CIMComp

EPSRC Future Composites Manufacturing Research Hub

2019/2020

ANNUAL REPORT

Underpinning the development of next generation composites manufacturing processes

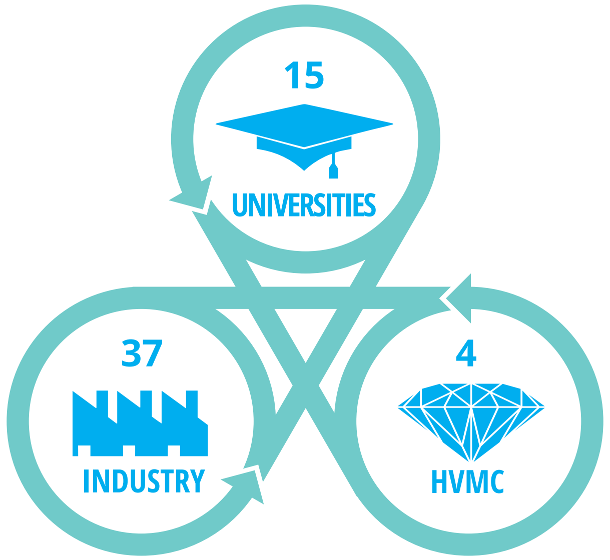
University of Bath
University of Bristol
Brunel University London
The University of Edinburgh
University of Cambridge
Cranfield Manufacturing
Imperial College London
Manchester 1824 The University of Manchester
University of Glasgow
The University Of Sheffield.
University of Southampton
University of Nottingham UK | China | Malaysia
Ulster University
Warwick The University of Warwick
Prifysgol Glyndŵr Wrecsam
Wrexham Glyndŵr University

UKRI Engineering and Physical Sciences Research Council

Contents

1. Headline Achievements

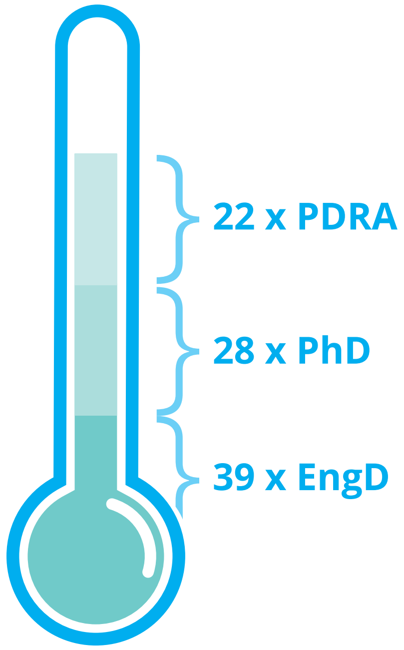
The Hub has grown to a network of



The Hub has expanded to include 15 academic partners, incorporating the leading groups in composites manufacturing within the UK.

Naturally as the Hub has grown, so too has interest from industry. Hub research projects are now supported by a network of 37 industrial partners and 4 High Value Manufacturing Catapult Centres.

We are currently training



The Hub is committed to enhancing the UK skills base in the vitally important composites manufacturing sector.

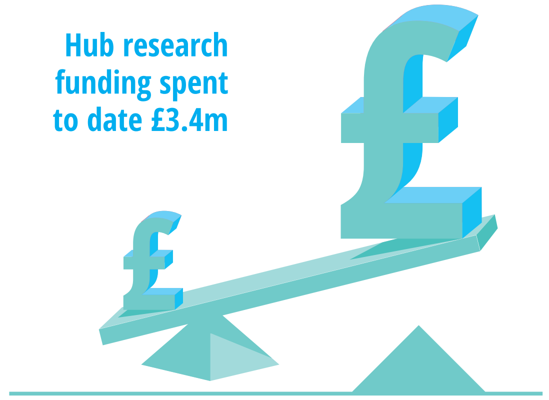
The Hub is acting as a focus for the next generation of composite engineers, currently offering training to 89 postgraduate students and postdoctoral researchers.

SINCE 2017

Publications support the delivery of the Hub programme and vision.

Our researchers have been working hard to disseminate their work widely in high impact factor journals and at international conferences.

For every £1m invested in research by the Hub, we have leveraged £5.8m

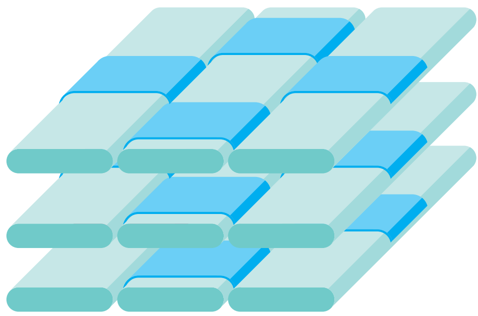


Some of our research has been accelerated thanks to links with associated leveraged projects (which you can see in Section 6.5).

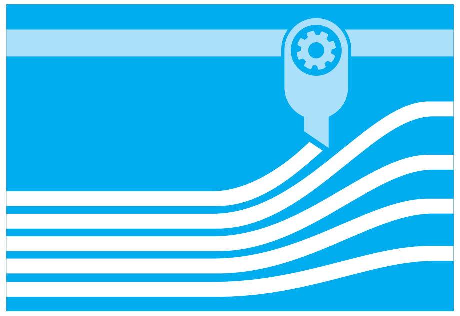
We have worked with our HVM Catapult and industry partners to leverage further funding to enable us to build a wider network and develop key skills, producing £5.8m of research funding for every £1m invested in research by the Hub.

Project Achievements

Optimisation algorithms to design the next-generation of 3D woven textiles for demanding applications

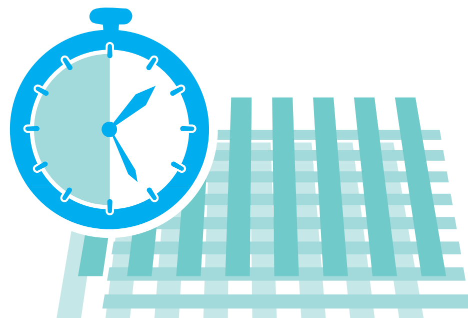


A research-dedicated automated fibre placement machine to understand the process science to improve rate and quality

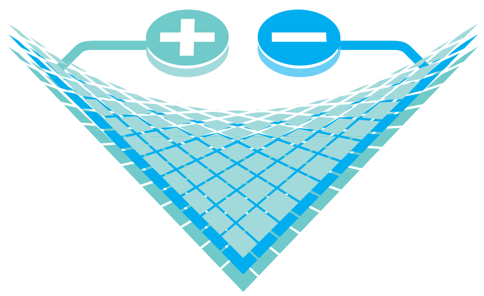


A real-time non-destructive method to evaluate the quality of AFP laminates using eddy currents

A 50% reduction in cure times for thick components using "layer by layer curing"



A viable method to enable structural power composites to be manufactured with complex geometries



2 Hub Vision

"Welcome to the third Annual Report for the EPSRC Future Composites Manufacturing Research Hub. 2020 marks the midway point, so as we look back on some of the highlights and successes of last year – we are also looking forward to new core research to ensure we continue to deliver world class knowledge and understanding against our Grand Challenges."

Prof Nick Warrior
Hub Director

Carbon fibre composite materials offer significant specific structural advantages over metals but continue to be disadvantaged by cost. Constituent material costs are higher than metals but in most cases are overwhelmed by even higher manufacturing costs. In addition, current manufacturing processes cannot meet rate and volume requirements. The aerospace sector has shown that the initial higher costs can be offset by fuel savings over the life of component and by reduction in servicing and inspection schedules, but to date the automotive sector has not overcome the cost barrier in segments outside of high-performance supercars. For many years market predictions have been forecasting a dramatic reduction in the cost of composite materials, but in 2020 this has still not been realised.

Composites manufacturing is the key to successful UK exploitation in aerospace, automotive, energy and rail sectors. The design and manufacture of composites are inextricably linked – the anisotropic nature of the carbon fibres offers opportunities for weight saving via optimised fibre architecture, but greatly increases manufacturing complexity over homogenous isotropic materials. Significant coordinated research funding since 2009 has brought the UK to the forefront of composites material science and design technologies, but investment in manufacturing research still lags behind Europe, USA and China.

Since the Hub launch in 2017 our vision has been to develop a national centre of excellence in fundamental research for composites manufacturing – delivering research advances in cost reduction and rate increase, whilst improving quality and sustainability. Building on the EPSRC and UKRI research funding portfolio investments across the materials, design, characterisation and manufacturing range for composites, the Hub vision is founded on the two key research grand challenges and five supporting research themes detailed in Section 3 of this report. These challenges and themes were originally identified in 2015 in conjunction with our industry partners and the wider composites community. The challenges and themes were revisited and refreshed in 2019 following a significant Hub roadmapping activity, the UK Composites Research Challenge Landscape (CiRCL), and these findings are presented in Section 6.

To date the Hub has expanded to become a consortium of fifteen universities with thirty-seven industrial companies and four HVM Catapult partners. The Hub has increased its research programme from the initial three Core Projects and two Feasibility Studies funded from the outset, to our current status of six Core Projects and eighteen Feasibility Studies, as shown by the timeline image in this section. Within a portfolio of this size there is significant opportunity to maximise productivity by cross-linking research activities and sharing best practice. A change for 2020 has been the move to a workstream based project management approach. Outputs from our research workstreams are detailed in Section 3. These new workstreams were identified and developed at two Synergy Workshops each attended by over forty Hub academics and researchers. We particularly welcome this opportunity to give early career researchers the chance to shape the future of the Hub, and the Synergy Promotion Fund has been launched in 2020 to support these activities. Videos have been created for each workstream, which can be accessed via the QR codes within the Section 3 of the report, where researchers describe their projects.

The Hub's Objectives are depicted below. Under our training remit, six new postgraduate students and seven new postdoctoral researchers have joined the Hub in 2019/20 to increase our cohort size to twenty-eight PhDs, thirty- nine EngDs and twenty- two postdocs respectively. The PhDs and EngDs are based at fifteen universities throughout the UK, working in a wide range of industrial sectors and all researchers are given the opportunity to study the taught EngD modules within the IDC at Bristol (see Section 5), widening their expertise and skills. All researchers meet regularly within the Hub Researcher Network, including presenting their work in a poster and a three minute elevator pitch at the annual Hub Open Day in September 2019. We are pleased in 2020 to announce the appointment of two new Hub Innovation Fellows; Dr Connie Qian (Warwick) and Dr Colin Robert (Edinburgh).

The Hub Open Day is an important element in delivery of our Partnerships objective – helping us to build and grow the UK community. At our Open Day in 2019 we welcomed over 130 visitors to the Advanced Manufacturing Building at the University of Nottingham. An important outreach activity is our annual attendance at the Advanced Engineering Show at the NEC, where in 2019 we hosted a morning full of presentations outlining the Hub and its contributions. Interested parties were able to meet us and continue discussions at our stand, conveniently located adjacent to the forum stage. In 2019 the Hub had a significant presence at the ICCM 22 conference in Melbourne, Australia, presenting seventeen papers and enabling us to continue to build our international networks. International visits were scheduled to Germany and the Netherlands, but these have been cancelled for 2020 - we are investigating the replacement of these with virtual visits with a wider range of partners.

The Hub aims to leverage a further £20m of funding and new projects for 2019/20 are summarised in Section 6. Two exciting international collaborations with the Institute for Advanced Composites Manufacturing Innovation (IACMI) and their partner companies and universities in the USA have recently started - these follow on from the Hub's participation in the Innovate UK International Mission in 2018.

We hope you enjoy reading about the Hub progress in 2019/20. This report and other publications are available to download at our website www.cimcomp.ac.uk.

Hub Objectives

Research

Promote a step-change in composites manufacturing science and technologies

Technology

Create a pipeline of next-generation technologies addressing future industrial needs and developing the national composites strategy

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EPSRC
Future Composites
Manufacturing Research Hub

Training

Train the next generation of composites manufacturing engineers

Partnerships

Build & grow national & international communities in design & manufacture of high-performance composites

Funding Decisions

Funding Decision	Date	Hub Growth
Hub launched	Jan 2017	Initial academic partners include Nottingham, Bristol, Imperial College, Manchester, Southampton and Cranfield
3 Core Projects funded		
	Mar 2017	
6 Feasibility Studies funded	Jul 2017	3 new Spokes join the Hub - Edinburgh, Cambridge, Glasgow
	Sep 2017	
2 Feasibility Studies funded	Dec 2017	1 new Spoke joins the Hub - Brunel
	Jun 2018	
2 Feasibility Studies funded	Aug 2018	
	Sep 2018	
	Dec 2018	
3 Feasibility Studies funded	Jan 2019	3 new Spokes Join the Hub - Ulster, Wrexham, Sheffield
1 Core Project funded	May 2019	
2 Innovation Fellows appointed	Jun 2019	1 new Spoke Joins the Hub - Warwick
3 Researcher feasibility Studies funded	Jul 2019	
	Sep 2019	
4 Feasibility Studies funded	Nov 2019	
	Dec 2019	
2 Core Projects funded	Jan 2020	1 new Spoke Joins the Hub - Bath
5 Synergy Promotion Projects funded	Feb 2020	
	Mar 2020	

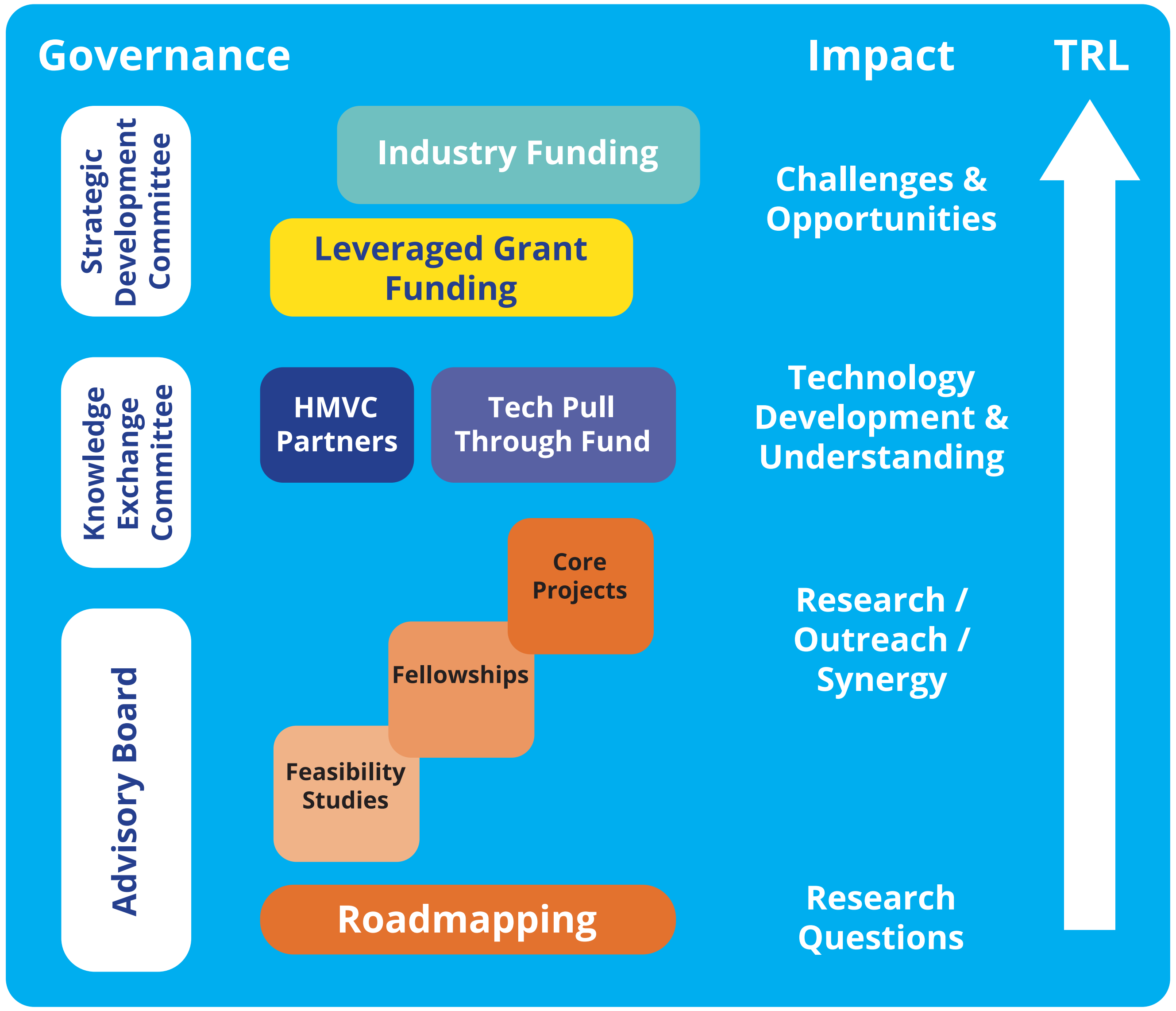
2.1 Pathways to Impact

The principal mechanism for academic partner engagement within the Hub is via Feasibility Studies where successful completion enables the researcher team to apply for Core Project funding.

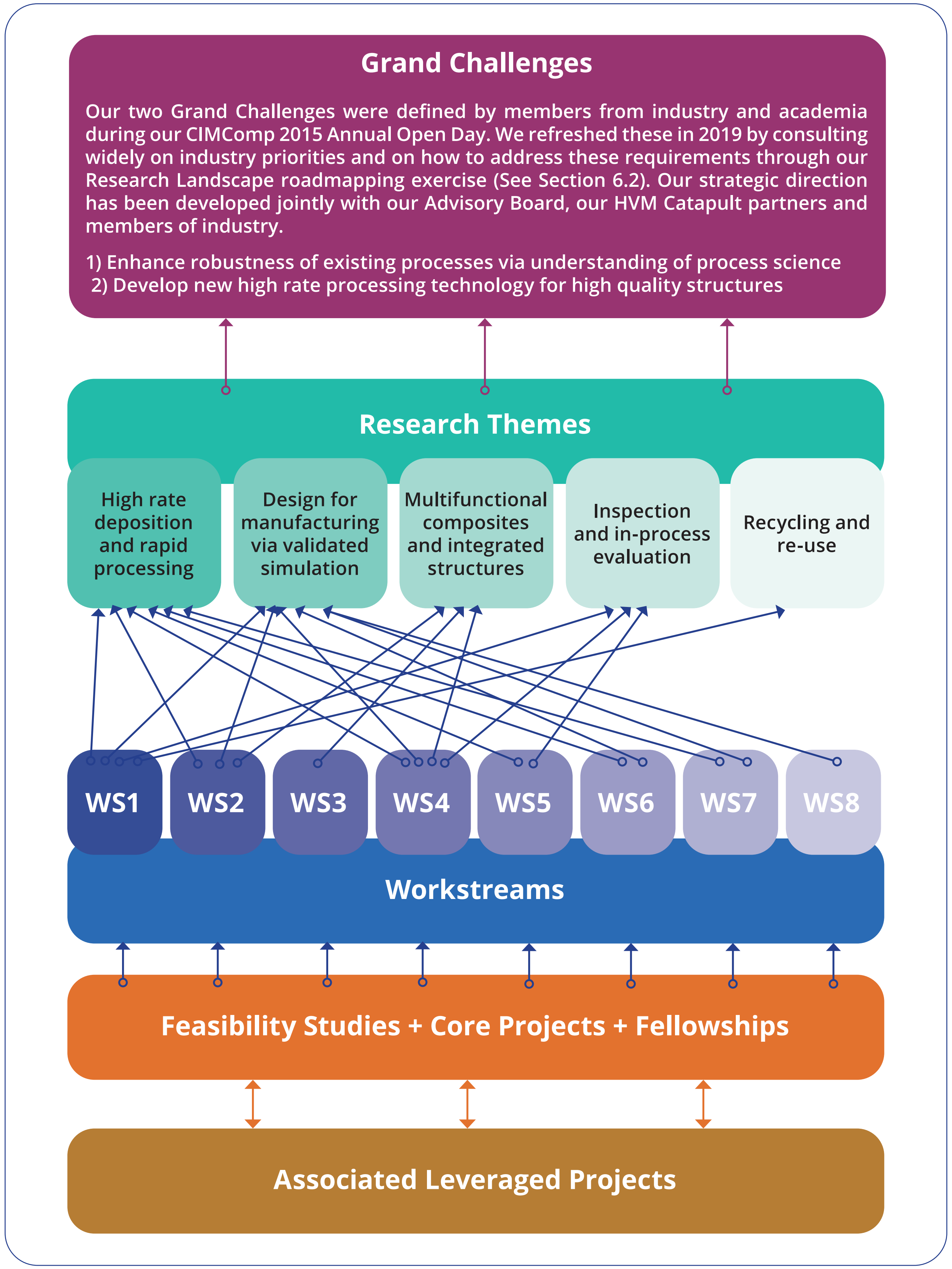
However this is not the only route. The figure below shows the progression of next-generation technologies through the Technology Readiness Levels (TRLs) within the Hub and onwards to our HVM Catapult Centres partners (NCC, AMRC, WMG and MTC).

Our Business Development Team assists in developing projects from completed Feasibility Studies to, for example, EPSRC Responsive Mode and Innovate UK proposals. The Technology Pull-Through fund, introduced by the NCC in 2017 has been expanded and is supporting three new projects for 2020.

The Hub's governance structure is detailed in Section 8. We wish to thank all students, researchers, investigators, members of the Management Board and in particular our Advisory Board for their contributions to the Hub in 2019/20!



3 Hub Research Programme



Research Themes

From the original consultation with our members in 2015, five research priority themes were established to address the two Grand Challenges. These include:

1. High rate deposition and rapid processing technologies: The output from this theme will be new manufacturing processes to enable demonstration of devices & systems that offer ability to challenge existing preconceptions. Key deliverables include fundamental understanding of primary drivers such as component complexity, automation limitations & optimal processing windows.
2. Design for manufacture via validated simulation: This theme aims to develop validated process simulations for automated manufacturing, capable of predicting arising component quality and viability. Use of such tools in component and process design, providing confidence in existing processes and enabling new processes to be introduced.
3. Multifunctional composites and integrated structures: This theme aims to realise the promise and potential of multifunctional composites and integrated structures by demonstrating routes to reliable, cost-effective manufacture. Research outcomes from this theme will provide a framework for developing design practices to support applications across industrial sectors.
4. Inspection and in-process evaluation: This theme considers ways to integrate sensors and sensing systems at the manufacturing process stage to determine the efficiency of the process and identify defects as they evolve. Development of novel prognostic inspection methodologies based on high resolution imaging tailored to the process and the application.
5. Recycling and reuse: Research within this theme will develop improved processes for recovery of high quality fibre from a wide range of waste composite materials, particularly end-of-life materials that are not suitable for existing commercial processes. Development of processes to upgrade recovered fibres for reuse in high grade applications.

Since the Hub was launched in 2017, research initiated through our open calls for Feasibility Studies has largely focused on Themes 1 and 2. Our roadmapping has indicated that these themes contain some of the largest fundamental research challenges, where the Hub is likely to make the most impact in terms of production rate and quality. As we enter the second phase of the Hub, our focus will shift towards the other 3 themes to address process robustness and sustainability, as the manufacturing routes developed within Themes 1 and 2 become more established.

Workstreams

Following a review of the Hub research portfolio and discussions with our academic partners at a series of Synergy Workshops (section 6.1), eight Workstreams have been established to focus the research programme more effectively towards achieving our Grand Challenges. Over thirty projects have been funded by the Hub to date and these Workstreams are being used to improve the synergy between the smaller investments and the large Core Projects.

