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Future Composites
Manufacturing Research Hub

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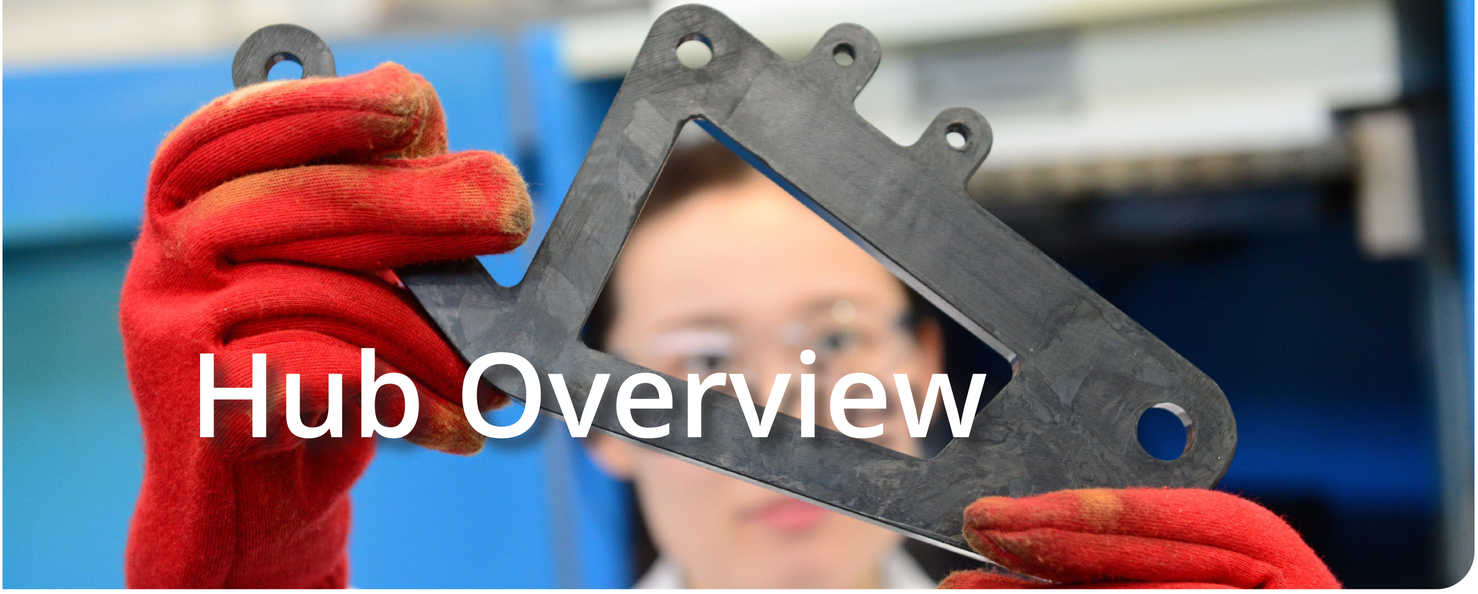
EPSRC
Future Composites Manufacturing Research Hub

Underpinning the development of next-generation composites manufacturing processes

POSTER BOOK
2019

University of Nottingham UK | CHINA | MALAYSIA
University of BRISTOL
Brunel University London
UNIVERSITY OF CAMBRIDGE
The University Of Sheffield.
THE UNIVERSITY of EDINBURGH
Prifysgol Glyndŵr Wrecsam / Wrexham Glyndŵr University
University of Glasgow
Imperial College London
MANCHESTER 1824 The University of Manchester
Cranfield Manufacturing
UNIVERSITY OF Southampton
WARWICK THE UNIVERSITY OF WARWICK



Hub Overview

Hub Vision

The EPSRC Future Composites Manufacturing Research Hub is a £10.3 million strategic investment by UK Research & Innovation (UKRI) to expand the national research effort in polymer matrix composites.

Established in January 2017, the Hub aims to be the national centre of excellence for fundamental research in the area of composites manufacturing, providing training to the next generation of composite engineers.

The Hub has two overarching **Grand Challenges** focused on **enhancing process robustness to deliver and accelerate growth**, and **developing high rate processing technologies for high quality composite structures**. To achieve this ambitious vision we have identified five **Research Priority Areas**, in collaboration with industry partners and the Composites Leadership Forum:

- **High rate deposition and rapid processing technologies**
- **Design for manufacture via validated simulation**
- **Manufacturing for multifunctional composites and integrated structures**
- **Inspection and in-process evaluation**
- **Recycling and re-use**

The Hub is led by the Universities of Nottingham and Bristol and includes an additional 12 Spoke members: Brunel University London, the University of Cambridge, Cranfield University, the University of Edinburgh, the University of Glasgow, Imperial College London, the University of Manchester, the University of Sheffield, the University of Southampton, Ulster University, the University of Warwick and Wrexham Glyndŵr University.

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Executive Summary

Welcome from the Director

Welcome to the EPSRC Future Composites Manufacturing Research Hub's 2019 Poster Book, which contains highlights from our annual Open Day and some updates since our recent end of year report.

The Open Day is an opportunity for the composites community to hear first-hand from all of the students and researchers working on projects within the Hub. In addition to the poster presentations, which are all included here, I particularly enjoyed the new elevator-style pitches, which gave every one of them the opportunity to present and discuss their research.

It was an honour to invite Dr Nuno Lourenço from Jaguar Land Rover to give the keynote presentation on composite structures for future electric vehicles. Nuno graduated with his PhD from the Composites Group at Nottingham in 2002, so it was a pleasure to show him around our new Advanced Manufacturing Facility and update him on our current research.

Another new highlight was the student "Design and Make" competition, organised in conjunction with the Society for the Advancement of Material and Process Engineering (SAMPE). Six teams competed to produce the tallest freestanding composite tower, to weigh no more than 250g and to support a 1kg mass. The winning structure from the University of Bristol was a remarkable 6.7metres tall!

I appreciate all of the hard work that goes into the organisation of these events and I would like to take this opportunity to thank all of those that contributed to the success of the day. Our next Open Day will be held in Edinburgh in August 2020, in conjunction with the ICMAC (International Conference on Manufacturing of Advanced Composites) conference. I look forward to seeing you there!

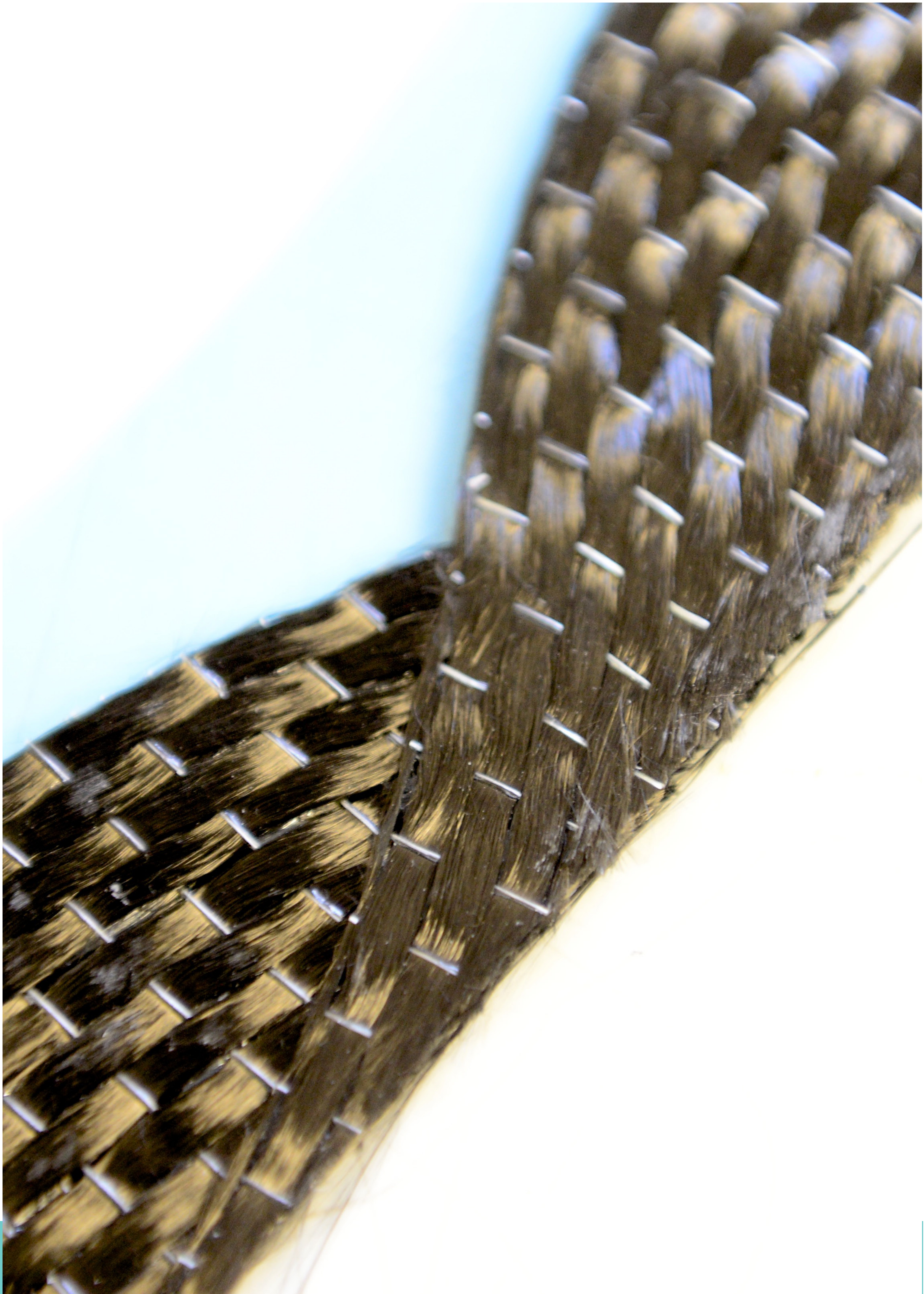
In other news, the University of Nottingham has recently been awarded an EPSRC Strategic Equipment Grant to develop a High-Volume Composites Manufacturing Cell with Digital Twinning Capability (HVCOMMAND; EP/T006420/1). With a focus on composite forming and process automation, the cell will deliver an internationally leading facility to support the Hub and the UK's academic and industrial communities.

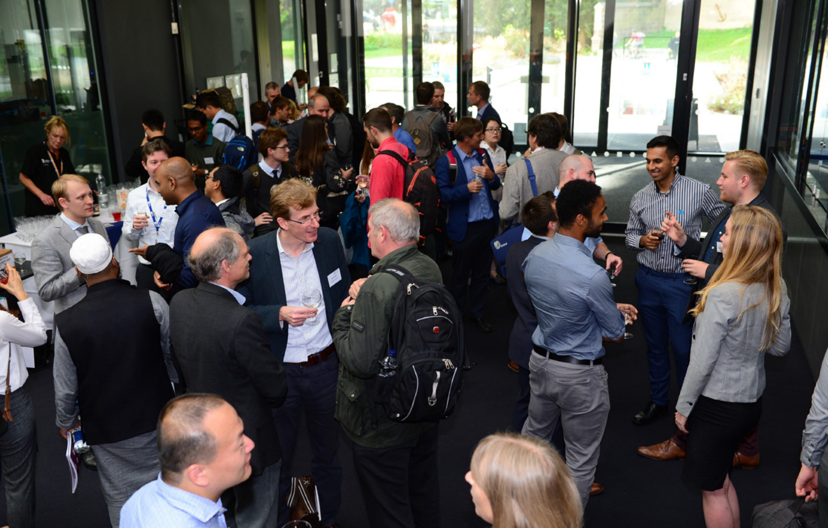
I am very pleased that a new UK/USA collaborative research project, ENACT, to investigate overmoulding for structural automotive applications, has been awarded through UK Research and Innovation (UKRI)'s Innovate UK. This will be funded in the UK by the Fund for International Collaboration (FIC), in collaboration with the Institute for Advanced Composites Manufacturing Innovation (IACMI) and their partner companies and universities in the USA. The ENACT project involves Michigan State University, Surface Generation and the University of Nottingham and will begin in early 2020. I was pleased to participate in the IUK International Mission in 2018 and am delighted with this outcome.

In September 2019 we welcomed two Innovation Fellows to the Hub: Dr Connie Qian (University of Warwick) will be developing a process simulation for compression moulding SMC, and Dr Colin Robert (University of Edinburgh) will develop powder-epoxy towpreg for low cost automated fibre placement. Through Dr Qian's fellowship, we also welcome the University of Warwick into the Hub and I am delighted that the Hub continues to grow and engage the academic community.

I hope you enjoy reading further about the progress of our students and researchers in this report. I would like to take this opportunity to extend my thanks to all those who are driving the Hub forward, including our members, industrial collaborators, Advisory Board and the EPSRC.

Professor Nick Warrior
Hub Director



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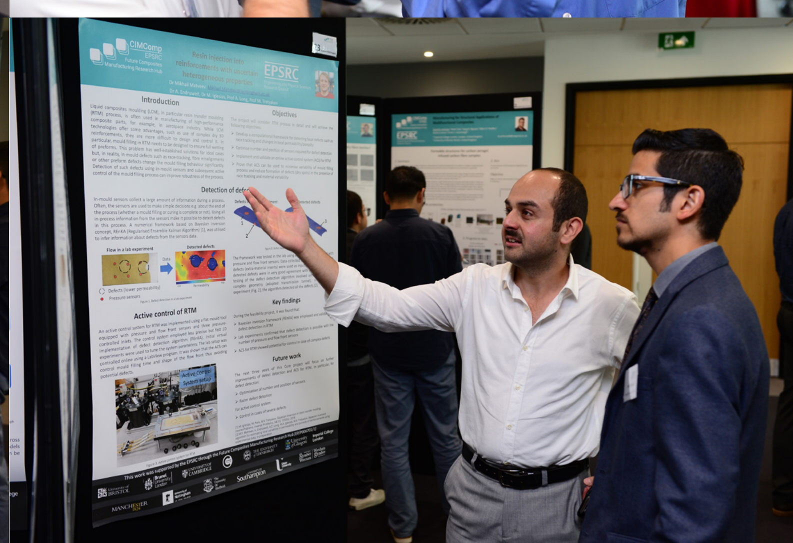
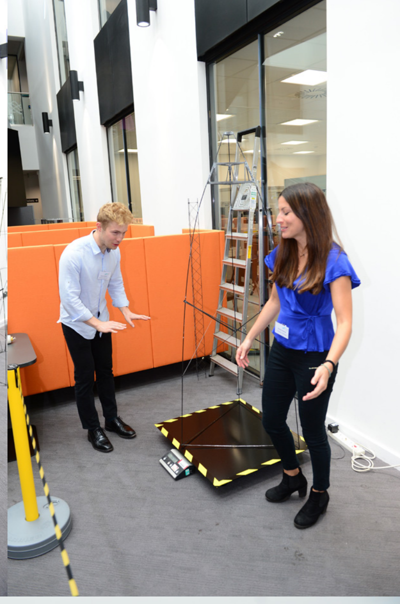
ESSENTIAL COMPONENTS


EPSRC
BECKHOFF


CIMComp
EPSRC
Introduction
Active control of RTM
Key findings
Future work

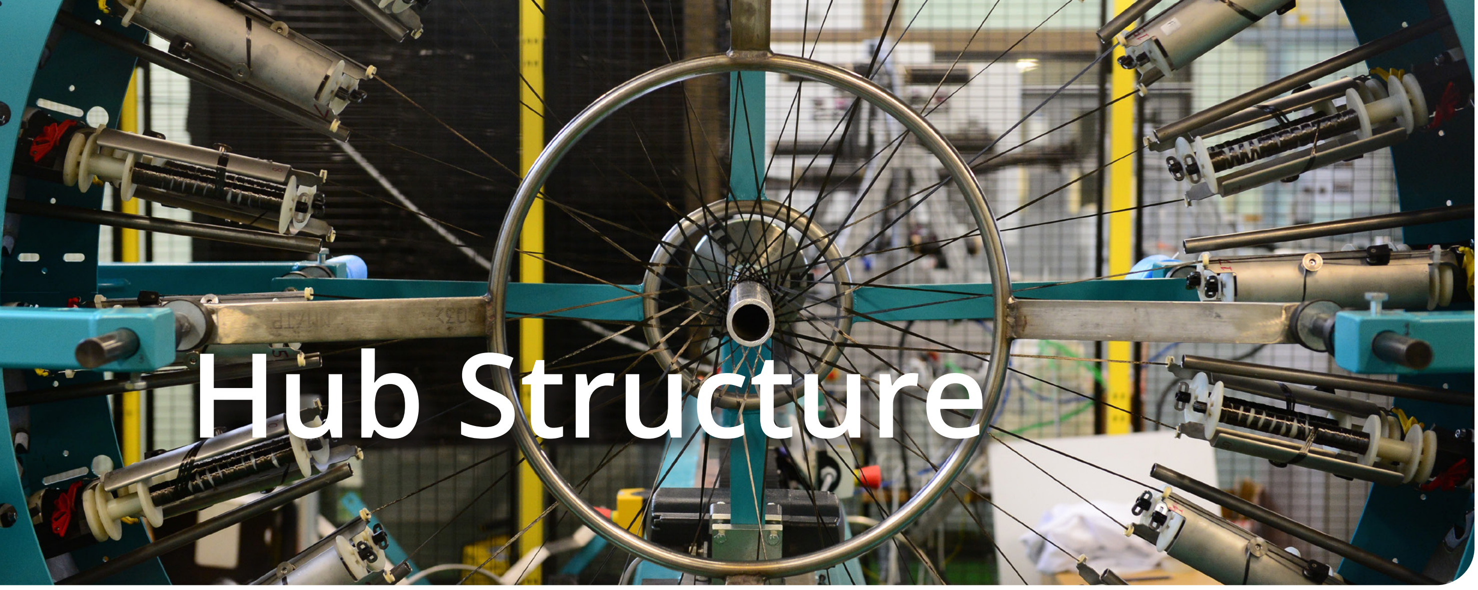









Hub Structure



Hub Structure

The Hub's management structure is responsive to the need to develop user engagements through the life of the Hub. The **Management Group (MG)** is responsible for the strategic direction of the Hub and the management of funding opportunities such as Innovation Fellowships, Feasibility Studies and Core Projects. The Management Group is chaired by the Director, supported by the two Deputy Directors, the Hub Manager, and the Chairs of the various committees.

The **Advisory Board (AB)** comprises independent academic and industrial members who take a high level, strategic view of the needs of Hub stakeholders. The AB helps to identify new areas for research and provides a perspective on current Hub research activities and how well it maps to the international context for quality and impact. The AB provides guidance on the quality and delivery of research, and ensures the needs of the UK composites community are addressed.

The **Strategic Development Committee** (SDC) is focused on developing knowledge and strategies to evolve the Hub's priority areas. This ensures that the Hub can effectively perform within the UK composites sector. Recently, the SDC has assumed responsibility for the Hub's roadmapping activities which bring together a number of data sources into a single resource. This includes understanding trends within the UK and EU composites research funding portfolio, mapping of centres of expertise and facilities, collating fundamental research challenges by technology area, and contextualising the activities of our Core Projects.

The **Knowledge Exchange Committee** (KEC) is the formal link between the Hub and our HVM-Catapult stakeholders and contains representatives from the NCC, AMRC, MTC, WMG and HVMC. This ensures that opportunities for closer collaboration between the Hub and RTOs are identified and acted upon. The KEC also assists in the management of the NCC's Technology Pull Through (TPT) programme which facilitates the scale up of fundamental research outputs towards TRLs 4-6. The KEC ensures that IP developed through Hub projects is recorded and protected.

The **Postgraduate Development Committee** (PDC) oversees the training and progression of research students, at doctoral level via the **Industrial Doctorate Centre** (IDC) in Composites Manufacture and at postdoctoral level via the **Researcher Network**. The PDC also manages an international student exchange scheme through the **International Researcher Network.** This network shares information and developments in the field, facilitates visits and exchange of people, and establishes partnerships in research programmes across 23 leading institutions in 12 countries.

The IDC is firmly embedded in the Hub and delivers specialist training at the National Composites Centre (NCC) in Bristol. The IDC facilitates the EngD in Composites Manufacture, a four-year postgraduate research programme for researchers who aspire to key leadership positions in industry. The Researcher Network is led by postdoctoral researchers to promote collaboration and enhance the cohort experience of postgraduate students and postdoctoral researchers. The Researcher Network also engages in Schools Outreach missions as STEM ambassadors, and administers funds for researchers to undertake Early Career Feasibility Studies.

Composites Leadership Forum (CLF) is working to influence Government and other bodies (including industry, research centres, academia, and skills providers) to bring together support for composites and ensure growth and industrial success for the UK. The Hub is recognised as a CLF delivery partner, representing our members and contributing to the fundamental research underpinning the UK's composites supply chain.

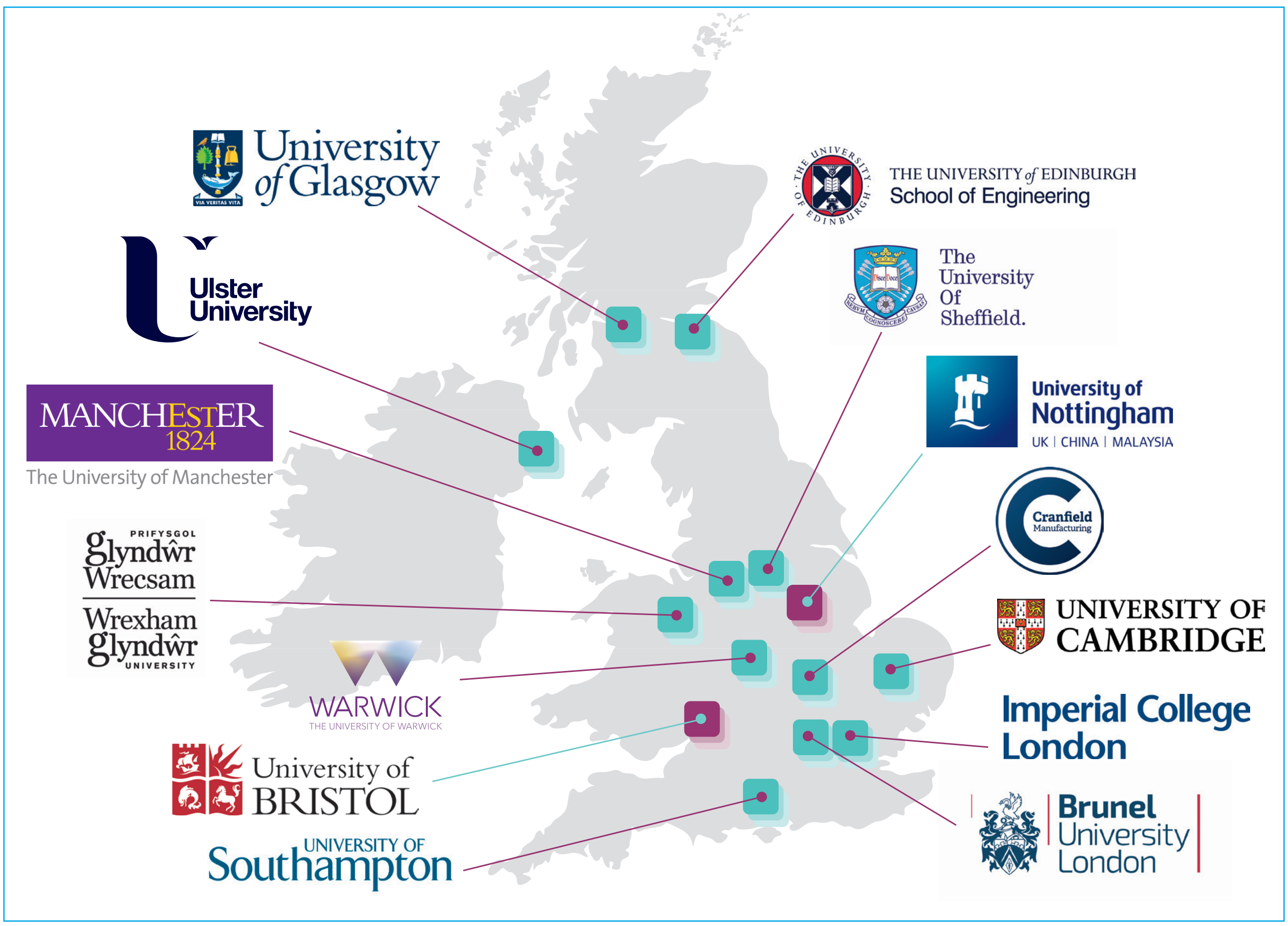
The Hub's academic and industrial partners are well represented on both the CLF committee, and across its seven sub-committees.

Partnerships

Academic Partners

The Hub currently comprises fourteen leading research groups working on composites manufacturing in the UK. The objective is to build and grow the national community in the design and manufacture of high performance composites. The Hub is led by the University of Nottingham and the University of Bristol and initially included four other Spokes: Cranfield University, Imperial College London, the University of Manchester, and the University of Southampton. The network expanded in 2017 / 2018 to include the University of Cambridge, the University of Edinburgh, the University of Glasgow and Brunel University London.

Most recently in 2019, The University of Sheffield, Ulster University, The University of Warwick and Wrexham Glyndŵr University have joined the network.



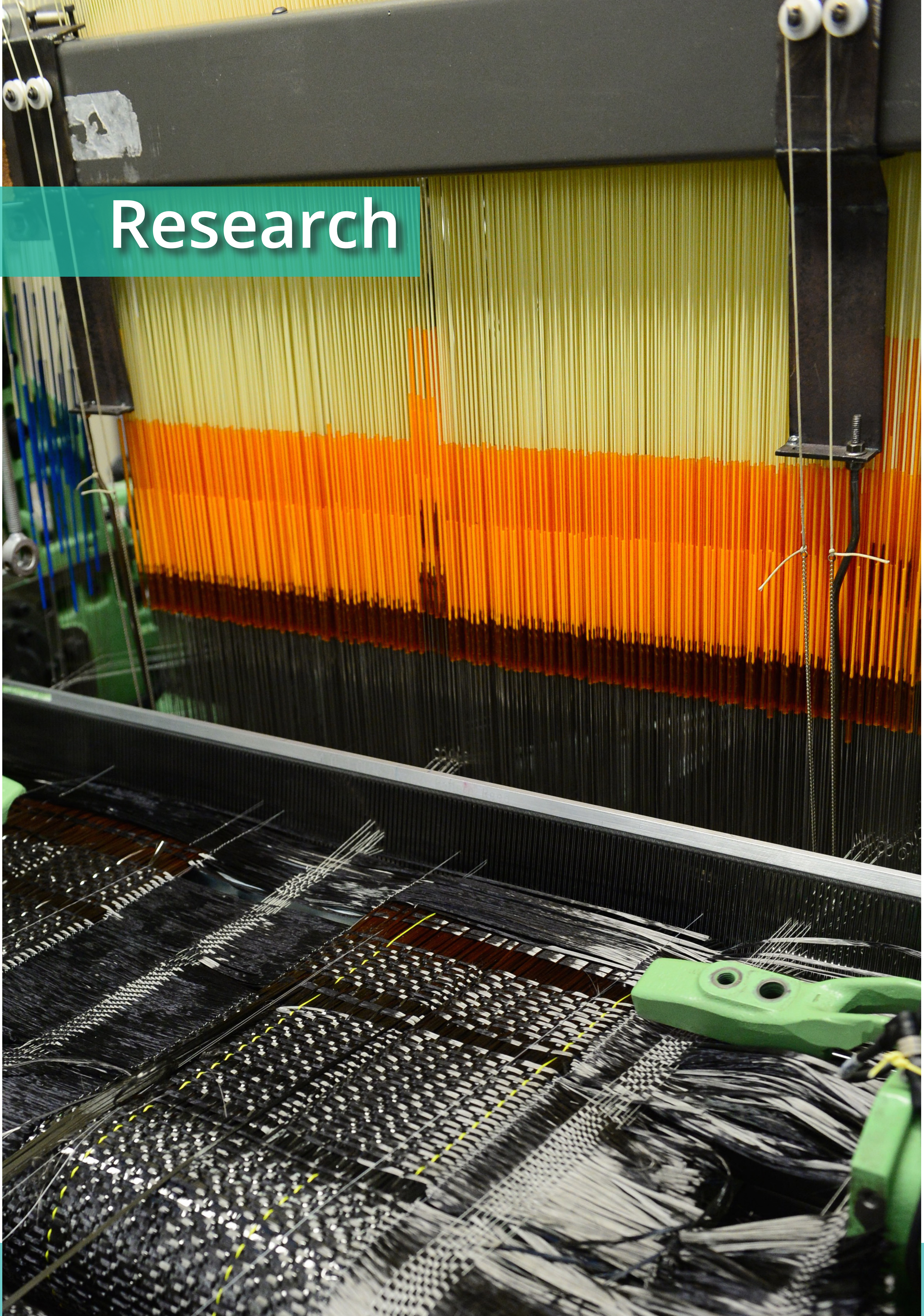
Industrial Partners

The Hub aims to meet the fundamental research challenges required to overcome barriers faced in industrial supply chains. Industrial collaboration is critical to this goal, and evidence of this engagement can be seen across the range of projects and activities funded by the Hub. We are pleased to be supported by 4 High Value Manufacturing Catapult Centres and 18 leading companies from the composites sector, collectively offering a further £12.7m in additional support. By establishing a framework for engagement to take place, we aim to create a collaborative environment where fundamental research can be developed with the support and involvement of industry. The following companies and organisations form our network of partners:

Since the launch of the Hub in 2017, a number of companies in addition to those mentioned above have supported Hub projects through in-kind contributions. This includes the following companies:

Alexander Dennis
Arkema
Dassault Systèmes
ÉireComposites Teo
Expert Tooling & Automation
FAR UK
Forrest Precision Engineering
Heraeus Noblelight
Induction Coil Solutions
KW Special Projects
LMAT
Porcher
Solvay
QinetiQ
Shape Machining
Surface Generation
Toray Advanced Composites

Research



Core Projects

Core Projects deliver fundamental research based on the Hub's five priority themes. They are typically a collaboration between two academic partners, employing two postdoctoral researchers and four PhD students. The Hub provides funding for up to three years, and industrial partners are invited to support the project by sponsoring postgraduate students affiliate to the project or offering in-kind contributions. Three Core Projects were launched at the start of the Hub in 2017 and are based on previous successful research funded through the CIMComp Centre. A fourth Core Project was launched in October 2019, which follows on from one of the successful Feasibility Studies, 'Active Control of the RTM Process under Uncertainty using Fast Algorithms'.

