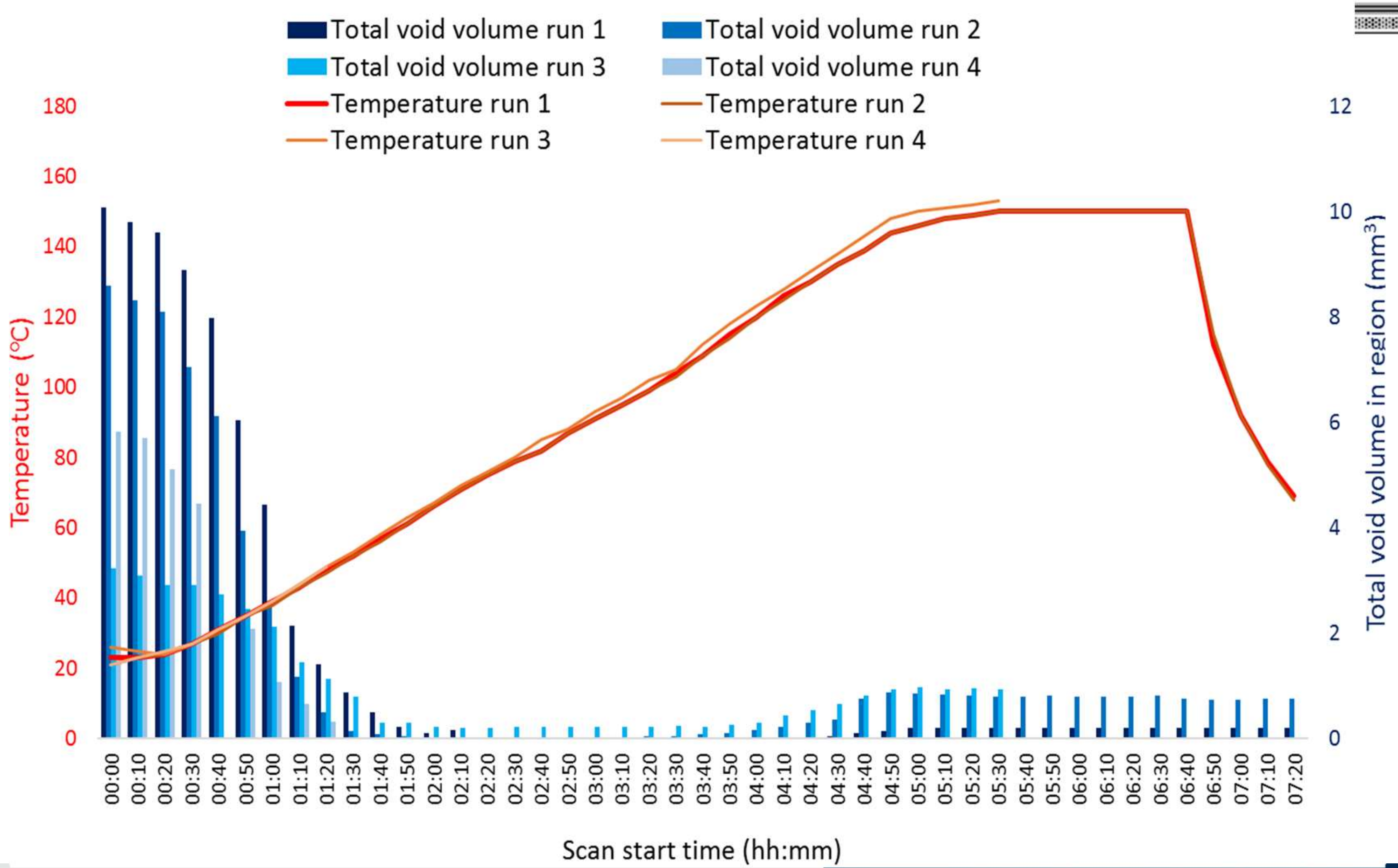
(a)