WS1: Automated Fibre Deposition Technologies
WS2: Optimisation of Fabric Architectures
WS3: Multifunctional Structural composites
WS4: Online Consolidation
WS5: Liquid Moulding Technologies
WS6: Composite Forming Technologies
WS7: Microwave Processing Technologies
WS8: Thermoplastic Processing Technologies

Research Projects

Underpinned by expertise from across our consortium, including our dedicated **Platform Fellows**, our Grand Challenges and associated research priorities are being addressed by a series of collaborative projects involving leaders from academia and industry.

To mitigate against technical risk, each project starts with a **Feasibility Study** which, if successful, leads to a full **Core Project** typically lasting three years. Since our last report in 2019 we have funded £2.2m of new research, including three new Core Projects as a result of four successful Feasibility Studies, two new Innovation Fellows and nine new Feasibility Studies.

These investments have increased the academic partner network to fifteen, including the University of Bath, the University of Sheffield, Ulster University, the University of Warwick and Wrexham Gyndŵr University.

Associated Leveraged Projects

We are committed to growing the research base for the benefit of all of the Hub stakeholders. Associated Leveraged Projects enable us to build a stronger partner network, share equipment and facilities, develop new ideas and retain key skills, see Section 6.5.

Workstreams	Institutions
WS1: Automated Fibre Deposition Technologies	
Core Project: Automated Dry Fibre Placement	Nottingham
Core Project: Fibre Steered Forming Technology	Bristol
Platform Fellow: Automated Manufacturing Technologies & Tactile Sensing	Bristol
Innovation Fellow: Powder-Epoxy Carbon Fibre Towpreg	Edinburgh
Feasibility Study: In-Process Eddy-Current Testing	Bristol
Feasibility Study: Strain-based NDE for online inspection	Southampton
Feasibility Study: Un-Manufacturing of Steered Preforms	Bristol
Feasibility Study: COMPrinting	Edinburgh
WS2: Optimisation of Fabric Architectures	
Core Project: Optimise	Manchester / Nottingham
WS3: Multifunctional Structural composites	
Core Project: Manufacturing for Multifunctional Composites	Bristol / Imperial College
WS4: Online Consolidation	
Core Project: Layer by Layer	Cranfield / Bristol
Feasibility Study: Layer by Layer Curing	Cranfield / Bristol
WS5: Liquid Moulding Technologies	
Core Project: Active Resin Transfer Moulding	Nottingham
Platform Fellow: Permeability testing methods	Nottingham
Platform Fellow: Local Resin Printing for Preform Stabilisation	Nottingham
Feasibility Study: Active Resin Transfer Moulding	Nottingham
WS6: Composite Forming Technologies	
Core Project: Design Simulation Tools for NCF Preforming	Bath / Cambridge / Nottingham
Innovation Fellow: Compression moulding simulation	Warwick
Feasibility Study: Sandwich Panel Forming	Nottingham
Feasibility Study: Composite Forming Limit Diagram (FLD)	Cambridge
Feasibility Study: Braid Forming Simulation	Nottingham
Feasibility Study: Incremental Sheet Forming	Bristol / Nottingham
WS7: Microwave Processing Technologies	
Feasibility Study: Microwave heating through embedded coaxial cables	Brunel
Feasibility Study: Monomer Transfer Moulding	Edinburgh / Nottingham / Sheffield
Feasibility Study: Microwaves for Automated Fibre Placement	Sheffield / Wrexham Glyndwr
WS8: Thermoplastic Processing Technologies	
Platform Fellow: Rapid Processing Routes for Carbon Fibre / Nylon6	Nottingham
Feasibility Study: Thermoplastic Framework	Cranfield
Feasibility Study: In-situ polymerisation of Fibre Metal Laminates	Edinburgh
Feasibility Study: Multi-step Thermoforming	Glasgow
Feasibility Study: Micro-integration of polymeric yarns	Ulster
Feasibility Study: VARIOTHERM	Warwick
Feasibility Study: Thermoplastic Double Diaphragm Forming	Edinburgh / Nottingham

3.2 Project Timeline

Hub Projects by Workstream	2017	2018	2019	2020	2021	2022	2023
WS1: Automated Fibre Deposition Technologies							
Core Project: Automated Dry Fibre Placement							
Core Project: Fibre Steered Forming Technology							
Platform Fellow: Automated Manufacturing Technologies & Tactile Sensing							
Innovation Fellow: Powder-Epoxy Carbon Fibre Towpreg							
Feasibility Study: In-Process Eddy-Current Testing							
Feasibility Study: Strain-based NDE for online inspection							
Feasibility Study: Un-Manufacturing of Steered Preforms							
Feasibility Study: COMPrinting							
WS2: Optimisation of Fabric Architectures							
Core Project: Optimise							
WS3: Multifunctional Structural composites							
Core Project: Manufacturing for Multifunctional Composites							
WS4: Online Consolidation							
Core Project: Layer by Layer							
Feasibility Study: Layer by Layer Curing							
WS5: Liquid Moulding Technologies							
Core Project: Active Resin Transfer Moulding							
Platform Fellow: Permeability testing methods							
Platform Fellow: Local Resin Printing for Preform Stabilisation							
Feasibility Study: Active Resin Transfer Moulding							
WS6: Composite Forming Technologies							
Core Project: Design Simulation Tools for NCF Preforming							
Innovation Fellow: Compression moulding simulation							
Feasibility Study: Sandwich Panel Forming							
Feasibility Study: Composite Forming Limit Diagram (FLD)							
Feasibility Study: Braid Forming Simulation							
Feasibility Study: Incremental Sheet Forming							
WS7: Microwave Processing Technologies							
Feasibility Study: Microwave heating through embedded coaxial cables							
Feasibility Study: Monomer Transfer Moulding							
Feasibility Study: Microwaves for Automated Fibre Placement							
WS8: Thermoplastic Processing Technologies							
Platform Fellow: Rapid Processing Routes for Carbon Fibre / Nylon6							
Feasibility Study: Thermoplastic Framework							
Feasibility Study: In-situ polymerisation of Fibre Metal Laminates							
Feasibility Study: Multi-step Thermoforming							
Feasibility Study: Micro-integration of polymeric yarns							
Feasibility Study: VARIOTHERM							
Feasibility Study: Thermoplastic Double Diaphragm Forming							

Workstream 1

Automated Fibre Deposition Technologies

At the centre of the Workstream is a Core Project involving the University of Bristol and the University of Nottingham. The work at Nottingham titled "Automated Dry Fibre Placement Technology" started in 2017 and aims to investigate the rate and quality limiting barriers during the deposition of dry fibres.

Scan to hear more about the ADFP project

New AFP processing equipment is being developed alongside a novel Digital Twin programming methodology to enable real-time influencing and inspection of the deposition process, ensuring optimum speed and part accuracy. The project is investigating ways to acquire large quantities of real-time data, which will be integrated within the machine to provide real-time control during fibre deposition. The digital twin will subsequently be used to quantify the local permeability effects post deposition to predict preform infusion behaviour through a network based model.

The work at Bristol called "Fibre Steered Forming Technology" started in September 2019 and complements the work at Nottingham. This work aims to rapidly produce components that are not currently manufacturable using conventional AFP, using a combination of novel prepreg material formats and new process developments. Part of the project is based on a successful Feasibility Study, which produced a simulation tool to optimise the fibre path for 2D flat preforms to aid post forming. The "un-manufacturing" simulation produces curved fibre paths to achieve optimal fibre orientations for "as-designed" part geometries. This tool supports the development of the Continuous Tow Shearing (CTS) process to produce curved tow paths to significantly reduce process-induced defects on complex double-curved tools, such as fibre wrinkling. The current work is attempting to modify the CTS process to feed highly-aligned discontinuous fibre tapes, produced from recycled fibres, to further optimise the drapeability of preforms and enable a step-change in material cost.

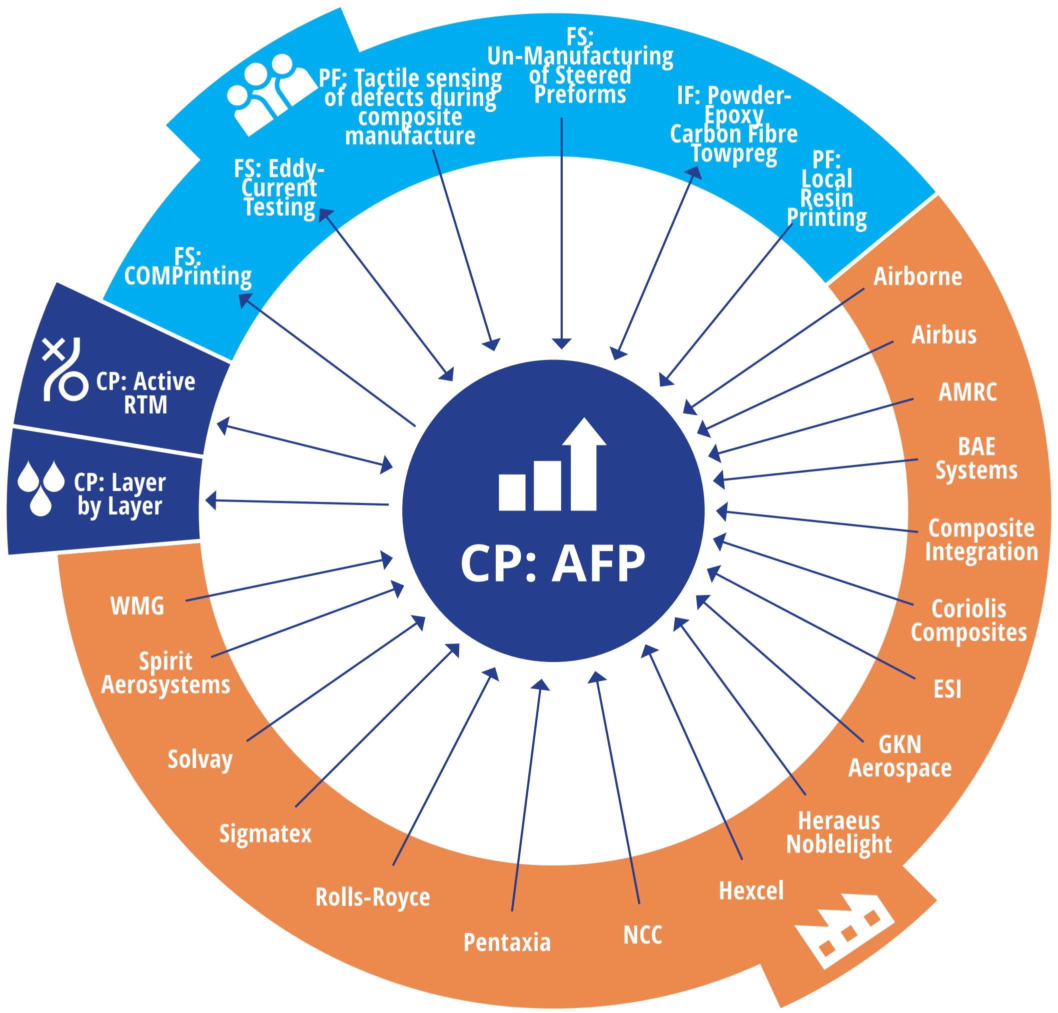
Industry Context

According to the Composite Leadership Forum's Aerospace roadmap, Automated Fibre Placement (AFP) has the potential to transform aerospace wing production to deliver cost effective, higher rate components. AFP of pre-impregnated material is already commonly used in the aerospace sector to produce parts with high speed and repeatability. GKN's production of the A350 wing spar at Western Approach near Bristol and Spirit's production of the 787 fuselage at their site in Wichita, US are just two examples. However, more research is required to enable AFP to deliver its full potential. This is demonstrated by GKN's acquisition of Mikrosam's AFP equipment for thermoplastic composite development and DLR's production of a full-scale wing cover using dry fibre placement in Germany. The UK's Aerospace Technology Institute has recently invested £36.7m in the NCC's iCAP programme, making the UK the best-equipped AFP/ATL research centre in the world. Flexibility in the use of different materials, such as dry preforms, thermoplastic tapes and recycled fibres, optimising design for manufacture and in-line process monitoring are key to broadening industrial applications of this technology. This Workstream is being led by a Core Project delivering cross-university collaboration to provide scientific understanding and analysis of these processes.

Workstream Synergy

Links have been made with the following Hub projects:

- **Core Projects:** A two-way exchange of data and knowledge is occurring between the AFP Core Project at Nottingham and the Active RTM Core Project. This includes preform permeability data and advice on real-time machine control. Similarly, different material deposition methods are being discussed between the Layer by Layer Core Project and the AFP Core Project.
- **Fellowships:** The powder epoxy towpreg being developed as part of the Innovation Fellowship at Edinburgh will be trialled on the ADFP machine at Nottingham once complete.
- **Feasibility Studies:** (1) "Virtual un-manufacturing of fibre-steered preforms" formed the basis for a number of work packages within this Core Project at Bristol. (2) "COMPrinting" will design and manufacturing a novel printer nozzle with a rectangular cross-section to process towpreg being developed at Edinburgh. The printer head shares many similar challenges to the work being delivered at Nottingham and Bristol. (3) "In-process inductive eddy current testing (ECT)" is being explored for AFP, to potentially eliminate separate, post-process inspection times, yielding a step-change in the rate of composite manufacturing. (4) A novel strain-based NDE approach was also investigated in 2017, which showed potential for on-line investigation of the cured composite component but also potential for through–life structural monitoring.



Progress to Date

Scientific highlights from "Automated Dry Fibre Placement Technology":

- Real-time simulations enable pre-manufacturing checks to be conducted for required parameters. Joule heating is under investigation for highly controllable high rate deposition.
- The open-source database file format (HDF5) enables the design, manufacturing and process data to be stored simultaneously in one location. The resulting Digital Twin provides feedback for machine control and offers data for machine learning and design for manufacture.
- The use of online applied powder epoxy and liquid resin printing for preform stabilisation is being investigated for ADFP processes.
- Real-time model-based machine control strategies, have been implemented that are currently not achievable on commercial systems. These enable accurate control of process parameters taking into account real-time changes in material parameters.
- Infusion simulations are being developed that are quicker and capture more application-specific detail than existing simulations.

Scientific highlights from "Fibre-Steered Forming Technology":

- The fibre paths required in flat, tailored preforms to deliver the design intent can be derived from a virtual 'un-manufacturing' simulation. A single ply demonstrator was used to validate the numerical tool, indicating that the fibre angles agreed with the design intent. Efficiency of the simulation tools and material model is being improved. Forming trials demonstrated the defect generation mechanisms on complex geometry and validated the simulation results.
- Sustainable recycled tape has been modified for the AFP process. Forming and CTS layup trials have been performed on tapes and preforms.
- Steering trials with recycled tape samples using the CTS prototype machine investigated the required modifications to feed the highly stretchable tape and to identify important process parameters.

Key Outputs

- Veldenz, L., Di Francesco, M., Giddings, P., Kim, B.C., Potter, K., Material selection for automated dry fiber placement using the analytical hierarchy process, Advanced Manufacturing: Polymer and Composites Science, 2019; Online: 24th January 2019 (): 83 -96
- Di Francesco, M., Veldenz, L., Dell'Anno,G., Potter, K., Heater power control for multi-material, variable speed Automated Fibre Placement, Composites Part A: Applied Science and Manufacturing, 2017; 101 (): 408-421
- Evans, A.D., Turner, T.A., Endruweit, A., Development of Automated Dry Fibre Placement for High Rate Deposition, 22nd International Conference on Composite Materials (ICCM22), Melbourne, Austrailia, 2019.
- Sun, X., Belnoue, J., Kim, B.C., Wang, W., Hallett, S., Virtual Un-manufacturing of Fibre-steered Preforms for Complex Geometry Composites, 23rd International Conference on Material Forming (ESAFORM), Cottbus, Germany, 2020.
- Lu, S., Evans, A.D., Endruweit, A., Turner, T.A., Model based control of automated dry fibre deposition, 12th International Conference on Manufacturing of Advanced Composites (ICMAC), Edinburgh, UK, 2020.

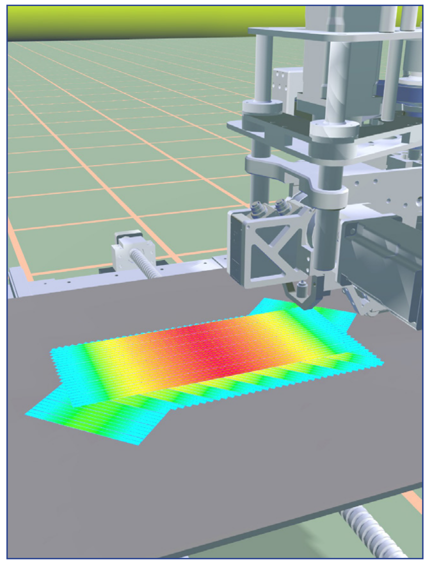


Figure 1 - Digital twin of the Automated Dry Fibre Placement machine at the University of Nottingham. Realtime data such as deposition speed (as shown), preform temperature, gap widths etc can be overlaid on the programmed paths and compared to design data

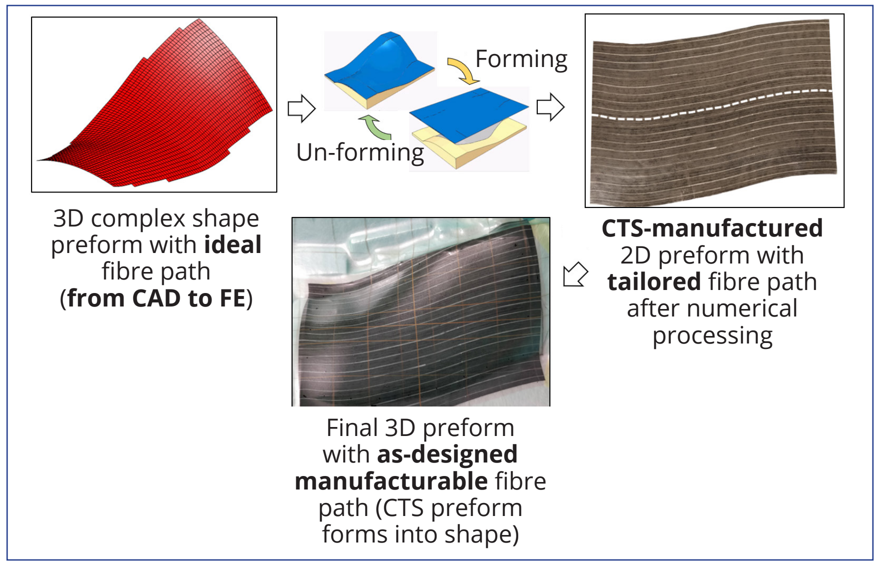


Figure 2 - Virtual 'un-manufacturing' and manufacturing of 2D to 3D preforms using Continuous Tow Shearing (CTS)

Leveraged Contributions

Leveraged Industry Support
£245,360

Leveraged Academic Support
£271,640

Leveraged Grants
£10,078,089

Workstream 2

Optimisation of Fabric Architectures

This Workstream is led by a Core Project which aims to discover new forms of 3D fibre reinforcements to complement and extend currently available 3D textiles such as orthogonal weaves or layer-to-layer weaves. Areas of focus will include braiding and cylindrical preforming. This aim is being achieved by establishing a computational framework for textile preform optimisation not limited to existing manufacturing technologies. The framework is being built and extended based on a series of case studies to identify classes of materials with improved properties. New manufacturing technologies are being developed for these materials and used to validate the predicted properties.

Scan to see our project webpage

A computational framework, based on a "virtual testing" approach, is evaluating properties of various composites designs and together with an optimisation algorithm selecting the best solution. Optimisation algorithms used within the framework enable prediction of the best possible solution or a range of optimal solutions (a Pareto front). A series of case studies, nominated by industrial partners, provide a test ground for the project and will demonstrate the weight-savings or improvement in performance achieved by optimisation of fibre preforms. New manufacturing techniques will be developed to create the optimised fibre preforms, either by the modification of existing textile processes, or by developing entirely new manufacturing processes. The manufactured samples will be used for the validation of the optimisation approach.

Industry Context

The CLF's Aerospace roadmap suggests that through-thickness performance of composites could be improved through the use of 3D woven materials, with the added benefit of reducing the manufacturing/machining time for thick sections using near-net shape preforms. An example of this has already being put into practice with the partnership between Albany and Safran, who are manufacturing 20,000 3-D woven composite fan blades for the LEAP commercial aircraft jet engine each year. One of the issues faced by companies wishing to investigate these technologies is the lack of understanding and global expertise in the design for both optimised material performance and for manufacture of 3D woven preforms.

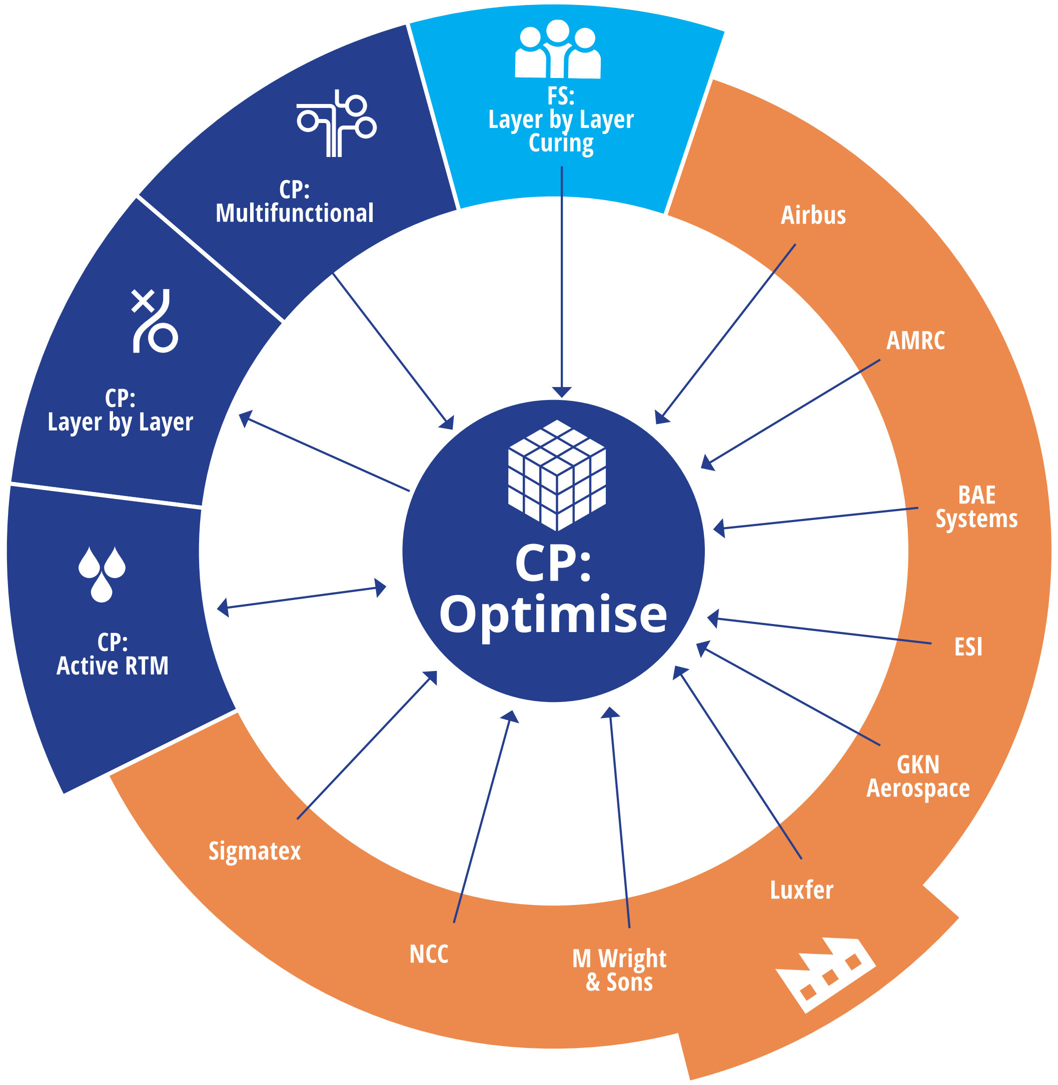
Recent investments in equipment have been made at the UK's High Value Manufacturing Catapult Centre, such as braiding systems and a Jacquard loom to help the UK supply chain research the use of 3D preforms for part production. This investment needs to be matched by a similar investment in the science behind 3D preform design.