A brief introduction of each Core Project is outlined in this section, including a summary of the overall aims and objectives. A synergy diagram has been produced for each project to identify inward and outward contributions from other Hub projects, leveraged grant funding and our industrial partner network. Posters are presented from students and researchers that are directly involved in the Core Project, plus those that are associated with leveraged projects.

New Manufacturing Techniques for Optimised Fibre Architectures

Establishing a computational framework for textile preform optimisation
(Manchester, Nottingham)

Manufacturing for Structural Applications of Multifunctional Composites

Exploration, development and evaluation of manufacturing processes for multifunctional composite structures
(Imperial, Bristol)

Technologies Framework for Automated Dry Fibre Placement (ADFP)

Establishing novel material delivery systems for advanced control of dry fibre distribution
(Bristol, Nottingham)

Active Control of the RTM Process under uncertainty using Fast Algorithms

Online process control for reduction of defects in liquid resin infused structures
(Nottingham)

New Manufacturing Techniques for Optimised Fibre Architectures

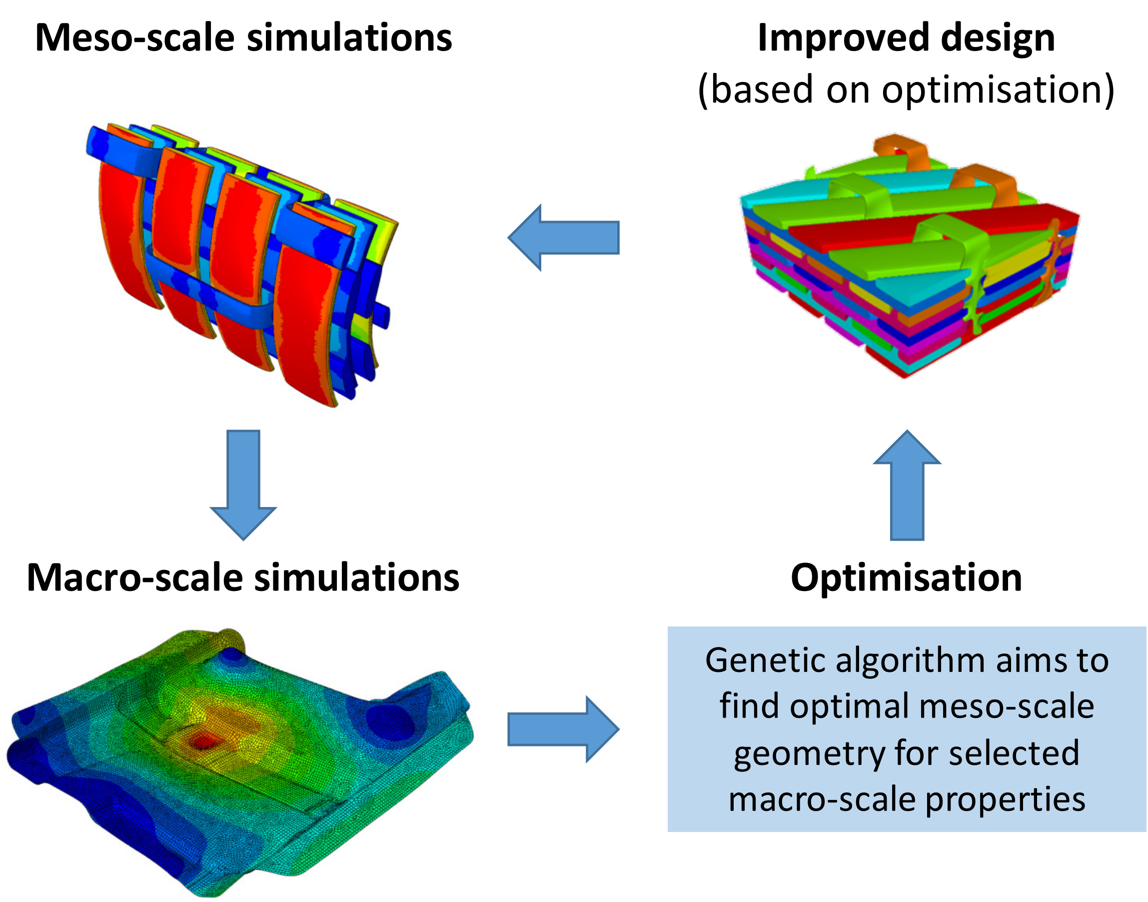
"Continuous fibre reinforced composites are typically manufactured from unidirectional or bidirectional plies, where the layup sequence is optimised to suit the loading conditions. The ply layup is constrained by current textile manufacturing solutions, which results in weight penalties from over-conservative design for manufacture constraints."

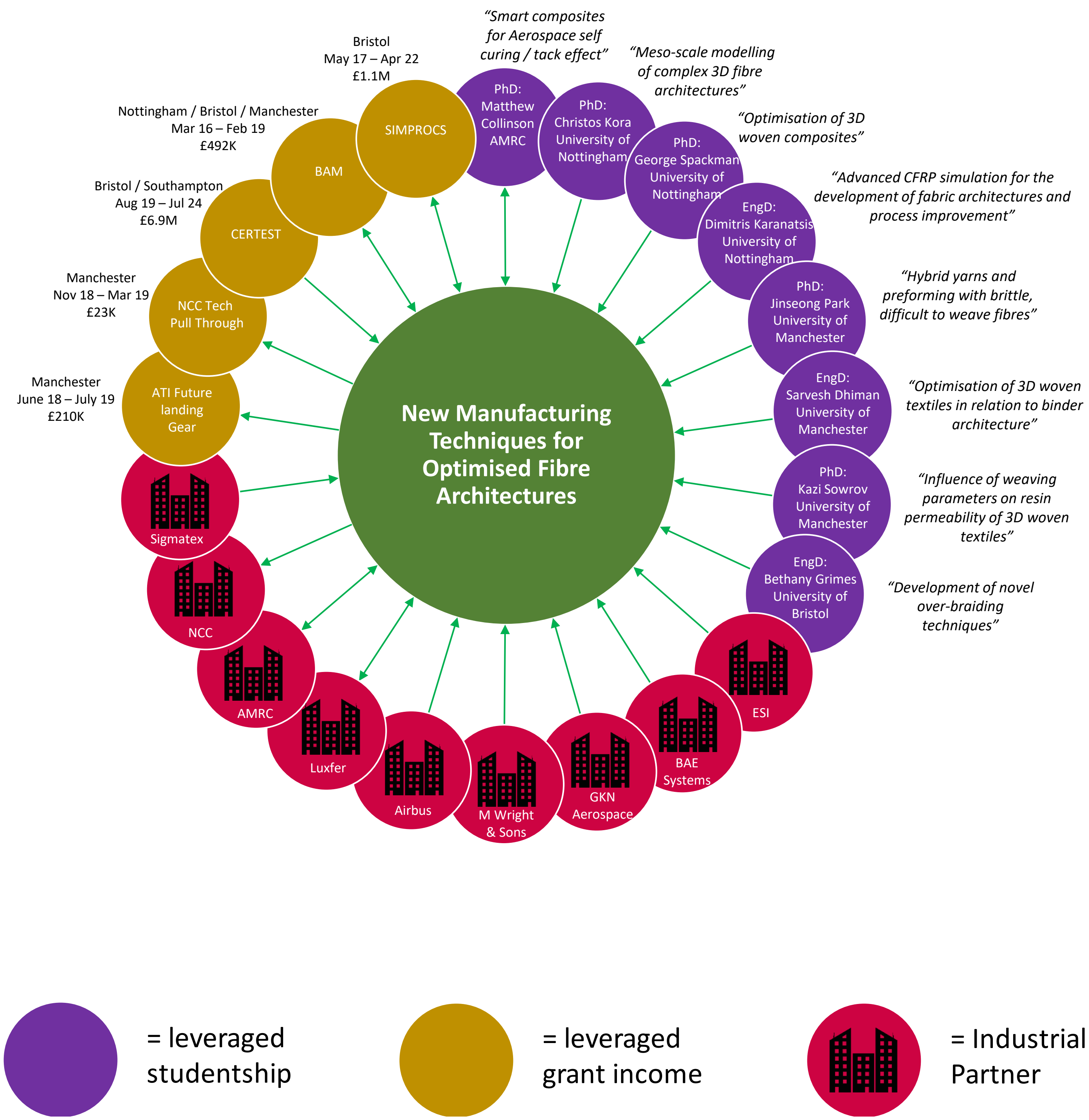
Aims and Objectives

The project aims to discover new forms of 3D fibre reinforcements, enabling composites with higher specific properties to be manufactured compared to conventional 3D reinforcements. These new reinforcements will complement and extend the currently available class of 3D textiles, such as orthogonal weaves or layer-to-layer weaves.

A computational framework will evaluate properties of various composites designs, and together with an optimisation algorithm, will select the best solution. The computational framework will implement a building-block approach where new models can be added at any stage to evaluate more reinforcements and resulting composites. Optimisation algorithms used within the framework will enable prediction of the best possible solution or a range of optimal solutions (a Pareto front).

A series of case studies, developed through collaboration with industrial partners, will be used to demonstrate potential weight-savings or performance improvements by preform optimisation.




New Manufacturing Techniques for Optimised Fibre Architectures
Bristol
May 17 – Apr 22
£1.1M
SIMPROCS
Nottingham / Bristol / Manchester
Mar 16 – Feb 19
£492K
BAM
Bristol / Southampton
Aug 19 – Jul 24
£6.9M
CERTEST
Manchester
Nov 18 – Mar 19
£23K
NCC Tech Pull Through
Manchester
June 18 – July 19
£210K
ATI Future landing Gear
"Smart composites for Aerospace self curing / tack effect"
PhD: Matthew Collinson AMRC
"Meso-scale modelling of complex 3D fibre architectures"
PhD: Christos Kora University of Nottingham
"Optimisation of 3D woven composites"
PhD: George Spackman University of Nottingham
"Advanced CFRP simulation for the development of fabric architectures and process improvement"
EngD: Dimitris Karanatsis University of Nottingham
"Hybrid yarns and preforming with brittle, difficult to weave fibres"
PhD: Jinseong Park University of Manchester
"Optimisation of 3D woven textiles in relation to binder architecture"
EngD: Sarvesh Dhiman University of Manchester
"Influence of weaving parameters on resin permeability of 3D woven textiles"
PhD: Kazi Sowrov University of Manchester
"Development of novel over-braiding techniques"
EngD: Bethany Grimes University of Bristol
ESI
BAE Systems
GKN Aerospace
M Wright & Sons
Airbus
Luxfer
AMRC
NCC
Sigmatex
= leveraged studentship
= leveraged grant income
= Industrial Partner

New Preforming Technologies for Optimised Fibre Architectures

Dr Mikhail Matveev, University of Nottingham, mikhail.matveev@nottingham.ac.uk
Academic Supervisor: Prof Andy Long
Co-authors: Dr Vivek Koncherry, Dr Sree Shankachur, Dr Louise Brown, Prof Prasad Potluri

Introduction

Composites with 3D fibre architectures, such as angle-interlock or orthogonal 3D woven textiles, demonstrate higher resistance to delamination than composites with no through-thickness reinforcement. At the same time, manufacturing of 3D reinforcement is currently constrained by preform thickness and fibre orientations. In this project, computational modelling based on an optimisation framework will be used to determine optimum 3D fibre preforms to be manufactured with novel preforming technologies.

Objectives

The project will achieve the following objectives:

- Develop a computational framework for multi-objective reinforcement optimisation without being constrained by existing manufacturing techniques.
- Develop preforming technologies for new material designs.
- Via a series of case studies, identify designs with improved properties over existing designs.

Optional Framework

Optimisation of a fibre preform can only be performed by application to a particular macro-scale problem (Fig. 1). However, it is impossible to model every yarn in a large composite part. Homogenisation of a meso-scale geometry and modelling a 3D composites via a generalised stiffness matrix offers a computationally efficient way to model a macro-scale problem [1]. Objective function values, a macro-scale response of a selected composite part, are used as input for an optimisation algorithm. The algorithm iterates over a large number of designs (but still smaller number than entire design space) to arrive at an optimal solution, or a set of optimal solutions (Pareto front) in the case of a multi-objective optimisation.

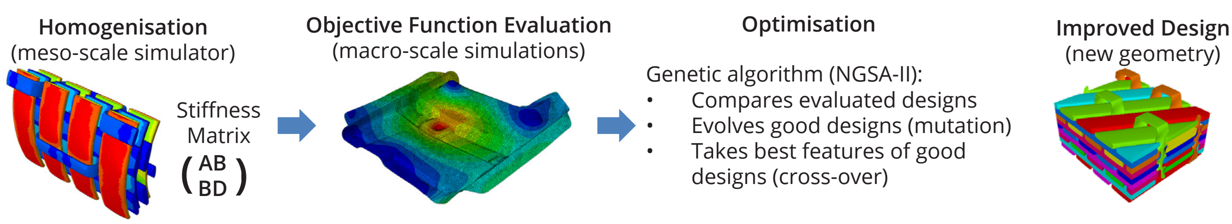


Figure 1. Numerical optimisation framework

Novel Preforming Technologies

Optimised fibre architectures require novel bespoke technologies. Several techniques were developed: multi-axial 3D preforming (Fig. 2) combined with multi-weft insertion system and 3D braiding with through-thickness fibres. Composites with multi-axial fibre reinforcement were shown to alleviate one of the main problems of 3D woven composites – lack of stiffness and strength in the off-axis direction [3]. The tensile modulus in the off-axis direction was found to be comparable to those of multi-axial laminates.

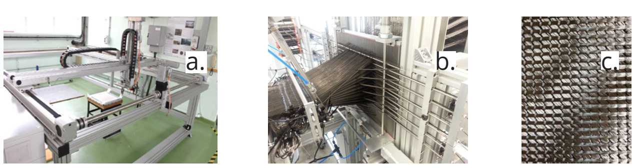


Figure 2. Multi-axial performing (a and b); multi-axial fibre preform (c)

Key Findings

During the project, new methods and technologies were developed:

- Numerical optimisation framework for multi-scale problems [1].
- Multi-axial 3D preforming technology [2].
- Multi-weft insertion system [3] (US patent 20150107715 [4]).

It was demonstrated that meso-scale optimisation of 3D fibre architectures can improve properties of composite parts and hence lead to further weight reduction.

Case Study - Automotive Component

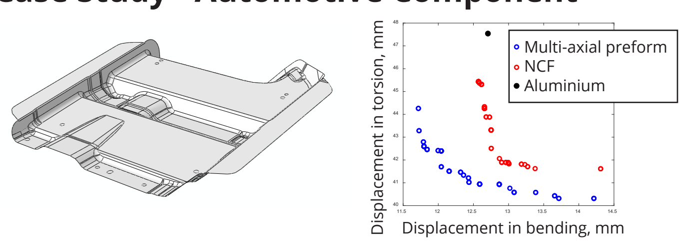


Figure 3. a. Geometry of a vehicle floor pan; b. Multi-objective optimisation of bending and torsional stiffness

Geometry and tooling of a vehicle floor pan was provided by AMRC (Fig. 3a). The optimisation framework was applied to find optimum reinforcement for improved bending and torsional stiffness. Using multi-objective optimisation (Fig. 3b) it was shown that use of multi-axial 3D preforms can result in 5-10% weight reduction compared to conventional non-crimp fabrics.

Future Work

The project is now in its final stages and will aim to:

- Optimise fibre architectures for two selected demonstrators.
- Experimentally demonstrate improved performance of optimised demonstrators.

[1] M.Y. Matveev, V. Koncherry, S.S. Roy, L.P. Brown, P. Potluri, A.C. Long. Meso-scale optimisation and manufacturing of continuous fibre 3D reinforcements, ICCM-22, Melbourne, Australia, 2019
[2] V. Koncherry, J.S. Park, K. Sowrov, M.Y. Matveev, L.P. Brown, A.C. Long, P. Potluri. Novel manufacturing techniques for optimised 3D multi-axial orthogonal preforms, ICCM-22, Melbourne, Australia, 2019
[3] M.Y. Matveev, V. Koncherry, S.S. Roy, P. Potluri, A.C. Long. Novel textile preforming for optimised fibre architectures, IOP Conference Series: Materials Science and Engineering, 406, 2018
[4] US Patent 20150107715, https://patents.google.com/patent/US20150107715

Braiding of Composite Structures

Matthew Thompson, University of Nottingham, matthew.thompson@nottingham.ac.uk
Academic Supervisors: Prof Nick Warrior, Dr Kishen Rengaraj

Introduction

Braiding of composites is a highly automated process with beneficial interlacement of fibres and near net shape production. However, challenges in predicting the braid properties hinders wide-scale adoption of this process in industry. This project aims to improve prediction of braid properties through the development of a more accurate and automated method of production of a braided unit cell within TexGen.

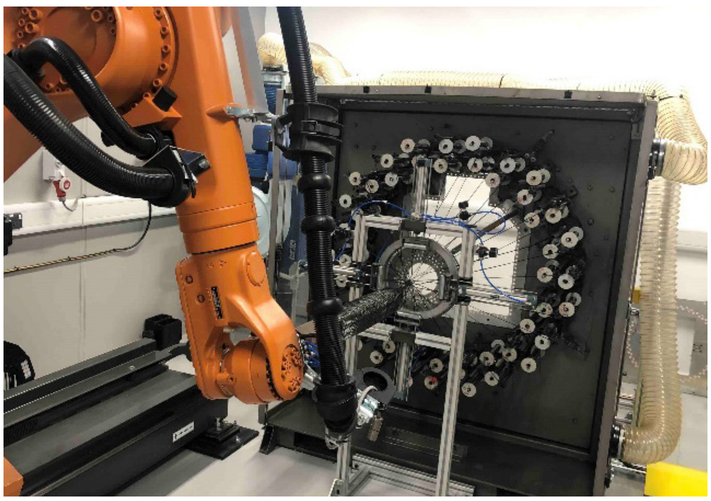


Figure 1. 48-Carrier axial braider at UoN

Current Research

A comparative study between a 48-carrier axial braider at UoN and a 288-carrier braider at the NCC has been undertaken to understand the scalability of braid structure. A cylindrical mandrel and an 'Oscar-shaped' mandrel (Figure 3) have been scaled and braided on both machines. Work to enable the prediction of the effect of scale on braid architecture is currently in progress.

Figure 2 shows the current state of the automated unit cell production within TexGen. The outcome to this stage allows for the adaptation of tow geometry, braid angle and pattern structure. As evident from Figure 2(b) the current model suffers from high levels of yarn intersection which will be reduced as the model is refined further.

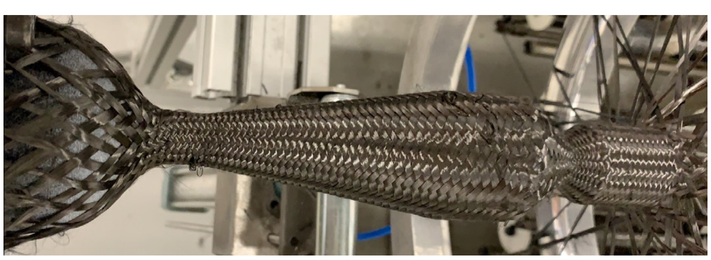


Figure 3. Oscar mandrel braided at UoN

Aims

- Investigate the effect of braid parameters on yarn geometry.
- Develop a TexGen braiding wizard for automated building of braid unit cells.
- Develop a "refine" function for TexGen to alter cross-section geometry to remove yarn intersections.
- Produce novel braiding architectures optimised for pre-determined load cases.

Methodology

A preliminary study investigating the braid parameters that effect yarn geometry will be conducted. This includes tow size, mandrel geometry, carrier tension, braid speed and guide ring effects. The most critical parameters will be determined and a larger study will be performed to gather more detailed data for the development of the braid unit cell model.

Through the use of optical microscopy, structured white light scanning and μCT the geometry of the yarns will be determined and allow for a automated braiding wizard to be developed. Additionally novel braiding architectures such as non-symmetric braids will be developed to optimise for predetermined load cases, with simulation testing conducted using TexGen wizard.

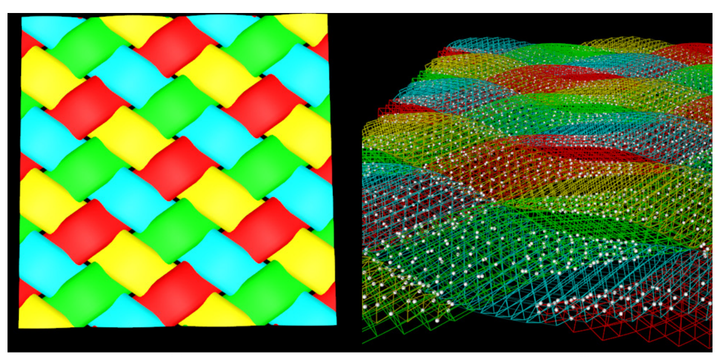
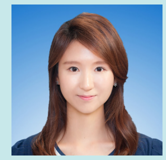


Figure 2: Current development of automated braid production in TexGen: (a) basic 2D biaxial braid (b) shows intersection points of the model.

This project is a collaborative project between the University of Nottingham (UoN) and the National Composites Centre (NCC)

Development of Stable Hybrid Yarns for 3D Woven Thermoset Composites

Jinseong Park, University of Manchester, jinseong.park@postgrad.manchester.ac.uk
Academic Supervisors: Prof Prasad Potluri, Dr Vivek Koncherry



Research Aims & Objectives

Thermoset matrix composites have the characteristic of high strength and stiffness. However, thermoset composites are brittle materials due to their high crosslink density (Figure 1). Therefore, this research aims to improve the impact damage tolerance of thermoset composites by hybridising carbon fibres (CF) with thermoplastic fibres. Key manufacturing of development of stable wrapping and comingling processes include fibre stretching. The wrapping yarn manufacturing process and analysis results are currently presented.

Figure 1. Boeing 787 Dreamliner's carbon fibre nose smashed in (Mail Online, 2019, Lpdlabservices.co.uk, 2019)

Hybrid Yarn Composite Manufacturing and Analysis

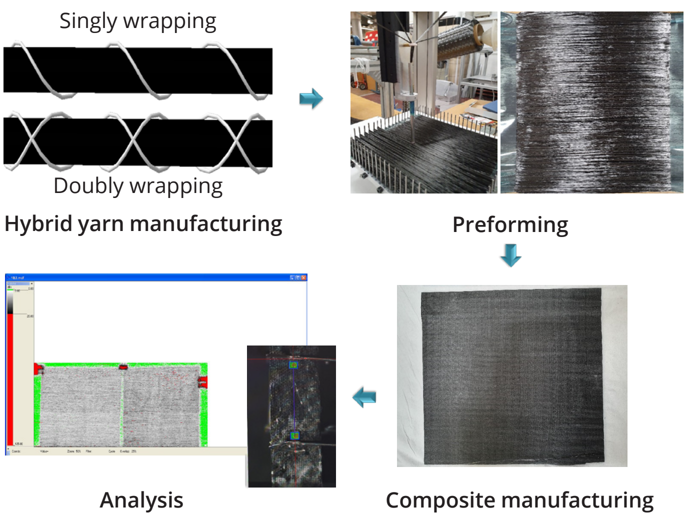


Figure 2. Composite analysis process

Hybrid Yarn Manufacturing Machine Assembly Process

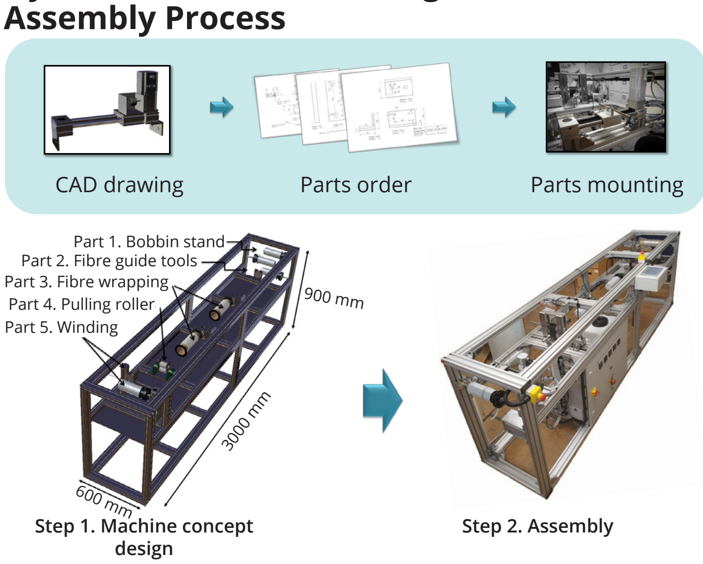


Figure 3. Development of hybrid yarn manufacturing process

Key Findings

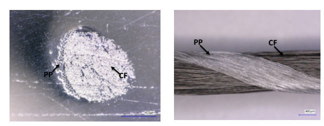


Figure 4. Cross and lateral section photo-microscopy images of wrapping yarn

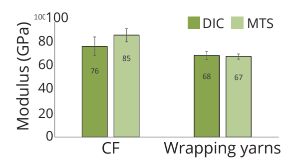


Figure 5. Tensile modulus of UD CF and CF/PP doubly wrapped yarn composite

- The wrapped yarn consists of carbon 85 % and PP 15 %.
- Carbon fibre volume fraction (FVF) of CF and wrapping yarn composite are 45 % and 43 % each.
- Composite strength of CF and wrapping yarn are 1307 MPa and 839 MPa each.

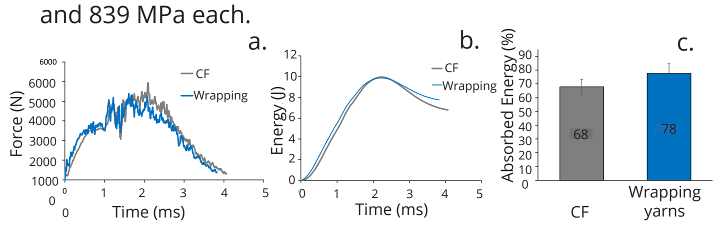


Figure 6. Force-time; (a) & energy-time history (b) of the composite samples at 10J and absorbed energy of CF and wrapping yarn composites (c)

- Wrapping yarn composite absorbs the energy of 78 % compared to CF composite (68 %) at 10J (Figure 6 .c).
- Damage area of wrapping yarn composite is smaller than CF composite at 10 J impact testing.

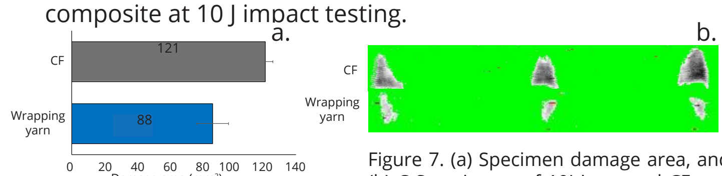


Figure 7. (a) Specimen damage area, and (b) C-Scan image of 10J impacted CF and wrapped yarn composites

Further Works

- Analysis of the degree of impact damage tolerance of hybrid yarn composite (CAI test with different low energy impact).
- Comparing the composite mechanical properties between UD and 3D woven structure using wrapped and commingled yarn.
- Programming setting to run the machine.