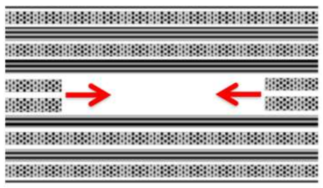
Pickard 2019

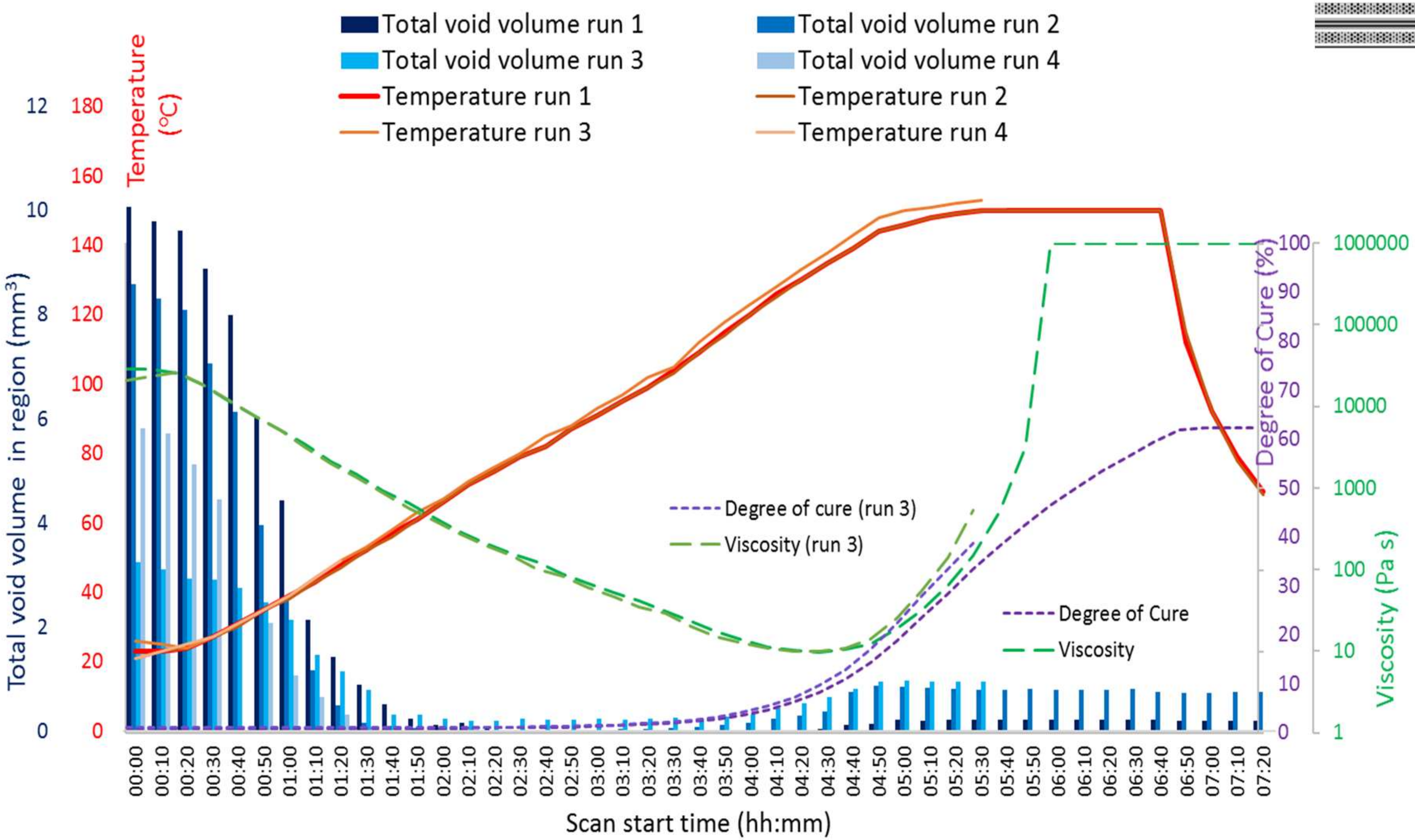
Evolution of tow gap



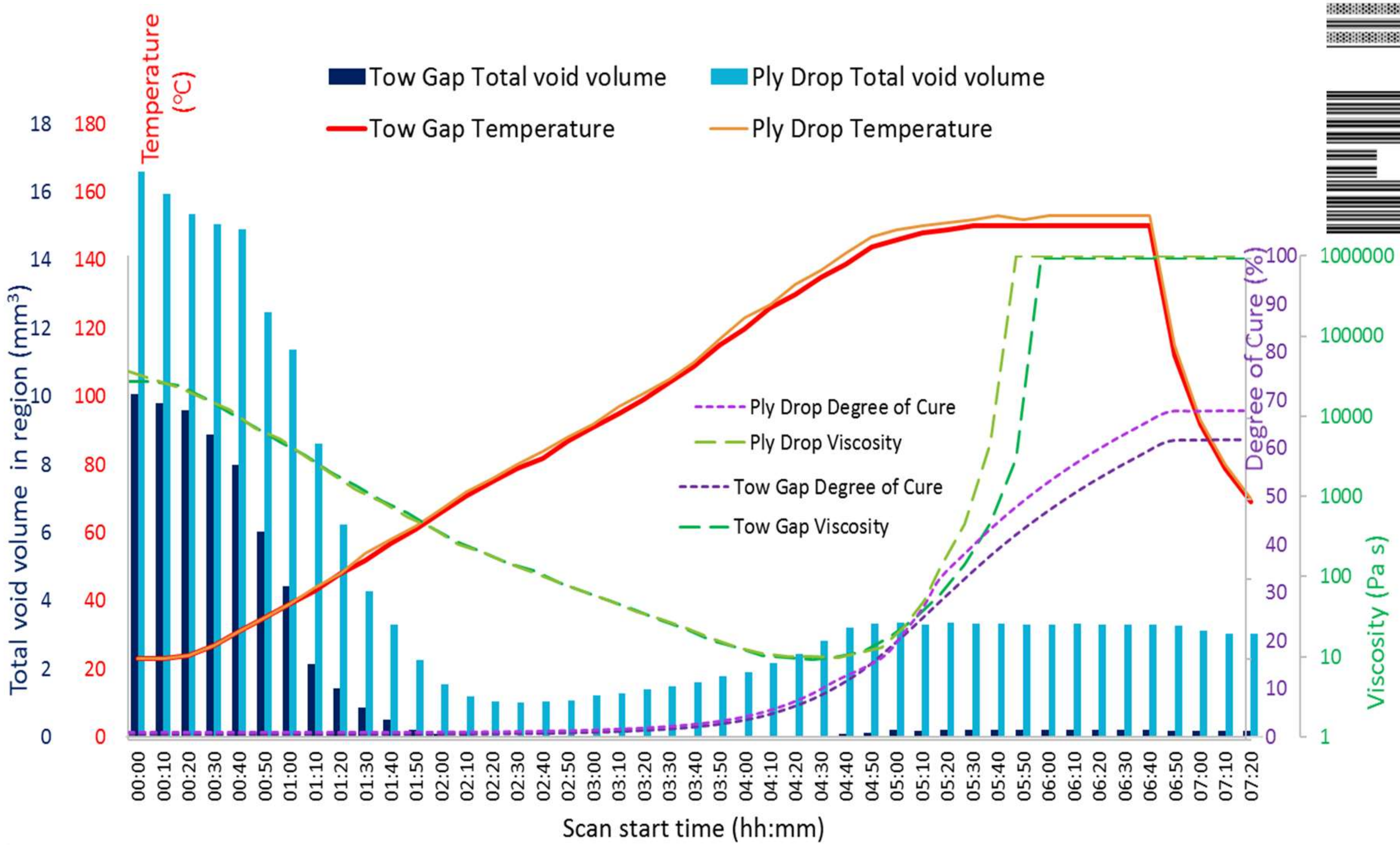