This Workstream is being led by a Core Project that was initiated at the start of the Hub, which was the result of a successful Platform Fellowship undertaken during the Centre for Innovative Manufacturing in Composites. "New manufacturing techniques for optimised fibre architectures" is a collaboration between the University of Nottingham and the University of Manchester to develop new simulation and manufacturing capability in the UK for 3D woven materials.

Workstream Synergy

Links have been made with the following Hub projects:

- There is a two-way flow of expertise in coding, modelling and permeability between the Optimise and Active RTM Core Projects.
- Optimise is providing preforming expertise and braided fabrics for the Multifunctional Core Project.
- The Layer by Layer Core Project will take advice from the Optimise project team when further developing the numerical optimisation code used in the earlier Layer by Layer Feasibility Study.



Progress to Date

The computational optimisation framework has been implemented and this has been used to support the development of new preforming technologies, which are being applied to selected demonstrators – a pressure vessel and an automotive floor pan. The 1m x 1m floor pan has successfully been created, as shown below

Scientific highlights:

- Implementation of efficient and accurate multi-scale modelling techniques linked to a multi-objective optimisation framework.
- The development of a near-conformal meshing technique to create models of reinforcements of arbitrary complexity. The source code for the meshing is available online as part of TexGen, the University of Nottingham's open-source for modelling the geometry of textiles, which is downloaded by more than 6,000 users/year.
- The development of novel preforming techniques to manufacture flat and tubular multi-axial 3D fibre preforms.
- The development of multi-functional, multi-material 3D preforming technique in conjunction with multi-axial preforming (trials are being conducted for the Multi-functional Core Project, as well as industrial partners including BAE Systems).
- The demonstration of novel optimised 3D multiaxial preforms to give at least an additional 10% weight-saving when compared to optimised non-crimp fabrics (NCFs).

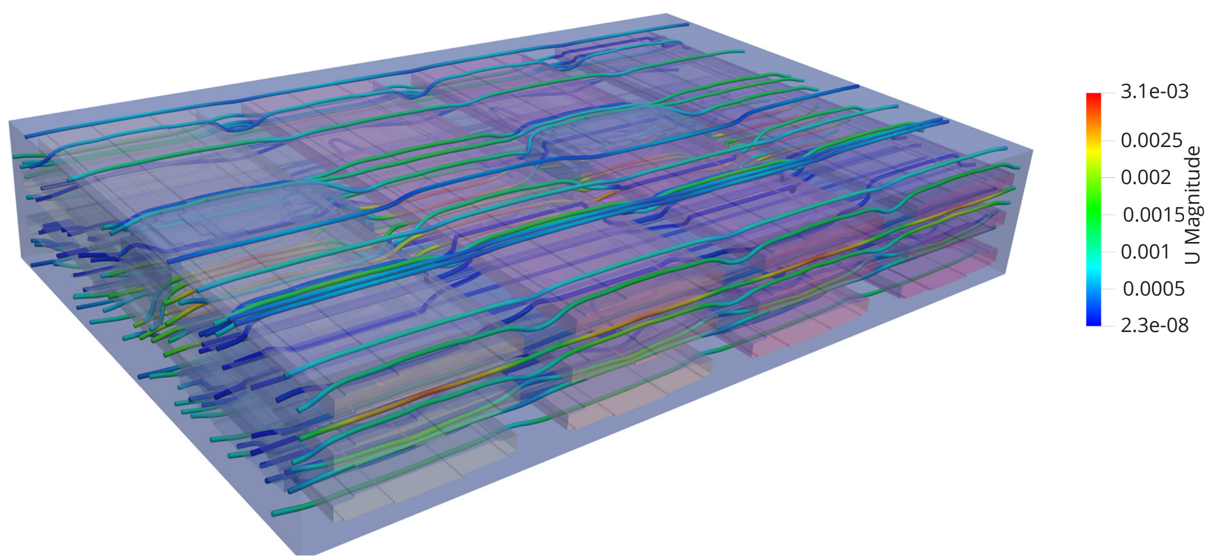
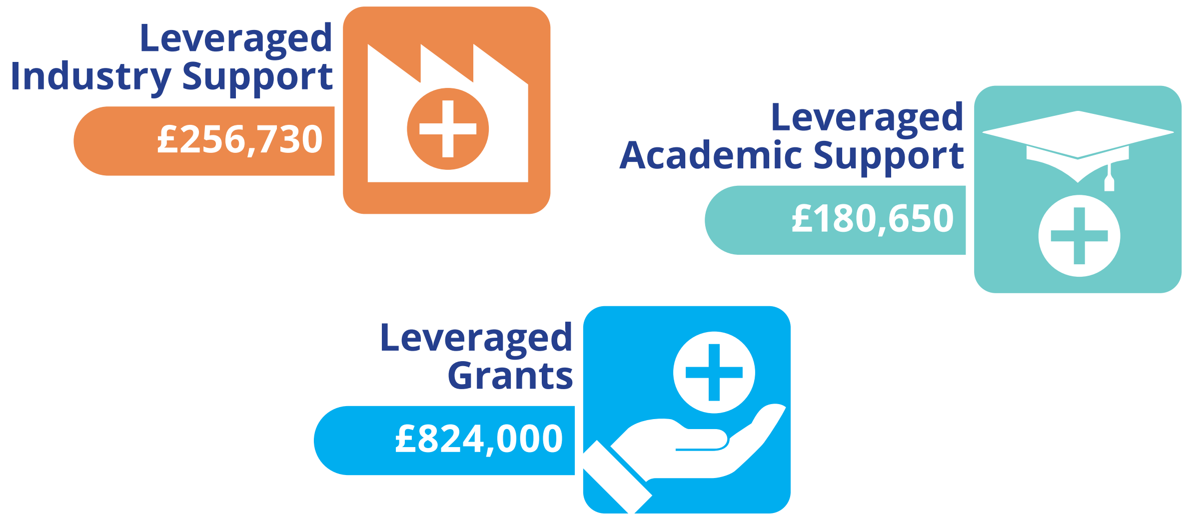


Figure 1. Vectors indicating resin flow velocity through a 3D woven fabric.

Key Outputs

- Yan, S., Zeng, X., Long, A.C., Meso-scale modelling of 3D woven composite T-joints with weave variations, Composite Science and Technology, Vol 171, pp 171-179, 2019.
- Koncherry, V., Park, J.S., Sowrov, K., Matveev, M., Brown, L.P., Long, A.C., Potluri, P., Novel manufacturing techniques for optimised 3D multiaxial orthogonal preform, ICCM 2019.
- Matveev, M., Long, A.C., Brown, L.P., Meso-scale optimisation of 3D composites and novel preforming techniques, ICCM 2019.
- Yan, S., Zeng, X., Long, A.C., Experimental assessment of the mechanical behaviour of 3D woven composite T-joints, Composites Part B, Vol 154, pp 108-113, 2018.
- Yan, S., Zeng, X., Brown, L.P., Long, A.C., Geometric modeling of 3D woven preforms in composite T-joints, Textile Research Journal, Vol 88(16), pp 1862-1875, 2018.
- Matveev, M., Koncherry, V., Roy, S., Potluri, P., Long , A.C., Novel textile preforming for optimised fibre architectures, IOP Conference Series: Materials Science and Engineering. 406. 012050.
- Patel, D., Koncherry, V., Yousaf, Z., Potluri, P., Influence of 3D weaving parameters on preform compression and laminate mechanical properties, ICCM 2017.
- Roy, S.S., Yang, D., and Potluri, P., Influence of Bending on Wrinkle Formation and Potential Method of Mitigation, ICCM 2017.
- Potluri, P., Jetavat, D., Sharma S. (2017) Method and Apparatus for Weaving a Three-dimensional Fabric, US Patent 9,598,798.
- Potluri P. - EPSRC Impact Acceleration Grant (£215k) with Axon Automotive.
- Potluri P. - Subcontract (£110k) from ATI Future Landing Gear Programme for complex 3D woven architectures.

Leveraged Contributions



Workstream 3

Multifunctional Structures

The overarching aim of the Core Project within this Workstream is to create a set of tools (models/case studies/good practice) to facilitate the design and manufacture of complex, multi-functional structures. These will be used to overcome the challenges associated with using multifunctional materials and provide a holistic methodology to compare and contrast current and future multifunctional systems. One specific application will be investigated – structural power from supercapacitors developed through embedding structural carbon fibres in a carbon aerogel (CAG). CAGs are currently unsuitable for structural applications alone, but they can be combined with structural carbon fibres to act as a scaffold to support them. This project will build on previous extensive materials R&D and investigate and address the design and manufacturing issues associated with these CAG-based multifunctional composites to facilitate industrial manufacture of multifunctional parts. There are two key objectives:

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1. To explore the manufacturing issues associated with the creation of structural power materials (structural supercapacitors) formed into complex geometries, which will simultaneously store and deliver electrical energy whilst carrying mechanical loads.
2. To explore the design and manufacture of multi-matrix / multi-fibre composites to optimise heat and electrical conduction.

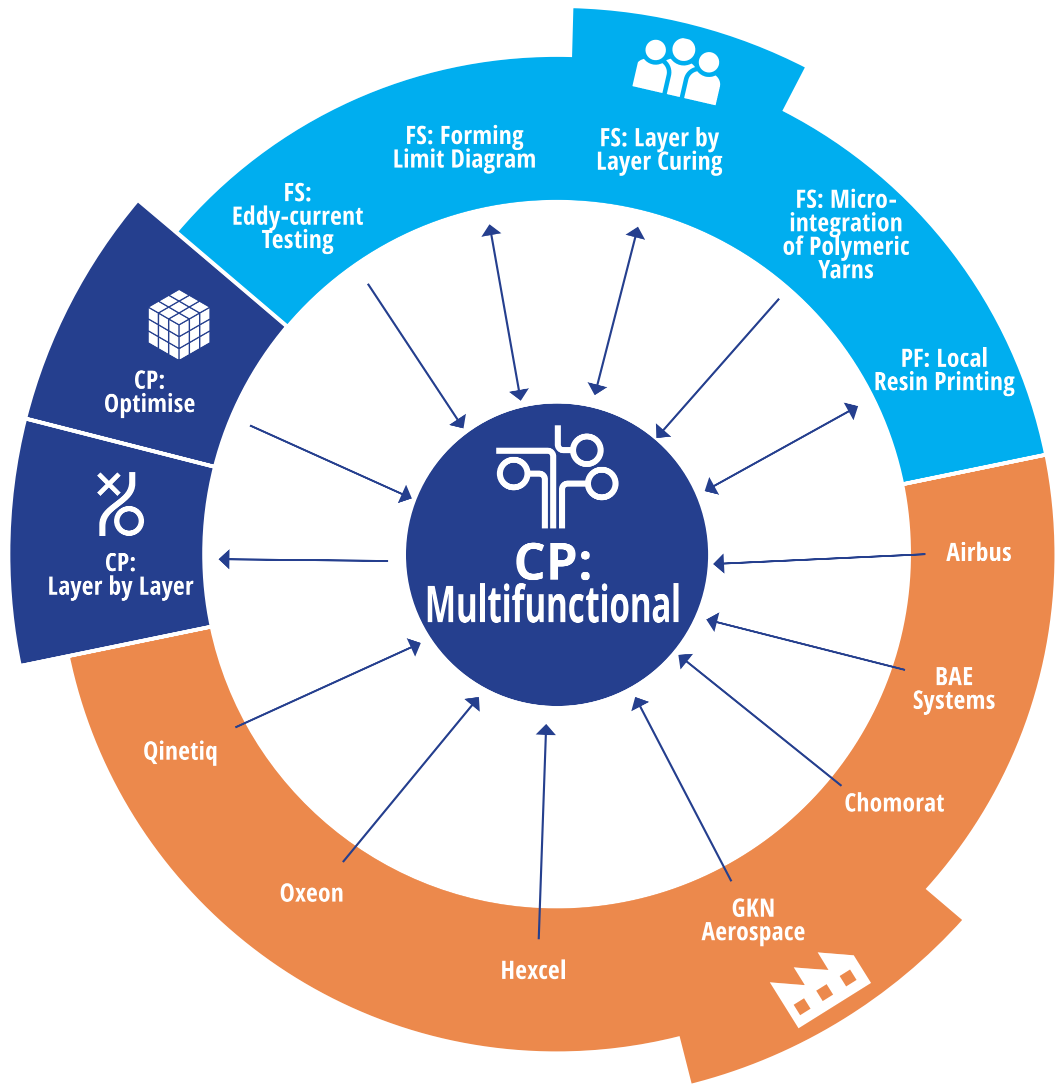
Industry Context

There is an international race to develop and capture the market for complex, multi-functional, integrated composite structures for use in the aerospace sector. The development of composites has historically focussed on structural performance, with any attempt to include functionality generally consisting of embedding systems rather than utilising multifunctional materials. Multi-functional composite structures could replace power systems, wiring or actuators, significantly reducing the complexity and weight of assemblies to provide significant market advantage. The UK is keen to retain its world-class position in the development of complex aerospace structures, as evidenced by the ATI's Aerostructures Roadmap. This roadmap demonstrates that the UK Aerospace sector is looking for solutions that deliver structural health monitoring, embedded systems, structural power and morphing. Projects within this Workstream aim to address the manufacturing challenges to integrate multifunctional mass/heat/charge transport capabilities within complex structural configurations, such as doubly-curved surfaces, sandwich panels, and plates with stiffeners and frames. The Workstream is led by a Core Project at the University of Bristol and Imperial College London, developing structural composite supercapacitors. The UK is well positioned to commercialise these technology developments, having three aerospace Tier 1s actively developing and delivering composite structures, including GKN Aerospace, Spirit Aerostructures and Aernnova.

Workstream Synergy

- **Core Projects:** The Core Project 'Optimise' is providing support to this project through the provision of knowledge and the supply of braided fabrics. The Multifunctional Core Project is providing support on local preform stabilisation to the new Layer by Layer project.
- **Fellowships:** There is a two-way exchange of information between the Multifunctional Core Project and the Platform Fellowship at the University of Nottingham, 'Local Resin Printing for preform stabilisation'.
- **Feasibility Studies:** The Feasibility Study 'Can a composite forming limit diagram be constructed?', which subsequently became a Core Project, has similar goals in terms of understanding wrinkle formation, so best practice is being shared.

  The use of eddy current inspection is being investigated with the support of the Feasibility Study at the University of Bristol 'Evaluating in-process eddy-current testing of composite structures'. Initial discussions have also taken place around sharing of know-how on through-thickness reinforcement from the Feasibility Study conducted at Ulster University, 'Controlled Micro Integration of Through Thickness Polymeric Yarns', to facilitate multifunctionality.



Progress to Date

A viable method has been developed to enable structural power composites to be manufactured with complex geometries. A novel printing process developed within the Hub has enabled the rigid regions of load-bearing supercapacitors to be integrated into standard formable textiles. Validated simulation tools have been created to support the manufacturing process, by optimising the position of the functional and stabilising elements to control the forming deformation and mitigate against defects.

The process for manufacturing carbon aerogel-reinforced structural power devices has also been scaled up, enabling batch production of laminates to be made with a higher carbon aerogel content than previously achieved. Current collection efficiency and CAG production have been identified as limiting factors to scale up, but solutions are currently being explored.

Functional sub-reinforcement has been successfully incorporated using a combination of microbraiding subsequent tufting to incorporate metallic filaments. Tailored matrix and reinforcement placement expands the number of added properties, such as electrical conductivity, providing potential solutions for current collection from the multifunctional parts. There is also the potential to enable sensing, develop new approaches to heating and curing, and facilitate laminate repair.

Small-scale multifunctional devices have been made and tested electrochemically. Electrochemical deposition has successfully been used to add active elements onto the carbon aerogel, along with the use of new separator materials, have further enhanced the electrochemical performance of the CAG material. Power density figures now exceed the original target of 1kW/kg.

Scientific highlights include:

- Energy and Power densities of 1.4Wh/kg and 1.1 kW/kg respectively achieved.
- Method demonstrated to mask/barrier multifunctional/ monofunctional zones in the CAGed lamina, facilitating complex part production.
- Scale up of CAGed lamina production (x15) demonstrated to give 1m² per batch.
- Sensing and accelerated heating of materials using micro-braids demonstrated.
- An approach to integrate functionalised resins into fabric without vacuum has been demonstrated, achieving high levels of local functional properties.

Key Outputs

- M.A. Turk, B. Vermes, A.J. Thompson, J.P.-H. Belnoue, S.R. Hallett, D.S. Ivanov, Mitigating forming defects by local modification of dry preforms, Composites Part A: Applied Science and Manufacturing, Vol 128, 2020, 105643
- S. Nguyen, D. B. Anthony, H. Qian, C. Yue, A. Singh, A. Bismarck, M.S.P. Shaffer, E.S. Greenhalgh, Mechanical and physical performance of carbon aerogel reinforced carbon fibre hierarchical composites, Composites Science and Technology, Vol 182, 2019, 107720
- M. Valkova, D.B. Anthony, A.R.J. Kucernak, M.S.P. Shaffer, E.S. Greenhalgh, Predicting the compaction of hybrid multilayer woven composite reinforcement stacks, Composites Part A: Applied Science and Manufacturing, Vol 133, 2020, 105851
- Greenhalgh, E., En route to "massless" energy storage with structural power composites, JEC Magazine, Nov 2019.

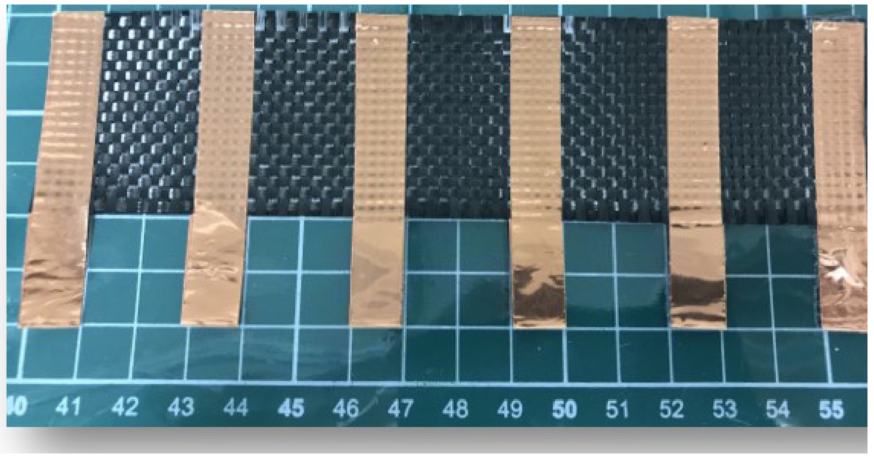


Figure 1 - Coupon used to investigate different current collection devices

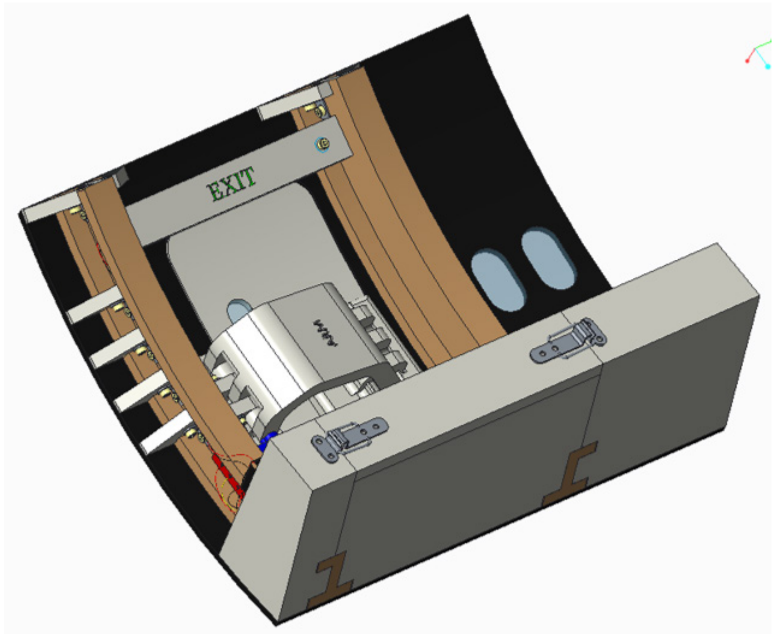


Figure 2 - Detailed design of aerospace door mechanism demonstrator incorporating structural supercapacitor C-section beam

Leveraged Contributions

Leveraged Industry Support £25,250

Leveraged Academic Support £388,500

Leveraged Grants £1,950,000

Workstream 4

Online Consolidation

This Workstream is led by Core Project Layer by Layer (LbL) Curing which aims to develop the scientific and technological tools necessary for industry to successfully implement the LbL concept, and to establish the new process at the scale and level of complexity required for application to advanced composite structures. This will be achieved by addressing the following objectives:

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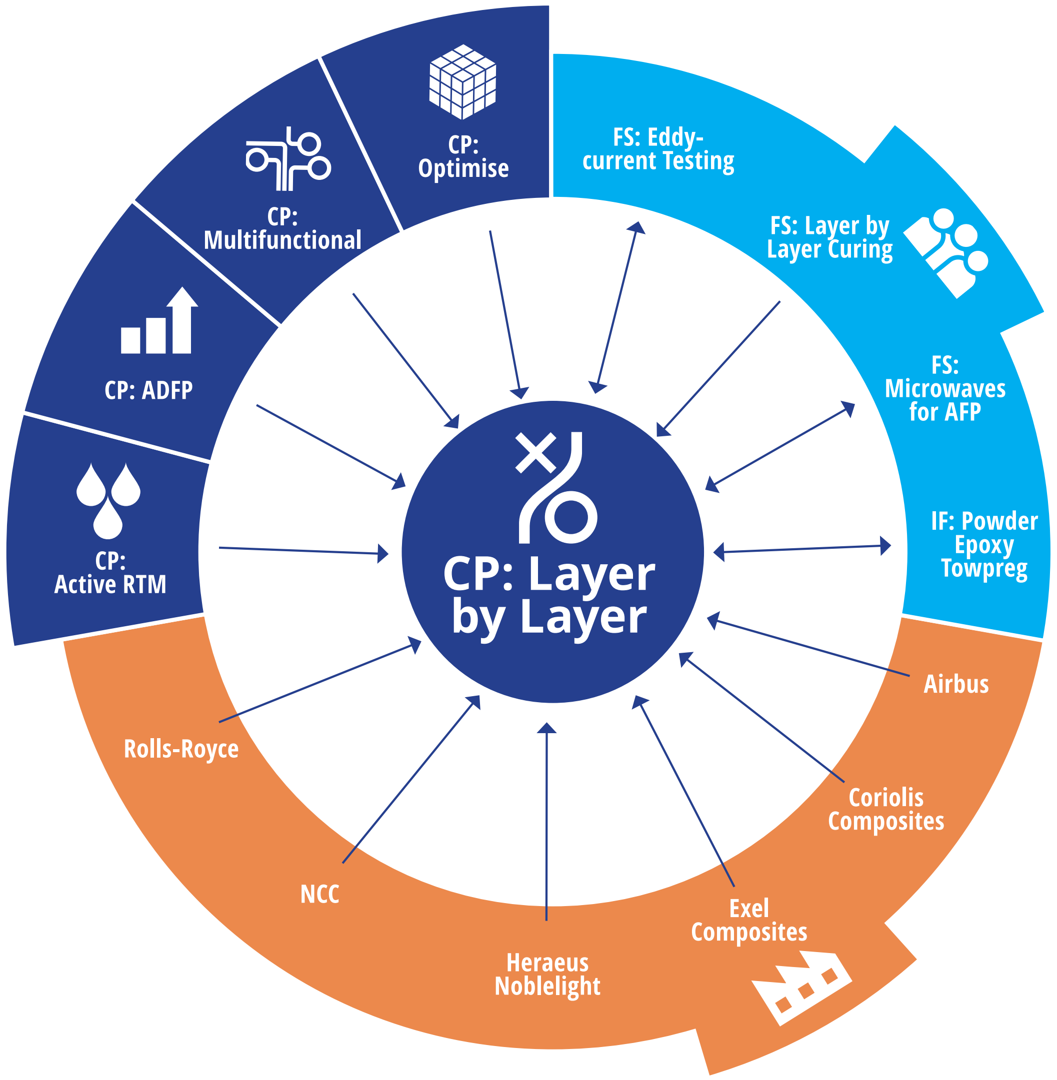
1. Development of fully coupled 3D simulation of the LbL process, combining appropriate modelling tools in an open source interface.
2. Development of constitutive models and associated characterisation using conventional and snap curing systems with LbL curing.
3. Process optimisation to maximise interfacial toughness, minimise process duration and control residual stresses.
4. Development of tailored process setups for complex geometries/components, including end effectors and zonally heated reusable bagging.
5. Optimisation of LbL process implementation to minimise defect generation due to ultralow viscosity, ply drop offs, gaps and curvature.
6. Demonstration of applicability based on pilot scale LbL implementations of automated fibre/tape placement, pultrusion and filament winding.
7. Demonstration of LbL process capabilities through the development of hybrid thermoset/thermoplastic components, stabilised preforms and laminates with tailored residual stress state.