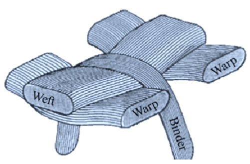
Manufacturing and Processing Mechanics of 3D Woven Composites

Kazi Sowrov, University of Manchester, kazi.sowrov@postgrad.manchester.ac.uk
Academic Supervisors: Prof Prasad Potluri, Dr Anura Fernando, Dr Vivek Koncherry

The 3D woven composite manufacturing using liquid composite moulding (LCM) is now attracting academic and industrial interest. The Z binder in the 3D woven structures improves the damage tolerance. At the same time, this Z binder creates fibre waviness and distortion resulting in reduction of in-plane mechanical properties. The structure of the 3D woven preforms and the resulting composite properties can be varied by changing the Z binder parameters. This project aims to systematically analyse the influence of Z binder parameters on preform and composite properties, improving the properties by using a new preform manufacturing technique and optimising the composite properties by incorporating the multiaxial fibres.

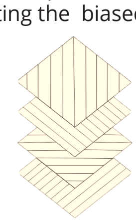
Project Methodology

Step I
Investigate the influence of binder parameters in 3D woven preform and composite properties.



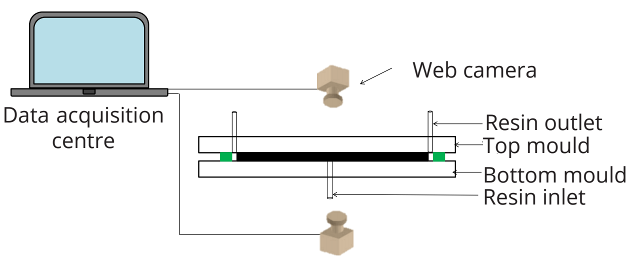
Step II
Improve the preform and composite properties by using the new 3D loom for preform manufacturing.

Step III
Optimize the mechanical properties in all directions i.e warp, weft and off-axis by incorporating the biased (±) fibres.

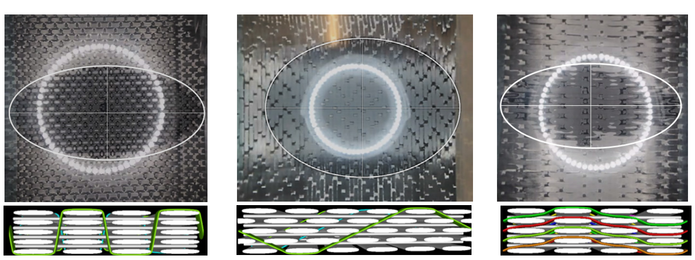


Influence of Z Binder Architecture in Resin Permeability

A non-intrusive permeability measurement set-up has been developed with the cavity thickness changing facility which enables the measurement unsaturated permeability in in-plane & transverse direction with variable fibre volume fraction.



In-plane permeability of 3D woven preforms with different binder architectures- Orthogonal, Angle Interlock and Layer-to-layer is measured for Epoxy IN-2 resin and hardener mixture with a viscosity of 0.225 Pa.s

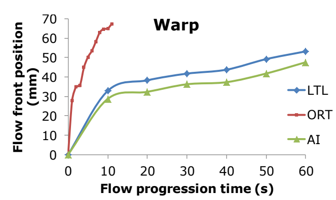


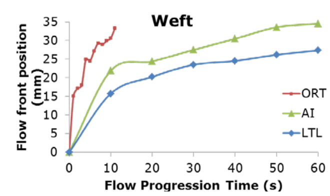
Orthogonal Angle Interlock Layer to Layer

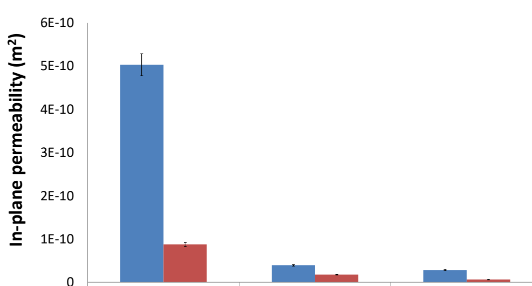
The principal in-plane permeability values K1 and K2 were determined based on least square fit technique for the elliptically shaped flow front as a function of time using the following equations which is well documented by Weitzenböck et al.[1,2]

$$K_1 = \frac{\mu \emptyset}{4t\Delta P}\{X_f^{\,2}[\,2\ln(\frac{X_f}{X_0} - 1)]\} + X_0^{\,2} \qquad K_2 = \frac{\mu \emptyset}{4t\Delta P}\{Y_f^{\,2}[\,2\ln(\frac{Y_f}{Y_0} - 1)]\} + Y_0^{\,2}$$

Orthogonal preform with more binder-stuffer crossing points allows easier resin flow and results in more in-plane permeability among the three preforms.







	ORT	AI	LTL
K1	5.02999E-10	3.94049E-11	2.86029E-11
K2	8.74071E-11	1.77506E-11	6.46501E-12

Conclusion

In 3D woven preforms, the Z binder constrains the whole structures giving it improved through-thickness properties, however it induces distortion and waviness on the load bearing tows. In-plane resin permeability measured for preforms with three different binder architectures shows a strong influence of binder parameters on preform properties. These three step research will enable us to investigate the influence of binder on preform and composite properties, improve the product quality by using the new manufacturing technology and optimize the composite properties by incorporating the off-axis fibres.

[1] Weitzenböck J, Shenoi R, Wilson P (1999) Compos Part A Appl Sci Manuf 30(6):781–796, [2] Weitzenböck J, Shenoi R, Wilson P (1999) Compos Part A Appl Sci Manuf 30(6):797–813

Optimisation of 3D Woven Structures

George Spackman, University of Nottingham, george.spackman@nottingham.ac.uk
Academic Supervisors: Dr Louise Brown, Prof Arthur Jones

Abstract

The aims of this project are to develop methods to facilitate the optimisation of the woven architecture for particular load cases, namely the T-joint under tensile loading. Optimisation is carried out using MATLAB with the functionality of the University of Nottingham's in-house textile modelling software Texgen [4] used to automatically generate the geometric models, set up the material properties and generate a voxel mesh before submission to the commercial FE solver Abaqus where displacement boundary conditions are applied. Once this has been completed for flat woven pieces, optimisation of the complex architectures found in bifurcated parts such as T-joints will be demonstrated.

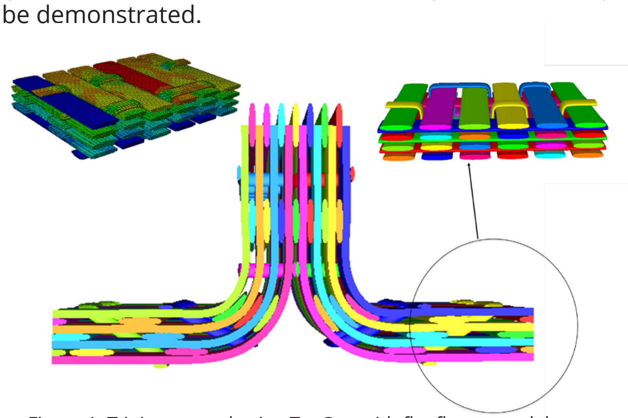


Figure 1. T-joint created using TexGen with flat flange models

Binder yarns in orthogonal 3D woven textiles provide through thickness reinforcement and ensure the integrity of the textile. While the configuration of their paths has been shown to have a negligible effect on the in-plane elastic properties of woven textiles, it has been shown to have a positive effect on the strength and damage resistance [1 - 3] and so can be considered as a design variable for input into an optimisation of functions of these properties.

Definitions regarding what types of weave result in textiles that maintain their integrity were defined and implemented as constraints into the optimisation framework. A novel algorithm has been developed to implement these now generalised constraints. They apply to all the binder yarns collectively and are as follows:

1. One binder must pass over the top and another must pass under the bottom of each weft stack to ensure all the weft yarns are bound.
2. No straight, non-reinforcing binder yarns above or below weft stacks.
3. At least one binder yarn must cross all horizontal planes between weft layers in the unit cell to prevent separation of the textile.

Each binder path is specified as a vector of its binder positions in each weft stack where the binder yarns cross over the wefts.

Results and Future Work

Weaves containing two and three binder yarns were optimised using the genetic algorithm. The objective function was the average von Mises stress output from the loads applied using the periodic boundary conditions developed in [5]. The main aim here is to demonstrate the ability of the optimisation framework to result in feasible weaves. In each case the algorithm converged to a feasible weave.

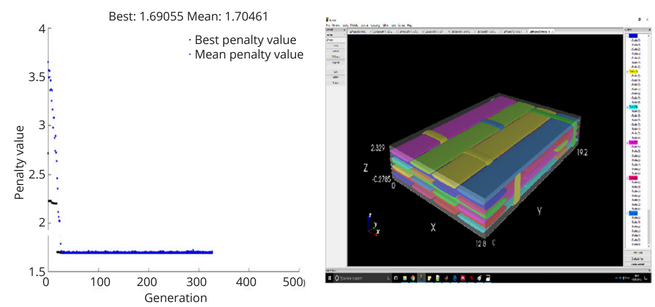


Figure 2. a) Graph of penalty value against generation, demonstrating effectiveness of checking algorithm. b) Final weave produced

The flanges of the T-joint undergo large through-the-thickness tensile loading so further optimisation will first be carried out on flat pieces representing an idealised version of this part of the T-joint (Fig1.) to find the best weave pattern for resisting delamination and other failure modes.

During this study a range of optimisation algorithms will be assessed to find the most suitable in terms of robustness and speed. The resulting algorithm will be applied to the optimisation of the yarn architecture in the T-joint. The typical algorithm currently used in composite optimisation is the genetic algorithm which is used for it's ease of implementation and many parameters that can be tuned to improve its performance. However, the genetic algorithm can end up getting stuck in local minima and its general applicability to woven composite optimisation can be questioned.

Finally, methods to mesh complex profile shapes such as T and I joints will be further developed and implemented in TexGen. This will facilitate automatic generation of FE models.

[1] Z. Wu, Acta Mech. Solida Sin., vol. 22, no. 5, pp. 479–486, Oct. 2009.
[2] K. Leong, B. Lee, I. Herszberg, and M. . Bannister,Compos. Sci. Technol., vol. 60, no. 1, pp. 149–156, Jan. 2000.
[3] S. Dai, P. R. Cunningham, S. Marshall, and C. Silva, Compos. Part A Appl. Sci. Manuf., vol. 69, pp. 195–207, Feb. 2015.
[4] H. Lin, L. P. Brown, and A. C. Long, Adv. Mater. Res., vol. 331, pp. 44–47, Sep. 2011.
[5] S. Li and A. Wongsto, Mech. Mater., vol. 36, no. 7, pp. 543–572, Jul. 2004.

Numerical Modelling and Optimisation of 3D Textile Composites

Christos Kora, University of Nottingham, christos.kora@nottingham.ac.uk
Academic Supervisors: Prof Andy Long, Dr Mikhail Matveev, Dr Louise Brown

Introduction

Three dimensional textile architectures offer exceptional through thickness properties and allow for near net shape preforming. The exploration of the design space resulting from the broad range of possible weaving configurations requires the development of an efficient and robust design tool that can effectively capture meso-scale variability. In this project, the capabilities of TexGen software are combined with the Abaqus Finite Element Analysis Software to examine the realistic meso-scale model generation methodologies that can be used in an optimisation loop considering time efficiency as a constraint.

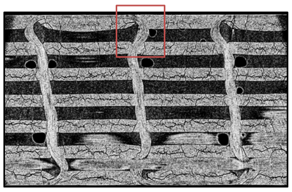


Figure 1. Binder yarn buckling and weft yarn cross-section variation in compacted orthogonal textile.

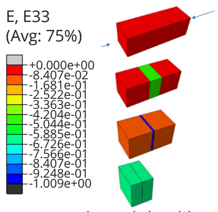


Figure 2. Material model calibration for hypo-elastic penalty contact simulation using a simple 3 element model.

Current Methodology

A method to avoid remeshing of complex compacted mesoscale geometry by employing a compliant matrix in a large displacement problem is examined. The method is compared to solid dry fibre contact simulation.

Constraints:

- Realistic Volume Fraction.
- Processing time.

Findings :

- Compliant hypo-elastic matrix method has better convergence behaviour compared to dry fibre for non-linear analysis.
- It could also produce usable mesh with small refinements and the periodicity can be easily maintained.
- It might increase simulation time in certain cases.It is unable to fully capture the buckling behaviour of binder yarns.
- It is prone to significant mesh distortions.

Aims & Objectives

Approach the problem of building a design tool framework :

- Develop a strategy for generating realistic unit cell models that includes manufacturing defects and geometry variability.
- Reduce pre-processing time by efficiently automating TexGen – Abaqus interaction.
- Explore different time efficient techniques for meshing of complex geometries.
- Benchmark for mechanical testing.

Test the framework in an optimisation case study.

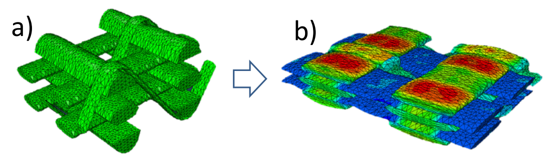


Figure 3. a) Nominal orthogonal weave mesh as generated from TexGen and b) the highly compacted yarn volumes as extracted from the hypo-elastic model.

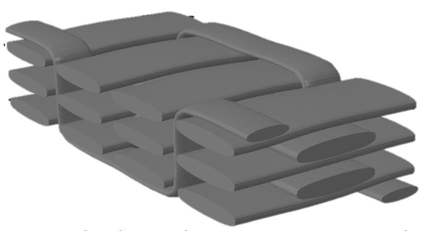


Figure 4. Nominal orthogonal weave geometry as produced from TexGen

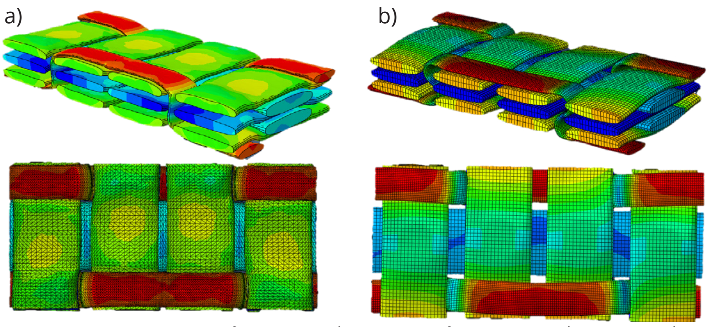


Figure 5 . Comparison of compacted geometry for a) Hypo-elastic Compliant Matrix model and b) Dry Fibre Contact Simulation.

Future Work

Approach the problem of building a design tool framework :

- Implement surface extraction from TexGen to test compaction simulation with hollow yarns by employing shell elements with the aim of reducing simulation time significantly.
- Examine methods to mesh generated geometries into a periodic unit cell.
- Collect μCT images to create a database for automatic geometry correlations and property adjustments for compaction models.
- Develop a methodology for accurately extracting fibre volume fraction distribution along yarn from compaction simulation.
- Perform comparative mechanical analysis between idealised and realistic geometry.

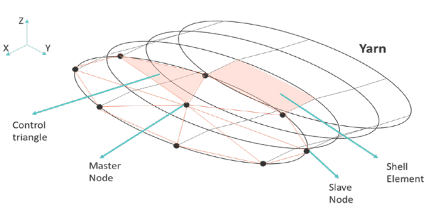


Figure 6. Schematic of hollow yarn – shell element methodology for dry fibre analysis.

Manufacturing for Structural Applications of Multifunctional Composites

"The development of composite materials has historically focussed on structural performance, but there has been a recent move to exploit polymer composites in multifunctional roles for combined structural and electrical energy storage functions."

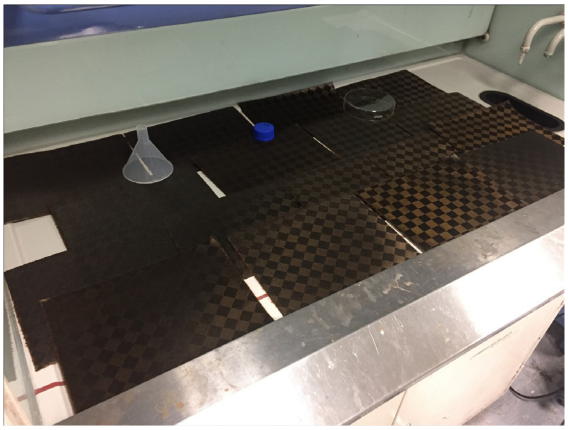
Aims and Objectives

The most promising approach for creating structural supercapacitors has been to embed structural carbon fibres in a monolithic carbon aerogel (CAG), which is a highly porous material consisting of a 3D network of interconnected nanosized particles. These materials have a typical surface area of 400–1100 m^2/g and are used in conventional supercapacitors. CAGs are not suitable for structural applications alone, but they can be combined with structural carbon fibres to act as a scaffold to support them. Such CAG modified fibres demonstrate a 500 fold improvement in surface area (160 m^2/g). Furthermore, the CAG offers huge improvements in critical mechanical properties, such as compression strength and delamination resistance (ILSS), as the CAG network extends into the polymer electrolyte/matrix, providing stiffening support.

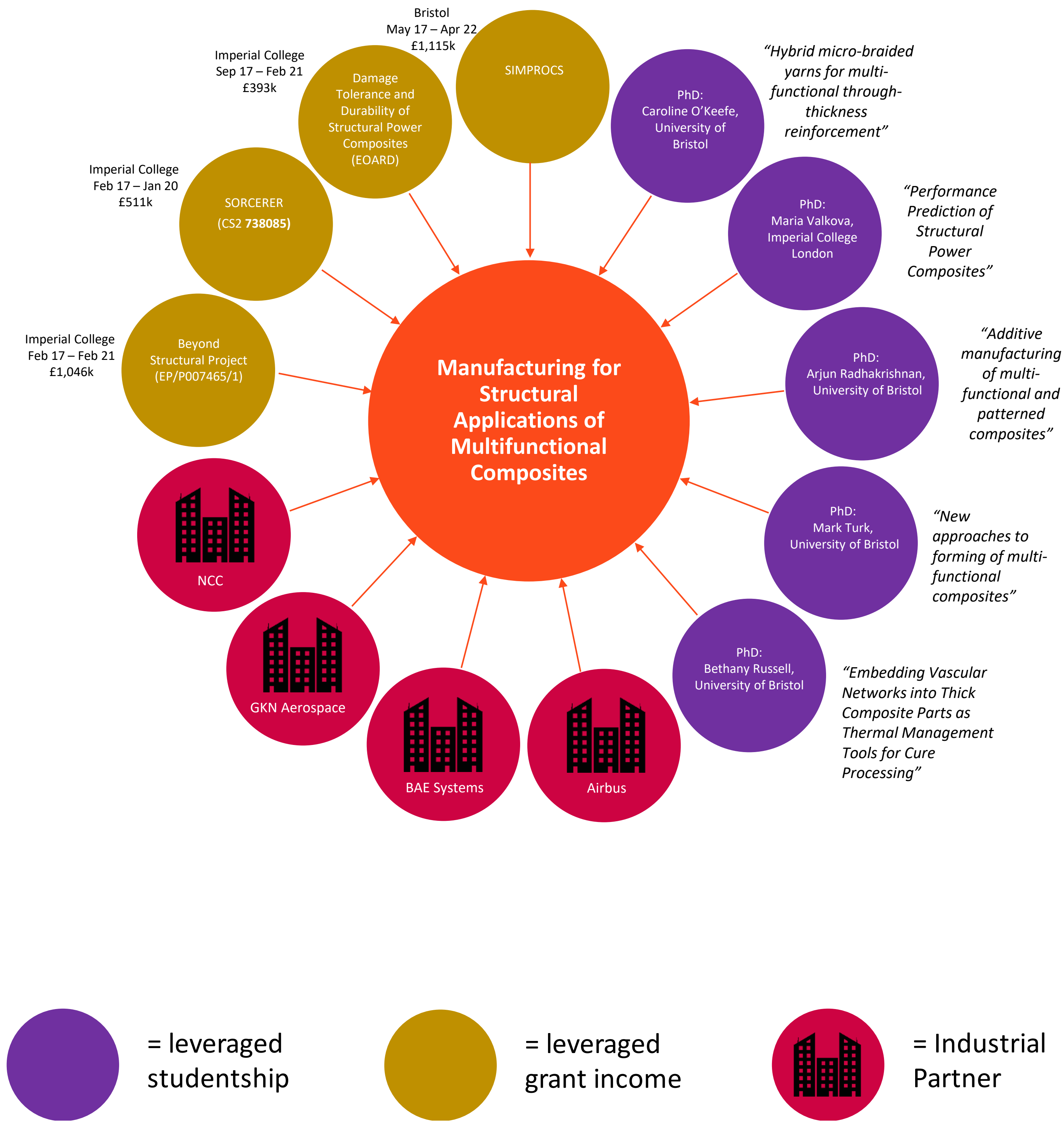
The over-arching aim of the project is to investigate and address the design and manufacturing issues associated with multifunctional composites. This will specifically address the formability of CAG based multifunctional composites, the seamless integration of functional elements and multi-material domains in a composite system, and the heating and curing of composite precursors with added functions.

Aim 1: To explore the design and manufacturing issues associated with the fabrication of structural supercapacitors, which simultaneously store, and deliver, electrical energy whilst carrying mechanical loads. Such multifunctional materials offer a completely different approach to using composites in transport and mobile electronics, and have the potential to provide a step change in weight and volume driven designs.

Aim 2: To explore novel manufacturing methods for creating multi-matrix and multi-fibre graded composites and local integration of functionalised patches. The locality within the matrix is achieved through liquid resin printing, enabling integration of additive-rich resins in predefined patterns throughout the laminates. The specific focus of the matrix study is on the relation between processing parameters (injection, consolidation, curing), chemorheology of injected resins, and the morphology of printed patches. The specific focus of the fibre modification is the insertion of novel multi-material threads and fibres into dry fibre preforms, both in-plane and out-of-plane of the structure.



Batch of CAGed lamina produced demonstrating scale-up of the process.


Manufacturing for Structural Applications of Multifunctional Composites
Bristol
May 17 – Apr 22
£1,115k
SIMPROCS
Imperial College
Sep 17 – Feb 21
£393k
Damage Tolerance and Durability of Structural Power Composites (EOARD)
Imperial College
Feb 17 – Jan 20
£511k
SORCERER
(CS2 738085)
Imperial College
Feb 17 – Feb 21
£1,046k
Beyond Structural Project (EP/P007465/1)
PhD:
Caroline O'Keefe, University of Bristol
"Hybrid micro-braided yarns for multi-functional through-thickness reinforcement"
PhD:
Maria Valkova, Imperial College London
"Performance Prediction of Structural Power Composites"
PhD:
Arjun Radhakrishnan, University of Bristol
"Additive manufacturing of multi-functional and patterned composites"
PhD:
Mark Turk, University of Bristol
"New approaches to forming of multi-functional composites"
PhD:
Bethany Russell, University of Bristol
"Embedding Vascular Networks into Thick Composite Parts as Thermal Management Tools for Cure Processing"
NCC
GKN Aerospace
BAE Systems
Airbus
= leveraged studentship
= leveraged grant income
= Industrial Partner

Manufacturing for Structural Applications of Multifunctional Composites

David B. Anthony, Imperial College London, d.anthony08@imperial.ac.uk
Academic Supervisors: Prof Milo S.P. Shaffer, Prof Emile S. Greenhalgh,
Co-authors: Dr Dmitry Ivanov, Mark Turk, Dr Sang N. Nguyen

Formable Structures for Carbon Aerogel Infused Carbon Fibre Samples

Summary

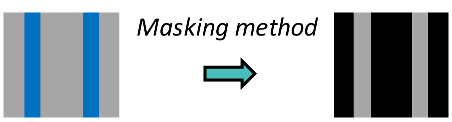
The ability to combine composites with energy storage functions/capabilities which simultaneously provide structural integrity has the potential to supersede monofunctional components.

To achieve this ambition, the multifunctional structure must perform both mechanical and energy storage functions sufficiently; carbon aerogels have been shown to contribute positively to both (electro-chemical double layer) capacitive performance and mechanical matrix performance in multifunctional carbon fibre based composite electrodes.[1, 2]

The synthesis of carbon aerogel around carbon fibres results in a rigid multifunctional composite-electrode product. A modified methodology was proposed to address this issue, to create fold lines of unmodified carbon fibre regions (monofunctional) within the panel. To produce these fold lines two methods were chosen: a masking or a barrier method using either polylactic acid (PLA), or an adhesive (epoxy) bonded to a film, respectively.

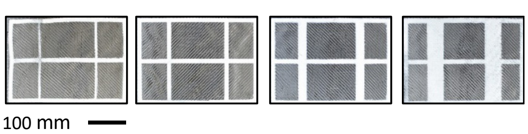
Aim: To demonstrate multifunctional components can be formed.
Objective: Make a C-section demonstrator through the use of fold lines:

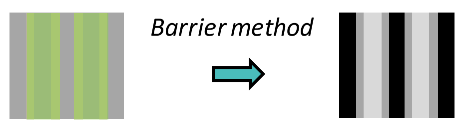
Incorporating fold lines into CAG-CF production



Masked region (blue) on CF (grey), using polylactic acid (PLA)

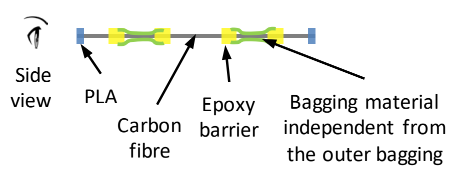
Pyrolyzed CAG-CF (black) with mask pyrolyzed to leave CF regions (grey)

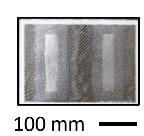




Barrier adhered to tooling bag (green) on CF (grey)

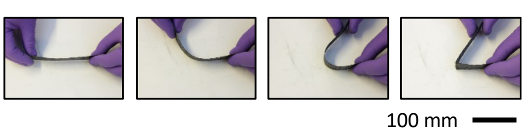
Pyrolyzed CAG-CF (black) with adhesive pyrolyzed to leave CF regions (grey) [light grey region no coating but thermally desized]



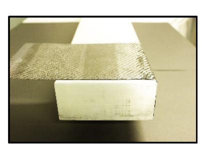


Initial folding experiments

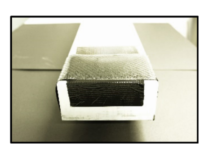
Testing the ultimate achievable fold using the masking method



Barrier method



Masking method



100 mm

[1] H. Qian, A.R. Kucernak, E.S. Greenhalgh, A. Bismarck and M.S.P. Shaffer. ACS Applied Materials & Interfaces, 5(13), 2013, pp. 6113-6122. https://doi.org/10.1021/am400947j
[2] M.S.P. Shaffer, E.S. Greenhalgh, A. Bismarck, Patent WO/2007/125282, Energy Storage Device, 2007.

Manufacturing Composites with Dual Structural and Energy Storage Functions

Mark Turk, University of Bristol, mark.turk@bristol.ac.uk
Academic Supervisors: Dr Dmitry Ivanov, Prof Ivana Partridge
Co-author: Prof Emile Greenhalgh

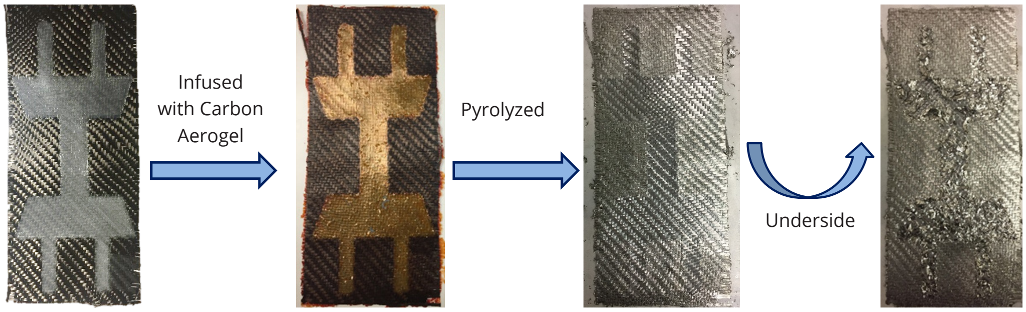
Aims / Objectives

The idea of storing electricity in structural composites is becoming increasingly popular. The weight of batteries or supercapacitors can be substantially reduced if their functions are passed to load carrying structures. The use of porous aerogels, pursued in Imperial College London, allows for the incorporation of storage functions in the composite laminates to create structural supercapacitors.