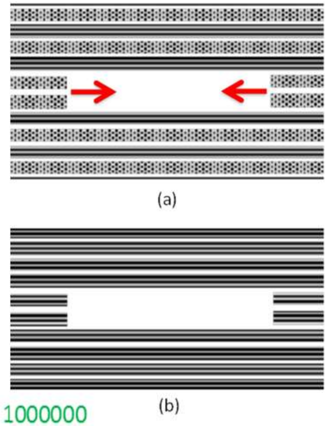
Comparison to resin behaviour





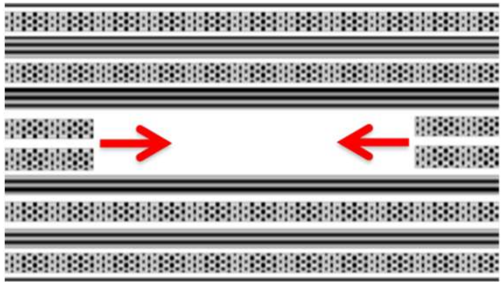
Tow gap vs Ply drop



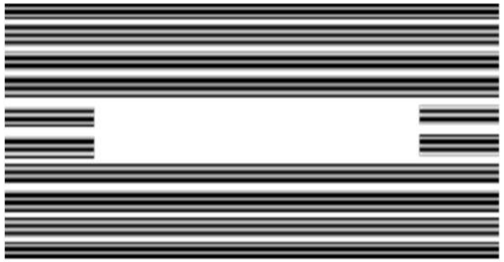


Tow gap vs Ply drop

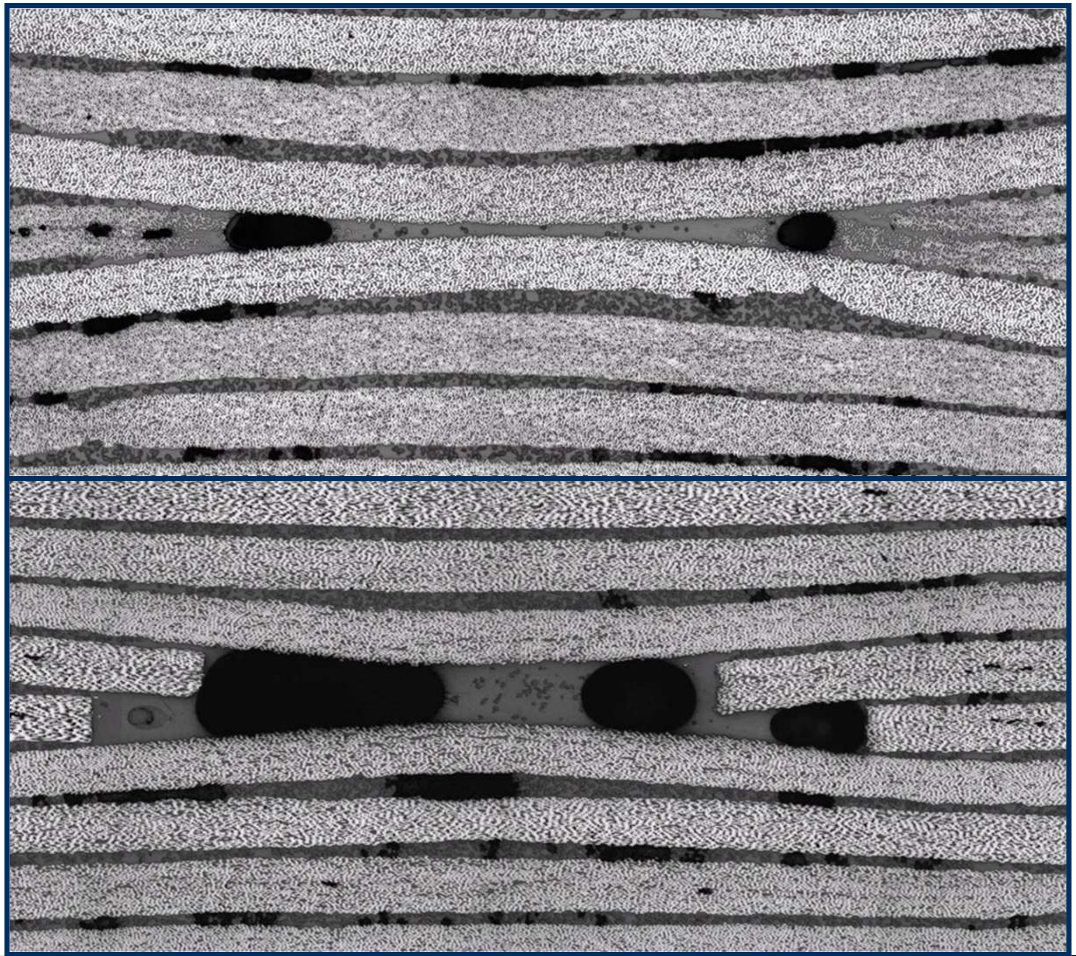
Proof of principle for In-Process Micro-XCT during composite cure