Industry Context

The UK's Composites Strategy (2016) identified that there was an urgent need to move to automated lay-up to reduce production time for high performance composite structures manufactured from pre-impregnated material. However, whilst hardware manufacturers strive to reduce material deposition time, the consolidation and/or cure time of the preformed material is also a major bottleneck, especially for thick thermosetting parts where risk of exotherm requires slow cure cycles. This was identified in more detailed roadmapping work performed by the CLF's Aerospace and Automotive Groups. The Aerospace Group identified that novel heating/curing systems was a potential route to resolve this problem and work by the Automotive Group recommended a reduction in the number of process steps. Projects within this Workstream aim to address both of these concepts, led by a Core Project at Cranfield University and the University of Bristol called Layer by Layer (LbL) Curing. This project started in June 2020 and was the result of a successful Feasibility Study, which demonstrated the potential for significant reduction in composite part production time by simultaneously curing prepreg during deposition.

Workstream Synergy

- **Core Projects:** Optimise and Active RTM will provide advice on numerical optimisation code. Multifunctional will provide expertise on forming of stabilised preforms.
- **Fellowships:** The powder epoxy towpreg being developed as part of the Innovation Fellowship, along with the know-how generated in the ADFP Core project for laying down dry fabric will be trialled to produce parts in combination with the LbL process. The processing outputs and modelling developed in LbL will be used to support the development of the epoxy towpreg manufacturing process.
- **Feasibility Studies:** Expertise developed as part of the Feasibility Studies to develop microwave heating and eddy current inspection for high rate automated deposition will be transferred to the LbL process in the future.



Progress to Date

The LbL Feasibility Study previously demonstrated:

- ~50% saving in cure times for thick components.
- Linear scaling of process time with component thickness, making manufacturing of ultra-thick components feasible.
- Using LbL process to merge consolidation with curing for planar geometries provides equivalent quality to conventional autoclave process.
- Interfacial properties preserved in partially cured interfaces for pre-cure below gelation.

Work is underway in the new Core Project to:

- Commission a filament winding rig at Cranfield University for the implementation of the LbL process.
- Investigate quality of partially cured interfaces, hybrid thermoplastic/thermoset laminates and AFP simulation, as part of leveraged postgraduate projects.

Figure 1 - 40 mm thick glass/epoxy composite successfully produced using the LbL process

Key Outputs

- Belnoue, J., Sun, R., Cook, L., Tifkitsis, K., Kratz, J., Skordos, A.A., A layer-by-layer (LbL) manufacturing process for composite structures. ICMAC 2018, July 2018, Nottingham
- Mesogitis, T., Kratz J., Skordos, A. A., Heat transfer simulation of the cure of thermoplastic particle interleaf carbon fibre epoxy prepregs, Journal of Composite Materials 2019, 53(15), pp. 2053–2064.
- An EPSRC Impact Accelerator Account was awarded for a project with Airbus (Oct 2019 to Mar 2020) 'Infusion of integrated structures with partially cured elements' with a leveraged grant value of £97,864. The concepts developed in the LbL Feasibility Project were used to partially cure a part that was integrated into a demonstrator. The scientific challenges identified in the higher TRL demonstrator are being addressed in the LBL Core Project, as part of an Airbus sponsored CDT studentship.

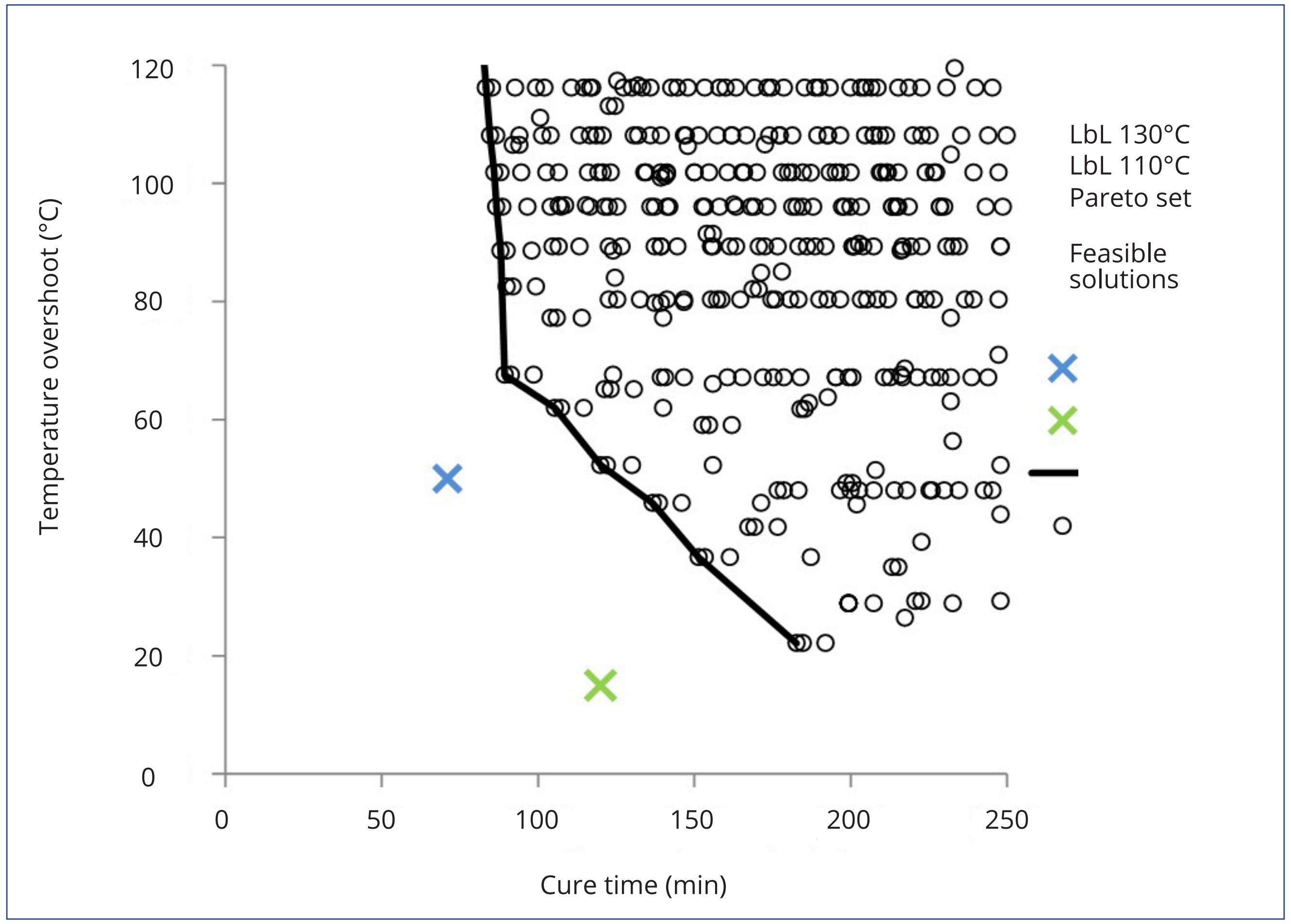


Figure 2 - Shifting of the time-temperature overshoot trade-off surface by using the LbL process for the curing of a 40 mm thick glass/epoxy prepreg

Leveraged Contributions

Leveraged Industry Support
£135,000

Leveraged Academic Support
£261,000

Leveraged Grants
£98,000

Workstream 5

Liquid Moulding Technologies

The aim of the core project within this Workstream is to create an in-process NDE system for the RTM process. There are two objectives to achieve this aim:

Scan to hear about the project

1. The creation of a digital twin for the RTM process to capture in-process data to estimate local deviations from the design for any manufactured part. The project will develop, improve and test innovative Bayesian inversion algorithms (BIA) to restore the local permeability of composite components, based on data collected from sensors during resin injection into the reinforcement.
2. The project will develop and test an active control system based on information frsensors and on physical models together with on-line parameter estimation algorithms to improve resin injection. This control system will minimise the occurrence of defects and ensure process robustness.

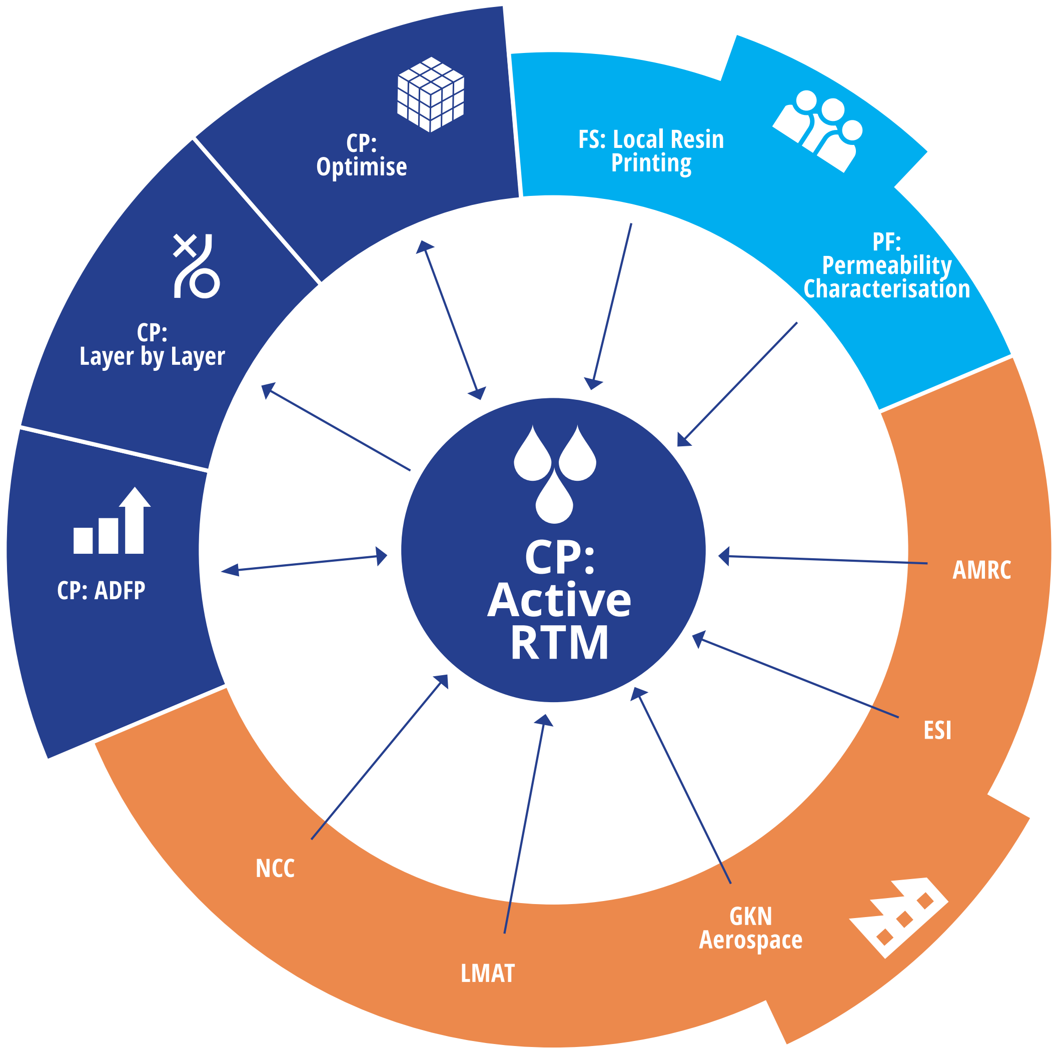
These objectives are being delivered using an interdisciplinary approach using a two-way flow of both challenges and solutions between engineers and applied mathematicians, which will lead to a set of algorithms and tools that can be applied across a wide variety of technologies and industry sectors.

Industry Context

The Composites Leadership Forum's (CLF) roadmap highlighted the need for the UK composite supply chain to offer composite processing technologies to OEMs that are capable of delivering cost-effective composites at higher production rates. Resin transfer moulding (RTM), which involves injection of resin into a dry fabric preform, is one of the processes being explored by industry. Spirit's development of the composite spoiler for the A320 at Prestwick and McLaren's production of the composite tub for their road cars in Sheffield are just two recent applications of this process in the UK. To ensure continued uptake across a variety of sectors, industry needs to be sure that the process is repeatable with minimal possibility for defects. Defects such as incomplete resin filling are caused by uncertainties in the material and process parameters, which cannot be fully eliminated. To counteract the effect of these, manufacturers use conservative designs with larger safety factors that increase manufacturing and life-cycle costs. Post process non-destructive evaluation (NDE) and rework of defects can take up to 30% of the overall manufacturing time in the aerospace industry. Finding in-process solutions for defect and deviation mitigation is of high priority to industry as recognised by its listing a short-term requirement in the CLF Aerospace Group technology roadmap. This Workstream is led by a Core Project at the University of Nottingham investigating the application of in-process information from sensors during resin injection to produce an active control system to counteract random deviations from the original design. The project is currently supported by Dr Andreas Endruweit, a previous Hub Platform Fellow, who was recently involved in an international exercise to benchmark fabric permeability characterisation methods. He brings experimental and simulation expertise on resin flow through porous media.

Workstream Synergy

- **Core Projects:** A two-way exchange of data and knowledge is occurring between the Active RTM Core Project and several of the other Core Projects:
  - **ADFP - Preform permeability and real-time machine control.**
  - **Optimise – Expertise in coding, modelling and**
  - **Layer by Layer - Advice on numerical optimisation code, control systems and data collection.**
- **Fellowships:** Potential for using the know-how generated in the Feasibility Study investigating the use of eddy currents for NDE has been recognised and will be explored.
- **Feasibility Studies:** Data gathered by the Platform Fellowship involved in the Round Robin on fabric permeability characterisation has been used to inform the project. The Platform Fellowship investigating 'Local resin printing for preform stabilisation' will help to modify the local permeability of preforms through resin printing. This will be used as a controlled way of validating the BIA method for restoring the local permeability.



Progress to Date

The Core Project only started in November 2019. Scientific highlights from the preceding Feasibility Study include:

- Novel Bayesian Inversion algorithms were developed for detecting defects during the RTM process using in-process data
- Virtually and laboratory testing of the algorithms has demonstrated that they can estimate location of defects of arbitrary shape including race tracking.

Ahead of the start of the Core project a three-month EPSRC Impact Exploration project involved meetings with seven companies. They all expressed an interest in the project and gave valuable feedback for further shaping the Core project towards the industrial needs. Further collaboration is currently being developed with three of the companies (Jaguar Land Rover, Surface Generation and ESI).

Key Outputs

- EPSRC Impact Exploration grant. Oct-Dec 2019, £8k.
- EPSRC Case studentship granted Mar 2020. ESI committed £32K cash and £360K in-kind contribution.
- M.Y. Matveev, A. Endruweit, A.C. Long, M.A. Iglesias, M.V. Tretyakov, Fast algorithms for active control of mould filling in RTM process with uncertainties. 14th International Conference of Flow Processing in Composite Materials (FPCM14), May 2018.

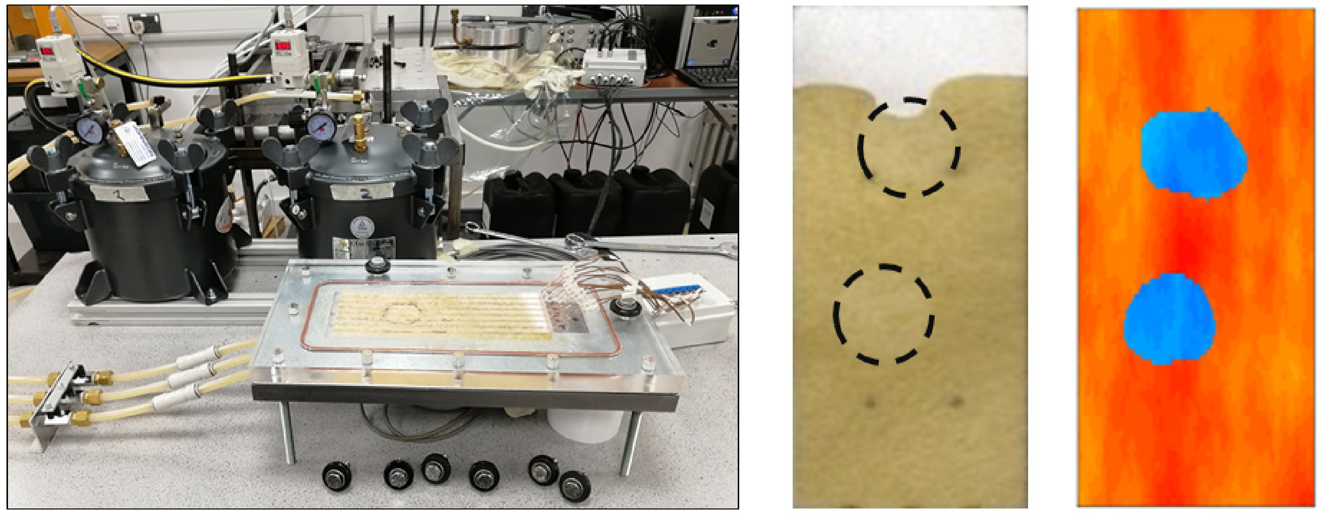


Figure 1 - Left: RTM tool with 6 pressure transducers and 7 linear flow front sensors; Centre: Flow front in a preform with defects (regions of higher fibre volume fraction shown with black circles); Right: Local porosities predicted using Bayesian Inversion based on real data from the sensors.

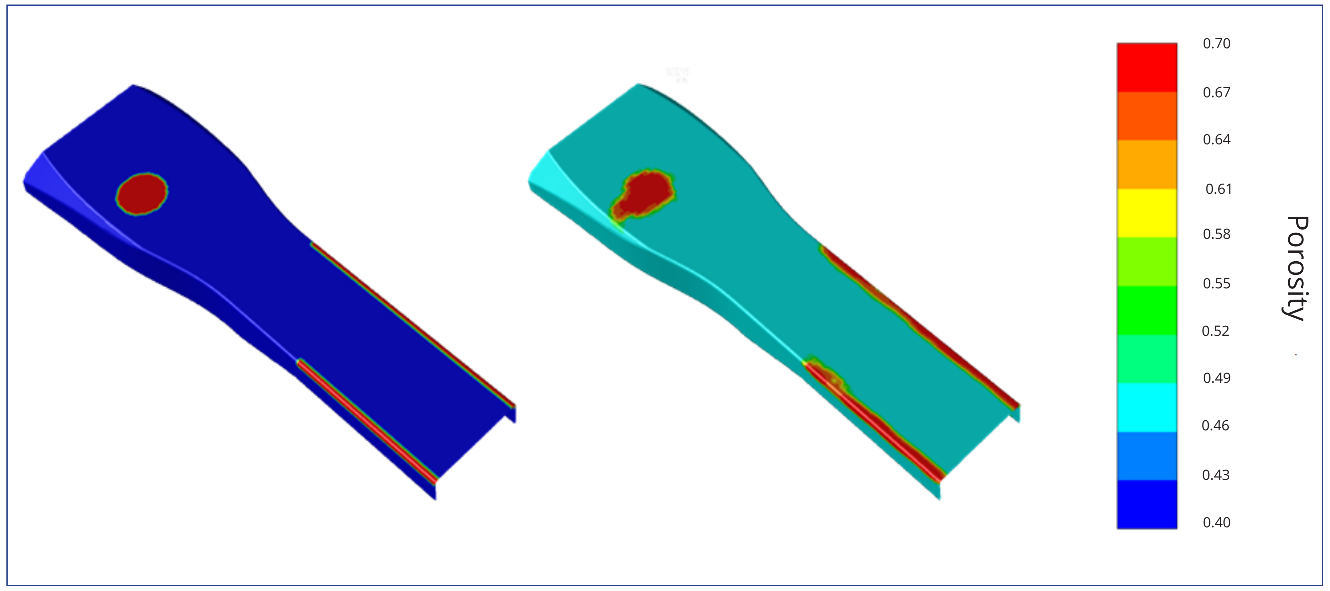


Figure 2 - Left: A 3D composite preform with a defect and local race-tracking along the corners; Right: Local porosity predicted using Bayesian Inversion

Leveraged Contributions

Leveraged Industry Support
£392,000

Leveraged Academic Support
£69,780

Leveraged Grants
£8,000

Workstream 6

Composite Forming Technologies

This Workstream is led by a new Core Project which aims to provide process improvements and simulation design tools that will enable composite components to be designed and manufactured from textile preforms more efficiently and with greater confidence about their performance. It builds on work completed in two previous Feasibility studies, which developed a process specific forming limit diagram for dry non-crimp fabrics (NCFs) and a finite element forming simulation of composite sandwich panels incorporating NCFs.