Aerogels are stiff and brittle which presents a challenge for manufacturing of complex components. This project tackles the problem of supercapacitor composites formability. Incorporation of internal impermeable barriers and stabilising elements enhance formability and aim at creating a hybrid multi-matrix structure where high shear regions remain purely structural while energy storage functions are applied in appropriate areas.

PLA Masking and Carbon Aerogel Infusion

Purely structural regions are protected by a PLA mask before infusion of Carbon Aerogel.

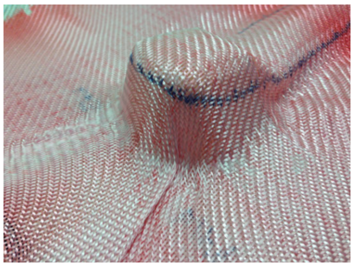


In this state the sample is ready to be formed but is also brittle highly susceptible to damage.

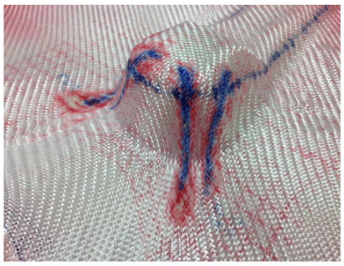
Carbon Fibre masked with PLA | After infusion | Top view | Bottom view

Formability Manufacturing Trials

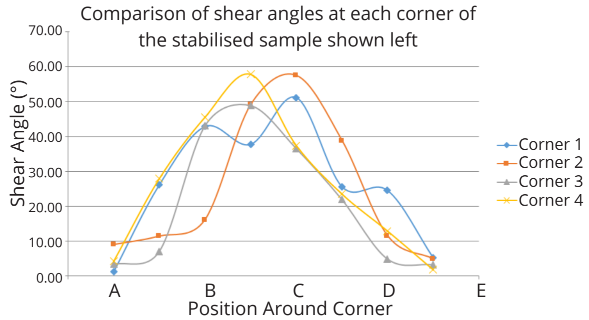
Resin patches are placed on dry fabric to enhance the formability of high shear zones and prevent wrinkling. These are intended to stabilize the fabric in critical zones whilst avoiding excessive bending resistance.



Dry woven glass fabric formed in a mould

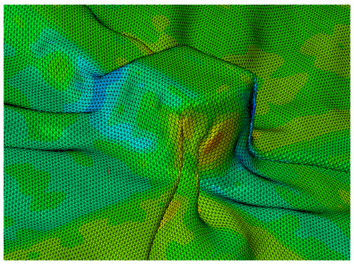


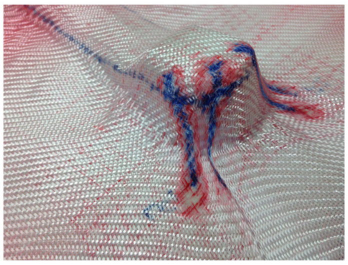
Glass fabric with stabilising resin patches



Mould Closure Simulations

A mould closure simulation model is validated against manufacturing trials to ensure accurate predictions for ideal patch placement locations. This model can then be used to inform and optimise the manufacturing process.





Multi-Matrix Formability Demonstrators

Two demonstrators have been made with a multi matrix system of epoxy and PLA maintaining continuous fibres throughout.

Hybrid Multimaterial Microbraids for Through-thickness Multifunctionality

Caroline O'Keeffe, University of Bristol, c.okeeffe@bristol.ac.uk
Academic Supervisors: Prof Ivana Partridge, Dr Giuliano Allegri

Motivation and Background

Fibre-reinforced composite materials are susceptible to delamination, particularly as a result of impact events. This difficult to detect interlaminar damage could potentially lead to catastrophic structural failures. This research introduces multifunctionality into a composite in the form of electrical conductivity to increase composite properties beyond purely structural strength. It provides the capability for real-time damage assessment via a structural health monitoring (SHM) system. The potential for self-sensing crack propagation and fault detection would enable the design of self-sensing structures without compromising space, weight or performance which is critical in the automotive and aerospace industries.

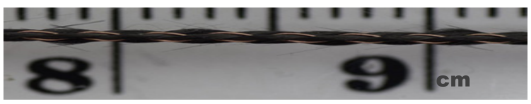


Figure 1. Copper/carbon fibre braid

Aims and Objectives

- Production of hybrid micro-braid. The tufting braid, shown in Figure. 1, is composed of copper wire and carbon fibre yarns. The combination of copper and carbon yarn enabled the exploitation of the excellent mechanical properties of carbon fibre, together with the electrical conductivity of copper.
- Introduction of through-thickness multifunctionality in composite materials by tufting (Figure 2) of a dry quasi-1D fabric.
- Measurement of electrical resistance change due to crack propagation.

Tufting Schematic

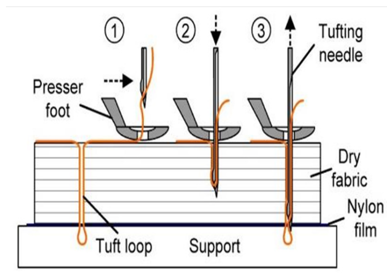


Figure 2. Tufting schematic

Figure 3. A Herzog 1/16 80 operates in a maypole fashion with each carrier following a specific path.

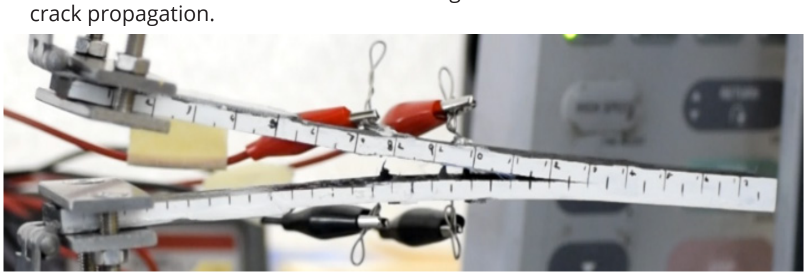


Figure 4. Experimental and coupon arrangement

Materials and Methods

- Herzog micro braider (Figure 3) - Diamond pattern braid of single overlap 1:1 pattern.
- Braid Materials: Carbon 1k tow and copper wire (Figure 1).
- DCB coupons: 400 gsm non-crimped fabric with [0/90]24 layup. 20 mm x 180 mm coupons tufted with 7 rows of two tufts (Figure 4).
- Shimadzu Universal Testing Machine.
- Keithley 2100 digital multimeter 4-wire method

Key Findings

- Systematic changes in electrical resistivity due to crack propagation through rows of tufts evident. Distinct step increases in resistance due to crack propagation between the tuft rows as shown in Figure 5.
- Three distinct steps in crack propagation observed in tufted coupons;
  - A gradual crack length increase in non-tufted areas
  - Crack progression restrained until after tuft failure
  - Tuft failure; rapid propagation of up to 20 mm.
- Untufted coupon; gradual crack propagation without restraint. Gradual increase in electrical resistance observed.

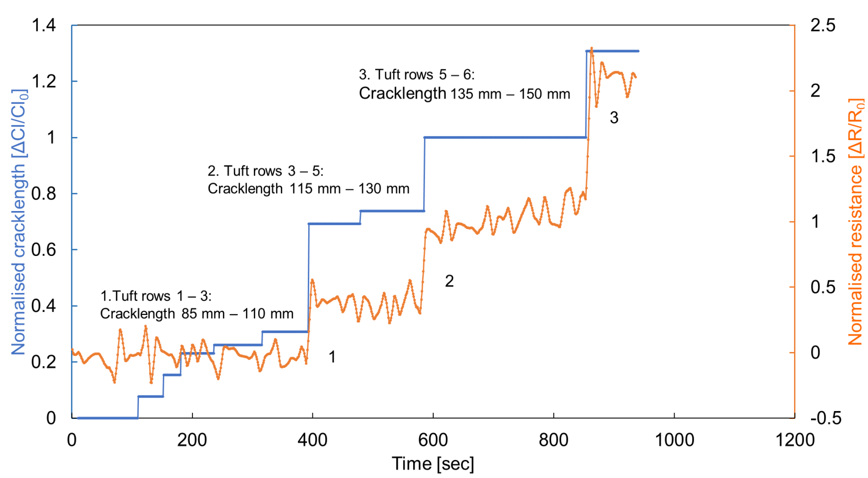
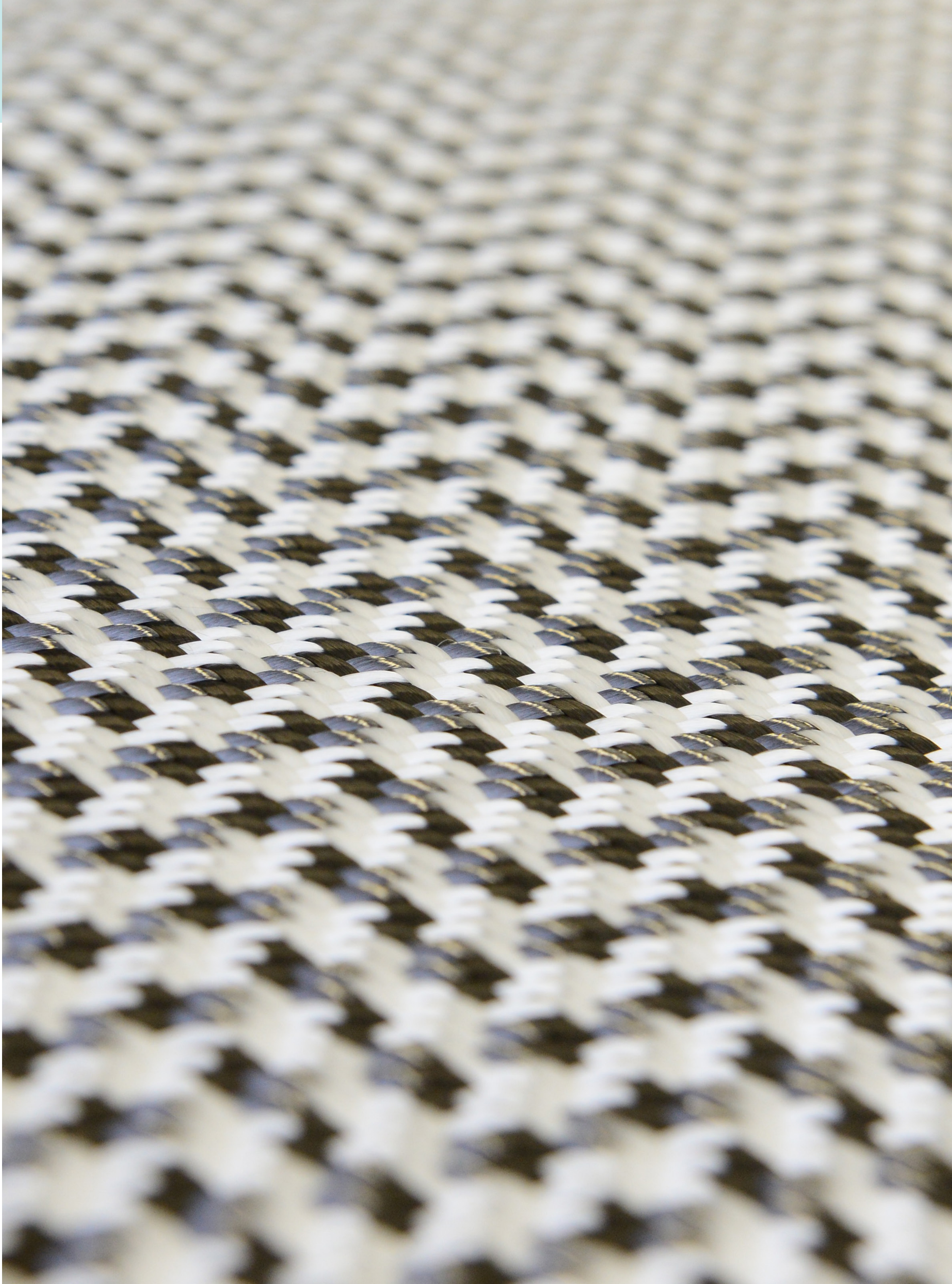


Figure 5. Tufted coupon: Crack propagation vs. electrical resistance

1. Treiber, J. W. G. (2011) 'Performance of tufted carbon fibre/epoxy composites', p. 268. Available at: http://dspace.lib.cranfield.ac.uk/handle/1826/5531.



Technologies Framework for Automated Dry Fibre Placement (ADFP)

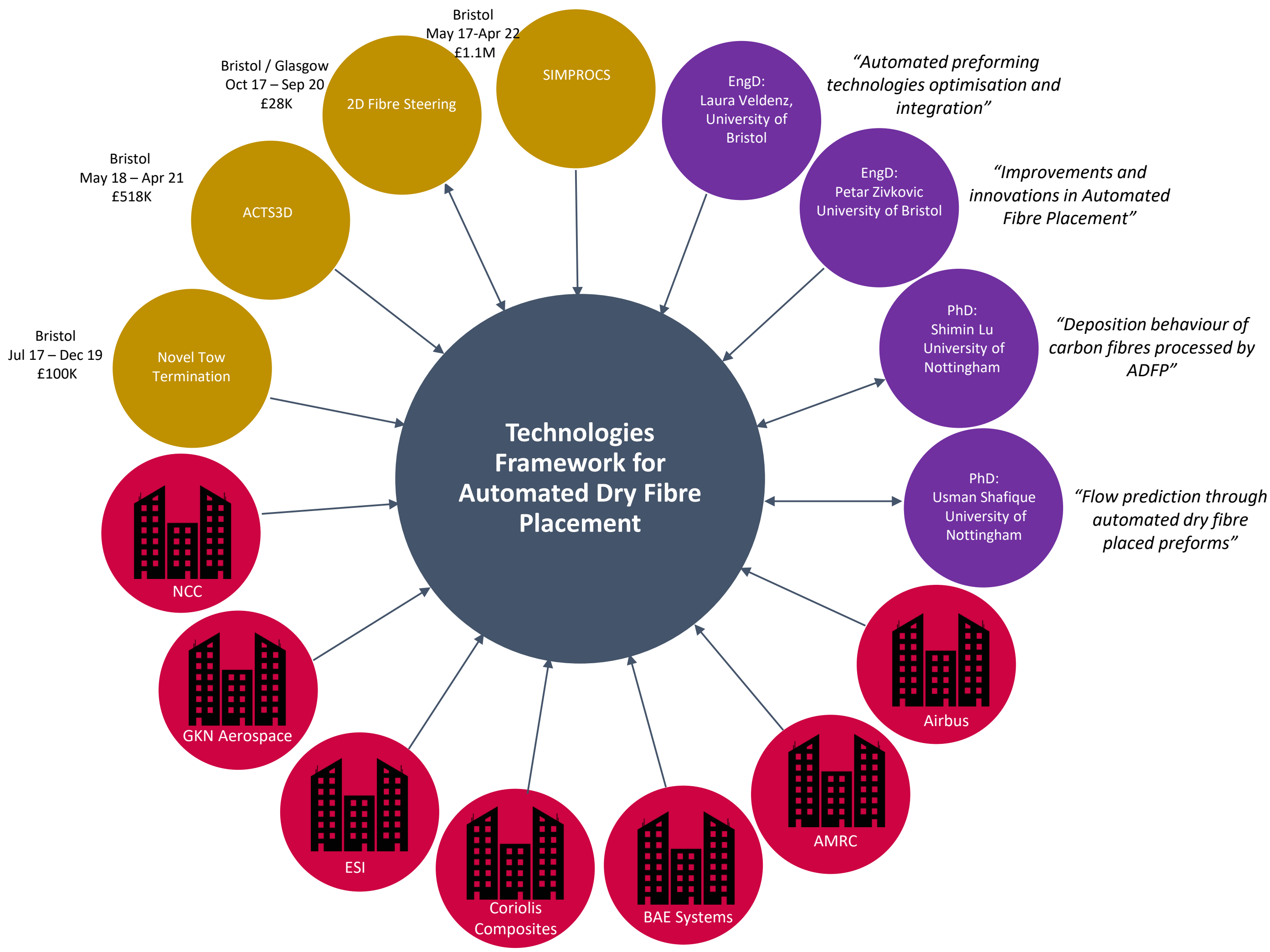
"Automated Dry Fibre Placement (ADFP) is a relatively new technology where dry fibre tows are robotically placed onto a tool and retained by a polymer binder to form complex, integrated components. Many manufacturing challenges exist, primarily around the fundamental understanding of the materials, effects of processing parameters and the influence of tailored preforms on the resin infusion stage."

Aims and Objectives

The overall aim is to understand the rate and quality limiting effects in the ADFP process, by developing numerical models to increase understanding of the critical factors. The project has the following objectives:

1. Developing laboratory scale equipment to determine hardware limitations and 'course-by-course' control of the deposition apparatus.
2. Develop real-time data acquisition methods to accompany the construction of the laboratory equipment and to support the development of the numerical models.
3. Investigate the fundamental structure of the tow/NCF, in order to optimise the binder content (type and volume) to provide optimum tack and to prevent fibre fuzzing during deposition.
4. Characterise the binder tack properties with respect to fibre laydown rate and temperature, studying the compaction of single tows or ply stacks and their interactions with the deposition roller.
5. Quantify the permeability of the ADFP fibre architecture post deposition and relate it to geometric features and processing rate.


Developments of the automated dry fibre placement test rig (left) and ongoing assembly of the deposition head (right)



= leveraged studentship

= leveraged grant income

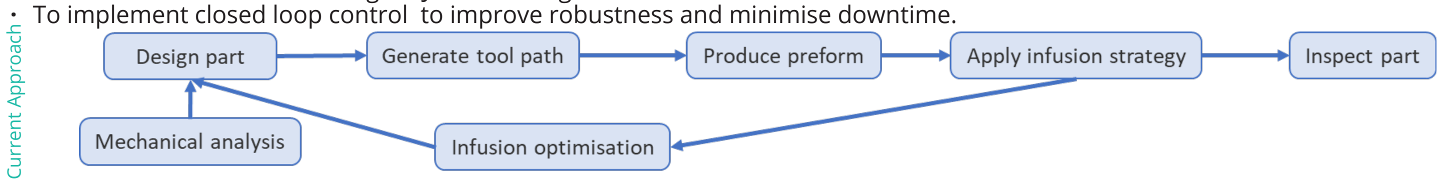
= Industrial Partner

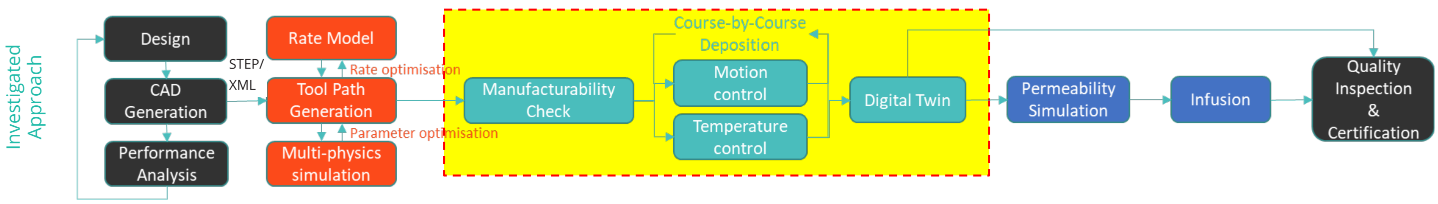
Technologies Framework For Automated Dry Fibre Placement

Dr Anthony Evans, University of Nottingham, anthony.evans@nottingham.ac.uk
Academic Supervisor: Dr Thomas Turner

Aims/Objectives

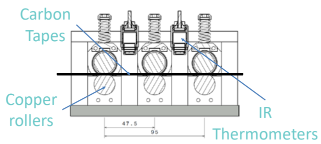
- Review existing rate limiting challenges faced with Automated Fibre Placement processes
- To develop an High Rate, Low Cost Automated Dry Fibre Placement machine for research applications:
  - Capable of 3m/s deposition and high rate data acquisition
- To utilise low cost fibre heating via Joule Heating
- To implement closed loop control to improve robustness and minimise downtime.



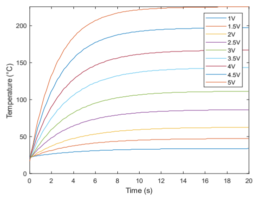


Methodology – Joule Heating Experiment

- 3 electrodes enabled two heating lengths to be investigated
- Adjustable compaction force
- 2x IR thermometers
- User interface created to transfer sensor data to server
  - Via PLC
  - with timestamp
- ¼" wide bindered tape
- Tested statically at 0.5V increments (until steady state temperature exceeds 250°C)

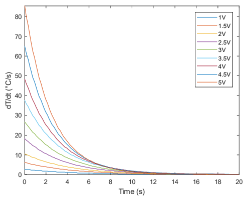


Progress to date – Joule Heating Experiment



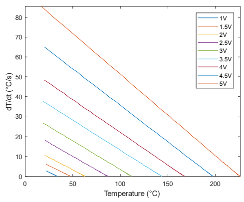
Temp vs. tme: $T = ae^{bt} + ce^{dt}$

Second order exponential fit applied to 3 repeats
R2 value >0.99



Heating Rate: $\frac{dT}{dt} = abe^{bt} + cde^{dt}$

Heating rate obtained by differentiating equation

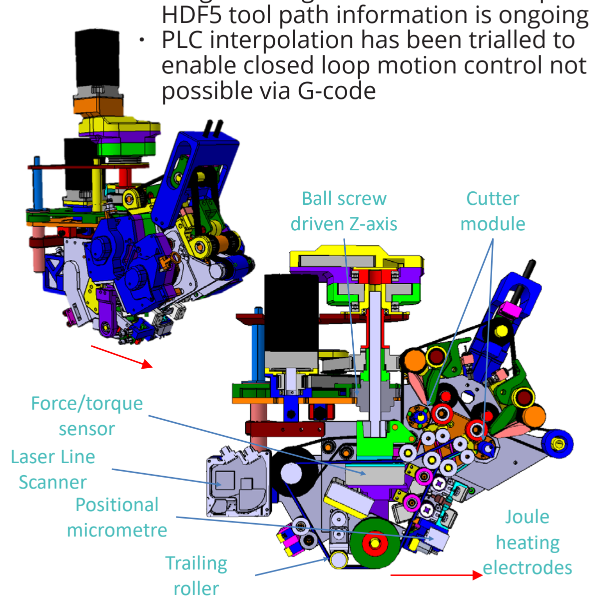


Heating Rate vs. Temperature

Heat rate for given temperature is then determined for heating control

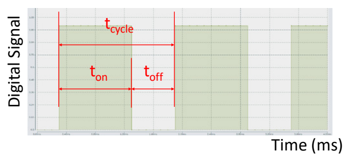
Progress to date - Rig Development

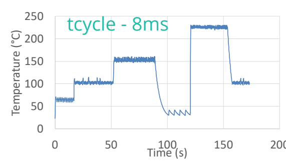
- High Rate, Low Cost ADFP machine currently being manufactured/ assembled
- EtherCAT technology enables <0.1ms cycle times for PLC and Numerical control
- Programming the creation and import HDF5 tool path information is ongoing
- PLC interpolation has been trialled to enable closed loop motion control not possible via G-code



Key Findings

- Real time monitoring and task optimisation prevents latency
- Joule heating method may be controlled using IR thermometers
  - Heating rate is inversely proportional to electrical resistance
  - Heating rates >1000°C/s have been achieved
- Sensor data used to make "course-by-course" adjustments
- HDF5 file format for tool path information and data output





A Novel Approach to Calculate Flow Rates in a Complex Gap Networks Within ADFP Preforms Using Linear Graph Theory

Usman Shafique, University of Nottingham, usman.shafique@nottingham.ac.uk
Academic Supervisors: Dr Thomas Turner, Dr Anthony Evans

Why Implement Linear Graph Theory in ADFP preforms?

ADFP produced preforms exhibit lower permeability in comparison with conventional fabric (by 1-2 orders of magnitude). Gap strategy can be adapted to enhance its global permeability. Flow is dominant in gap regions and highly affects the process parameters (flow pattern/position, fill time etc.). Linear Graph Theory disregards the flow in fabrics, considers flow only in gap regions and computes the flow distribution and pressure loss across the network. It can process complex gap network containing n number of pipes. Initially, Linear Graph Theory can be implemented by considering a unit cell of a single layer containing 9 gaps as shown in figure 1 & 2.

What is Linear Graph Theory?

1. A constitutive relation (a non linear equation in which flow resistance relates pipe pressure drop to discharge)
2. The formulation of system equations (Nodal and loop equations)
3. A solution algorithm (Iterative solutions)

Constitutive relation

For uni-directional flow, Darcy's law can be applied to axial flow in a single duct(gap), the equivalent duct permeability can be determined by,

$$K = \frac{v\eta L}{\Delta P} \qquad (1)$$

Where,
V = Velocity of fluid (m/s) = Q/A
η = Viscosity of fluid (Pa.s)
L = Length of gap (m)

Pressure loss along a hydraulic duct (Darcy-Weisbach equation) can be used and the equivalent permeability can be given by,

$$K = \frac{2{D_h}^2}{c} \qquad (2)$$

Where D_h is hydraulic diameter of the gap ,C is friction factor

$D = \frac{4A}{P}$,A = Cross sectional area of gap & P = perimeter of gap

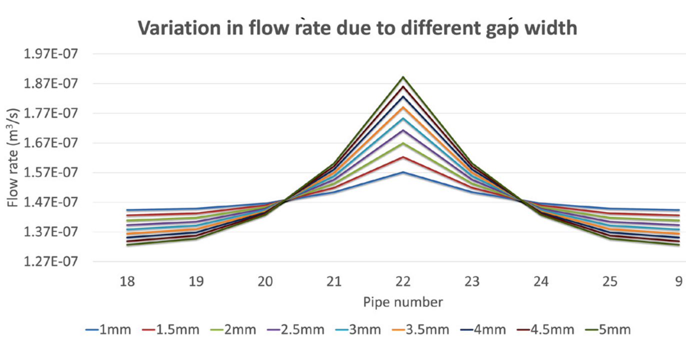
From equation 1 & 2, pressure loss across the duct can be expressed as:

$$\Delta P = \left(\frac{\eta L c}{2{D_h}^2 A}\right).Q$$

Friction factor (c) can be approximated based on the data tabulated by (White 1994)

$$C = 56.4\rho^{0.17}$$

Where ρ is aspect ratio, $\rho = \begin{Bmatrix} \frac{h}{s-2R} \; if\ (s-2R) \le h \\ \frac{s-2R}{h} \; if\ (s-2R) > h \end{Bmatrix}$



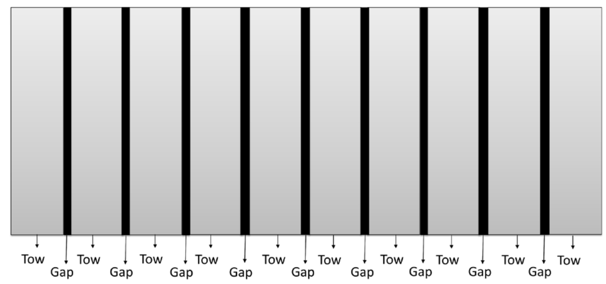


Figure1. Unit cell of ADFP preform containing 10 tows & 9 gaps

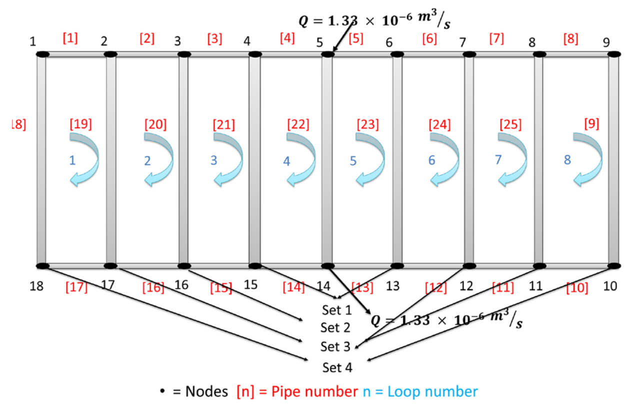


Figure2. Closed gap network withing the layer and its constituent

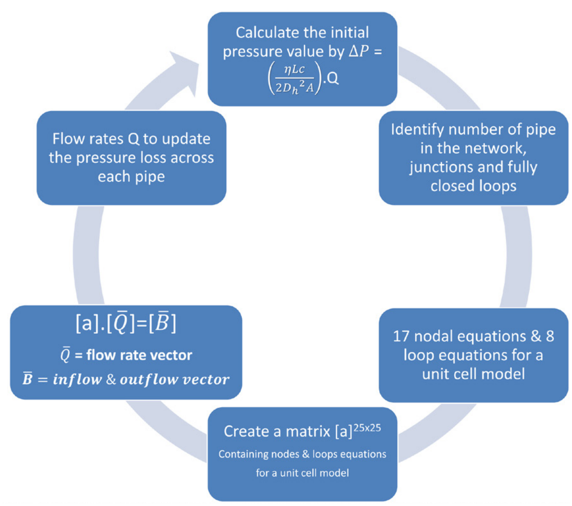


Figure3. Flow chart of the iterative process to calculate flow rates in a complex gap networking using Linear Graph Theory

Conclusion

Linear Graph Theory can predict the flow distribution and pressure loss across the gap network faster (seconds) as compared to standard simulation models (2D – minutes, 3D – hours). The same model for each part produced can be easily modified based on real deposition data. (actual tow positioning)

Next steps

Development of a model containing gaps in multiple layers.