(a)

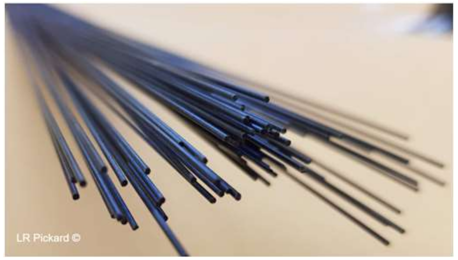


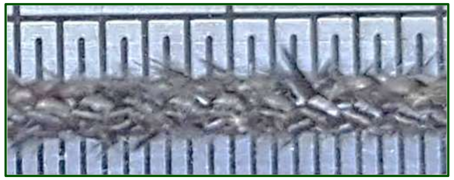
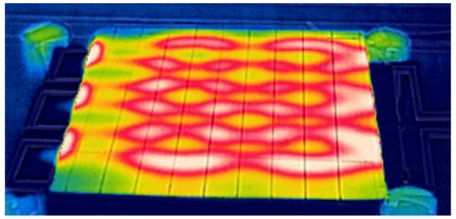
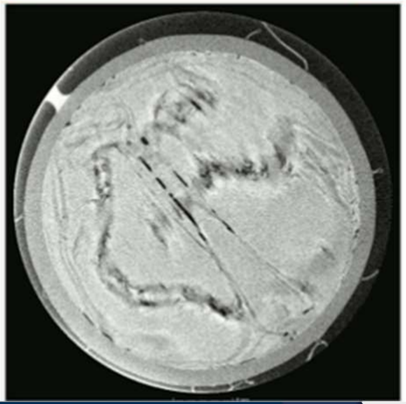
(b)



Summary

- Bristol Composites Institute has a wide range of research interests and activities
- NextCOMP: Hierarchical, nature inspired composites for improved compressive performance
  - Pultruded rod based systems
  - Rods overbraided to constrain kink band formation
  - ‘Fuzzy carbon’ overbraid provides shear support
- Energy Efficient cure pursued through Active Process Control and Electromagnetic Induction
- In-Situ XCT can be used to better understand the cure process



Extend your R&D

Patenting/ licensing

Spin-outs

Secondments and placements

Fund a PhD student working on your dedicated project

Summer internships

Collaborative research – new funding opportunities

Work with us

work-with-bci@bristol.ac.uk

www.bristol.ac.uk/composites/workwithus

@UoBrisComposite

Propose Masters and undergraduate student projects

Use our lab facilities

Impact Acceleration Projects

Knowledge Transfer Partnerships

Tap into the academic expertise

Engage with our Doctoral training centres

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- EPSRC Future Composites Manufacturing Research Hub [EP/P006701/1]
- EPSRC Centre for Doctoral Training in Composites Manufacture [EP/L015102/1]
- EPSRC Industrial Doctorate Centre in Composites Manufacture [EP/K50323X/1]
- National Composites Centre
- EPSRC Atoms to Applications Grant [EP/K035746/1]

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Bristol Composites Institute

Thank you for listening

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Imperial College London
The Composites Centre
for research, modelling, testing and training in advanced composites

Next COMP
Next Generation Fibre-Reinforced Composites