Scan to hear about our project

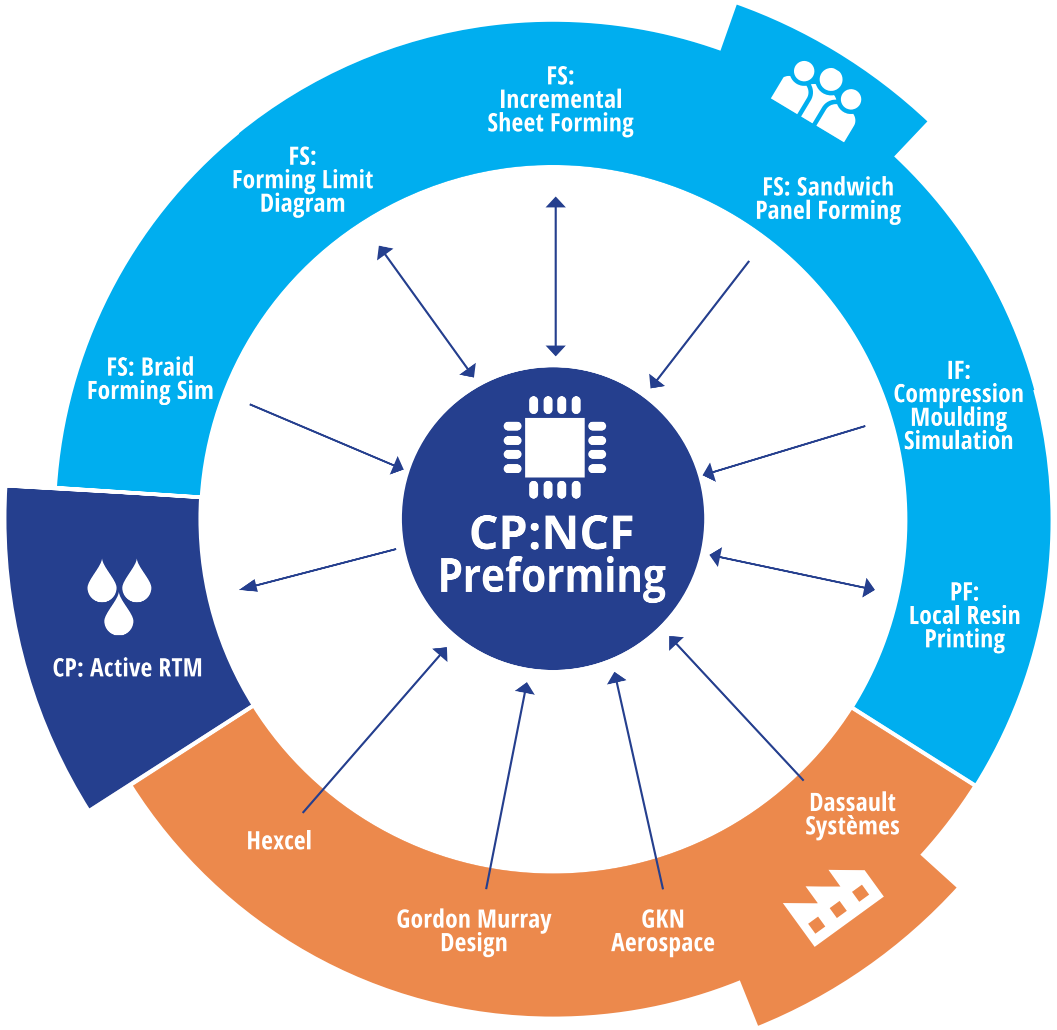
The project will require underpinning science advances in forming simulation and material characterisation to ensure that these tools are accurate and effective. The project will focus specifically on dry NCFs and DDF, to create high-performance preforms suitable for liquid moulding. Many of the research challenges that the project will address have been highlighted in the Hub's recent Roadmapping exercise: improved understanding of forming limits, defect formation mechanisms and significance, mixed material architectures, geometrical constraints, multi-ply forming and friction. Whilst the mechanics of fabric deformation in forming is relatively well understood, there is uncertainty about the mechanisms of defect formation in forming processes and a lack of experimental methods and simulation tools to characterise, understand and model these defects.

Industry Context

The UK Composites Strategy specifies a need to develop technologies to deliver high volume composite production capability. The CLF's Aerospace roadmap provides more detail, specifying that out-of- autoclave processing should be investigated, such as dry fabric preforming and resin infusion. Double diaphragm forming (DDF) is a highly scalable preforming process that uses vacuum-only generated forming forces and has enabled large structures to be formed without the need for similar-sized press tools, as proven by GKN Aerospace in the production of A400M wing spars. DDF is now increasingly being used for both forming and cure of composites, providing process step reduction. Solvay for example, have recently developed a DDF cell at their UK-based Application Centre to automate dry fibre pre-forming, prepreg pre-forming or press moulding into a single-step process for large, relatively simple components such as the bonnet for the BMW M4 GTS. Production of smaller components with more complex geometries increases the probability of defects, increasing the need for new prediction tools to facilitate design for manufacture of these parts. Composite forming is recognised as an important enabling technology and there has been active research in this area since the Hub started, through a number of 6-month Feasibility Studies. This research has become focused towards delivering simulation tools for designing and manufacturing structures from non-crimp fabrics via the DDF process, through a new Core Project led by the University of Cambridge, involving the University of Nottingham and the University of Bath.

Workstream Synergy

- **Core Projects:** There are strong links with the Active RTM Core Project leading the Workstream on Liquid Moulding Technologies, as the forming process will directly influence downstream processes such as resin infusion. Outputs from the forming simulation will be used to inform local fabric permeability for the development of the RTM digital twin.
- **Fellowships:** The work to be conducted in the Innovation Fellowship 'Compression moulding simulation for SMC and prepreg' will have direct relevance to the simulation being performed in this project. Knowledge generated in the ongoing Platform Fellowship 'Local resin printing for preform stabilisation' will be used to control textile deformation in this project.
- **Feasibility Studies:** The understanding of forming and the simulation know-how generated in the three feasibility studies 'Can a composite forming limit diagram be constructed?', 'Forming Simulation of curved sandwich panels' and 'Manufacturing of closed-section composite profiles' have led to the establishment of this Core project and will be used in its delivery. The inspection know-how generated in the feasibility study 'Evaluating the potential for in-process eddy-current testing of composite structures' and the understanding of automation being generated in the Platform Fellowship 'Developing automated manufacturing technologies for composite laminate structures' are relevant and may be investigated for use in this project as work progresses.



Progress to Date

The Core Project leading this Workstream has not yet started, but regular meetings with the industrial collaborators have been key to shaping the previously funded Feasibility Studies and the Core Project proposal.

Industry are keen to contribute to the research being performed in this area and this Hub project provides that opportunity. Industry requirements for user-friendly tools for design of manufacturing are a priority for this project, which will be delivered by the university partners as they develop the underpinning science. Selected materials and manufacturing routes have been strongly influenced by the experience of the collaborative partners. These include GKN Aerospace, Gordon Murray Design, Hexcel Reinforcements, Dassault Systemes.

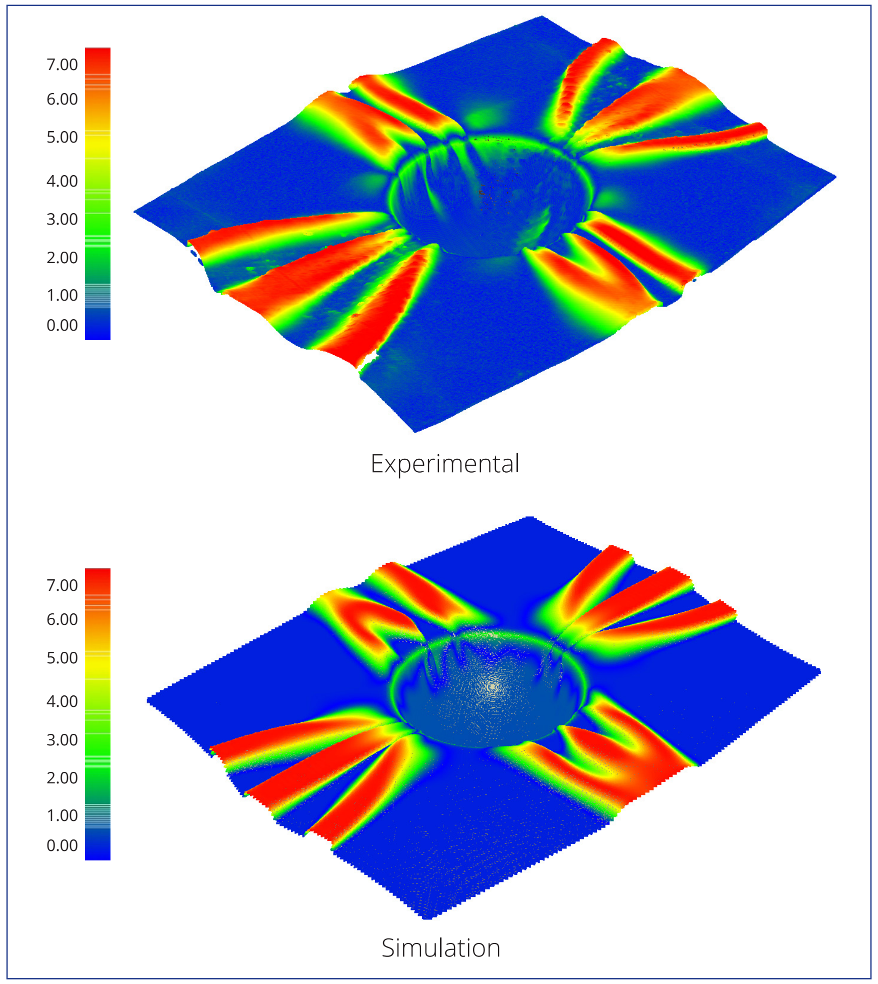


Figure 1 - The output from a FEA forming simulation using a new non-linear material model that incorporates the asymmetric bending behaviour for non-crimp fabrics. The scale on the left indicates the wrinkle amplitude in millimetres.

Key Outputs

- F. Yu, S. Chen, J.V. Viisainen, M.P.F Sutcliffe, L.T. Harper, N.A. Warrior. A macroscale finite element approach for simulating the bending behaviour of biaxial fabrics. Composites Science and Technology, Vol 191, 108078, (2020).
- S. Chen, O.P.L. McGregor, A. Endruweit, L.T. Harper, N.A. Warrior. Simulation of the forming process for curved composite sandwich panels". International Journal of Material Forming (2019). Open Access: https://doi.org/10.1007/s12289-019-01520-4.
- V. Viisainen, J. Zhou, M.P.F. Sutcliffe. Development of a composite forming limit diaphragm: A feasibility study. 22nd International Conference on Composite Materials (ICCM22), Melbourne, Australia, August 2019.
- S. Chen, O.P.L. McGregor, A. Endruweit, L.T. Harper, N.A. Warrior, Finite element forming simulations of complex composite sandwich panels. 22nd International Conference on Composite Materials (ICCM22), Melbourne, Australia, August 2019.

Leveraged Contributions

Leveraged Industry Support
£72,000

Leveraged Academic Support
£183,466

Leveraged Grants
£619,998

Figure 2 - Preform being removed from the Double Diaphragm Forming facility at the University of Nottingham

Workstream 7

Microwave Processing Technologies

Three feasibility projects have been conducted within this Workstream to optimise the use of microwave heating for three different sets of materials and production methods. Detailed aims for each of these projects include:

Scan to hear about our project

1. "Microwave in line heating to address the challenges of high rate deposition". Aim: To facilitate a 100kg/hour deposition rate in carbon fibre thermoplastic and thermosetting tape laying and/or filament winding, by:
   i. Developing microwave cavities suitable for in line heating of tows which couple to an existing microwave system.
   ii. Assessing the potential heating rates achievable on narrow static tows in the laboratory using a sealed system.
   iii. Investigating designs to ensure that the radiation is contained during processing with conductive fibres.
   iv. Conducting simple trials to assess the potential for enhancing the lay down rate of wide (100 mm) tape.

2. "Acceleration of Monomer Transfer Moulding using microwaves". Aim: Investigate use of microwave heating to accelerate in-situ polymerisation of glass fibre reinforced thermoplastic composites by:
   i. Producing small- and large-scale flat panels via microwave polymerisation.
   ii. Showing benefits to quality of matrix when using microwaves for glass fibre preparation.
   iii. Defining benefits of composites made from monomer pre-solution rather than polymer resin precursor system.

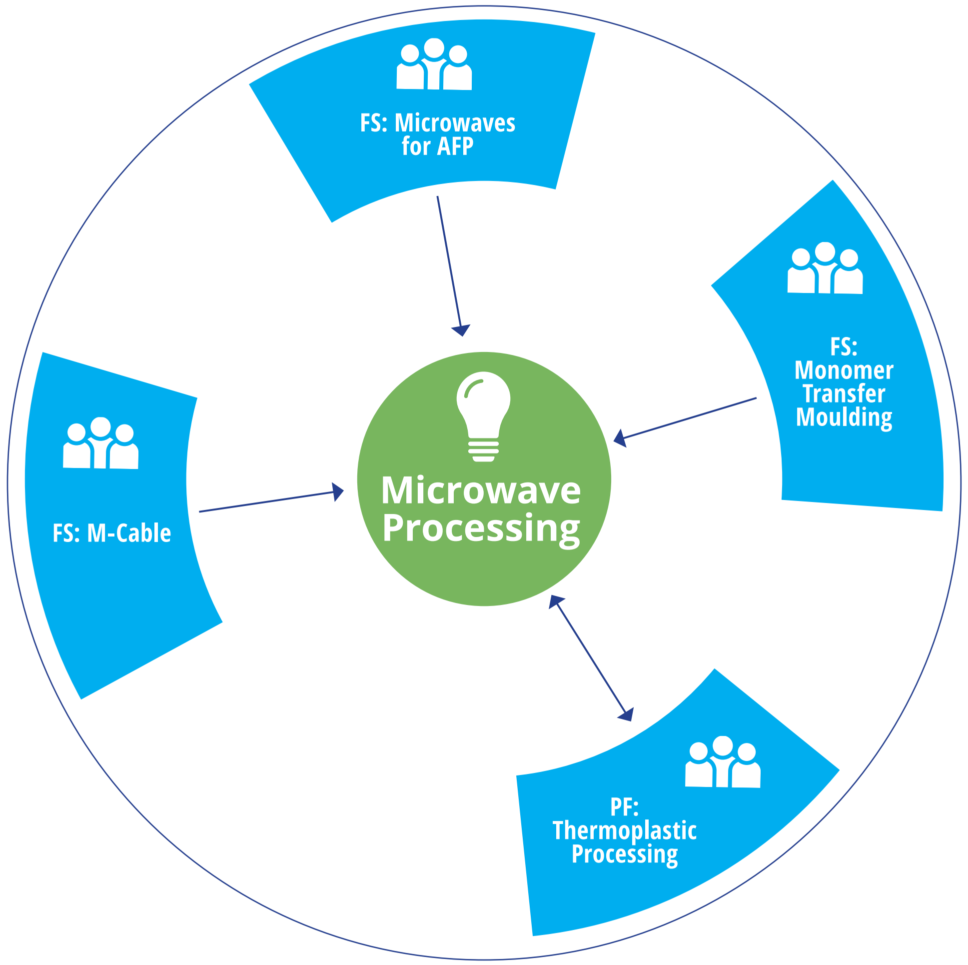
3. "Microwave heating through embedded slotted coaxial cables for composites manufacturing (M-Cable)". Aim: Demonstrate feasibility of curing carbon fibre prepreg laminates (thermoset) using waveguides rather than microwave ovens by:
   i. Achieving heating rates of >5 oC/min and a temperature distribution during curing of +5ºC.
   ii. Manufacturing laminates with uniform Tg and cure.
   iii. Demonstrating energy savings of 25% compared to conventional heating.

Workstream Synergy

This Workstream was established in February 2019 following the Hub Synergy Workshop, which identified Microwave Processing Technologies as a key enabler for high rate material deposition and processing. Consequently, there is no Core Project to lead this Workstream, but this presents an opportunity for the three Feasibility Studies and future projects within this research area.

Industry Context

The CLF Aerospace Group roadmap identifies the need for novel heating/curing systems to speed up the rate of composite production over the next 10 years. Internationally, companies are working on innovative heating solutions for a range of composite processing technologies, including Corebon who are using inductive heating of carbon fibres to provide heating for a variety of processes and Heraeaus Noblelight who, in collaboration with the NCC in the UK, have developed a Xenon flashlamp to provide rapid heating during automated fibre placement (AFP). Microwave volumetric heating can greatly increase the speed of polymerisation and overcome undesirable thermal gradients within tooling, reducing cure cycles from hours to minutes and reducing energy consumption compared to thermal conduction. However, there are some major challenges, such as maintaining a uniform energy distribution, arcing, tooling design and part quality. These challenges need to be addressed before microwave heating/curing can be considered for structural industrial applications. A dedicated call for microwave-based, composite manufacturing projects was launched by the Hub in October 2019, following high levels of interest in this research area from earlier calls and successful projects funded by the CIMComp Centre. Two Feasibility Studies were funded, one to develop novel microwave tooling and the other to investigate the use of microwaves to accelerate monomer transfer moulding. The enthusiasm for this research topic has continued, with a third Feasibility Study being funded in May 2019. This project is investigating ways to use microwave heat sources to increase the placement throughput of thermosetting and thermoplastic tows to 100kg/hour. Subsequently a Workstream has been created to focus the research efforts in this area, bringing together cross-discipline groups from manufacturing, materials science and physics.



Progress to Date

Microwave in line heating to address the challenges of high rate deposition

- A validated model has been developed to help industry understand the limits of microwave heating in tape laying. Cavity size and heating rates rule out use of the first cavity, but trials on the second show promise.
- Simulation has proven that a microwave choke would be too large for this application, so a Faraday containment cage will be used.
- Two shielded facilities are currently being built to measure tape temperature as a function of speed and power.

Acceleration of Monomer Transfer Moulding using microwaves

- Rapid heating and accelerated polymerisation of polycaprolactone was achieved using uni- and multi-modal microwave cavities.
- Microwave heating dried the glass fibres which improved the mechanical performance of the resulting matrix polymer.
- A microwave transparent mould was produced and used to produce small-scale panels, which demonstrated that more work is required to understand the temperature profile through the mould and that the process should use positive pressure rather than a vacuum.

Microwave heating through embedded slotted coaxial cables for composites manufacturing (M-Cable)

- This project has shown that printed circuit boards can be used as a microwave waveguides in tooling, replacing microwave ovens to produce carbon fibre thermoset laminates with equivalent properties to those produced in conventional ovens.
- Heating rates of up to 9°C/min were achieved, which were 80% higher than the target rate, but the temperature uniformity was too low. Local variations of +10°C were observed, compared to the +5°C target.
- The potential for energy savings has been shown to be much higher than 25%, but is dependent on the materials and the shape of the component.
- Laminates were produced with uniform cure, but one sample out of four was outside the +2°C target for Tg.

Key Outputs

- Discussions are underway to have a demonstration facility for microwave-based tape laying at AMRC in Sheffield.
- A follow-on project is being undertaken in collaboration with BAE Systems to understand susceptibility of BMI -based materials to high frequency microwaves.
- Proposal submitted to EPSRC (Nov 2019) by Nottingham, Sheffield, Aston and Bradford Universities (£3.4 million). Currently under review.

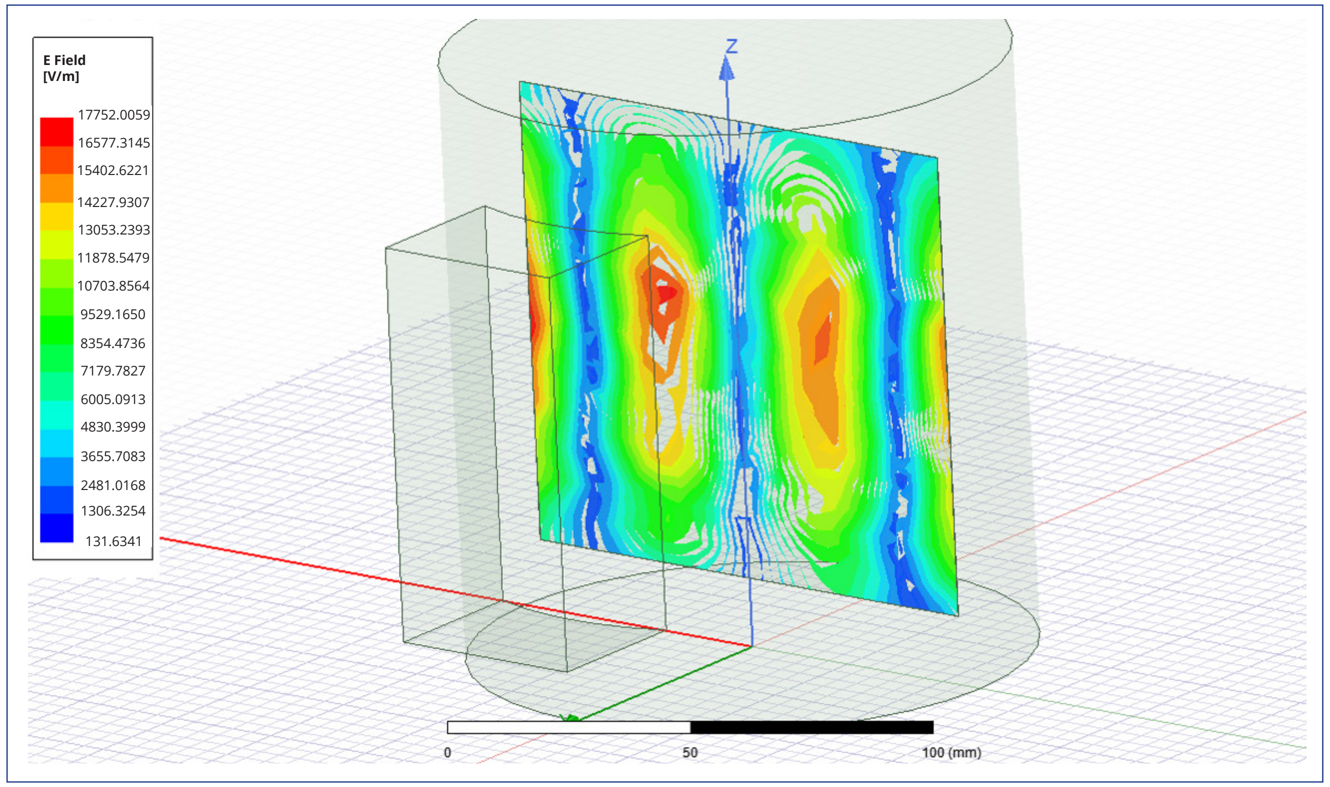


Figure 1 - COMSOL model of microwave waveguide used to process thermoplastic and thermosetting tapes during AFP/ATL

Workstream 8

Thermoplastic Processing

The overarching aim of this Workstream is to support and expand the UK's thermoplastic research activities and capabilities, promoting the benefits of thermoplastic composites and establishing new collaborations.

Research into Thermoplastic Processing has been active since the Hub began, but the recent Hub Synergy Promotion event has enables links to be created between a number of Hub investments.

Scan to hear about our project

Industry Context

Thermoplastic composites can be rapidly processed and offer a relatively straight forward route for end of life recycling compared to thermosets, but the UK lacks experience and supply chain capability for these materials, which is why we are falling behind other countries in Europe. Herone in Germany won a 2019 JEC Innovation award with an all-thermoplastic drive-shaft system overmoulded with an integral gear. It is also noteworthy that GKN, one of the UK's leading Tier 1 aerospace suppliers, has its centre for thermoplastic composite development in the Netherlands, supported by the country's thermoplastic composites research centre TPRC.

In the automotive sector, the CLF's Automotive group has specified thermoplastic processing as a key requirement for capability development. This has been driven forward by collaborative projects such as the Innovate UK funded TOSCAA (Thermoplastic Overmoulding for Automotive Applications) project with JLR and Prodrive's development of the P2T (Primary to Tertiary) process for recyclable thermoplastic composites, but much more is required to prevent the UK from falling behind the rest of the world in this high-potential processing technology.