Deposition Behaviours of Carbon Fibres Processed by Automated Dry Fibre Placement (ADFP)

Shimin Lu, University of Nottingham, shimin.lu@nottingham.ac.uk
Academic Supervisors: Dr Thomas Turner, Dr Anthony Evans

Introduction

Automated fibre placement uses a deposition head mounted on a robot arm or a gantry system to place prepreg tapes on a flat or slightly curved tool with the assistance of the roller compaction and the heating, while automated dry fibre placemet (ADFP) places bindered dry fibre tapes instead of prepregs, which could be combined with low cost out-of-autoclave processes. Figure 1 shows the entire process of automated dry fibre placement (ADFP) and some research areas of the hub core project Technologies Framework for Automated Dry Fibre Placement (ADFP). The core project aims at improving the quality of preforms made from ADFP with a high deposition rate, while as a part of the core project, this work focuses on investigating the deposition behaviours of carbon fibres processed by ADFP and building simulation tools to optimise process parameters and assist real time course-by-course deposition control, which could contribute to the high quality high rate deposition. In the ADFP deposition process, the roller compaction and the heating have great impact on the quality of the preforms made from ADFP. Thus, models for the roller compaction and the heating transfer have been built and the details are shown in next two sections.

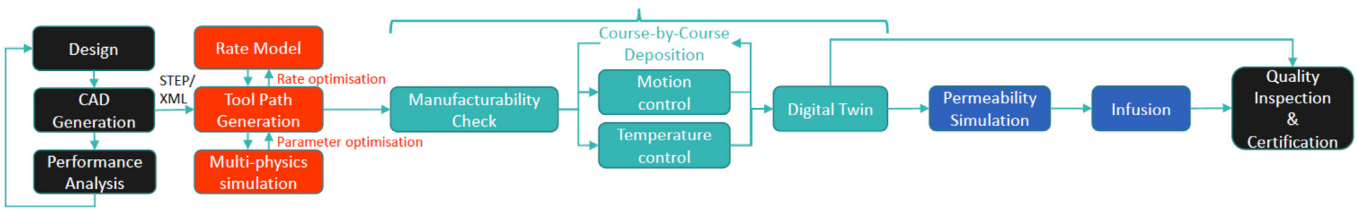


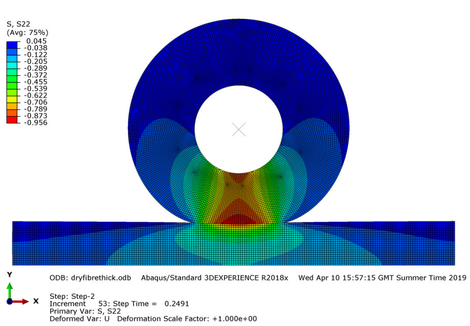
Figure 1. Flow Chart for Automated Dry Fibre Placement (ADFP) Process

Roller Compaction

During the ADFP deposition process, a soft roller is used to place the dry fibre tapes to the right positions and compact them to obtain the desired fibre volume fraction. The deposited dry fibre tapes are compacted several times during the whole deposition process. Cyclic compaction test was conducted on slit bindered dry fibre tapes and dry fibre tows. The compaction responses of them are different and the slit bindered dry fibre tapes showed a more stable response. The compaction responses from the experiments were then applied in a roller compaction model, as shown in Figure 2. This model could be used to compare pressure distribution underneath the roller contact area between different types of dry fibre tapes and different thickness of fibre bed and also to optimise roller designs.

Heat Transfer

During the ADFP deposition process, the bindered dry fibre tapes are heated and the binders are melted or activated to bond current tapes to the tool surface or the substrate tapes. The properties of binders are sensitive to the thermal history during the deposition process. To obtain the thermal history of the tapes, a element activation heat transfer model was built, as shown in Figure 3. Pieces of deposited tapes with nip-point temperature are activated step by step to simulate the continuous heat transfer during the whole deposition process. The temperature history of dry fibre tapes and the tool could be generated from the model, as shown in Figure 4. Further research on the thermal conductivity of dry fibre tapes should be conducted because it could vary with the change of the pressure and the temperature.



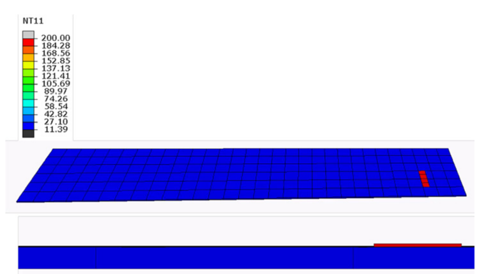


Figure 3. Element Activation Heat Transfer Model

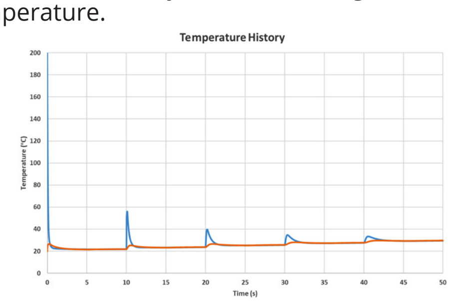


Figure 4. Thermal History Results from the Heat Transfer Model

Future Work

- Apply the roller compaction model and the heat transfer model in more complex situations such as various pressure, curved tools and corners
- Investigate the effect of process parameters on the quality of preforms made from ADFP by experimental work such as peel tests and bending tests
- Build a priori multi-physics model based on the two current models and then use the model to optimise process parameters
- Build a simplified real-time model based on the *a priori* multi-physics model to achieve course by course online control with the help of sensor data
- Build a manufacturing database using HDF5 format to assist online control and optimise the process parameters by data mining

Active Control of the RTM Process under Uncertainty using Fast Algorithms

"Variations in material or process parameters give rise to uncertainties during mould filling for processes such as Resin Transfer Moulding (RTM), including dry spots or variable fill times. The quality of the moulding directly influences the mechanical performance of the component and therefore this uncertainty prevents wider uptake for high value structural applications."

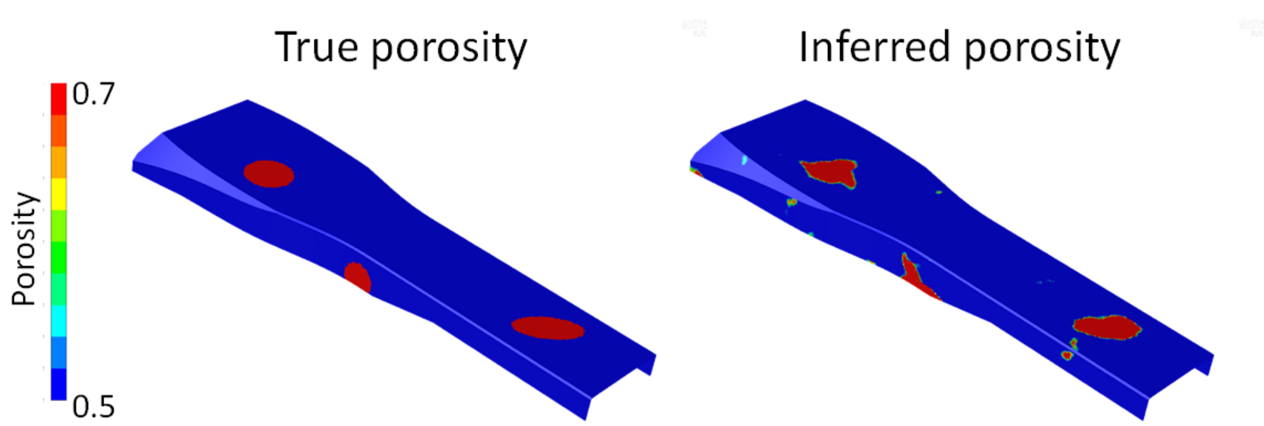
Aims and Objectives

The aim for this Core Project is to use in-process information from sensors during resin injection to develop an Active Control System (ACS) to counteract stochastic variations. Utilisation of in-process data will make it possible to move from a conventional process model to a "digital twin" for the Resin Transfer Moulding (RTM) process, to capture and estimate local deviations from the design for any manufactured part. This significant advancement will deliver a major step-change in composite manufacturing by reducing the cost and increasing the robustness of the manufacturing process, thus improving confidence in the parts quality.

The main objectives for this project are as follows:

- To develop, improve and test Bayesian Inverse Algorithms (BIAs) for online estimation of local permeability and porosity, using data from an in-process monitoring system during resin injection
- To develop and test an ACS for the infusion of complex geometry preforms, based on information from sensors, physical models and the BIA to minimise defects and ensure robustness.

These objectives will deliver a deeper fundamental understanding of the manufacturing science, which is crucial for developing further fundamental step-changing technologies. Uncertainty Quantification (UQ) capabilities provided by BIA and ACS are of great importance for evidence-based decision making under uncertainty and risk management. This project will focus on RTM processing, but the methodology can be transferred to other areas of composite manufacturing, including prepreg consolidation and cure. There is therefore an opportunity to share this expertise with the other Core Projects, such as the resin infusion process under investigation for "Technologies Framework for Automated Dry Fibre Placement" and the development of novel 3D textiles in "New Manufacturing Techniques for Optimised Fibre Architectures".




Nottingham
May 19 – Nov 22
£8K
Nottingham Impact Accelerator: Exploring industrial cases for active control RTM
PhD: Experimental implementation of defect detection system for RTM (funded by UoN / Eng)
PhD: Uncertainty quantification for random moving boundary problems (funded by UoN SoMS)
PhD: Modelling of RTM with defects (funded by UoN / Eng)
Active Control of the RTM Process under Uncertainty using Fast Algorithms
AMRC
NCC
LMAT
GKN Aerospace
ESI


= leveraged studentship
= leveraged grant income
= Industrial Partner

Resin Injection into Reinforcements with Uncertain Heterogeneous Properties

Dr Mikhail Matveev, University of Nottingham, mikhail.matveev@nottingham.ac.uk
Co-authors: Dr Andreas Endruweit, Dr Marco Iglesias, Prof Andy Long, Prof Michael Tretyakov

Introduction

Liquid composites moulding (LCM), in particular resin transfer moulding (RTM) process, is often used in manufacturing of high-performance composite parts, for example, in aerospace industry. While LCM technologies offer some advantages, such as use of complex dry 3D reinforcements, they are more difficult to design and control. In particular, mould filling in RTM needs to be designed to ensure full wetting of preforms. This problem has well-established solutions for ideal cases but, in reality, in-mould defects such as race-tracking, fibre misalignments or other preform defects change the mould filling behaviour significantly. Detection of such defects using in-mould sensors and subsequent active control of the mould filling process can improve robustness of the process.

Objectives

The project will consider the RTM process in detail and will achieve the following objectives:

- Develop a computational framework for detecting local defects such as race tracking and changes in local permeability/porosity
- Optimise number and position of sensors required for defect detection
- Implement and validate an online active control system (ACS) for RTM
- Prove that ACS can be used to minimise variability of mould filling process and reduce formation of defects (dry spots) in the presence of race tracking and material variability

Detection of defects

In-mould sensors collect a large amount of information during a process. Often, the sensors are used to make simple decisions e.g. about the end of the process (whether a mould filling or curing is complete or not). Using all in-process information from the sensors make it possible to detect defects in this process. A numerical framework based on Bayesian inversion concept, REnKA (Regularised Ensemble Kalman Algorithm) [1], was utilised to infer information about defects from the sensors data.

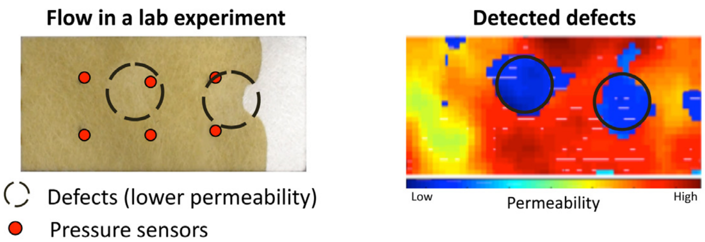


Figure 1. Defect detection in a lab experiment

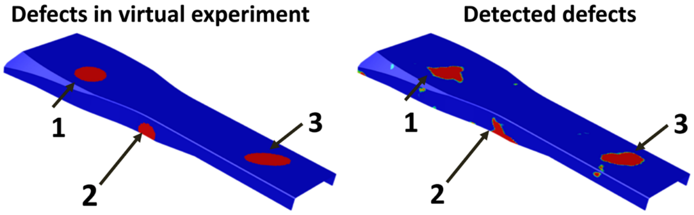


Figure 2. Defect detection in more complex problems

The framework was tested in the lab using a simple mould equipped with pressure and flow front sensors. Data collected during a mould filling with defects (extra-material inserts) were used as input for REnKA (Fig. 1). The detected defects were in very good agreement with the experiment. Further testing of the defect detection algorithm involved simulations of more complex geometry (adapted transmission tunnel). In this virtual experiment (Fig. 2), the algorithm detected all the defects [2].

Active control of RTM

An active control system for RTM was implemented using a flat mould tool equipped with pressure and flow front sensors and three pressure-controlled inlets. The control system employed less precise but fast 1D implementation of defect detection algorithm (REnKA). Initial virtual experiments were used to tune the system parameters. The lab setup was controlled online using a LabView program. It was shown that the ACS can control mould filling time and shape of the flow front thus avoiding potential defects.

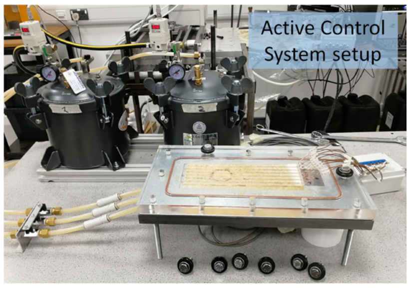


Figure 3. Active control system for RTM

Key findings

During the Feasibility Study, it was found that:

- Bayesian inversion framework (REnKA) was employed and validated for defect detection in RTM
- Lab experiments confirmed that defect detection is possible with low number of pressure and flow front sensors
- ACS for RTM showed potential for control in case of complex defects

Future work

The next three years of this Core project will focus on further improvements of defect detection and ACS for RTM. In particular, for defect detection:

- Optimisation of number and position of sensors
- Faster defect detection
- For active control system:
- Control in cases of severe defects

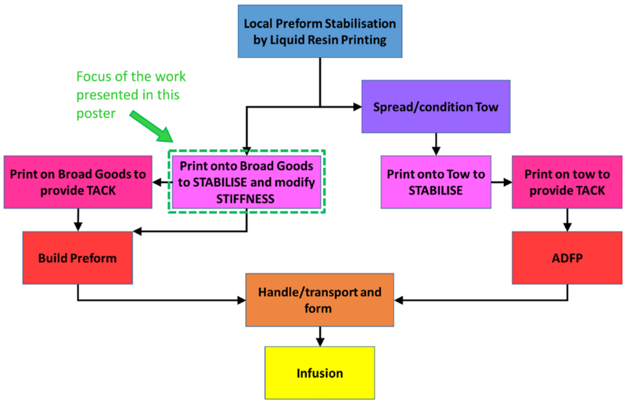
[1] M. Iglesias, M. Park, M.V. Tretyakov. Bayesian inversion in resin transfer molding. Inverse Problems, Inverse Problems, 34(10), 105002, 2018
[2] M.Y. Matveev, A. Endruweit, A.C. Long, M.A. Iglesias, M.V. Tretyakov. Bayesian inversion algorithm for estimating local variations in permeability and porosity of reinforcements using experimental data, in preparation

Local Preform Stabilisation by Liquid Resin Printing

Dr Adam Joesbury, University of Nottingham, adam.joesbury@nottingham.ac.uk
Academic Supervisors: Prof Nick Warrior, Dr Lee Harper

Can inkjet printing be used to modify the mechanical characteristics of dry fibre textiles?

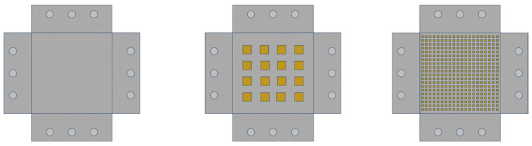
Aims / Objectives



Develop tailorable fibre stabilisation methods, which can be applied online with fibre placement systems:

1. Understand the process of printing binder material onto fibre.
2. Investigate how printed binder can be selectively activated post printing process.
3. Develop the capability to use only the necessary amount of binder and only where it is needed.
4. Understand how selective binder printing effects subsequent manufacturing process, and ultimately, the composite material properties

Methodology

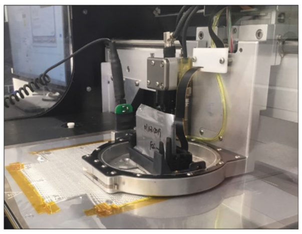


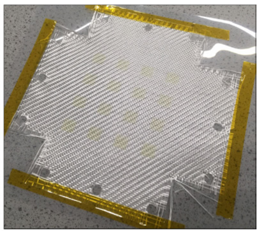
Use of inkjet printing technologies to deposit liquid polymers onto dry fibre.

- Acrylate UV-curing liquid printed polymer (TPDGDA)
- Woven glass 2/2 twill 280 GSM

Evaluate the effect on textile stiffness by characterisation of in-plain shear using trellis frame testing method [J. Cao et al. / Composites: Part A 39 (2008) 1037-1053]

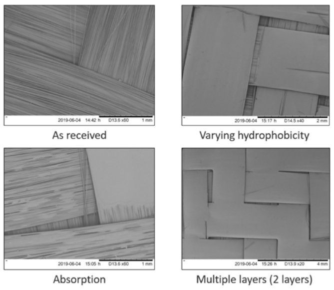
Baseline against epoxy powder binder (EPIKOTE 05390), match areal weights, vary printed patterns.





Patterns printed using research grade inkjet printers (FujiFilm Dimatix DMP2831)

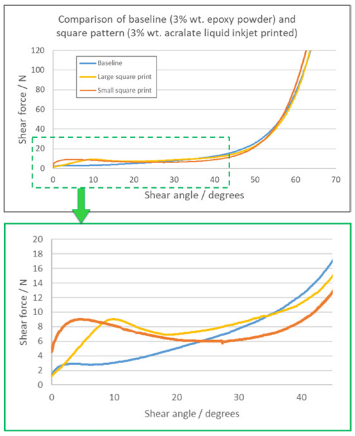
Progress to date



Scanning Electron Microscopy has been used to observe interactions between inkjet printer deposited liquid polymer and dry fibre substrates.

The results indicate that polymers can be selected that tend to wet-out fibre by varying amounts. This could lead to tailoring whether printed polymers acts to primarily stabilise fibrous materials or to be available on their surface to tack together plys during laminate lay-up and preform building.

Key findings



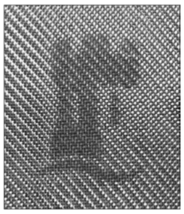
Printed polymers modify textile stiffness. Maintaining the total quantity of deposited polymer, to be common in all instances, varying printed patterns (to control the distribution of polymer) effects the stiffness to varying amounts. This effect is most pronounced within the first 20° of in-plane shear.

Early results suggest:

- The more evenly distributed the polymer is (many small squares, as opposed to, fewer large squares) then the onset of in-plane stiffening increase is seen at smaller shear angles.
- The maximum shear force is depended on total quantity of polymer deposited.

Evidence of impact

This work as been conducted in collaboration between the University of Nottingham's Composites Research Group and the Centre for Additive Manufacturing, and has supported the Nottingham Summer Engineering Research Programme (NSERP)



Emerging Research

This section summarises all of the emerging research resulting from new Feasibility Studies and the Platform Fellows. Feasibility Studies are the primary mechanism through which new academic partners can gain Spoke status with the Hub.

Successful Feasibility Studies are awarded £50,000 for short-term projects (up to 6 months) to address a fundamental step-change in composites manufacturing technology aligned to one or more of the Hub's five research priorities. Proposals can address the development of new manufacturing technologies, analytical studies to develop a fundamental understanding of state-of-the-art process modelling and optimisation techniques.

Access to further Hub funding can be released if feasibility is demonstrated, with the potential to expand the Feasibility Study into a three-year Core Project.

Cranfield University
Affordable Thermoplastic Matrix CFC / Metallic Framework Structures Manufacture

University of Southampton
Novel Strain-Based NDE for Online Inspection of Composite Sub-Structures with Manufactuing Induced Defects

Cranfield University
Layer by Layer Curing

University of Nottingham
Simulation of Forming 3D Curved Sandwich Panels

University of Cambridge
Can a Composite Forming Limit Diagram be Constructed?

University of Edinburgh
Manufacturing Thermoplastic Fibre Metal Laminates bu the In-Situ Polymerisation Route

University of Glasgow
Multi-Step Thermoforming of Multi-Cavity Multi-Axial Advanced Thermoplastic Composite Parts

University of Nottingham
Active Control of the RTM Process Under Uncertainty using Fast Algorithms

Brunel University London
Microwave Heating Through Embedded Slotted Coaxial Cables for Composites Manufacturing

University of Nottingham
Acceleration of Monomer Transfer Moulding using Microwaves

University of Nottingham
Manufactruing Process Simulation for Pre-Forming of Complex Composite Tubular Structures

University of Bristol
Evaluating the Potential for In-Process Eddy-Current Testing of Composite Structures

Ulster University
Controlled Micro Integration of Through Thickness Polymeric Yarns

Wrexham Glyndŵr University
Microwave In-Line Heating to Address the Challenges of High Rate Deposition

University of Bristol
Virtual Un-Manufacturing of Fibre-Steered Preforms for Complex Geometry Composites

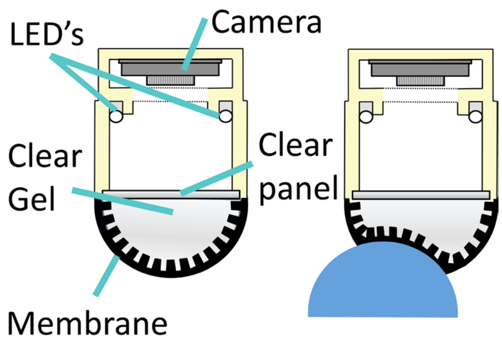
Automation That Can 'Feel': End Effectors Equipped with Tactile Shape Sensing

Michael Elkington, University of Bristol, michael.elkington@bristol.ac.uk
Academic Supervisors: Prof Nathan Lepora (Bristol Robotics Laboratory), Dr Carwyn Ward

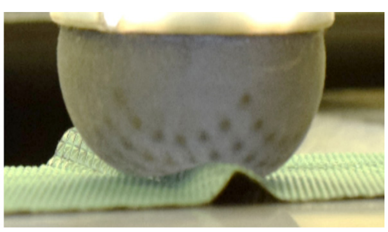
Motivation and Background

In traditional manual layup, workers constantly use tactile sensing to gain real time feedback on the quality of their work. In automated processes, this sensing method is currently not utilised and could be a powerful new quality assurance tool. Researchers at the Bristol Robotics Laboratory have developed a customizable tactile sensor (the TacTip) capable of detecting sub-millimetre surface features. In this project, a stiffer and more robust version of the TacTip is developed for specific application to composite layup. The resulting end effector can apply through-thickness compression forces of up to 400N to consolidate prepreg plies onto the mould. Simultaneously, the sensor elements of the end effector can capture the geometry of the preform being compacted beneath the end effector. By comparing the geometry of test preforms against 'correct' examples, variation and defects such as wrinkles, stray backing film or can be identified in real time during layup.

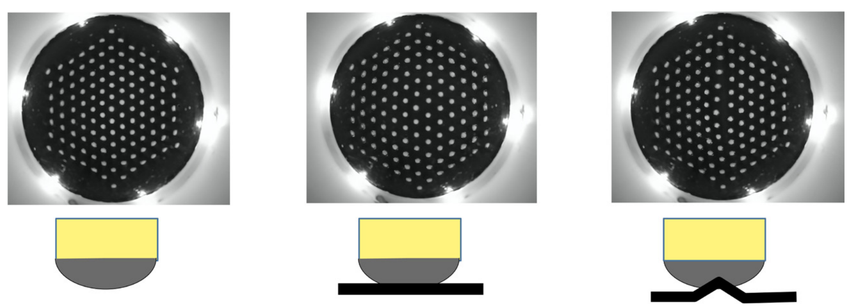
TacTip: How it works



The original TacTip was developed by the Bristol Robot Laboratory (BRL) and operates by probing onto the surface of objects. It features a flexible membrane which deforms around a object surface. The inner surface of the membrane is covered in small pins with white tips. As the membrane deforms, a camera records the movement of the white pin tips and Image analysis in MATLAB then converts the camera footage into processable data. The data is then compared to a pre recorded reference 'correct' version of the tap. If there is a significant difference between the 'test' and 'reference' data, a potential defect is flagged.

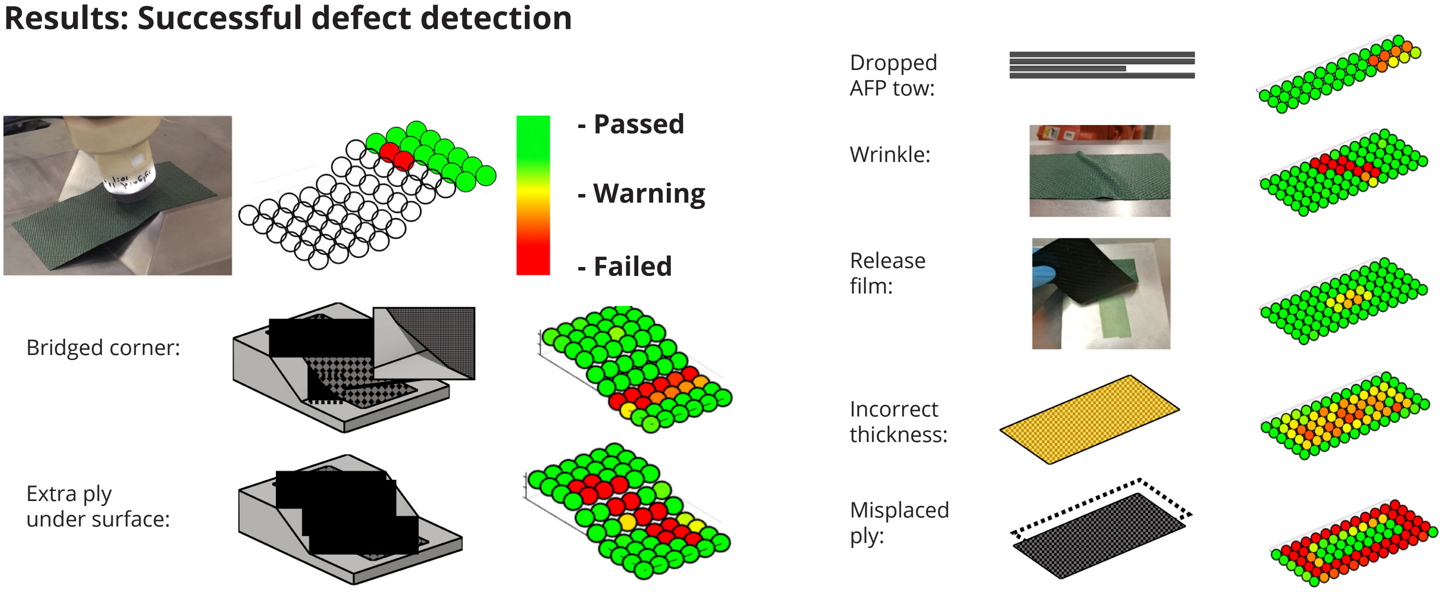


Bristol Robotics Laboratory



No contact | Contact - flat | Contact - ridge

Results: Successful defect detection

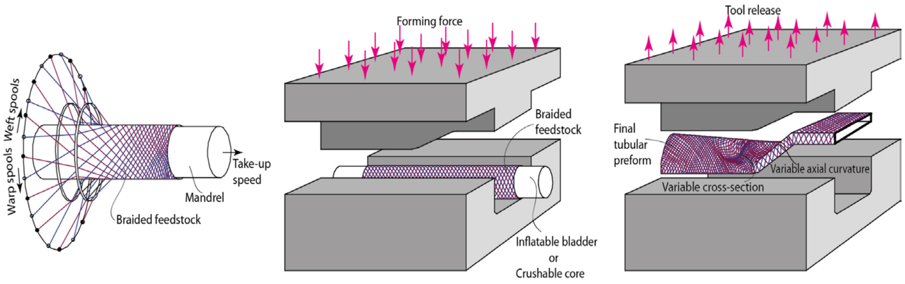


An Innovative Approach to Manufacturing Closed-section Composite Profiles

Dr Shuai Chen, University of Nottingham, shuai.chen@nottingham.ac.uk
Academic Supervisors: Prof Nick Warrior, Dr Lee Harper

Summary

This feasibility study introduces a novel concept to manufacture low-cost complex composite beams by forming sleeves from braiding, as shown in Figure 1. It offers a **step change** in composites manufacturing rate by taking advantage of the high-speed braiding for cylindrical sleeves and a subsequent high-speed forming process for complex features.