To date, the Hub has funded eight Feasibility Studies and one Platform Fellowship in Thermoplastic Processing Technologies:

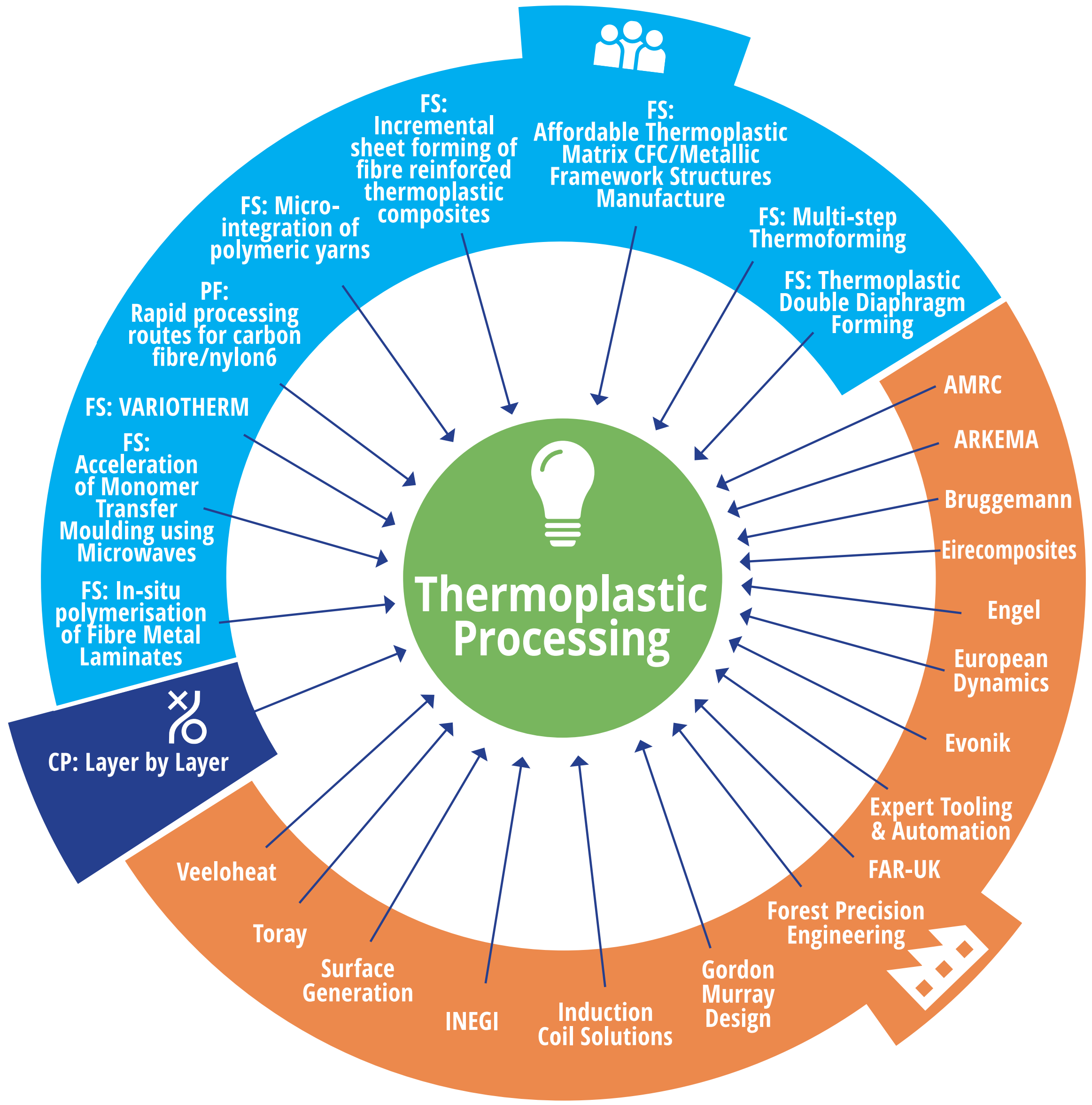
1. Feasibility Study: Manufacturing Thermoplastic Fibre Metal Laminates by In-Situ Polymerisation
2. Feasibility Study: Acceleration of Monomer Transfer Moulding using microwaves
3. Feasibility Study: Affordable Thermoplastic Matrix CFC/Metallic Framework Structures Manufacture
4. Feasibility Study: Incremental sheet forming of fibre reinforced thermoplastic composites
5. Feasibility Study: Optimised Manufacturing of Composites via Thermoelectric Vario-thermal Tooling
6. Feasibility Study: Multi-Step Thermoforming of Multi-Cavity, Multi-Axial Thermoplastic Parts
7. Feasibility Study: Controlled Micro Integration of Through Thickness Polymeric Yarns
8. Feasibility Study: Incorporation of thermoplastic in situ polymerisation in double diaphragm forming
9. Platform Fellow: Development of rapid processing routes for carbon fibre / nylon6

Workstream Synergy

Fellowships: Dr Andrew Parsons is currently leading this Workstream in the absence of a Core Project, setting up a cluster of people with interests in Thermoplastic Processing to discuss project ideas, with the intention of submitting a proposal for an externally funded collaborative project. Dr Parsons' work on carbon fibre reinforced PA6 has led to a Feasibility Study (Incorporation of thermoplastic in situ polymerisation in double diaphragm forming) and a new collaborative project with Michigan State University and Surface Generation (ENACT: Enhanced Characterisation and Simulation Methods for Thermoplastic Overmoulding).

Core Projects: There is significant synergy with the Layer by Layer Core Project, as thermoplastic tape materials are key to this process.

Feasibility Studies: A number of Feasibility Studies have investigated the forming behaviour of fibre reinforced thermoplastic sheet materials, but are under the Composite Forming Technologies Workstream. These include "Incremental Sheet Forming of Thermoplastics", "Monomer Transfer Moulding using Microwaves", and the "Layer by Layer" Feasibility Study.



Key Outputs

- ENACT "Enhanced Characterisation and Simulation Methods for Thermoplastic Overmoulding" funded by Innovate UK Mar 2020 (£350k). New international engagement with Michigan State University and a new UK Hub partner, Surface Generation.

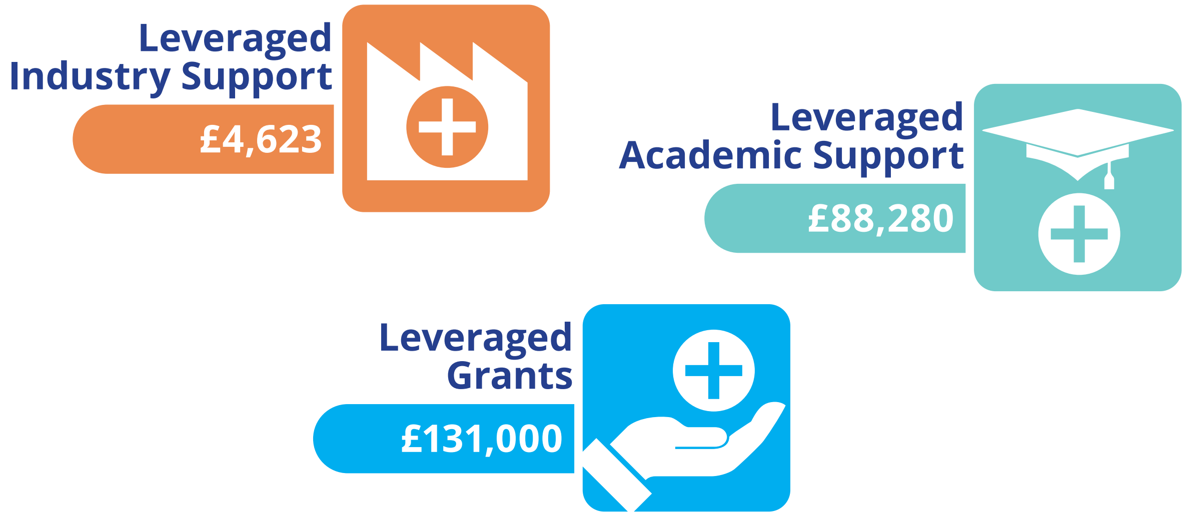
- Two new Hub Feasibility Studies funded following Synergy Promotion event, 'Incorporation of thermoplastic in situ polymerisation in double diaphragm forming' and 'Incremental sheet forming of fibre reinforced thermoplastic composites'.

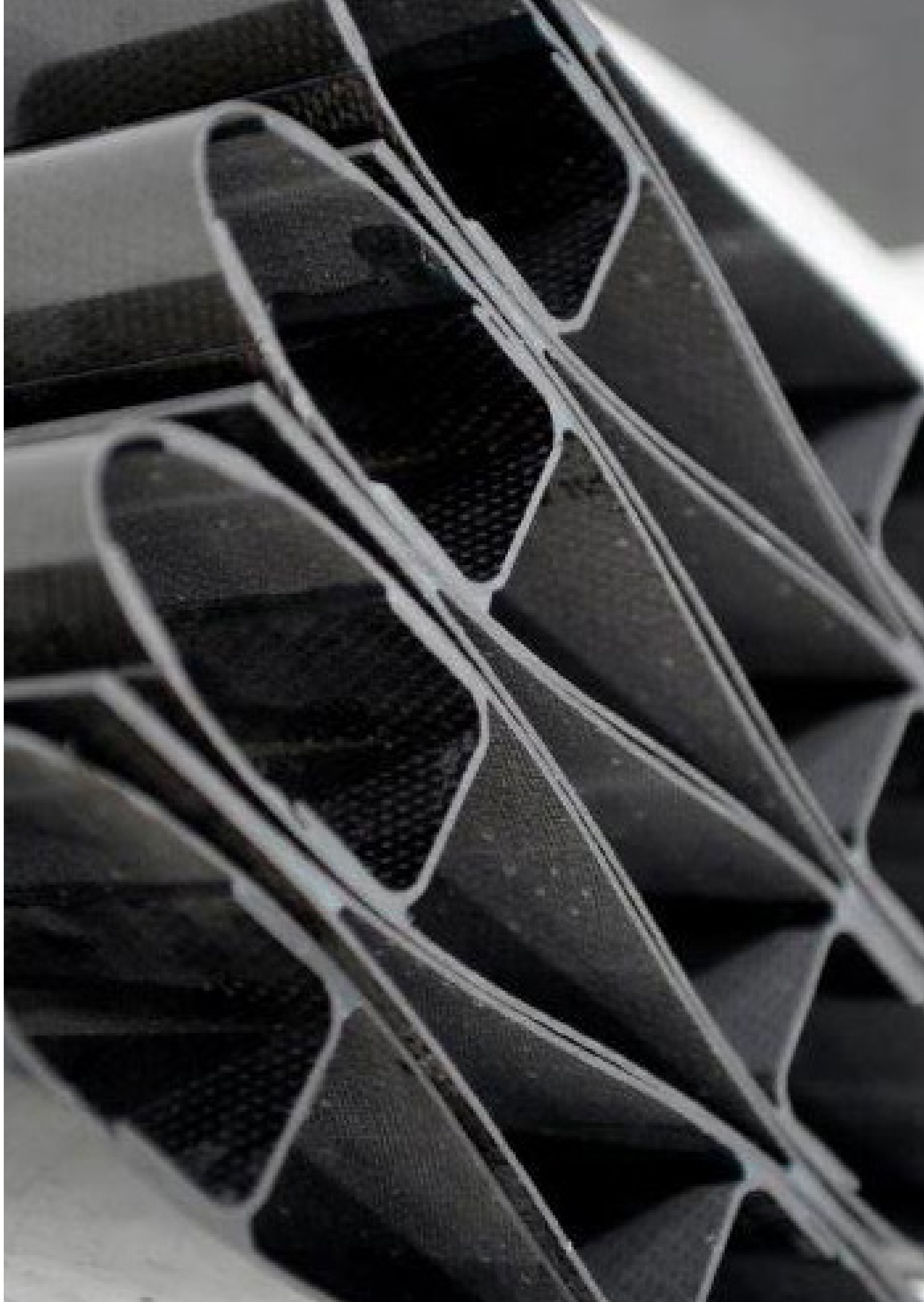
- D. Mamalis, W. Obande, V. Koutsos, J.R. Blackford, C.M. Ó Brádaigh, D. Ray, Novel thermoplastic fibre-metal laminates manufactured by vacuum resin infusion: The effect of surface treatments on interfacial bonding, Materials & Design, Volume 162, 2019, Pages 331-344.

- A. Mills, L. Cook and A. Bras, Affordable Thermoplastic Matrix C FC / Metallic Framework Structures Manufacture, 8th International Symposium on Composites Manufacturing for High Performance Applications (ISCM 2018), November 2018, Marknesse, Netherlands.

- A Researcher from University of Edinburgh has visited University of Auckland, New Zealand to support their work in developing a next generation mixing system for in-situ polymerisation of nylon.

Leveraged Contributions





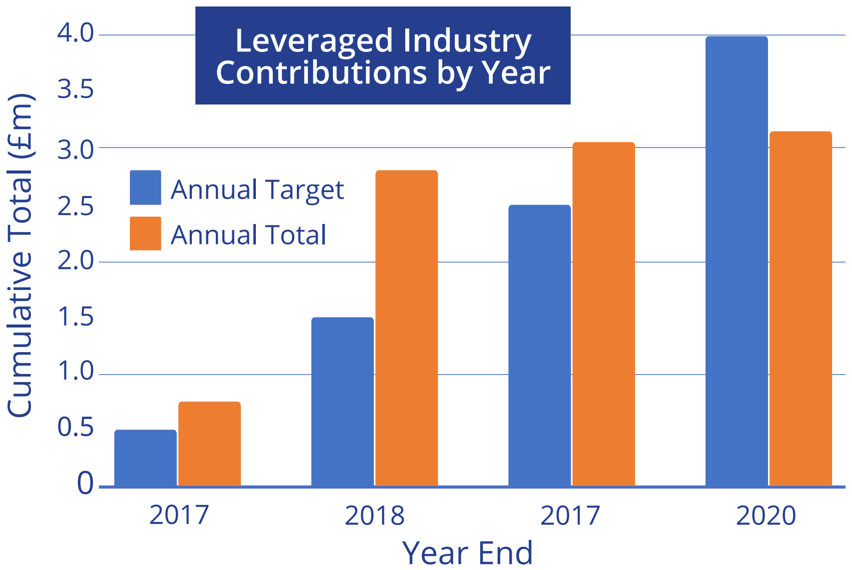
4 Industrial Engagement

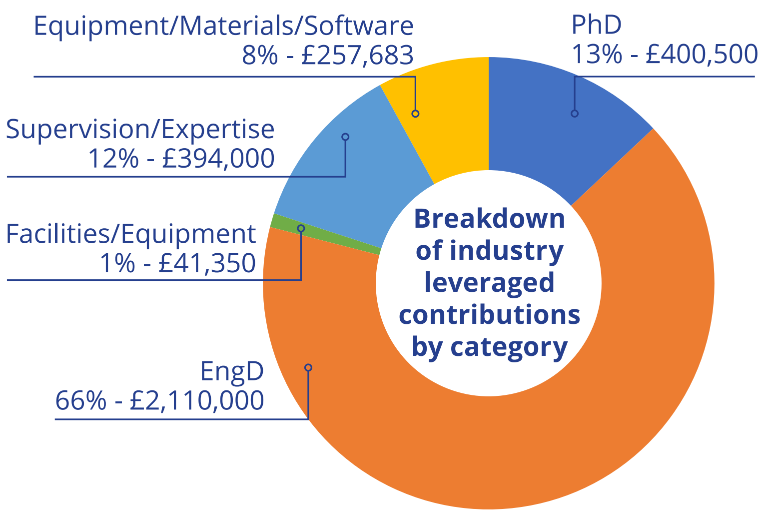
"Whilst the Hub typically conducts research at TRL 1-3, we welcome early support from our industry partners to ensure our research is industrially relevant and outputs progress towards commercialisation."

Dr Richard Gravelle
Hub Business Development Manager

4.1 Industrial Leveraged Contributions

Industrial collaboration is critical to the aims and direction of the Hub, and evidence of this engagement can be seen across our range of funded projects and activities. We are fortunate to be supported by eighteen industrial partners, and four High-Value Manufacturing Catapult centres, all of whom have written letters of support offering contributions including student support, supply of materials, access to facilities and software. At the end of 2019, we had surpassed our £2.5m annual target, and are on course to meet our 2020 target of £4m. Additional support has been provided by a further twenty-eight companies, who have engaged with Core Projects and Feasibility Studies, including a range of OEMs, Tier 1 suppliers and SMEs.





The National Composites Centre (NCC) is the Hub's largest contributor to date, providing £1.4 million of support. These contributions take various forms including sponsoring postgraduate students, manufacture of demonstrator parts and access to the NCC's facilities for a range of Hub projects. The relationship between the Hub and the NCC is critical, facilitating the scale up of technologies into the High-Value Manufacturing Catapult and ultimately into industry.

One area where this is collaboration is evident is composite braiding. Through the recent Digital Capability Acquisition Programme (iCAP), the NCC has invested significantly in their over-braiding capabilities and is home to Europe's largest two ring braider. Two NCC funded Hub postgraduates, Bethany Grimes (EngD) and Matt Thompson (PhD) are currently investigating the scalability of braided structures, using facilities at the NCC and the University of Nottingham. This work will improve predictions of the effect of scale on braid architecture, and overcome industrial challenges in the manufacture of complex, 3D components.

ESI Group, a world leader in virtual prototyping software and services, have been an active and valued collaborator of the Hub since its inception in 2017. In addition to providing software licenses for their composite forming and resin infusion simulation packages to support the ADFP, Optimise and Active-RTM Core Projects, ESI have also embedded a research engineer within the Hub (at the University of Nottingham) for two days a week to directly support simulation activities undertaken within Hub projects. They have also recently supported an EPSRC industrial Cooperative Awards in Science & Technology (CASE) studentship aligned with the Active-RTM project focusing on uncertainties in resin injection for composites manufacturing.

ESI wish to use the research outcomes from these projects to develop and improve their software, ensuring they are capable of simulating the latest composite manufacturing processes. Dr Rajab Said, Academic and R&D Collaboration Manager at ESI said "the relationship with the Hub is enabling ESI to develop an in-depth understanding of the ways in which our software is currently being used, so that we can develop new features that are desirable for the UK academic community and their industrial partners".

In December 2019, we welcomed our newest industrial partner to the Hub. Based in Standish, Wigan, Bitrez manufactures synthetic resins, catalysts and curing agents for a variety of world class companies across the globe in aerospace, rail, automotive, oil and gas, nuclear and renewable energy. Joining the Hub was a strategic venture for Bitrez, who seek to secure their position as a leading supplier to the composites sector and as a research collaborator. Paul Jones, Managing Director at Bitrez Ltd, said: "Our formulated materials are already used in the development and manufacture of prepreg, so we are well placed to support the demands of projects coming out of the Hub."

Although Feasibility Study funding is only available to academic partners, we have actively encouraged our industrial partners to put forward ideas for academics to adopt, ensuring the research is industrially relevant but also ambitious and high-risk. One recent example of a collaborative Feasibility Study involved the University of Nottingham and Gordon Murray Design (GMD), an innovative SME developing niche automotive designs. GMD's patented iStream® process involves the manufacture of complex composite sandwich panels at a step-changing rate. This project gave GMD access to sophisticated finite element code to evaluate the performance of mould tools prior to manufacture, mitigating defects at the design stage and reducing overall development time.

4.2 Industry Partners

It is important that mechanisms for engagement with the Hub are both well-defined and varied to ensure that companies of all sizes are able to benefit from access to our research, facilities and expertise. These are outlined in the Hub's Industrial Engagement Strategy, first published in June 2019, which acts as a guide to help industry partners and researchers build relationships and collaborations within the Hub network. Potential mechanisms include 1) sponsoring a postgraduate student, 2) supporting an existing Hub project, 3) becoming a member of a consortium to support external funding applications and 4) supporting the development of a Feasibility Study application.

We have endeavoured to create a balanced portfolio of partners, including material suppliers, Tier Ones and OEMs, supporting both aerospace and automotive sectors equally. We have also engaged with SMEs who play important roles in the wider supply chain.

In addition to our formal partners, we are also grateful to a number of companies who have engaged with the Hub to support projects and postgraduates. These companies include:

Partner Name	Workstream Involvement
Airborne	WS1: Automated Fibre Deposition Technologies
Arkema	WS8: Thermoplastic Processing Technologies
Beemcar	WS8: Thermoplastic Processing Technologies
Bombardier	WS6: Composite Forming Technologies
Chomorat	WS3: Multifunctional Structural Composites
Composite Solutions Ltd	WS8: Thermoplastic Processing Technologies
Dassault Systèmes	WS6: Composite Forming Technologies
Eirecomposites Teo	WS8: Thermoplastic Processing Technologies
Engenuity	WS1: Automated Fibre Deposition Technologies
Expert Tooling & Automation	WS8: Thermoplastic Processing Technologies
Far UK	WS4: Online Consolidation
Freilacke	WS1: Automated Fibre Deposition Technologies
Heraeus Noblelight	WS4: Online Consolidation
Induction Coil Solutions	WS8: Thermoplastic Processing Technologies
Inegi Porto	WS8: Thermoplastic Processing Technologies
Jaguar Land Rover	WS7: Microwave Processing Technologies
KW Special Projects	WS7: Microwave Processing Technologies
LMAT	WS5: Liquid Moulding Technologies
National Physical Laboratory	WS8: Thermoplastic Processing Technologies
Porcher	WS8: Thermoplastic Processing Technologies
Shape Machining	WS2: Optimisation of Fabric Architectures
Solvay	WS1: Automated Fibre Deposition Technologies
Spirit Aerosystems	WS1: Automated Fibre Deposition Technologies
Surface Generation	WS5: Liquid Moulding Technologies
Toray Advanced Composites	WS8: Thermoplastic Processing Technologies
TU Dresden	WS8: Thermoplastic Processing Technologies
Ultrawise Innovation	WS8: Thermoplastic Processing Technologies

Our Project Partners

The University Of Sheffield. Advanced Manufacturing Research Centre Boeing
Airbus
Aston Martin
BAE Systems
Bentley
Bitrez
Composite Integration ltd
Coriolis composites
ESI get it right®
GE Aviation
GKN Aerospace
Gordon Murray Design
Hexcel
Luxfer Gas Cylinders
mtc Manufacturing Technology Centre
M.Wright & Sons Ltd. Engineered Textile Structures (Established 1860)
National Composites Centre
Network Rail
Pentaxia
Rolls-Royce
Scott Bader
sigmatex material innovation
WMG The University of Warwick

5 Developing the Hub Team

"Our Staff Development Policy outlines a culture where postgraduate students, researchers and academics are supported to grow both personally and professionally during their affiliation with the Hub."

Dr Mike Johnson
Chair of the Postgraduate Development Committee

The Hub has committed to training 150 researchers over the lifetime of the project, to support the anticipated growth in the UK composites sector over the next ten years. The development of postgraduates and researchers is therefore of considerable importance to the Hub and we support this through a number of funding and training opportunities.

With over seventy researchers and postgraduates spread across fifteen institutions, it is important to ensure that all staff and postgraduates are able to benefit equally from these opportunities. Our Staff Development Policy presents a framework in which development needs and opportunities can be identified and acted upon within the Hub.

The policy aims to provide information to Hub staff and postgraduates about how the Hub can support their career development, the roles of different job families and suggests ways to evaluate the effectiveness of development activities. It is therefore relevant to all academic researchers, administrative and business development staff, technicians, and postgraduates.

To date the Hub has funded three Platform Fellows and two Innovation Fellows across four Hub institutions. These offer a first step into an independent research career for young engineers and scientists working on innovative manufacturing processes for composite components and structures.

- Dr Colin Robert (University of Edinburgh – Innovation Fellow)
- Dr Connie Qian (University of Warwick – Innovation Fellow)
- Dr Adam Joesbury (University of Nottingham – Platform Fellow)
- Dr Andrew Parsons (University of Nottingham – Platform Fellow)
- Dr Mike Elkington (University of Bristol – Platform Fellow)

These Fellows, as well as other postdoctoral researchers benefit from a flexible funding model which enables early-career researchers to express their own ideas with confidence and independence.

In addition to membership of the Hub's Researcher Network, which offers a dedicated forum for researchers and postgraduates, researchers are encouraged to attend Advisory Board meetings and engage with the Management Board, gaining valuable experience of presenting their research to senior, industrial audiences.

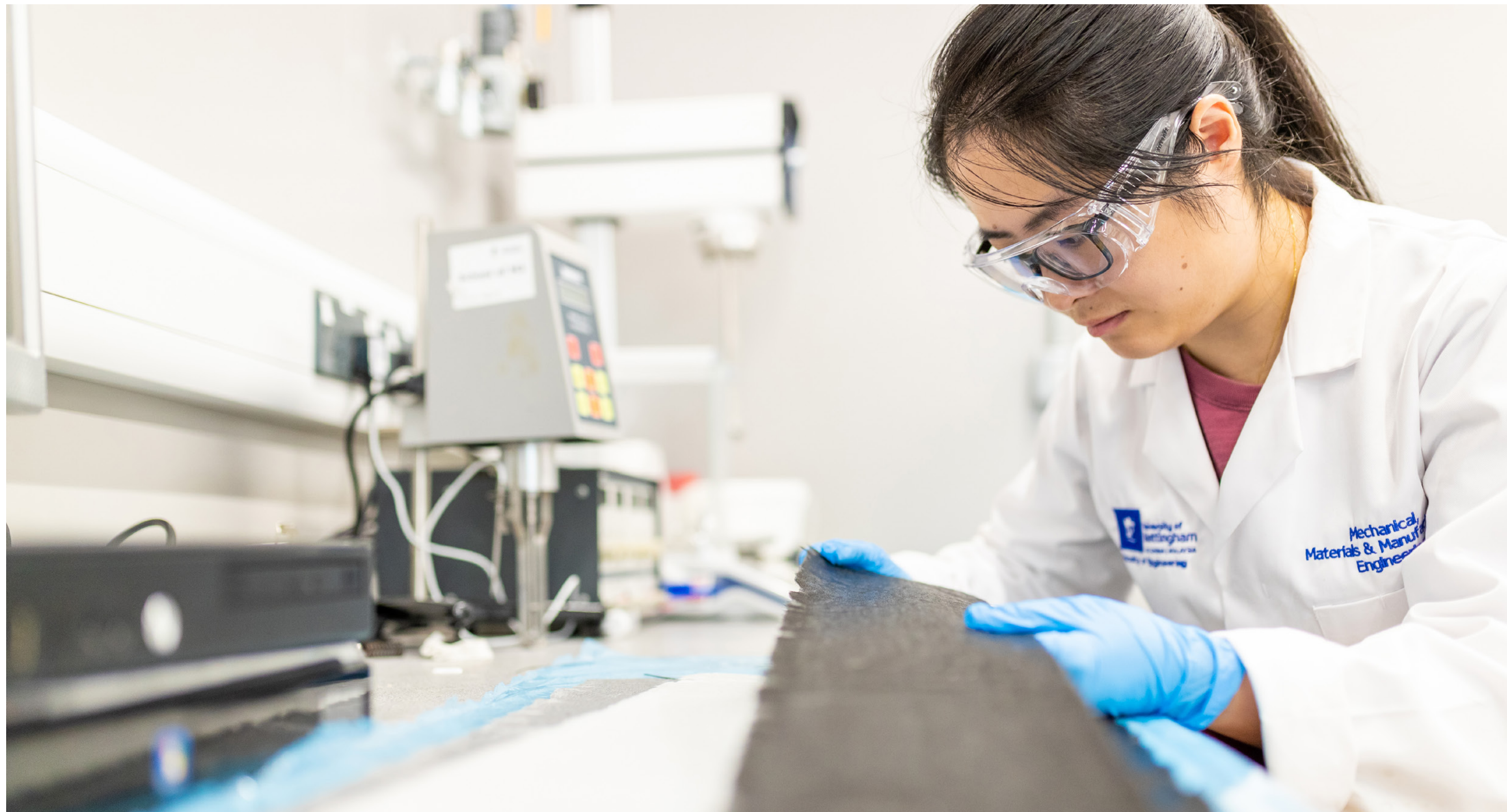
Through our Synergy Workshops (section 6), researchers are also able to engage with other project leads to understand how their research fits within the Hub's wider Workstreams.

5.1 Equality, Diversity and Inclusion

We encourage a culture of equality, diversity and inclusivity to ensure that all Hub staff are positively valued. To support this, the second version of our Equality, Diversity and Inclusion (EDI) policy was published in October 2019. This document was created by consulting all of the individual policies from Spoke members, ensuring our approach going forward is unbiased, reflects the best practice available and is proactive in initiating change. The full policy can is available to all and can be accessed at: https://cimcomp.ac.uk/wp-content/uploads/2019/10/Hub-EDI-Policy-v2.0.pdf.

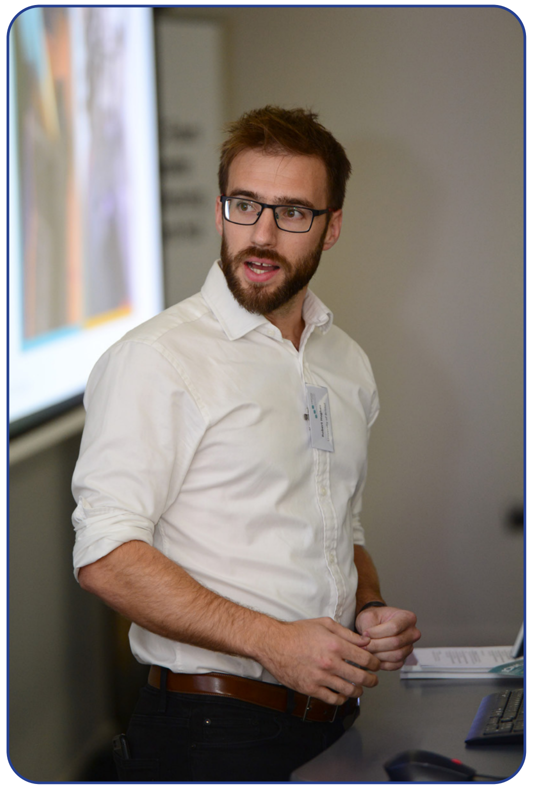
The Hub operates in a field where both female and Black, Asian or Minority Ethnic (BAME) engineers are under- represented. We are committed to overcoming these biases through progressive recruitment practices and have made significant progress in this area. However, we recognise that there is still room for improvement and our goal is to increase the percentage of females to 30% and ethnic minorities to 20% across all working levels within the Hub, by the end of 2023. Our current statistics are below:

	Male : Female	BAME
Postgraduates	79% : 29%	24%
Fellowships	75% : 25%	25%
Researchers/Investigators	96% : 4%	20%
Management Board	62% : 38%	8%
Advisory Board	73% : 27%	13%
Hub Overall	83% : 17%	20%



5.2 Early Career Investigators

Our Early Career Researchers and Investigators are the future of composite manufacturing research and we seek to offer these groups every opportunity for both personal and professional development during their time in the Hub. It is particularly encouraging that a number of researchers and academics who were involved in CIMComp have now progressed to lead their own independent research. Since the Hub started in 2017, several of our members have progressed into more senior roles and, in many cases, their first academic position. We are delighted at their success and offer our warmest congratulations to all.



Dr Rob Hughes presenting at the Hub's 2019 Open Day

Dr Byung Chul Kim (University of Bristol)
Researcher to Assistant Professor

Dr Rob Hughes (University of Bristol)
Researcher to Assistant Professor

Dr Calvin Ralph (Ulster University)
Researcher to Assistant Professor

Dr Andreas Endruweit (University of Nottingham)
Researcher to Associate Professor

Dr Lee Harper (University of Nottingham)
Researcher to Associate Professor

Dr Shuai Chen (University of Nottingham)
Research Fellow to Senior Research Fellow

5.3 EPSRC Industrial Doctorate Centre in Composites Manufacturing

Our Industrial Doctorate Centre (IDC) offers a 4-year EngD programme in composite manufacturing that fits within the general framework of materials, manufacturing and design, funded by EPSRC until the end of 2022. It is led by the University of Bristol with students also located at Cranfield University and Universities of Nottingham and Manchester. The IDC works in close collaboration with NCC and the hub industrial partners. The EngD programme comprises an industrially based project which is the research component delivered at TRL 3-5 entirely within industry to enable direct impact of the research through immediate integration into industrial practice. The taught component comprises the following series of one week-long technical units:

- **Constituents of composites** is a foundation unit, which covers the chemistry and materials science underlying the design of lightweight structures and components manufactured from fibre reinforced polymer composites. The unit provides the basic ingredients for the skills developed the other technical six units.
- **Manufacturing of composite structures** enables students to understand the manufacturing procedures and tooling requires to produce complex composite components utilising liquid resins and prepreg. The unit also comprises an introduction to costing and plant design.
- **Laminate analysis, modelling and design of composites** this unit introduces the analytic methods, data and software tools for design of laminated composite structures.
- **CAD for composites design and manufacture** provides comprehensive introduction to the state-of-the-art tools for digital composite design and manufacture, including CATIA and finite element analysis to promote understanding of composite product development.
- **Mechanical performance of composites** introduces the experimental techniques used to obtain the stiffness and strength properties of laminated composites, including the use of test standards, to provide inputs into design, modelling and quality assurance.
- **Process modelling and control in composites** manufacture state-of-the-art commercial and bespoke process modelling procedures are introduced. The mechanics of consolidation during a variety of manufacturing processes, which includes precursor deformation at component and structural scales, heat transfer and cure, residual stress and distortions, defect generation and mitigation are studied in a digital process control context.
- **Design for manufacture of composites** covers aspects of digital design, focusing on the impact of manufacturing on the product design and development process. This includes cost modelling and probability of defects, numerical analysis tools to understand structural performance, automation and digital process control is linked to design for manufacturing in the two remaining units.

To widen experience a credit-bearing 'Study Tour' with an industry/governmental/charitable organisation (different to the main sponsor) is completed. The Study Tour can take up to three months to conduct a business case study, which is not directly related to the research project but complements and enhances the research as well as broaden the horizons of the students.

A new unit this year called **Technology Strategy and Organisation** introduces supply chain management, marketing, sustainability and life cycle costs. The focus is on entrepreneurial activity and how technology can enhance organisational capabilities, including the impact of standards on competition, alongside political and cultural considerations.

To support our staff development policy the units from the IDC can be taken as part of CPD by all academic staff, researchers and students associated with the hub and are also offered to our industrial partners. They can be collected into a training portfolio that can be tailored to meet the industrial need. At present the assessment of the units is done by coursework in a distance learning mode. At present we are modifying the units to offer them in a blended learning mode to widen access for the new academic year.

Professor Janice Barton formerly of University of Southampton has been appointed at the University of Bristol and has been deputy director of the IDC since September 2019.

Recent EngD Awards and Destinations

Pete Calvert, Pursuit of dimensionally compliant complex mouldings via adaptive, data-driven processing, sponsored by Rolls Royce and is now working for **Airbus** based in Toulouse, France.

Catorina Palange, Sustainable cellulose nanofibre composites sponsored by Albany and is now working as a project engineer at **Pall Life Sciences**.

Alex Cochrane, Virtual manufacturing: validation of laminate deformation processes in automated composite material deposition and moulding sponsored by Rolls Royce and is now working at the **Scottish Lightweighting Centre based** at University of Strathclyde.

Harry Barnard, Composite to metal joining methodologies for high tensile load applications sponsored by **National Oilwell Varco** and is now working as a senior project engineer in their Wireline and Flowline division.

Vincent Gill, is close to finalising his EngD, and has started a new role with **Rolls-Royce Singapore** as a materials engineer in the Capability Technology Group responsible for multiple collaborative projects in the Rolls-Royce laboratory at the Nanyang Technical University (NTU).

Dimitris Karanatis, Advanced CFRP simulation for the development of fabric architectures and process improvement sponsored by Hexcel and has returned to Greece working in his **family's business**.

Harry Clegg, Exploring the possibilities and pushing the boundaries of TTR sponsored by NCC is now based in the USA and **self-employed**.

This year three new students have joined the IDC. Huw Edwards, sponsored by the NCC with research focusing on Liner less composite pressure vessels. David Langston, sponsored by the offshore renewable, energy catapult, with research covering new test methods to facilitate the analysis long blades under critical loading conditions, and Lachlan Williams, sponsored by Airbus, researching forming simulation capabilities for use in large-scale next-generation composite aerospace structures.

Huw Edwards

David Langston

Lachlan Williams

As the IDC students conduct their research in industry, they are located in different places geographically. Although attending the units provides a great opportunity for students to gather, additional special cohort building activities are arranged. A two-day event took place in October where all the IDC students met to share their experiences. The study tours were a key area where students who had completed this activity where able to describe their motivations and help guide other students on choices for their study tour. There were presentations from each student describing their industrially based project work or their study tour. The event also covered activities such as 'getting chartered' and provided an opportunity to discuss the IDC with the external examiner Professor Oana Ghita from the University of Exeter.

We have also initiated a series of events that take place online entitled 'IDC Interactive' the first of these took place in June and involved poster presentations of project work in breakout groups, reports from two study tours and a lively discussion about research in lockdown. An example of a study tour was reported by Lewis Munshi who completed a three-month secondment with the composites start-up iCOMAT, the opportunity was provided by the EPSRC National Productivity Investment Fund (NPIF) and advertised by the Bristol Doctoral College. It gave Lewis the opportunity to undertake the role of business development engineer, which helped him develop a new set of skills to those usually practiced in his day to day research activities.

5.4 Researchers Network

"Collaboration and networking between the Hub researchers is important for the Hub success. Creating and promoting informal links between researchers enables more cohesive professional community. The Researchers Network works on bringing the researchers together for friendly professional and social events where the researchers from different universities can discuss their work and exchange ideas."

Dr Mikhail Matveev
Chair of the Researchers Network

The Researchers Network brings together researchers from all fifteen Hub-affiliated universities and serves as an effective mechanism for promoting collaboration, training, and enhancing the cohort experience amongst researchers. It provides researchers with opportunities to extend their network of professional contacts, exchange ideas and discuss their projects with peers.

Workshops are organised and designed to develop composite manufacturing skills, and a series of 'design and make' challenges have taken place. These offer practical experience to students, who might otherwise only be involved in simulation-based projects. The Network also supports outreach activities such as school and STEM events.

During the last year, the Researchers Network has organised two events and supported several activities, including a competition for short feasibility study projects, social events and laboratory visits. In addition, all members of the Network are invited to attend the specialist taught modules delivered by the IDC in Composites Manufacturing (Bristol), regardless of their status or affiliation.

Researcher Network Feasibility Studies

The Researcher Network launched a new initiative, the Hub Researcher Network Awards, set up to fund short duration research projects lead by postdocs and research students. The aim of the Awards is to encourage researchers to explore new research ideas or take existing projects into a new direction, and provide them with the opportunity to take their first steps towards an independent research career.

Researchers from four Hub universities, the University of Cambridge, the University of Glasgow, the University of Manchester and the University of Nottingham, competed for up to three awards of £5000 each. Projects were required to focus on composites manufacturing and to align with the Hub's priority research areas. Candidates presented their projects to peers and an invited panel, consisting of Mr Andrew Mills from Cranfield University, and two CIMComp alumni, Dr Frank Gommer and Dr Haseeb Arshad.

The following candidates and projects were selected:

- Verner Viisainen from the University of Cambridge: The Effect of Shear-Tension Coupling on the Shear Wrinkling of Biaxial Non-Crimp Fabrics.
- Dr Vivek Koncherry from the University of Manchester: Development of a Portable Artificial Intelligence and Industrial Internet of Things System for Inspection and In-process Evaluation for Composites.
- Dr Zhe Liu from the University of Nottingham: Forming Behaviour of Multi-ply Advanced Recycled Carbon Fibre Preforms with Highly Aligned Fibre Orientation.

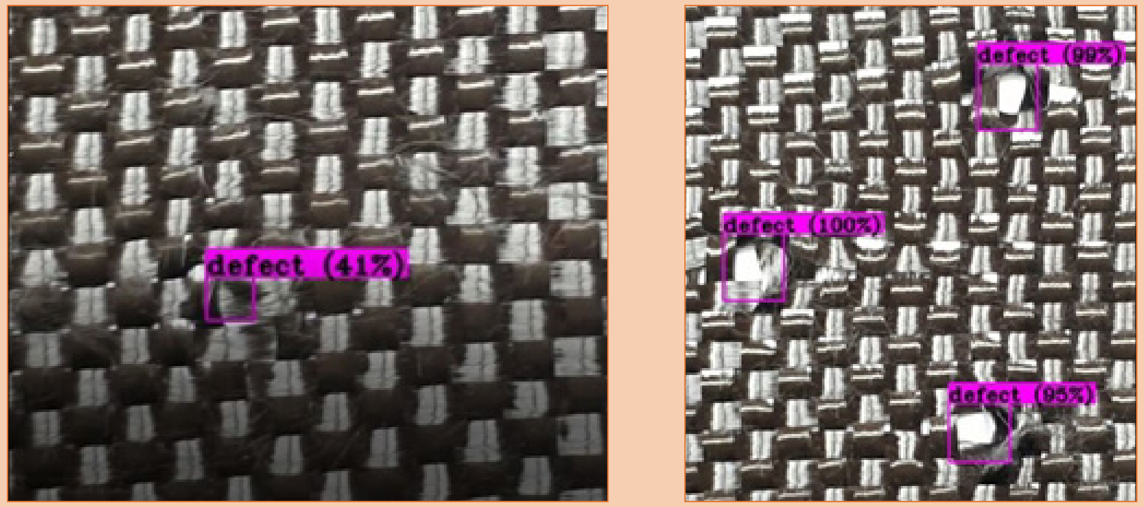
Verner Viisainen, University of Cambridge
"The Effect of Shear-Tension Coupling on the Shear Wrinkling of Biaxial Non-Crimp Fabrics"

Project Overview
The project is an international collaboration between the University of Cambridge and the University of British Columbia (UBC), with the experimental tests being done at UBC, while the post-processing and analysis is done at Cambridge. The project considers the interaction between in-plane fabric shear and fibre tow tension on the wrinkling behaviour of biaxial non-crimp fabrics (NCFs). This is done using a custom built experimental rig for shear and biaxial tension loading of a cross shaped fabric sample with the resultant wrinkling amplitude measured via 3D digital image correlation technology. The NCF used is a biaxial NCF with pillar stitches and a [-45/45] architecture. By varying the ratio between the applied tension and shear, the relationship between the shear angle, applied tension and wrinkle amplitude can be identified. Both the cases of pre-tension and simultaneous shear-tension are considered to identify any differences in behaviour. This study provides necessary data for the accurate material characterisation of the material for finite element simulations and insight into the shear wrinkling mechanisms for biaxial NCFs.

Dr Vivek Koncherry, University of Manchester
"Development of a Portable Artificial Intelligence and Industrial Internet of Things System for Inspection and In-process Evaluation for Composites"

Project Overview
Quality control methods can be a significant weakness in existing carbon fibre preform manufacturing techniques in the composites industry. The measurement of defects in the preform stage often relies on the skill and subjective measurement of a quality inspector. In recent years, advances in Artificial Intelligence (AI) and Internet of Things (IoT), along with the implementation of Industry 4.0 systems in manufacturing technologies, enable a more objective approach in measuring defects. The system developed in this study can be used as an in-process evaluation, and use AI-IoT system to detect defects from multiple locations. In addition, the output of the system can be used to control the robotics motion. It is now possible to standardise the carbon fibre preform made by various manufacturers using object recognition to minimise any variability during the preforming process with the use of AI-IoT. Furthermore, the Digital Twin of this system can be used in biomedical applications from detecting wound healing to defects in textiles etc. A spin-out company, AI Vision systems Limited (Company Number 12632530), has recently been incorporated by Dr Koncherry.

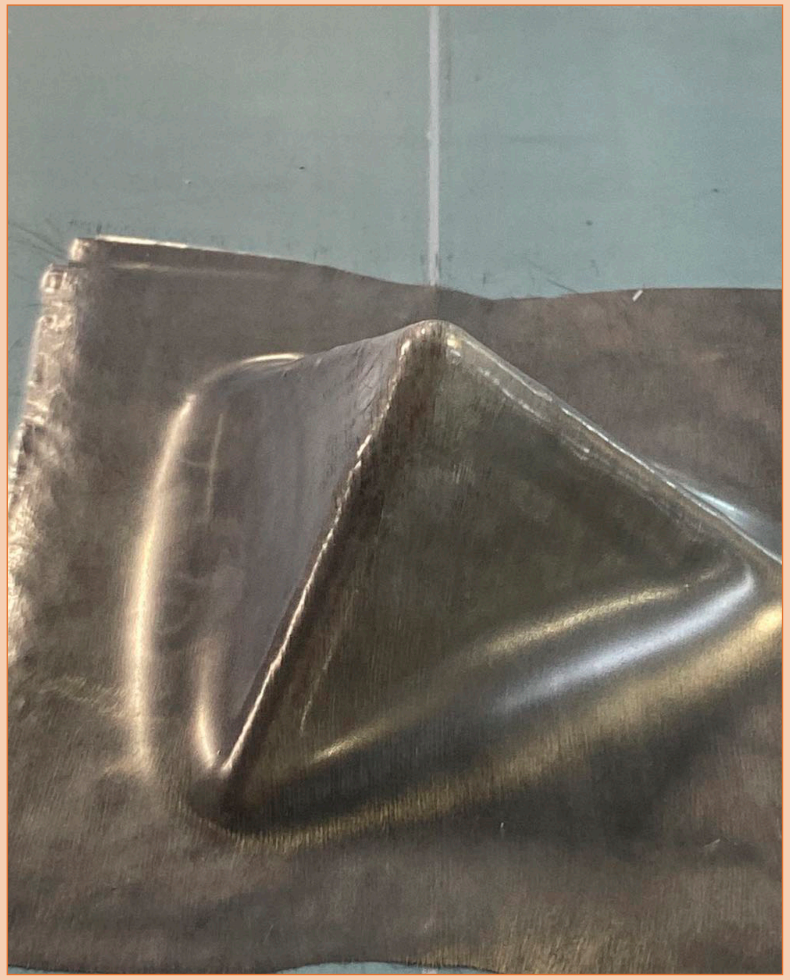
Vision system with Artificial Intelligence and Internet of Things



Defect detection in a woven carbon fibre fabric

Dr Zhe Liu, University of Nottingham, now at Lightweight Manufacturing Centre, National Manufacturing Institute Scotland
"Forming behaviour of multi-ply advanced recycled carbon fibre preforms with highly aligned fibre orientation"

Project Overview
Recycled carbon fibre cannot be used as a direct substitute for virgin materials as the fibres are, discontinuous, in a fluffy format and lacking fibre sizing. A key enabler of wider reuse of recovered carbon fibre is the development of a high-performance, low-cost intermediate product which can be applied in the production of structural components at industrial rates. Recycled carbon fibre has been converted to SMC and BMC (with randomised or partially aligned fibre orientation) with suitability for a range of moulding processes. The highly aligned recycled fibre preform has been developed with the Hydrodynamic Alignment Process at the University of Nottingham, as a discontinuous fibre reinforced material, it is not only comparable to SMC in manufacturability to complex shapes but also more cost-effective and environmentally sustainable. This project investigated the formability of multi-ply highly aligned recycled carbon fibre preforms. The forming potential of aligned short fibre preform was visually assessed by double diaphragm forming with a tetrahedral tool. The deformation of 0/90 lay-up aligned short fibre preform is shown in Figure 1 which can visually identify the outstanding formability of aligned recycled carbon fibre preform.