(a) Step 1 – Braiding (b) Step 2 – Forming (c) Step 3 - Demoulding

Figure 1. Preforming of complex tubular composites.

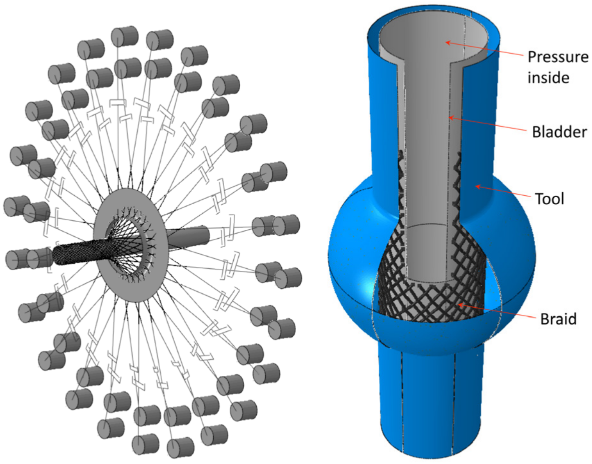
Aims & Objectives

The aim of this research is to develop a digital twin to assist with process design and optimisation for defect-free fabric preforms by stamping braided sleeves into desired complex shapes, enabling the proposed step change. The main objectives are (1) to develop an explicit FE model of the braid process, (2) to develop an explicit FE model of the forming process, and (3) to understand the primary factors of producing a defect-free component. This research fits within the Hub priority areas of both "High rate deposition and rapid processing technologies" and "Design for manufacture via validated simulation".

Methodology

Braiding process modelling

A FE model was developed to replicate the braiding process based on Abaqus/Explicit. It was used to provide digital braids for forming simulation in the next step. The braiding pattern can be modified by updating bobbins' trajectories. For simplification, a single-strand model was created, where each yarn was modelled as a circular cable. This model provides a tool for quick trials. Also, a multi-strand model was established as well. It is able to supply more realistic braids for the forming simulation.



(a) Braiding model (b) Forming model

Figure 2. FE models for braid forming process

Braid forming modelling

The braid forming model was developed based on Abaqus/Explicit, which includes the braid, the tool surfaces and the bladder. An internal pressure is applied inside of the bladder to conform the preform. The process can be refined by selecting a suitable woven pattern, applying a practical constraining scenario and designing an appropriate loading scheme. The post-forming technique offers a rapid way to manufacture different cross-section shapes and local features from a standard circular pre-braided sleeve.

Key findings

Figure 3 shows that: (1) The proposed braid forming process is able to extend the capability of braiding for reinforcement manufacture, such as concave feature; (2) The technique is more time-efficiency, requiring only standard circular sleeves from classic braiding rather than elaborate 3D braiding; (c) The developed modelling technique provides an effective tool for process design and optimisation to produce complex tubular composites without defects.

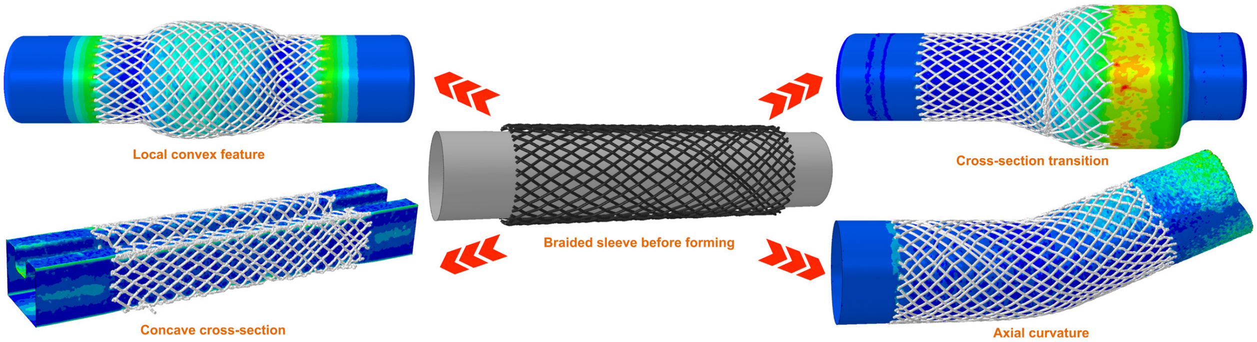


Figure 3. Formable tubular features using the proposed braid forming process

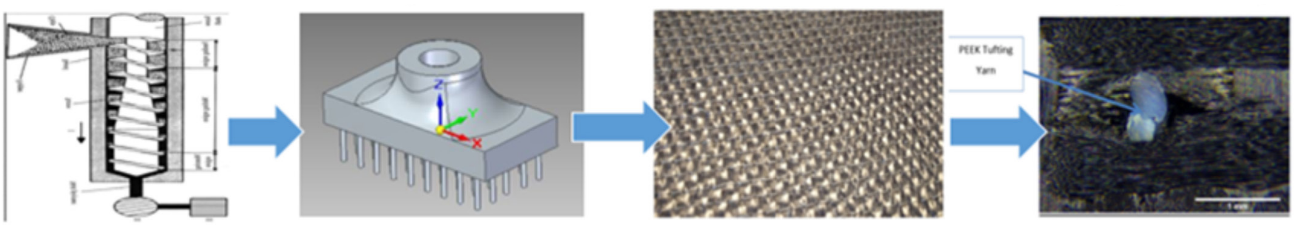
Controlled Micro Integration of Through Thickness Polymeric Yarns

Dr Thomas Dooher, Ulster University, t.dooher@ulster.ac.uk
Academic Supervisors: Dr Edward Archer, Prof Alistair McIlhagger, Dr Dorian Dixon, Calvin Ralph

Background

The performance of conventional laminated composites is frequently limited by their poor through thickness mechanical performance. A number of approaches exist to address this but have been limited by material properties of the through thickness fibre, the high levels of yarn flexibility and robustness required, and the need for robust stitching needles resulting in significant levels of fabric damage. Also, several methods have caused undesirable defects such as resin pockets, localised fabric compression, breakage of in-plane fibres and tufting loops created within the cured composite. With tufting the necessity to use a substrate to grip the yarn, lack of accurate control and irregular stitching results in low throughput. Z-pinning has proven most useful for prepreg but the necessity of having relatively large pins causes disruption. Many of these methods lack control and the resultant fibre preform is stiff and not conducive to complex shapes. The use of 3D woven fabrics is costly and can produce composites with lower in-plane Vf. Research at Ulster University has focussed on the design and development of through thickness reinforcements (generally 3D woven - recently through EU (ICONIC, MARINCOMP), DSTL, MCM ITTP, NIAECC etc.). A recent project (EPSRC grant EP/L02697X/1) developed tailored through-thickness fibre reinforced extruded/drawn thermoplastic monofilament yarns which were stitched/ tufted into preforms; this work showed improved properties in open-hole tension and toughness.

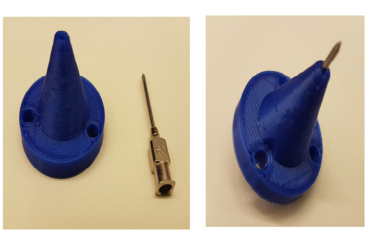
Micro Extruder — Micro Injection Head — Injection into preform — Analysis of TT yarn



Aims

The overall objective of this project is to research the underlying polymer material properties to develop a novel micro injection array system for the direct placement of through thickness polymeric yarns within dry fibre preforms; this will overcome several manufacturing related challenges to improve quality, reduce cost and increase rate. The project will develop a laboratory scale micro extrusion injection system and an understanding of the principles required to ensure that the specified polymer is "dosed" into the dry fibre preform throughout its thickness accurately and uniformly. The subsequent dry fibre material will be analysed to determine resultant damage effects and composite performance, and will be benchmarked against other methodologies through literature. To achieve this goal, much research is required regarding the rheology of the molten high temperature yarns, the visco-elastic response during the yarn formation process, and the effect of parameters such as cooling rate (crystallisation if semi-crystalline thermoplastics are investigated). This work helps to address the two over-arching Grand Challenges and could provide a ten-fold increase in rate compared to tufting or stitching; it is especially aligned with the priority area of high rate deposition and rapid processing technologies.

Current Work



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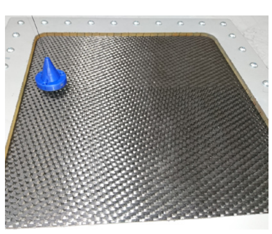

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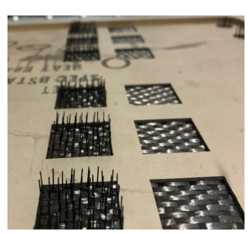

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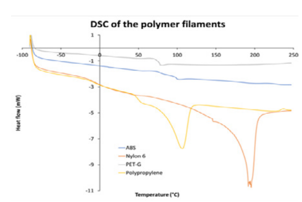

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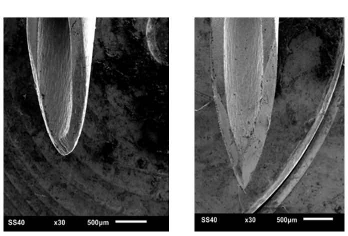

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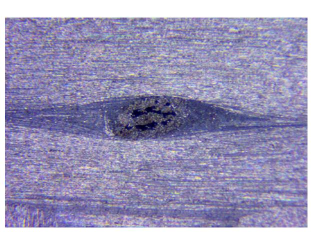


g

a. 3D printed nozzle and needle
b. Insertion of needle and carbon/ nylon yarns into preform
c. Yarns in the preform prior to compaction
d. Locally reinforced composite
e. DSC curves of the polymer filaments tested
f. Micrograph showing the needle as received and worn
g. Micrograph showing disruption of the fibres in preform

Evaluating the Potential for In-process Eddy-current Testing of Composites

Dr Robert R. Hughes, University of Bristol, robert.hughes@bristol.ac.uk

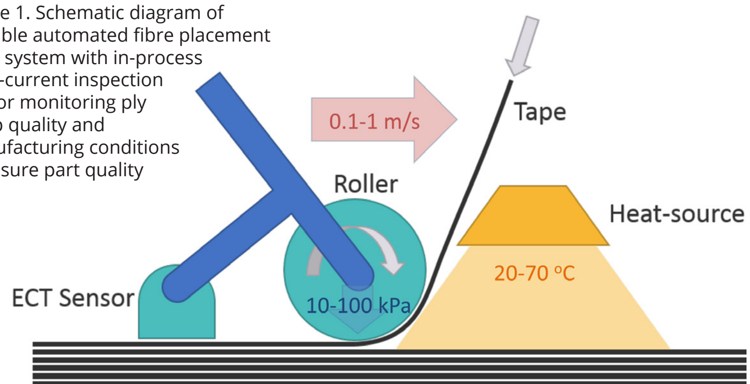
Aims & Objectives

This Feasibility Study seeks to evaluate the potential for in-process eddy-current testing (ECT) for monitoring the quality of uncured carbon fibre reinforced polymers (CFRPs) during manufacture using automated fibre placement (AFP).

The aims of this project are:

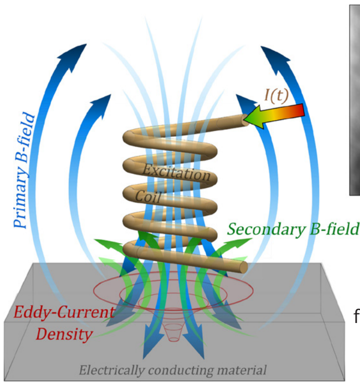
1. Determine ECT effectiveness at monitoring critical material properties in uncured CFRP parts.
2. Evaluate how typical AFP manufacturing conditions affect measurement sensitivity and data evaluation.

Figure 1. Schematic diagram of possible automated fibre placement (AFP) system with in-process eddy-current inspection sensor monitoring ply layup quality and manufacturing conditions to ensure part quality



Methodology

Eddy-current testing (see Figure 2) of CFRP is possible due to the electrical conductivity of the fibres.



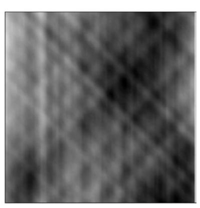


Figure 2.b. Experimental ECT scan image of cured CFRP composite sample showing the fibre orientations and variations in fibre density

Figure 2.a. Diagram of eddy-current magnetic sensing principle showing a coil excited with alternating current, generating a varying magnetic field that induces eddy-currents in electrically conducting materials which interact with the coil.

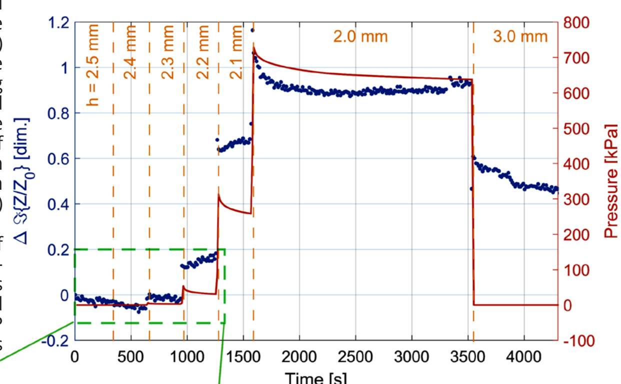
- Interlinking between fibres in ply layers increases the effective bulk conductivity changing the ECT response.
- Manufacturing errors; delaminations and gaps/ overlaps, as well as variations in fibre-volume fraction (FVF) and fibre alignment all influence ECT.
- MHz frequency eddy-current coil used to measure material properties (starting with FVF) of uncured prepreg layups of IM7 8552.

Progress: Monitoring Fibre Density

Eddy-current measurements were made on an uncured sample layup under compression are show in **Figure 3**.
Results indicate ECT measurements are capable of detecting changes in the fibre-density of the sample in the pressure range expected for AFP systems (**Figure 3.b**).

Figure 3.a Experimental resu.lts of example prepreg (IM7 8552) uncured sample compression, showing applied pressure and eddy-current impedance data (Z) as a function of time during compression routine at room temperature (~25°C)

Figure 3.b. Plot of compression and eddy-current measurements within the expected pressure range for AFP systems



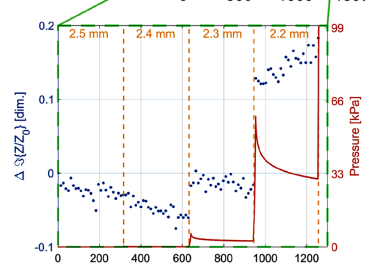


Figure 3.a .Shows the relaxation of the sample measured using ECT once pressure is removed after 3500s . This type of response will be observed behind the AFP roller head (see Figure 1)

Figure 3. Element Activation Heat Transfer Model

Key Findings

- Variations in fibre-density due to compression of uncured prepreg layups is measurable with eddy-current testing methods.
- In-line monitoring of FVF with ECT is therefore a possibility.

Next Steps

- Investigate affect of heating on ECT measurement of FVF.
- Determine the operating distance limit for ECT above CFRP samples.
- Evaluate the affect of scan speed on measurement sensitivity

Virtual Un-manufacturing of Fibre-steered Preforms for Complex Geometry Composites

Dr Xiaochuan (Ric) Sun, University of Bristol, ric.sun@bristol.ac.uk
Academic Supervisors: Dr Jonathan Belnoue, Dr ByungChul (Eric) Kim, Prof Stephen Hallett

Aims and Objectives

Automated Fibre Placement (AFP) technology is ideally suited to manufacture structures with simple geometry due to its robustness, speed and repeatability. However AFP is not well-adapted for directly laying up on complex 3D shapes as the geometry and need for defect free manufacture constrain the head speed, making manufacture time consuming and thus costly. In most cases, complex geometry composites components are designed based on ideal or theoretical fibre angles, with little or no consideration of the manufacturing processes or constraints involved in delivering them.

This Feasibility Study aims to take a novel virtual approach to “un-manufacture” these ideal designs for the case of formed composites, so that flat tailored preforms can be created via the continuous tow shearing (CTS) technique, which results in the required ideal fibre architectures after forming (see Fig. 1). The primary manufacturing process envisaged to deliver this is the diaphragm forming of thermoset prepregs deposited using automated deposition. However, it is anticipated that the concept developed will be applicable to textile preforms (including non-crimp fabrics) and thermoplastic prepregs. The objectives of this project is to demonstrate the proof of concept and feasibility of the proposed manufacture processes and to develop numerical tools needed, along with experimental validation.

Work Flow

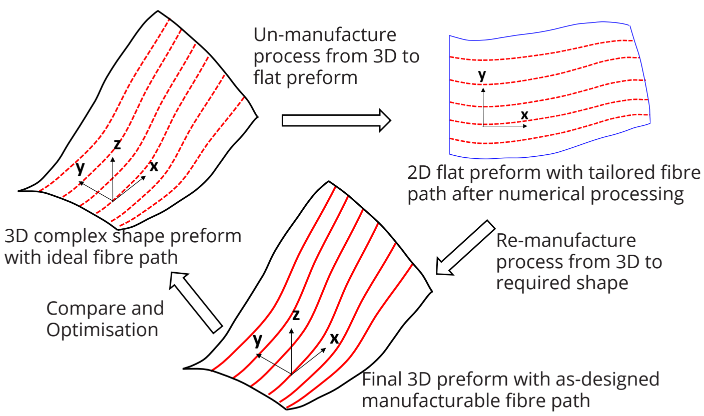


Figure 1. Schematic of the lay-flat and form

Methodology

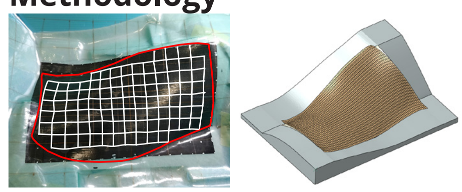


Figure 2. experimental results (left) of forming using UD prepreg with marked grids and model prediction (right) for the re-forming of prepreg tailored fibre path

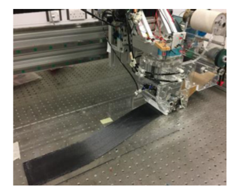


Figure 3. Wide tape CTS machine steering a 100 mm wide unidirectional prepreg tape

Work packages:

- WP1. Numerical modelling of forming and un-forming of steered fibres prepreg stacks on representative complex 3D shape
- WP2. Experimental characterisation of prepreg in-plane properties
- WP3. Manufacture of technology demonstrator and quality inspection

Numerical Results

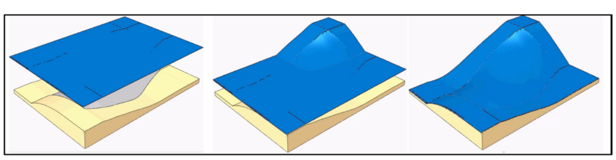


Figure 4. Numerical process modelling of double diaphragm forming (note the part in blue is diaphragm)

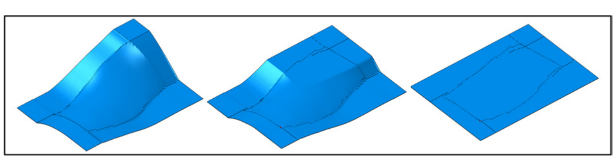


Figure 5. Numerical process modelling of double diaphragm un-forming (note the part in blue is diaphragm, prepreg model is sandwiched between two diaphragm parts)

- Two processes were fully reversible
- 2D flat prepreg with tailored fibre path after post-processing was obtained.
- Fibre path was extracted from prepreg model and passed to manufacture CTS tapes
- 2D flat prepreg model was then put back to forming simulation, the result of which is compared with the ideal fibre path to form a complete optimisation cycle

Experimental Results

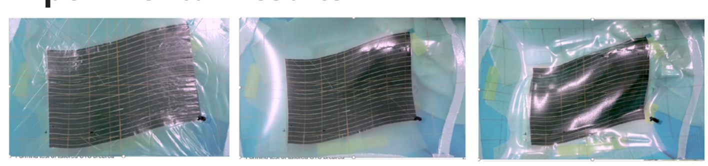
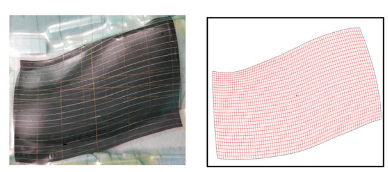


Figure 6. Double diaphragm forming test on tailored CTS prepreg where fibre path was derived from un-forming simulation



- Steered fibre tape was made using CTS technique with fibre trajectory derived numerically
- Reformed steered prepreg was found to be similar to modelling results.

Figure 7. Comparison between Formed tailored CTS prepreg and Reformed preform with tailored fibre path

Key Findings

- Validated numerical and experimental results demonstrated the feasibility of the proposed manufacture processes which can have lower cost and greater efficiency compared to direct AFP on complex shape
- Steered fibre paths on demonstrator was found to have less wastage and more continuous fibre across the whole part

Investigating and Modelling the Low Shear Region in Non-crimp Fabrics

Albert Gibbs, University of Nottingham, albert.gibbs@nottingham.ac.uk
Academic Supervisors: Prof Nick Warrior, Dr Lee Harper

Introduction

This investigation looks at the low shear high stiffness region and accompanying hysteresis effect that is seen at the onset of shear in biaxial non-crimp fabrics (NCF's). It aims to apply the known causes of this effect from woven fabrics, to biaxial NCF's. The outcome is for a better understanding of the assumptions used when modelling NCF's as continuum materials and to properly include this low shear region into current material models.

Aims

- To understand the mechanisms causing the high stiffness region seen at the onset of shear in biaxial NCF's, approximate the shape and magnitude of this effect directly from the material properties and identify the sensitivities.
- Observe the effect using a 3D scanned model of the fabric under load.
- Identify the effect this region has on final formed shape when it is included in finite element models and whether these models gain accuracy in shear distribution with it's inclusion.

Methodology

Theory
In a woven fabric the low shear hysteresis effect seen is due to the frictional force from the crimp stopping fibre slippage at low shear load. In NCF's it is thought that the same effect occurs except that the stitch replaces the crimp and the stitch tension causes the normal force required to inhibit tow rotation. For the fabric to strain without shearing, deformation occurs In the form of in-plane bending of tows in-between stitches. As load increases the slippage boundary at each stitched tow crossing point increases until tows can rotate freely. This gives the hysteresis effect seen in the shear angle. The amount of slip is given in terms of the variable a/d which is the ratio of tow slippage from 0-1 based on the current loading.

$$\theta=\frac{F}{12BL}\left\{\frac{P_1}{P_2}\left[l_2-d\left(1-\frac{a}{d}\right)\right]^3\right\}+\left\{\frac{P_2}{P_1}\left[l_1-d\left(\frac{1}{d}-a\right)\right]^3\right\}$$

Equation 1. Force shear angle equation in terms of tow slip (P1/2 Tow spacing; l1/2 Tow length; θ Shear angle; B Bending stiffness; L sample width; d Contact length; F Applied shear force

The stitch causes a normal force on the crossed tows as the looped stitch in tension compresses the tow bundle. The reduction in radius of this loop has been equated with the stitch extension and the compression of the tow bundle to give the normal force.
Assumptions:

- Cylindrical stitch and fibres.
- Stitches maintain orientation to the fibres.
- Constant contact length.

Scanning
A sample of Hexel FCIM-359 pillar stitched biaxial Non-crimp fabric, was clamped into a picture frame testing rig with a HP Pro-3D, scanner mounted opposite. The sample has been coated with a non bound matt white coating to reduce glare and allow for a higher quality scanned image. The sample was then extended by small amounts giving results across the low shear region with the extension being stopped and the sample scanned and multiple intervals.

Progress to date

The predicted low shear region has been mapped and compared to experimental results, the process has also been observed via 3D scanning. An approximate thread tension has been used, but with this included the predicted curve shape is very similar to what is observed.

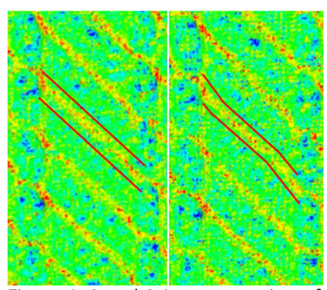


Figure 1. 0 and 0.1mm extension of NCF showing fibre bending under shear load 3D scanned

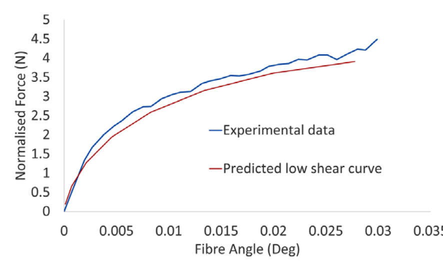


Figure 2. Predicted low shear region compared to experimental data collected

Multiple shear dominated materials with altered low shear regions have also been created using the VFABRIC subroutine for Abaqus explicit. These materials have been sheared in a virtual picture frame test and been simulated forming over a hemisphere to look at the impact that alterations to the region have on shear distribution.

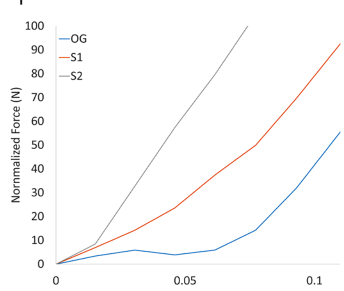


Figure 3. 3 different low shear regions

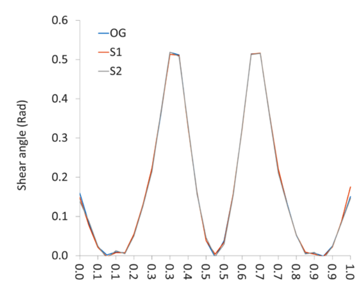
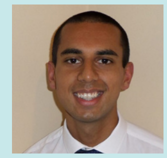


Figure 4. Differences in formed shape between low shear regions

Initial results show that there is very little difference to the shear angle distribution seen on the formed shape using current models, but the forces required to form do vary. Further work is needed to properly implement the bending dominated deformation mode that appears in this region, and see how introducing the new bending mode impacts forming simulations.

Carbon Fibre Thermoplastic Composites for Lightweighting Rail Vehicle Structures

Preetum Mistry, University of Nottingham, preetum.mistry@nottingham.ac.uk
Academic Supervisors: Dr Mike Johnson, Dr Lee Harper, Prof Nick Warrior

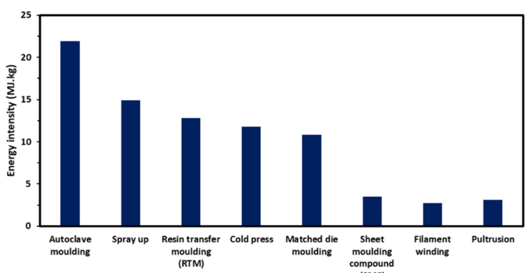


Background

Weight reduction of rolling stock vehicles has been a major issue within the railway industry [1]. This is due to the demand for trains to become more efficient, faster and accommodate more passengers. Heavier rail vehicles result in increased track damage and energy to operate. Thus contribute to higher costs for operation, infrastructure, maintenance and renewal [2]. With increasing environmental and economic regulations surrounding energy consumption, the lightweighting of rail vehicles is of prime importance. One way to achieve this is by material substitution utilising advanced composite materials. Composite materials are currently used for semi-structural rail applications, such as carriage interiors. However, to maximise the high strength-to-weight ratio inherent of polymer composite materials it is necessary to integrate composites into primary rail vehicle structures [3].

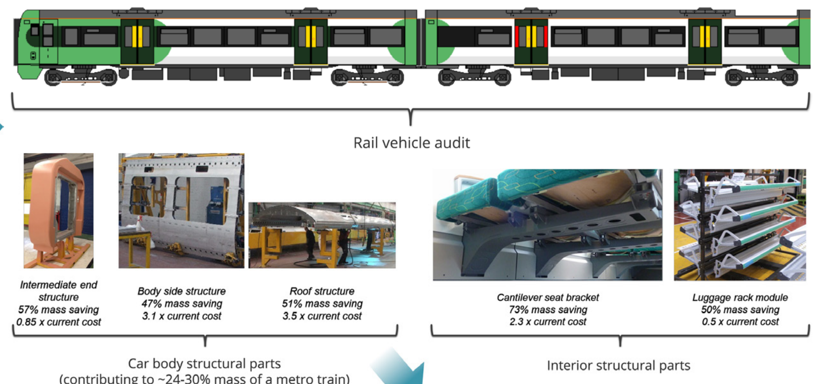
Composite Manufacturing

A summary of energy intensities for common manufacturing processes is shown below [5]. The rail industry requires a low cost and low volume (<1000 parts/year) process to support production of large structures for composite rail car body structures.



Key areas for lightweighting

As part of the ACIS (Advanced Composite Integrated Structures) UK rail project [4], a team of engineers from Bombardier Transportation, The University of Nottingham, Haydale Composite Solutions Ltd and The National Composites Centre collaborated to address the lightweighting of rail vehicles. A rail vehicle audit of a typical metro train was carried out, assessing over 200 components and evaluating the most commercially viable (in terms of a life cycle costing analysis) components of a rail vehicle to be lightweighted utilising composite materials. The chosen demonstrator parts were grouped into interior structural parts and car body structural parts (with % mass savings and approximate costs for a composite design indicated).

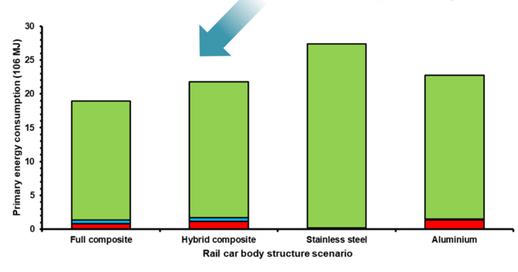


Composite car body structures

Filament wound carriage – Schindler Waggon – 1995, Switzerland

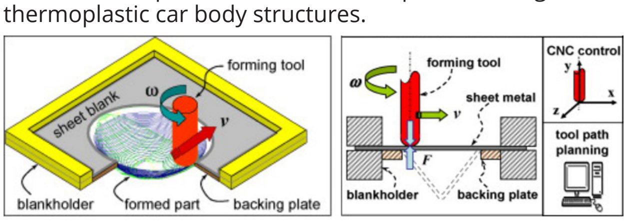
Autoclave cured bodyshell –Tilting train express (TTX) – 2001, Korea

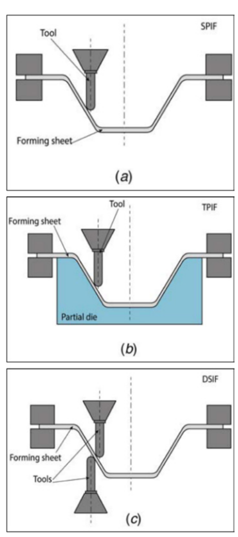
Pultruded carriage panels – CG Rail – 2018, Germany



Incremental sheet forming of composites

Incremental Sheet Forming (ISF) is a common and well established process for forming sheet metal products. The main advantages of ISF for metal forming include its "dieless" feature, easy adaptation, and simple structure of the tool system as compared to conventional sheet-forming processes, which require a complex press and dedicated tool system. The process consists of a sheet being formed by means of a round-tipped tool (or punch), which makes a series of small incremental deformations in the sheet on a predefined path that is governed by a numerical control. This work aims to explore ISF of carbon fibre thermoplastic composites as a low cost manufacturing process for the rail industry, which has the potential to be scaled up to form large thermoplastic car body structures.





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Defect Detection and Mitigation in Advanced Sheet Moulding Compounds

Daniel Wilson, University of Nottingham, daniel.wilson@nottingham.ac.uk
Academic Supervisors: Dr Lee Harper, Prof Nick Warrior

Aims and Objectives

- Identify a suitable method of NDT for use with SMCs
- Study defects in carbon SMC parts

Progress

- Manufactured 4 DFC (Directed Fibre Compounding) and 18 HexMC flat panels
- Collaboration with UNNC University of Nottingham and Ningbo Campus

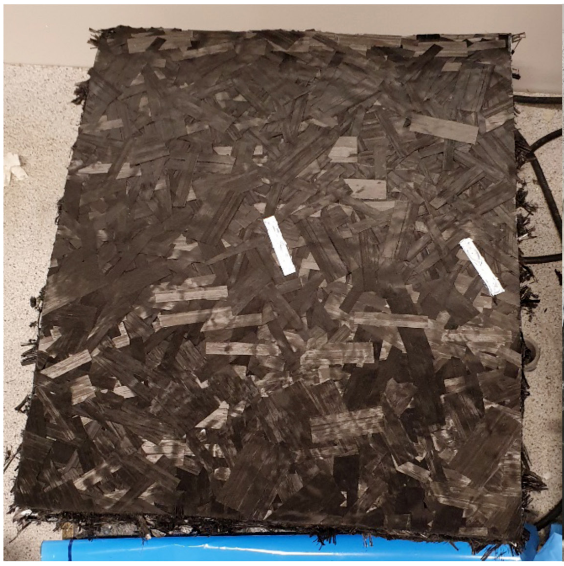


Figure 1a. Hexcel HexMC charge with tracer tows prior to moulding

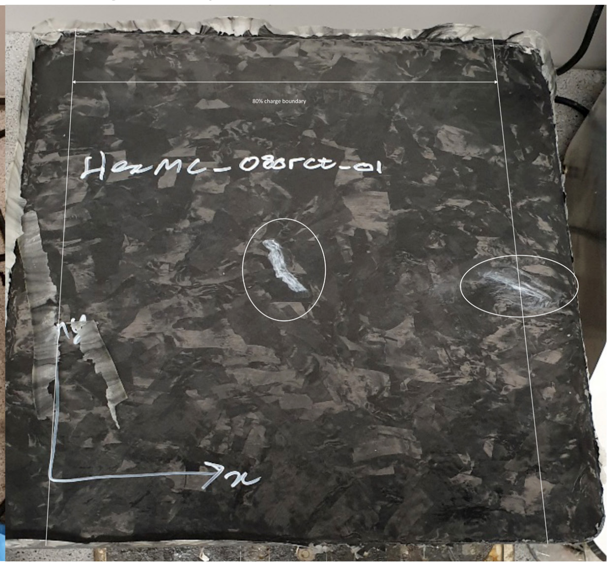


Figure 1b. Moulded Hexcel HexMC plaque showing shift of tracer tows

Key Findings

- Micro-CT scanning ideal method of NDT – would provide best results
- However, expensive and time-consuming
- C-scanning preferable – results not as good (only 2D), but quicker and cheaper
- Promising results from C-scans – detected internal defects which seem to correspond to visible surface defects

Future Work

- Micro-CT scanning and microscopy of defective areas for validation of C-scans
- Detailed study of defects using micro-CT scans and microscopy to determine cause
- Investigate effects of different manufacturing parameters on formation of defects
- Study effects of defects on mechanical properties

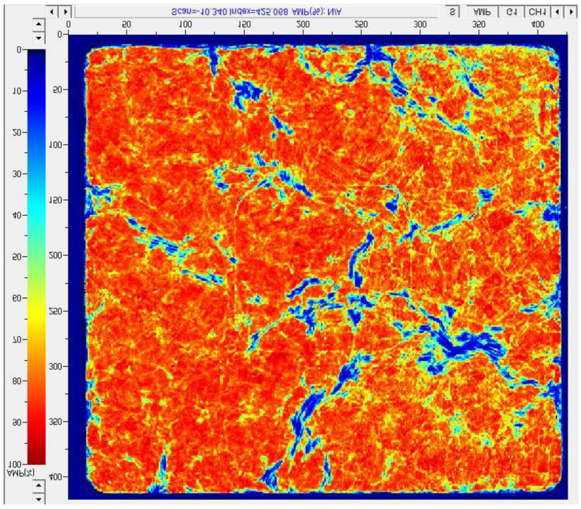


Figure 2a. C-scan of 100% coverage HexMC plaque

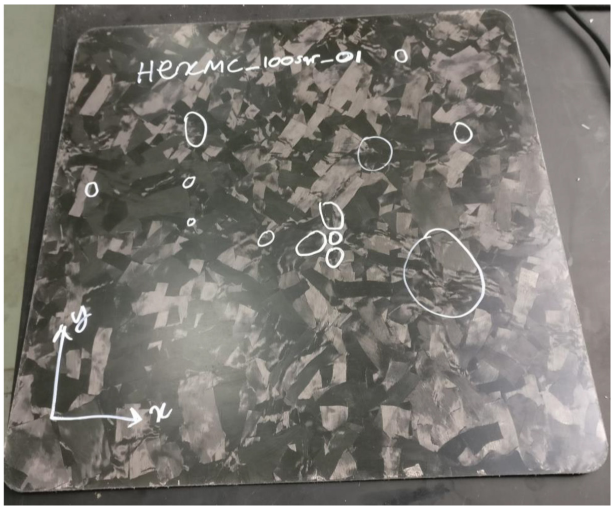


Figure 2b. top surface of 100% coverage HexMC plaque

Novel Integrated Imaging Approaches for Damage Characterisation of Composite Materials and Structures

Irene Jiménez Fortunato, University of Southampton, i.Jimenez-fortunato@soton.ac.uk
Academic Supervisors: Prof Ole Thomsen, Prof Janice Barton, Dr Daniel Bull

Aims / Objectives

Damage detection and characterisation (strain and stress fields) by integrating two **imaging techniques: Lock-In Digital Image Correlation (LIDIC)** and **Thermoelastic Stress Analysis (TSA).**

Application of TSA and LIDIC simultaneously to **large composite structures** (complex geometry and loading). **Reduction of acquisition and operational costs** by using low-cost infrared (IR) cameras i.e. bolometers and low frame rate white light cameras. primary rail vehicle structures [3].

Methodology / Progress to date

Demonstrator: wind turbine blade substructure i.e. **T-joint** formed of different materials (wood, resin, fibre epoxy composite). Use **simultaneous** of **TSA** and **LIDIC**, post-processing of both techniques with **least-square algorithm** and results presented at the **same spatial resolution**.

Least-square algorithm (fitting) to extract mean (T_0 and ε_0), peak-to-peak amplitude (ΔT and $\Delta(\varepsilon_{xx}+\varepsilon_{yy})$) and phase ($\theta$) with respect the applied load.

$$T(t) = T_0 + \frac{\Delta T}{2}\sin(2\pi f t + \theta)$$

$$\varepsilon_{xx} + \varepsilon_{yy}(t) = \varepsilon_0 + \frac{\Delta(\varepsilon_{xx}+\varepsilon_{yy})}{2}\sin(2\pi f t + \theta)$$

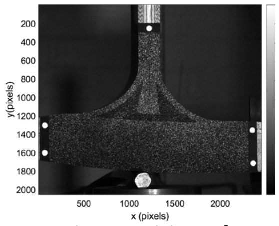


Figure 1. T-joint surface preparation

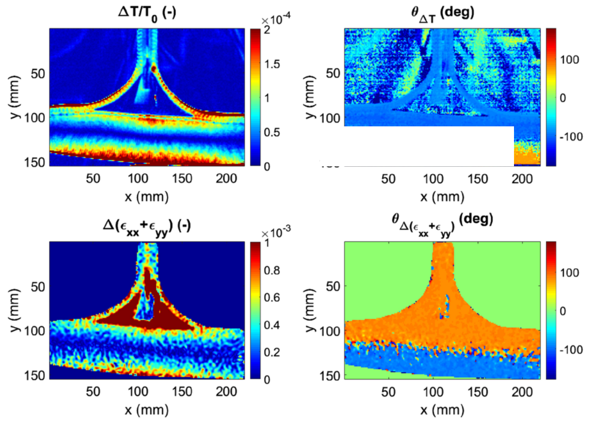


Figure 2. Normalised temperature change (TSA) and phase with respect the load applied (top) and change of strain in x and y sum (UDIC) and phase with respect the load applied (bottom)

Damage Identification: $\frac{TSA}{LIDIC} \leftrightarrow \frac{\sum \Delta\sigma}{\sum \Delta\varepsilon}$ related to $\frac{\frac{\Delta T}{T_0}}{\Delta\varepsilon_{xx}+\Delta\varepsilon_{yy}}$

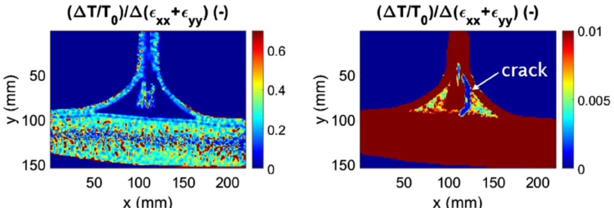


Figure 3. Damage identification by integrating TSA and UDIC at different scales

Thermoelastic response (ΔT) depends on the **stiffness** (Q – ply or A – global laminate) and the Coefficient of Thermal Expansion (α - CTE), while the strains depend only on the stiffness.

- Surface ply

$$\Delta T = -\frac{T_0}{\rho C_p}[\alpha]_{1,2}^T[\Delta\sigma]_{1,2} = -\frac{T_0}{\rho C_p}[\alpha]_{1,2}^T[Q]_{1,2}[T][\Delta\varepsilon]_{x,y}$$

- Global laminate

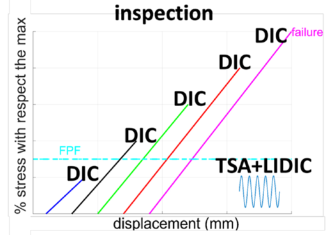
$$\Delta T = -\frac{T_0}{\rho C_p}[\alpha]_{1,2}^T[\Delta\sigma]_{1,2} = -\frac{T_0}{\rho C_p}[\alpha]_{x,y}[A]_{1,2}[\Delta\varepsilon]_{x,y}$$

Understand the **combined strain and thermoelastic response** (ΔT) on different composite lay-ups, i.e. $[\pm 45]_{3s}$, $[90,0]_{3s}$ and $[0,90]_{3s}$ GFRP and CFRP coupons. When integrating with the strains obtained with LIDIC, a **damage parameter** can be obtained that provides information about the **material state**.

Analytical FPF (ESAComp) ↔ Surface damage (DIC)

Set stress level for damage inspection that will not generate any damage (TSA + LIDIC)

Generation of damage and inspection



Detection of the stress redistribution signifying damage

Key Findings / Evidence of Impact

Successfully applied TSA and LIDIC techniques **simultaneously** during cyclic loading using **low-cost camera systems** for data acquisition and **least-square algorithm** for post-processing.

TSA and LIDIC results presented at the **same spatial resolution** and integrated by means of a **damage parameter** indicative of **stiffness**.

Detection of the **different materials** and a **crack** due to the difference in **stiffness** in a **substructure**.

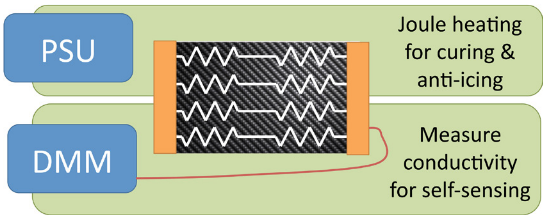
Potential to **inspect** various regions of **larger structures** by installing **arrays of IR and white light** cameras surrounding the structure.

Refinement of FEA models to create **high-fidelity** testing and modelling.

Smart Composites for Aerospace Applications

Matthew Collinson, Advanced Manufacturing Research Centre, m.collinson@amrc.co.uk
Academic Supervisor: Dr Simon Hayes, Dr Clara Frias, Dr Tim Swait

Smart Composites Background



Carbon fibres in CFRP are conductive, therefore woven CFRP can be likened to a large network of resistors. If these are actuated like an electrical component, then extra functions can be gained from what is usually a structural component, which is also known as multi-functionality or as smart composites. Examples described below and being developed in this project are electrical self-sensing, and electric self-curing.
These functions are limited by the insulating nature of the resin used most CFRP components, as it is a barrier to the conductive fibres, leading to high contact resistance as an electrical component. Research into conductive resins, by integrating carbon nanotubes, is also underway to enable better function of the smart functionalities.

CNTs being dispersed in resin using a 3 Roll Mill to increase the electrical conductivity of the resin

Resin and Composite Conductivity

Resin conductivity is a large barrier to these technologies, as the contact resistance is a large part of the overall resistance of the part, reducing the effectiveness of both smart functionalities.
An investigation on the dispersion of CNTs in resin using 3 roll mill and shear mixing has been completed. This loaded resin is currently being infused in composites to check distribution is currently ongoing. The lower contact resistance should increase sensitivity of self-sensing and reduce hotspots occurring during electrical curing.

CNT dispersed in resin being infused into a glass fibre preform to determine manufacturing method of the composite

Electrical Self-Sensing

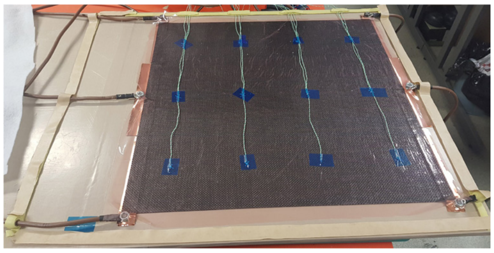
If the electrical conductivity of carbon fibres is monitored, when a fibre breakage occurs through external damage, such as barely visible impact damage, then this damage can be detected without external detection.
This concept has been extended to detecting conductivity over a whole surface, though the integration of a flexible PCB as an interleave in a composite, to detect conductivity in equally distributed areas over a part using a digital multimeter.
Reducing the conductivity of the resin using CNTs will allow for more accurate measurement of the fibre conductivity, as well as for potential detection of matrix cracking before catastrophic failure.

8-Ply CFRP with a mid plane flexible PCB to enable electrical conductivity measurements over the panel

Electrical Self-Curing

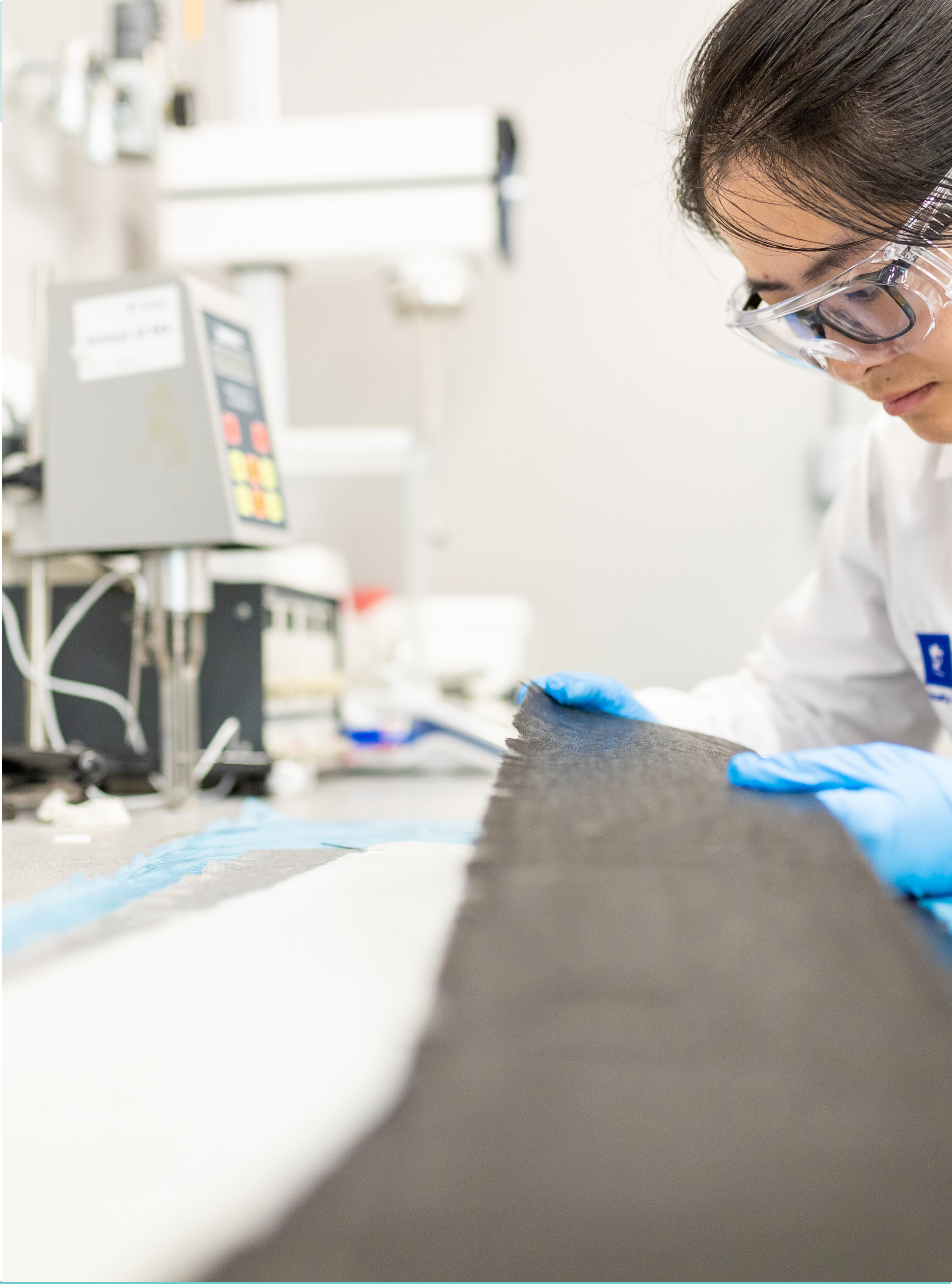
Running a current through an electrical conductor, such as carbon fibres, induces the joule effect, which allows for localised heating of a part or component. If a current is applied to CFRP using a high current power supply, then the Joule effect can be used to reach cure temperature of the CFRP, or in a final product could be used for anti-icing.
This method has been used to successfully cure a pre-preg CFRP system up to 120°C at 500x500mm whilst using less than 200W.
One of the main challenges is getting an even temperature distribution over the part during cure, which is up to 20°C from the target temperature in some areas.

An example experimental setup of electrical self-curing, with copper connectors on the left and right connected to the PSU, and an array of thermocouples on the surface to detect temperature differences over the panel



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°760940. mastro-2020.eu

MASTRO



Shaping the Future

Hub Roadmapping

UK Composites Research Challenge Landscape (CiRCL)

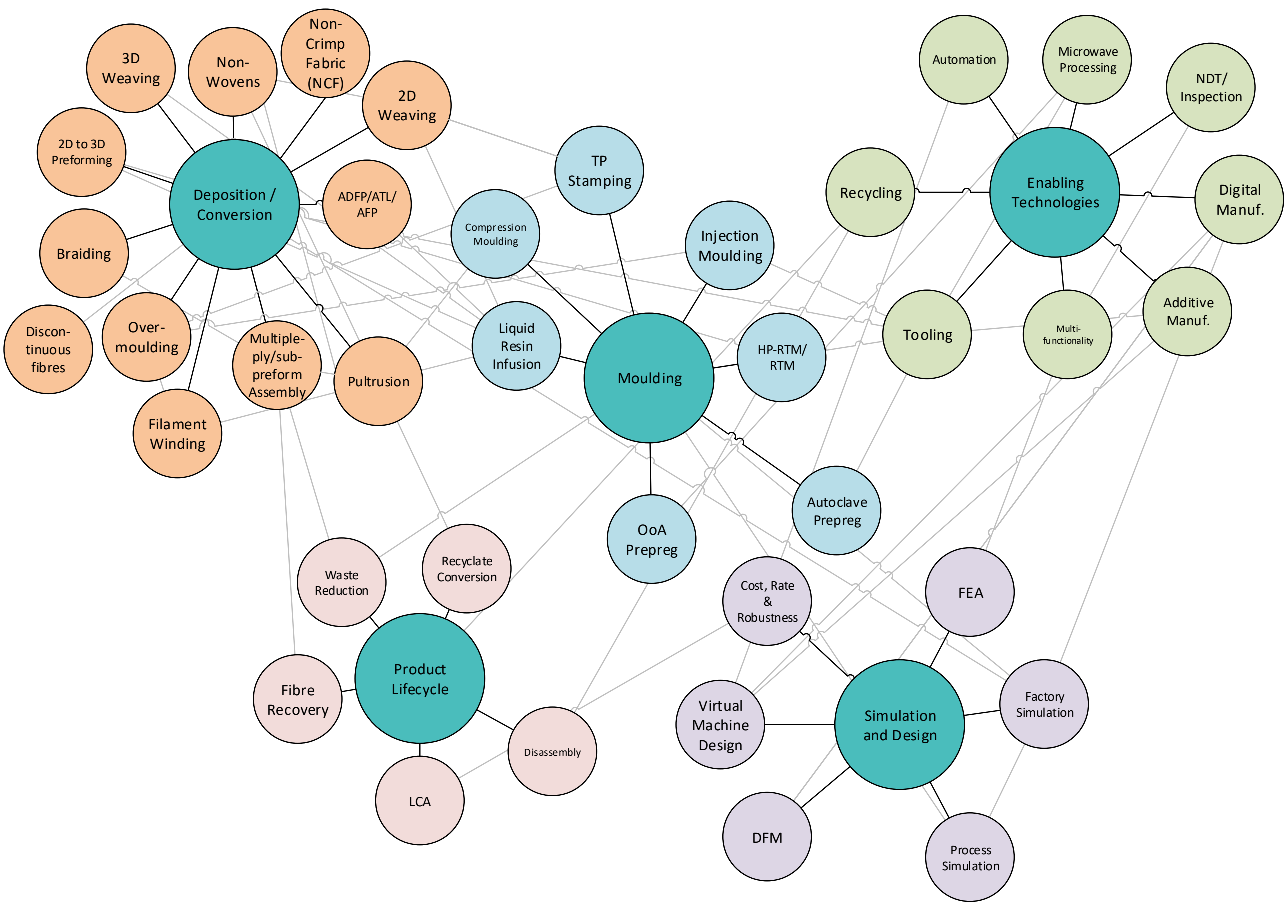
The Hub plays a key role in funding fundamental composites manufacturing research in the UK. This is aligned with our five research priority themes and two grand challenges. However, in order to ensure that we are funding the most critical and timely projects we need to remain up to date with research trends. The aim of the Composites Research Challenge Landscape is to develop a process for identifying fundamental research challenges for composites manufacturing to be addressed within the next 20 years. These will be used to:

- Inform future funding decisions and shape calls for Feasibility Studies
- Refine Hub 'Grand Challenges' – rate and robustness
- Ensure that Hub research themes remain relevant
- Help the academic community justify resource needs
- Shape future policy
- Underpin knowledge & technology transfer into HVMC
- Identify areas of research synergy between technology areas
- Help align Hub projects to those with similar objectives

Methodology

In order to most accurately represent our current research portfolio, CiRCL focuses on high-rate processing technologies in fibre deposition, conversion and moulding. Over 170 challenges were identified from peer-reviewed literature and formed a draft landscape to initiate discussion with the wider composites community. Challenges were subsequently captured through a series of meetings and workshops with academics and HVM Catapult engineers. These followed a framework based on an Institute for Manufacturing (IfM) roadmapping approach where participants identified challenges and scored them by severity, reflecting the urgency with which they need to be addressed. Participants were also invited to suggest a different score for existing challenges, ensuring that the landscape is moderated and reflects the views of all respondents.

Composites Manufacturing Technologies within CiRCL

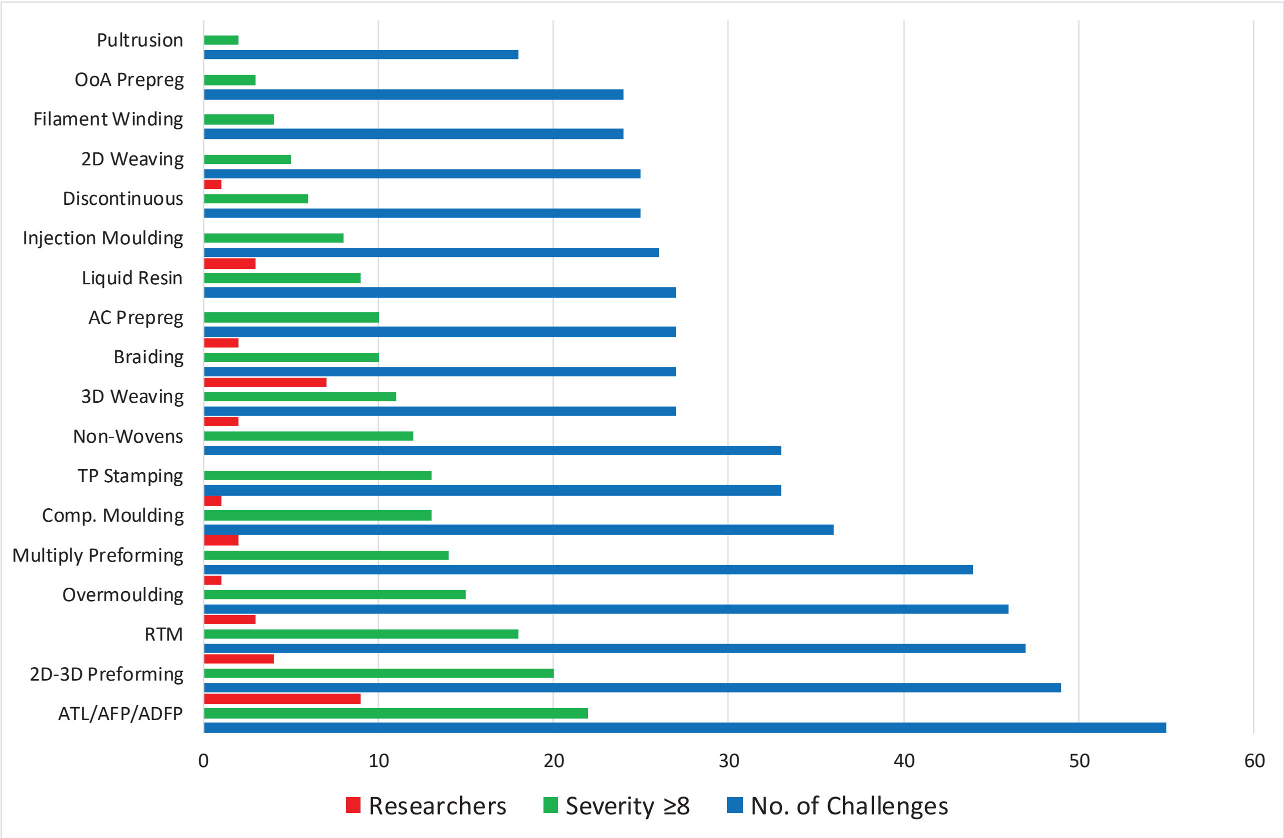


Results

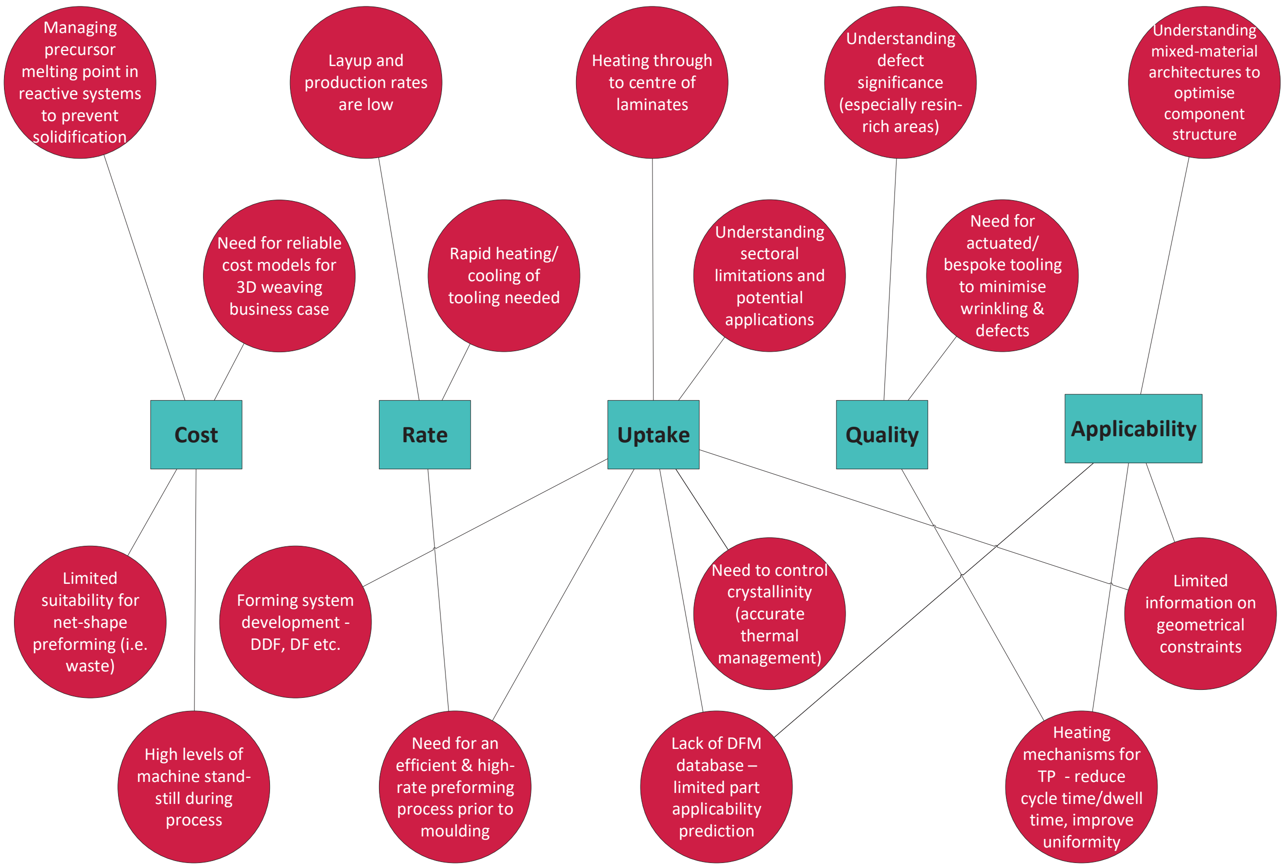
Over 30 academics and Catapult engineers were involved in the preparation of CiRCL, contributing almost 600 challenges across the 18 technology areas. Of these challenges, 195 (around 33%) were assigned a severity of greater than 8, indicating that these are challenges that required urgent attention.

Technologies	18
Challenges identified	593
Challenges considered urgent ≥8	195
Contributors	30
Average challenges per technology	33

The graph below shows the number of challenges identified in each technology area, and the number scoring above 8. The number of researchers and postgraduates working on Hub-funded projects is also shown, indicating areas in which the Hub is active in meeting these challenges.



Challenges were also classified by the impact that could be expected if they were addressed. These reflect the cost of the process, process rate, increased uptake of composites or specific processes, component quality, and applicability of a process to a specific industry need. The diagram below shows the most critical challenges (scoring 10) and the potential impact that solving these challenges could unlock.



The initial outputs of CiRCL can be found at https://cimcomp.ac.uk/research-landscape. If you are interested in contributing to the landscape, please contact Richard Gravelle (Richard.gravelle@nottingham.ac.uk).

Publications

Journal Papers

EP/P006701/1 : EPSRC Future Composites Manufacturing Research Hub

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EP/I033513/1: EPSRC Centre for Innovative Manufacturing in Composites

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32. Roy, S., Potluri, P., Soutis, C. (2017) Tensile Response of Hoop Reinforced Multiaxially Braided Thin Wall Composite Tubes, Applied Composite Materials 24 (2), 397-416.
33. Saleh, M., Wang, Y., Yudhanto, A., Joesbury, A., Potluri, P., Lubineau, G., Soutis C. (2017) Investigating the Potential of Using Off-axis 3D Woven Composites in Composite Joints Applications, Applied Composite Materials 24 (2), 377-396.
34. Yousaf, Z., Potluri, P., Withers, P. (2017) Influence of Tow Architecture on Compaction and Nesting in Textile Preforms, Applied Composite Materials 24 (2), 337-350.

Conference Papers

22nd International Conference on Composite Materials 2019, Melbourne, Australia, 2019

1. Anthony, D., Nguyen, S., Senokos, E., Bismarck, A., Greenhalgh, E., Shaffer, M. Hierarchical Carbon Aerogel Modified Carbon Fibre Composites for Structural Power Applications, ICCM22, Melbourne, Australia, August 2019.
2. Chen, S., McGregor, O., Endruweit, A., Harper, L., Warrior, N., Finite Element Forming Simulation of Complex Composite Sandwich Panels, ICCM22, Melbourne, Australia, August 2019.
3. Clegg, H., Dell'Anno, G., Scott, M., Partridge, I., Suppressing Delamination in Composite Intersections with Tufting and Z- Pinning, ICCM22, Melbourne, Australia, August 2019.
4. Evans, A., Turner, T., Endruweit, A., Development of Automated Dry Fibre Placement for High Rate Deposition, ICCM22, Melbourne, Australia, August 2019.
5. Gent, I, Mann, N,L, Ward, C. Localised Inkjet Printing of Resin Additives for Selective Property Enhancement, ICCM22, Melbourne, Australia, August 2019.
6. Greenhalgh, E., Shaffer, M., Kucernak, A., Senokos, E., Nguyen, S., Pernice, M,F., Zhang, G., Qi, G., Anthony, D., Balaskandan, K., Valkova, M. Future Challenges and Industrial Adoption Strategies for Structural Supercapacitors, ICCM22, Melbourne, Australia, August 2019.
7. Jimenez Fortunato, I., Bull, D., Dulieu-Barton, J, M., Thomsen, O, T. Damage Characterisation of Composite Components Using Full-Field Imaging Techniques, ICCM22, Melbourne, Australia, August 2019.
8. Koncherry, V., Park, J., Sowrov, K., Potluri, P., Matveev, M., Brown, L., Long, A.C. Novel Manufacturing Techniques for Optimised 3D Multiaxial Orthogonal Preform, ICCM22, Melbourne, Australia, August 2019.
9. Matveev, M., Roy, S., Koncherry,V., Brown., Potluri., Long, AC. Meso-scale Optimisation and Manufacturing of Continuous Fibre 3D Reinforcements, ICCM22, Melbourne, Australia, August 2019.
10. Murray, J, Gleich, K, McCarthy, E,D, O'Bradaigh, O, Properties if Polyamide-6 Composites using Thermoplastic Resin Transfer Moulding, ICCM22, Melbourne, Australia, August 2019.
11. Nguyen, S., Pouyat, A., Greenhalgh, E., Shaffer, M. Linde, P. Structural Power Performance Requirements for Future Aircraft Integration, ICCM22, Melbourne, Australia, August 2019.
12. O'Bradaigh, C, M, Mamalis, D, Flanagan, T, Doyle, A, Tidal Turbine Blade Composite Using Basalt Fibre Reinforced Powder Epoxy, ICCM22, Melbourne, Australia, August 2019.
13. Pappa, E, Optimisation of Carbon Fibre Re-Inforced Polymer (CFRP) Composites with a Thin Embedded Polyurethane Film, ICCM22, Melbourne, Australia, August 2019.
14. Thomsen, O,T, Buckling Behaviour of UD Carbon/Epoxy Panels Subjected to Direct Lightning Strike, ICCM22, Melbourne, Australia, August 2019.
15. Valkova, M., Greenhalgh, E., Shaffer, M., Predicting the Consolidation of Fabric-Reinforced Structural Power Composites, ICCM22, Melbourne, Australia, August 2019.
16. Vissainen, V., Zhou, J., Sutcliffe, M., Characterisation of the Wrinkling Behaviour of a Biaxial Non-Crimp-Fabric During Forming, ICCM22, Melbourne, Australia, August 2019.
17. Yu, F., Chen, S., Harper, L., Warrior, N., Finite Element Modelling of Bi-Axial Fabric with Considering Bending Stiffness for Composites Preforming, ICCM22, Melbourne, Australia, August 2019.

Other Presentations and Events

18th European Conference on Composite Materials, Athens, Greece, 2018

1. Karanatsis, D., James, T., Endruweit, A., Long, A.C. Influence of Stitch Thread Tension on the Permeability of Carbon Fibre Non-Crimp Fabrics, Proc. 18th European Conf. on Composite Materials (ECCM-18), Athens, Greece, June 2018.

11th International Conference on Manufacturing of Advanced Composites ICMAC, 2018: Poster Presentations

1. Belnoue, J., Sun, R., Cook, L., Tifkitsis, K., Kratz, J., Skordos, A. A Layer by Layer Manufacturing Process for Composite Structures, Project poster at ICMAC, July 2018, University of Nottingham.
2. Elkington, M., Gandhi, N., Libby, M., Kirby, A., Ward, C. Collaborative Human-Robotic Layup, Project poster at ICMAC, July 2018, University of Nottingham.
3. Harrison, P., McGookin, E., Mulvihill, D., Richards, D., Campbell, I. Multi-step Thermoforming of Multi-cavity Multi-axial Advanced Thermoplastic Composite Parts, Project poster at ICMAC, July 2018, University of Nottingham.
4. Mamalis, D., Obande, W., Koutsos, V., Ó Brádaigh, C., Roy, D. Novel Infusible Thermoplastic Matrix in Fibre Metal Laminates, Project poster at ICMAC, July 2018, University of Nottingham.
5. Bethany Russell, Embedding Vascular Networks into Thick Composite Parts as Thermal Management Tools for Cure Processing, Project poster at ICMAC, July 2018, University of Nottingham.
6. Sutcliffe, M., Zhou, J., Viisainen, V. Wrinkle Formation Characterisation During the Forming of Non-crimp Fabrics, Project poster at ICMAC, July 2018, University of Nottingham.
7. Sutcliffe, M., Zhou, J., Viisainen, V. Can a Composite Forming Limit Diagram be Constructed? Project poster, Dr Norman de Bruyne FRS Heritage Award Plaque unveiling in Cambridge, March 2018.
8. Tretyakov, M., Long, A.C., Iglesias, M., Endruweit, A., Matveev, M. Active Control of the RTM Process Under Uncertainty using Fast Algorithms, Project poster at ICMAC, July 2018, University of Nottingham.
9. Veldenz, L., Di Francesco, M., Giddings, P., Kim, B.C., Potter, K. Overcoming Challenges in Manufacturing Complex Structures with Automated Dry Fibre Placement, Project poster at ICMAC, July 2018, University of Nottingham.
10. Warrior, N.A., Chen, S., McGregor, O., Harper, L. Forming Simulations for 3D Curved Sandwich Panels, Project poster at ICMAC, July 2018, University of Nottingham.

Advanced Engineering Show 2019: Oral Presentations

1. Warrior, N. Overview of the EPSRC Future Composites Manufacturing Research Hub, Presented at the Advanced Engineering Show 2019, NEC, October 2019.
2. Gravelle, R. Composites Research Challenge Landscape, Presented at the Advanced Engineering Show 2019, NEC, October 2019.
3. Evans, A. Technologies Framework for Automated Dry Fibre Placement, Presented at the Advanced Engineering Show 2019, NEC, October 2019.
4. Anthony, D. Manufacturing for Structural Applications of Multifunctional Composites, Presented at the Advanced Engineering Show 2019, NEC, October 2019.
5. Endruweit, A. Active Control of the RTM Process Under Uncertainty using Fast Algorithms, Presented at the Advanced Engineering Show 2019, NEC, October 2019.
6. Archer, A. Controlled Micro Integration of Through Thickness Polymeric Yarns, Presented at the Advanced Engineering Show 2019, NEC, October 2019.
7. Chen, S. An innovative Approach to Manufacturing Closed-Section Composite Profiles, Presented at the Advanced Engineering Show 2019, NEC, October 2019.
8. Belnoue, J. Virtual Un-Manufacturing of Fibre-Steered Preforms for Complex Geometries, Presented at the Advanced Engineering Show 2019, NEC, October 2019.

Advanced Engineering Show 2018: Oral Presentations

1. Elkington, M. Tactile Sensing of Defect During Composite Manufacture, Presented at the Advanced Engineering Show 2018, NEC, October 2018.
2. Koncherry, V. New Manufacturing Techniques for Optimised 3D Multiaxial Orthogonal Preforms, Presented at the Advanced Engineering Show 2018, NEC, October 2018.
3. O'Keeffe, C. Multimaterial Hybrid Microbraids, Presented at the Advanced Engineering Show 2018, NEC, October 2018.
4. Potter, K. Automated Fibre Placement: What are the Challenges? Presented at the Advanced Engineering Show 2018, NEC, October 2018.
5. Skordos, A. The Feasibility of Layer by Layer Curing, Presented at the Advanced Engineering Show 2018, NEC, October 2018.
6. Voto, G. Composites Optimised for Rapid Production of Aerospace Components, Presented at the Advanced Engineering Show 2018, NEC, October 2018.
7. Warrior, N. Overview of the EPSRC Future Composites Manufacturing Research Hub, Presented at the Advanced Engineering Show 2018, NEC, October 2018.

Bristol Composites Institute Conference 2018 Poster presentations

1. Radhakrishnan, A., Hamerton, I., Shaffer, M., Ivanov, D.S. Localised Control of Composite Properties using Liquid Resin Printing, Bristol Composites Institute Conference, Bristol, November, 2018.
2. O'Keeffe, C. Hybrid Microbraids – Through Thickness Multifunctionality, Bristol Composites Institute Conference, Bristol, November, 2018.

Oral Presentations

1. Radhakrishnan, A. Can We Achieve Controlled Localised Grading of Composite Properties using Out-of-autoclave Process? Euromech 602 Congress, March 2019, Lyon, France.
2. Turk, M. Optimising the Placement of Localised Resin Patches to Enhance the Formability of Dry Preforms, Euromech 602 Congress, March 2019, Lyon, France.
3. Kazilas, M. Microwave (MW) Heating Through Embedded Slotted Coaxial Cables for Composites Manufacturing (M-Cable), LinkedIn news release: http://www.twi-innovation-network.com/news-events/bcc-successfully-delivers-its-first-epsrc-funded-project/#.XEshRnYw50Q.linkedin
4. Campbell, I. Multi-step Thermoforming of Multi-cavity Multi-axial Advanced Thermoplastic Composite Parts, Project presentation, The IMechE PostGrad Researcher Conference, Glasgow, December, 2018.
5. O'Keeffe, C. Hybrid Multimaterial Microbraids for Through-Thickness Multifunctionality, Project poster at The 4th Edition Smart Materials & Surfaces Conference, SMS, October, 2018.
6. Russell, B. The Processing of a Novel Polymer Matrix for Wind Turbine Blades, Thermosetting Resins, Berlin, September 2018.
7. Sutcliffe, M., Zhou, J., Viisainen, V. Can a Composite Forming Limit Diagram be Constructed? Project poster at high- profile Dr Norman de Bruyne FRS Heritage Award Plaque unveiling in Cambridge, March 2018.

Patents

1. Potluri, P., Jetavat, D., Sharma S. (2017) Method and Apparatus for Weaving a Three-dimensional Fabric, US Patent 9,598,798.

Key People

PhD Students

Matthew Bower
Advanced Manufacturing Research Centre

Iain Campbell
University of Glasgow

Matthew Collinson
Advanced Manufacturing Research Centre

Ubong Equere
Cranfield University

Salem Erouel
University of Nottingham

Dimitris Fakis
Brunel Composites Centre

Albert Gibbs
University of Nottingham

Rob Iredale
University of Bristol

Irene Jimenez-Fortunato
University of Southampton

Christos Kora
University of Nottingham

Chanhui Lee
Imperial College, London

Shimin Lu
University of Nottingham

Wini Obande
University of Edinburgh

Caroline O'Keeffe
University of Bristol

James Mortimer
University of Nottingham

William Mosses
Ulster University

Jinseong Park
University of Manchester

Arjun Radhakrishnan
University of Bristol

Calvin Ralph
Ulster University

Bethany Russell
University of Bristol

Usman Shafique
University of Nottingham

Alice Snape
Advanced Manufacturing Research Centre

Kazi Sowrov
University of Manchester

Matthew Thompson
University of Nottingham

Kostas Tifkitsis
Cranfield University

Mark Turk
University of Bristol

Maria Valkova
Imperial College, London

Verner Viisainen
University of Cambridge

Daniel Wilson
University of Nottingham

Jibran Yousafzai
University of Bristol

Researchers

Dr Debabrata Adhikari
University of Nottingham

Dr David Anthony
Imperial College London

Dr Jonathan Belnoue
University of Bristol

Dr Kaan Bilge
Imperial College London

Dr Aurèle Bras
Cranfield University

Dr Daniel Bull
University of Southampton

Dr Shuai Chen
University of Nottingham

Dr Lawrence Cook
Cranfield University

Dr Dorian Dixon
Ulster University

Dr Thomas Dooher
Ulster University

Dr Michael Elkington
University of Bristol

Dr Andreas Endruweit
University of Nottingham

Dr Anthony Evans
University of Nottingham

Dr Ian Gent
University of Bristol

Dr Robert Hughes
University of Bristol

Dr Alex Ilchev
University of Nottingham

Dr Adam Joesbury
University of Nottingham

Dr Vivek Koncherry
University of Manchester

Dr Dimitrios Mamalis
University of Edinburgh

Dr Asimina Manta
Wrexham Glyndŵr University

Dr Mikhail Matveev
University of Nottingham

Dr Sang Nguyen
Imperial College London

Dr Shankhachur Roy
University of Manchester

Dr Ric (Xiaochuan) Sun
University of Bristol

Dr Logan Wang
University of Bristol

Dr Jin Zhou
University of Cambridge

Investigators

Dr Edward Archer
Ulster University

Professor Janice Barton
University of Bristol

Professor Richard Day
Wrexham Glyndŵr University

Professor Chris Dodds
University of Nottingham

Professor Emile Greenhalgh
Imperial College London

Professor Stephen Hallett
University of Bristol

Dr Philip Harrison
University of Glasgow

Dr Marco Iglesias
University of Nottingham

Professor Derek Irvine
University of Nottingham

Dr Dmitry Ivanov
University of Bristol

Dr Mihalis Kazilas
Brunel University

Dr Eric Kim
University of Bristol

Professor Vasileios Koutsos
University of Edinburgh

Dr James Kratz
University of Bristol

Professor Andy Long
University of Nottingham

Dr Euan McGookin
University of Glasgow

Professor Alistair McIlhagger
Ulster University

Dr Daniel Mulvihill
University of Glasgow

Professor Conchur O'Bradaigh
University of Edinburgh

Dr Andrew Parsons
University of Nottingham

Professor Steve Pickering
University of Nottingham

Professor Prasad Potluri
University of Manchester

Dr Daniel Richards
University of Glasgow

Professor Paul Robinson
Imperial College London

Dr Dipa Roy
University of Edinburgh

Professor Milo Shaffer
Imperial College London

Professor Ian Sinclair
University of Southampton

Dr Alex Skordos
Cranfield University

Professor Michael Sutcliffe
University of Cambridge

Professor Ole Thomsen
University of Bristol

Professor Michael Tretyakov
University of Nottingham

Dr Carwyn Ward
University of Bristol

Advisory Board

Professor Remko Akkerman
University of Twente
Scientific Expert

Dr Rob Backhouse
Rolls-Royce
Industrial Representative

Craig Carr
GKN Aerospace
Industrial Representative

Dr Enrique Garcia
National Composites Centre
Industrial Representative

Dr Tracy Hanlon
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BAE Systems
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Luxfer Gas Cylinders
Deputy Chair of Advisory Board

Professor Mike Hinton
CTO, HVM Catapult
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Hexcel Reinforcements
Industrial Representative

Dame Professor Jane Jiang
University of Huddersfield
Scientific Expert

Professor Ian Kinloch
University of Manchester
Scientific Expert

Professor Veronique Michaud
EPFL
Scientific Expert

Dr Lien Ngo
Innovate UK
Funding Body

Andy Smith
Gordon Murray Design
Industrial Representative

Tim Wybrow
Solvay
Industrial Representative

Leadership Team

Professor Janice Barton
University of Bristol
Deputy Director of IDC

Dr Lee Harper
University of Nottingham
Hub Manager

Dr Warren Hepples
Luxfer Gas Cylinders
Deputy Chair of Advisory Board

Professor Mike Hinton
HVM Catapult
Chair of Advisory Board

Dr Mike Johnson
University of Nottingham
Chair of PDC

Dr Mikhail Matveev
University of Nottingham
Chair of Researcher Network

Mr Andrew Mills
Cranfield University
Deputy Chair of PDC

Professor Ivana Partridge
University of Bristol
Director of IDC

Dr Dipa Roy
University of Edinburgh
Hub Spoke Representative

Professor Ole Thomsen
University of Bristol
Deputy Director – Chair of KEC

Dr Tom Turner
University of Nottingham
Deputy Director – Chair of SDC

Professor Nick Warrior
University of Nottingham
Hub Director – Chair of MG

Support Staff

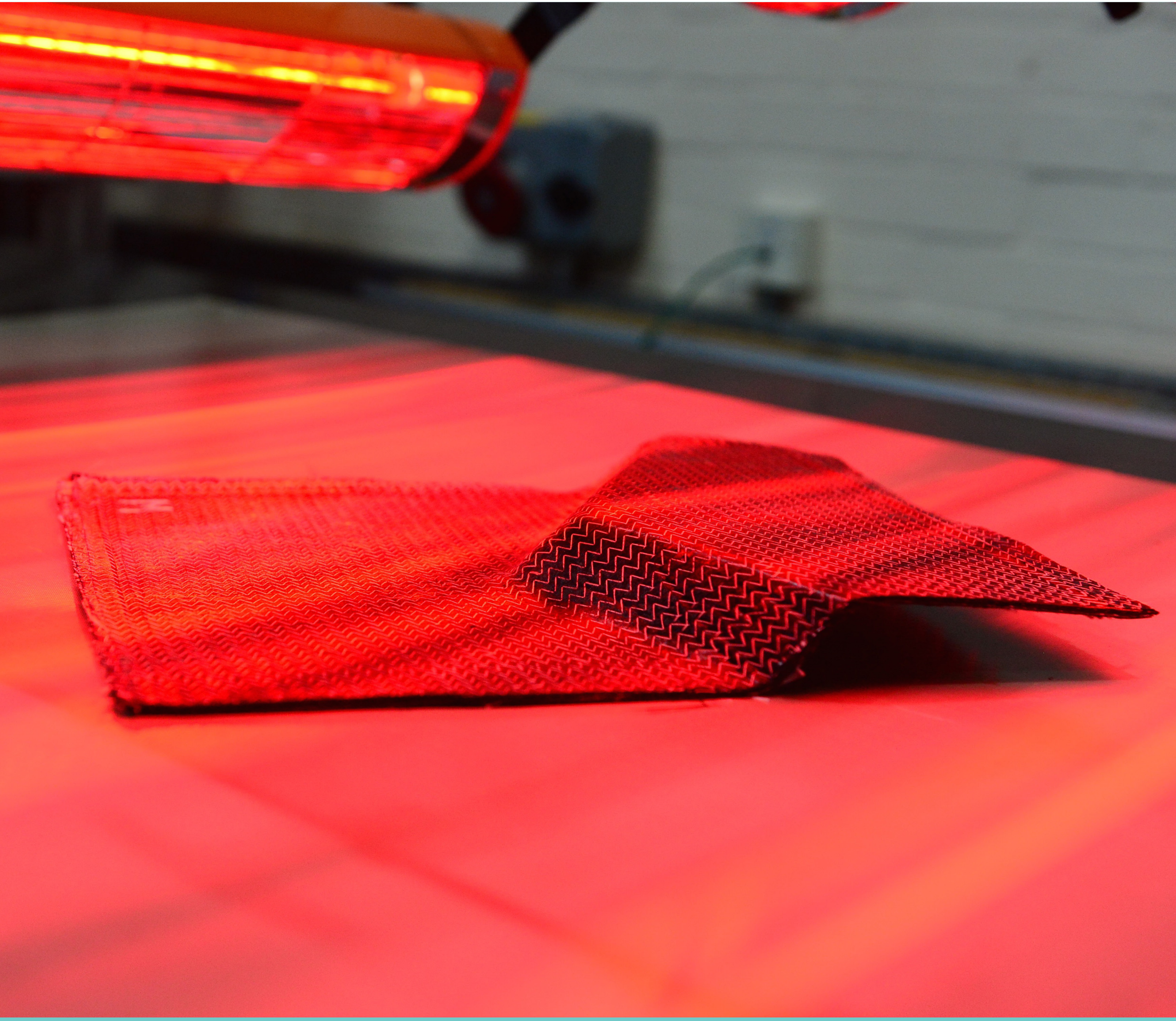
Dr Richard Gravelle
University of Nottingham
Research and Business
Development Manager

Joanne Bradley
University of Nottingham
Hub Administrator

Maria Aviles
University of Bristol
IDC Manager

Kathleen Swales
University of Bristol
IDC Administrator

Simon Wadey
NCC / University of Bristol
Hub Business
Development Manager



cimcomp.ac.uk
hello@cimcomp.ac.uk
EPSRC_CIMComp
+44 (0) 115 951 3823

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Future Composites
Manufacturing Research Hub