Multi-layered dry-fabric forming–deformation of aligned short fibre preform (0/90 lay-up)

Other Researchers Network Events

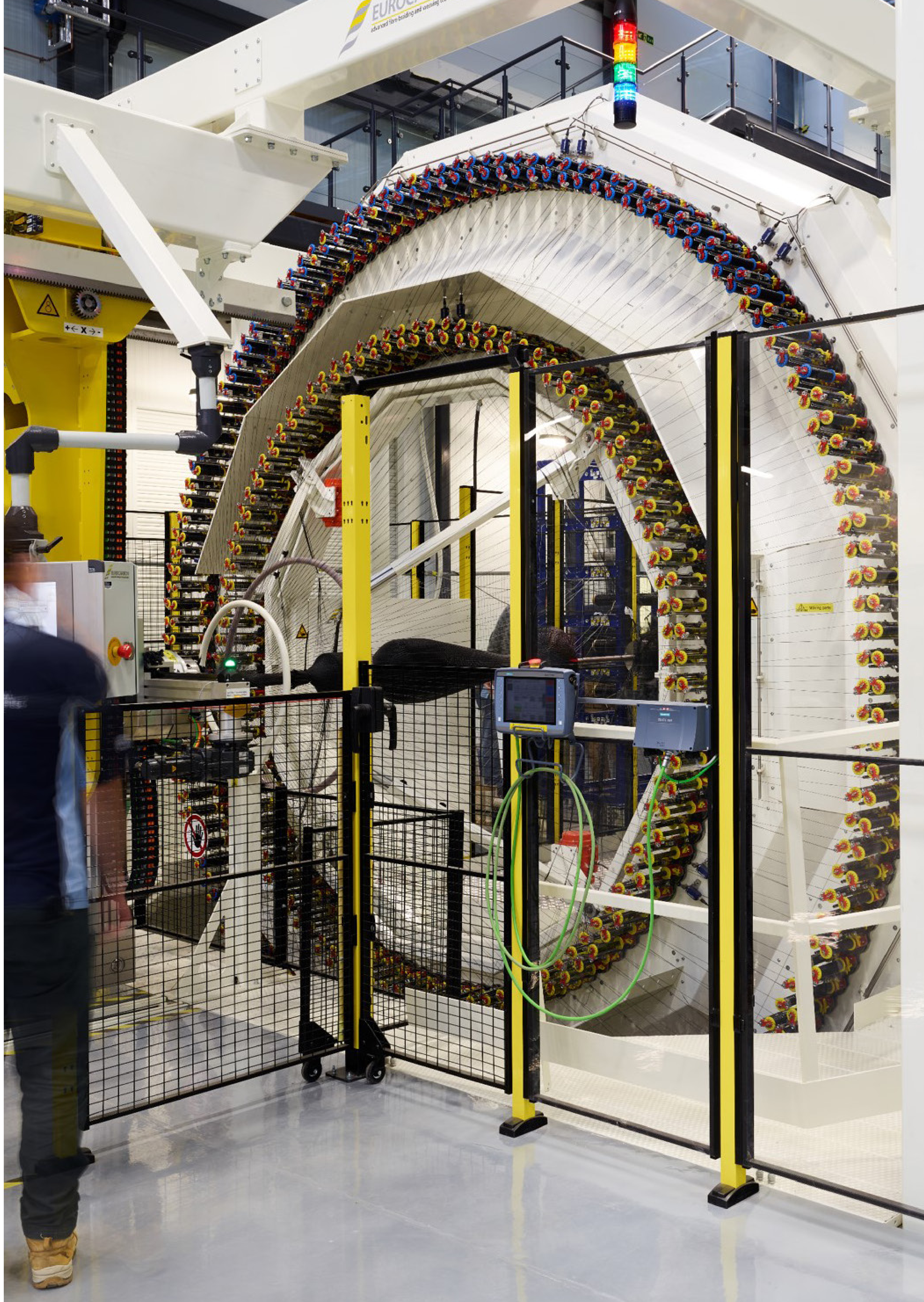
The Researchers Network organised two separate lab tours and demonstrations. The events were each attended by over 30 researchers from Hub affiliated Universities. The first event hosted at the University of Manchester in July 2019 involved a lab tour with running demonstrations of several weaving machines. The second event, at the University of Bristol, was held in February 2020 and involved a tour of Bristol's composites labs with demonstrations from related research. The lab tours provided excellent opportunities to network and share knowledge and ideas amongst the composites research community.

Hub researcher cohort at University of Bristol, February 2020

Undergraduate Supervision

Hub researchers actively support supervision of undergraduate projects and summer placements at their universities. Recent projects included Nottingham's summer placement programme (NSERP) which supported collaborative project between EPSRC Composites Hub and Additive Manufacturing Research Group at Nottingham. Guy Lawrence was supervised by our Platform Fellow, Dr Adam Joesbury for the duration of the project. Guy will start a PhD at Nottingham in July 2020 on the recently awarded NCF Forming Core Project.

Another example of researchers getting involved in undergraduate supervision took place at the University of Bristol. The project focussed on low cost automated vision inspection of composite layup and the undergraduate, Amaam Chohan, was supported by Dr Michael Elkington to develop use of a simple webcam and image analysis system to complement the capabilities of the Tactile sensor developed during his Platform Fellowship.



6. Acting as a National Hub

"The remit of the Knowledge Exchange Committee (KEC) is to develop and manage the industry and Catapult interface, capture and record emerging IP from the Hub and help identify technology push-pull opportunities where Hub project outcomes can either be progressed through the HVM Catapult Innovation Spokes or exploited directly by industry stakeholders. Further to this, the KEC has an active role in identification on trends in the UK composites business that require a response from the Hub to ensure that emerging technology demands can be met."

Prof Ole Thomsen
Chair of the Knowledge Exchange Committee

The KEC works closely with the Strategic Development Committee (SDC) to support its role in identifying local, national and international sources of follow-on funding at the appropriate TRLs.

The KEC has been more active than in the first 2-3 years of the Hub, where focus has been more on launching new initiatives and projects. Particular activities during the last year include supporting the NCC in evaluation of the Technology Pull Through project proposals for kick-off in 2020, as well as a review of outcomes in terms of outputs and potential for impact and further funding opportunities for the first ten completed Hub Feasibility studies (period 2017-2019). Finally, a process of reviewing the remit and terms of reference for the KEC has been instigated, aiming to streamline the operation of the KEC and its interactions within then Hub, most notably the SDC, as well externally with the HVMC spokes.

6.1 Synergy Workshops and Synergy Promotion Fund

To further develop interactions and identify/promote synergies between Hub researchers and projects, we organised a series of Synergy Workshops which were each attended by over 40 Hub affiliated academics and researchers. The first of these synergy workshops took place at the University of Nottingham in November 2019. The focus of the workshop was to identify existing and hitherto unrealised, and in some cases completely new, links and interactions between the various Hub activities including feasibility projects, core projects and platform activities. Project synergies and interactions were identified and mapped out, and they were used to develop the SharpCloud representation of the Hub organisation, interactions and workstreams that are described in Section 3 of this report. The second synergy workshop was organised in Bristol in February 2020. Based on the outcomes of the first workshop, the aims of this workshop were to further develop the identified synergies and to review and update the general understanding of the Hub focus and direction of research. A particular objective of the second workshop was to launch the so-called Synergy Promotion Fund set up by the Hub management through the KEC to provide seed funding to enable development of Hub synergies between past/ongoing Hub research/activity or based on emerging/novel research/activity.

The format of Synergy Promotion Fund is to support a series of short duration projects of between 3 and 12 months, and with a maximum budget of up to £15,000. It was decided to allocate up to £80,000 of Hub fund for this activity in 2020/2021. During the second workshop ideas for synergy promotion projects were developed in breakout sessions and presented for discussion. Following on from the workshop a brief application and review process was established utilising KEC members as well as some members of the Advisory Board as reviewers. A total of 13 proposals were received, and five very high quality synergy promotion projects involving several Hub partners and research groups were subsequently funded, with a total budget of ca. £56,000. The five synergy promotion fund projects that were awarded are:

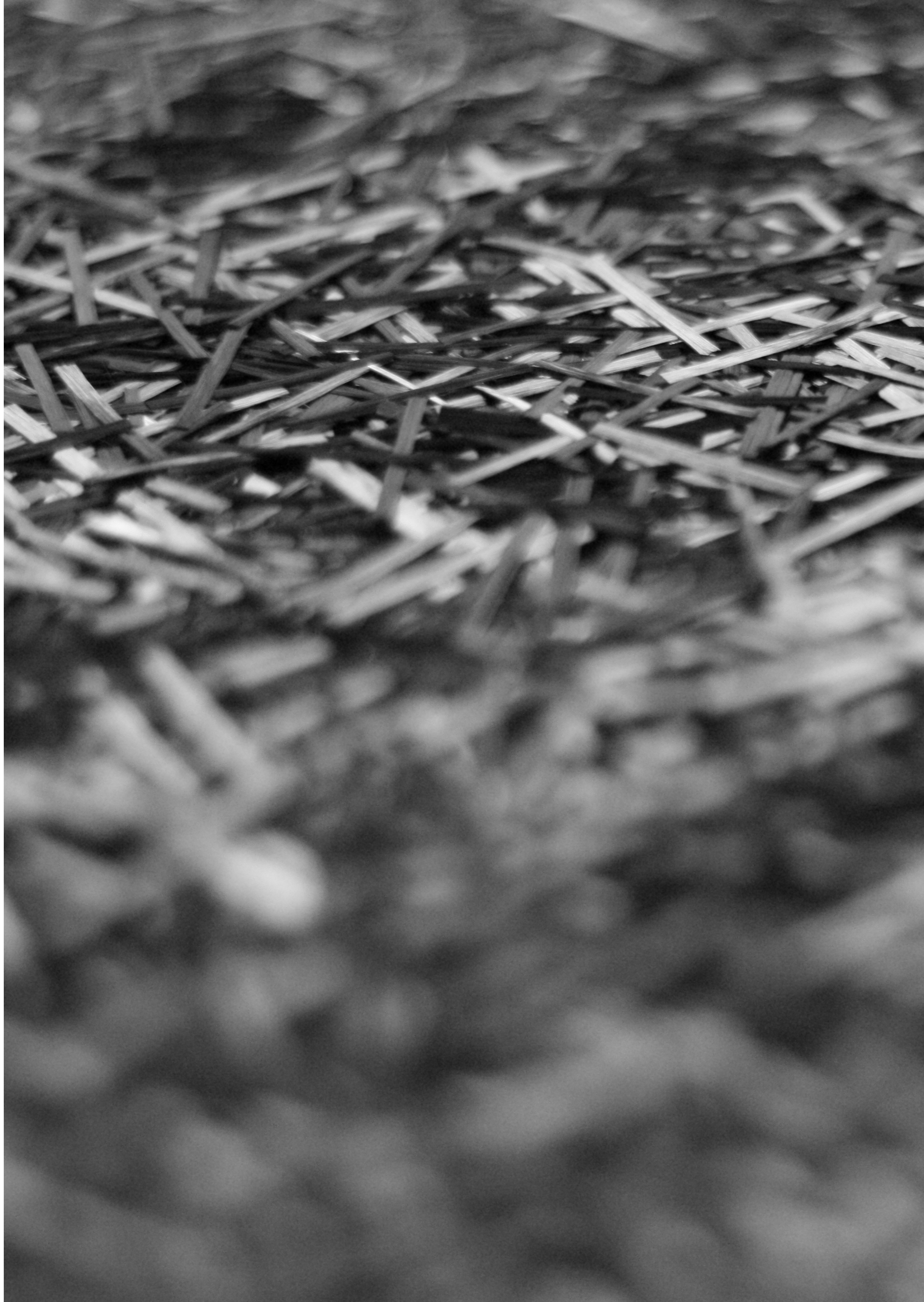
1. Organisation of workshops organised jointly between the hub and the Data-centric Engineering community at the Alan Turing Institute. The focus will be on forming synergies between Hub projects and current projects at the Alan Turing Institute and to generate new project ideas. PI: Dr. Adam Sobey (Turing Fellow), University of Southampton and Turing Institute. Hub partners: Turing Institute, and all Hub partner universities. Award amount: £5,000.

2. Manufacture of powder epoxy composite preforms and bond them using both stitching and co-cure processes. PI: Dr Colin Roberts, University of Edinburgh. Hub partners: University of Edinburgh, Ulster University, University of Nottingham. Award amount: £14,400.

3. Development of database of raw micro-CT scans from current and past projects funded by the Hub and affiliated projects. The outcome will a catalogue with classification by fabric/material scanned, and how the samples were prepared and scanning system was used. PI: Dr. Mikhail Matveev, University of Nottingham. Hub partners: University of Nottingham, University of Bristol. Award amount: £7,000.

4. Residual stresses in microwave cured components and temperature evolution within microwave cured components. PI: Professor Janice Barton, University of Bristol. Hub partners: University of Bristol, University of Southampton, Wrexham Glyndwr University. Award amount: £15,000.

5. Development of shared knowledge base and tool set for numerical optimisation research within the Hub. This will provide software for numerical optimisation that will make 10 leading Genetic Algorithms and 5 Particle Swarm Optimisation codes easy to incorporate into projects with Hub and industrial partners. PI: Dr. Adam Sobey (Turing Fellow), University of Southampton and Turing Institute. Hub partners: University of Southampton, Turing Institute, University of Nottingham. Award amount: £15,000.



6.2 The National Agenda

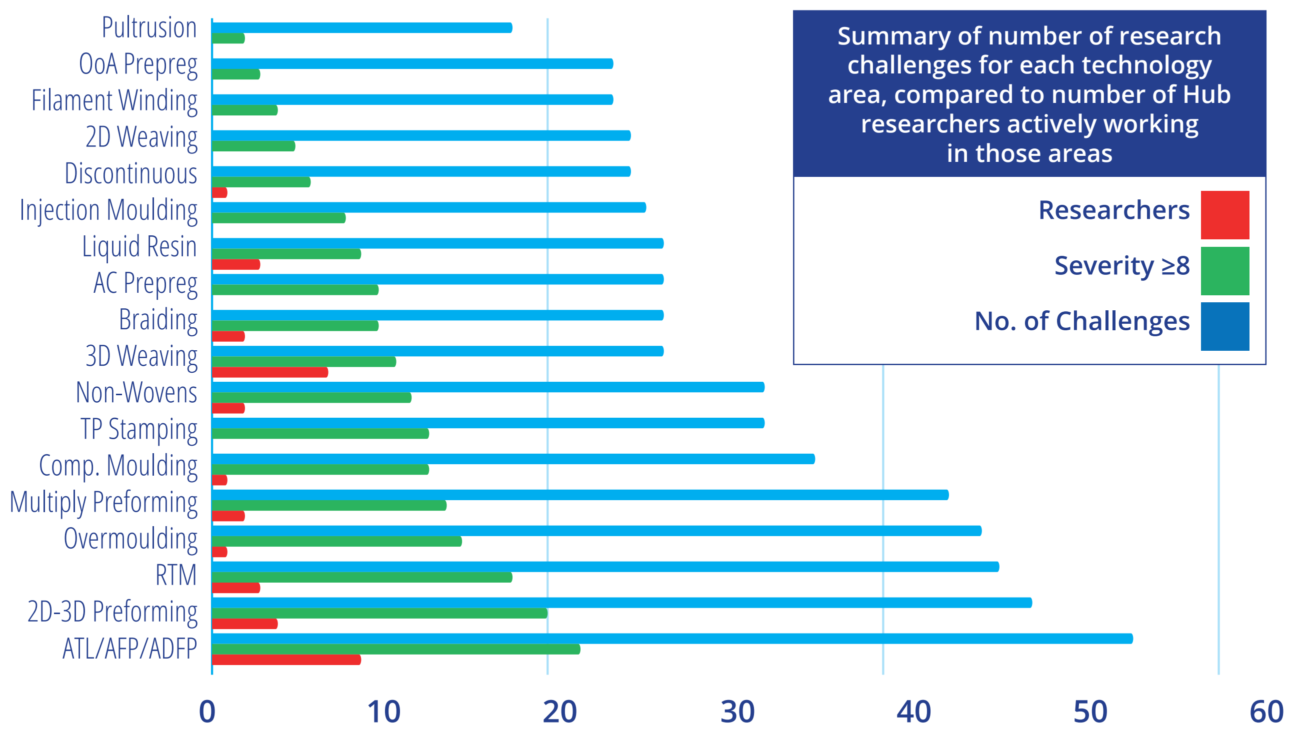
"As part of the Hub's planning the Strategic Development Committee conducts a variety of activities on behalf of the Management Group. The SDC comprises representatives from various funding bodies as well as industry partners and feeds back into the hub via the business development managers. The SDC also actively supports hub feasibility studies which are not successful in gaining core project funding to look at other funding mechanisms and enhance partnerships. The following sections describe some of the SDC activities this year, including some work to better understand contemporary fundamental challenges in composites manufacturing across a range of deposition processes."

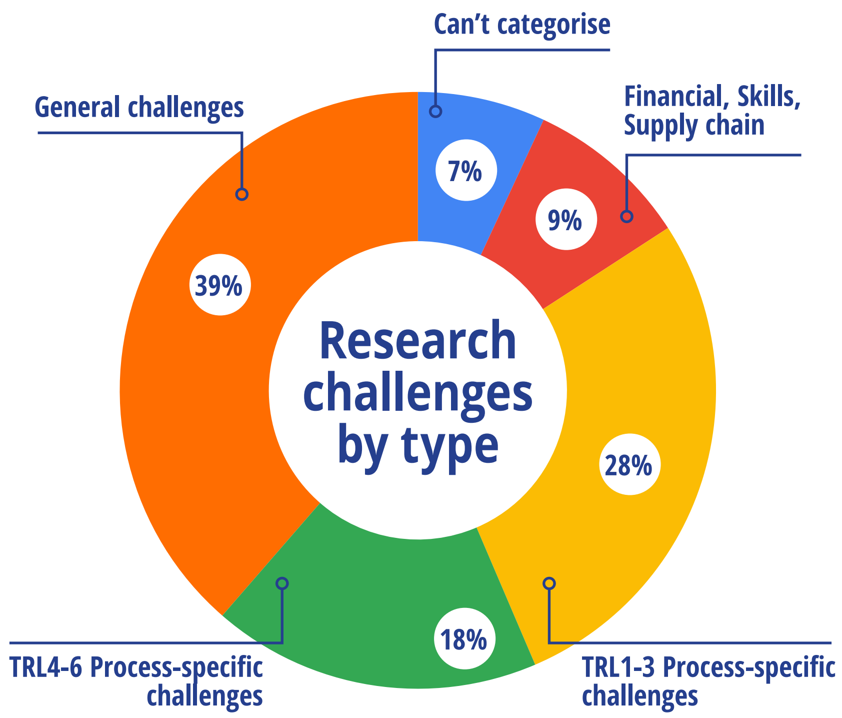
Dr Tom Turner
Chair of the Strategic Development Committee

UK Composite Manufacturing Research Landscape (CiRCL)

The UK Composite Manufacturing Research Landscape provides an academic perspective on established composite manufacturing technologies. Conventional roadmaps typically address new or emerging technologies in the context of industrial end applications. CiRCL identifies fundamental, low-TRL research challenges which can potentially deliver a step-change to improve or streamline widely used processes within the next twenty years. The EPSRC Future Composites Manufacturing Research Hub comprises fifteen of the composites manufacturing (as opposed to material science) focused institutions in the UK. This expertise, and our close links with four High-Value Manufacturing Catapult (HVM-C) centres make the Hub uniquely placed to deliver this ground-breaking analysis of composites manufacturing technologies.

CiRCL focuses on high-rate processing technologies in fibre deposition, conversion and moulding. Over 170 research challenges were identified from peer-reviewed literature, forming a draft landscape which was reviewed by members of the academic and HVM Catapult community through a series of meetings and workshops. Both new and existing challenges were scored according to their severity, reflecting the urgency with which they need to be addressed. Over 30 academics and Catapult engineers contributed to CiRCL, resulting in almost 600 challenges across 18 technology areas.





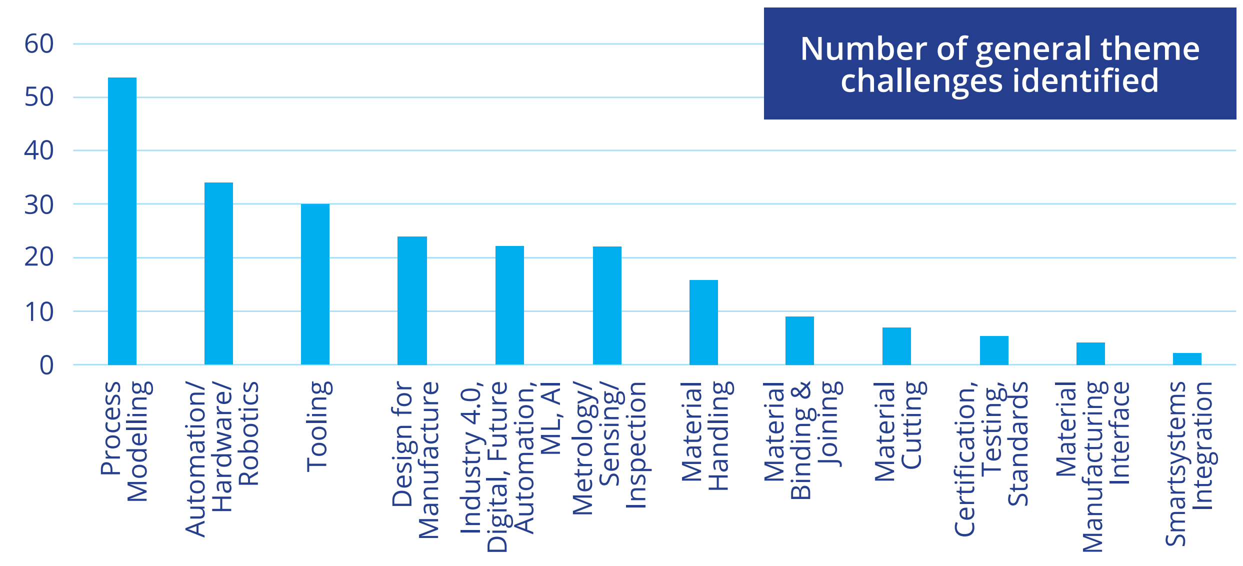
The UK Composite Manufacturing Research Landscape has potential interest for several audiences. Primarily, the landscape is designed to inform the Hub's future funding decisions and ensure the ongoing relevance of our grand challenges and research themes. Identifying important and timely research challenges will also have benefits across the sector. For academics and researchers,

CiRCL highlights potential areas of research to researchers and enables them to better justify requests to funding bodies. Conversely, funding bodies and policy makers are able to identify and fund areas of critical research importance as identified by the composites community. Finally, in promoting urgent research challenges, CiRCL will facilitate effective technology transfer into the HVM Catapult as new developments are scaled up for industrial applications.

Data on individual manufacturing research challenges was ranked and progressively refined by respondents on a 1-10 scale of criticality and the exact area where the barrier impacts the process (i.e. on a Cost, Rate, Uptake, Quality or Applicability basis). This allowed comparisons between the manufacturing processes which facilitated a mapping of hub activities (number of personnel and spend) against the various processes to validate the balance of Hub effort overall.

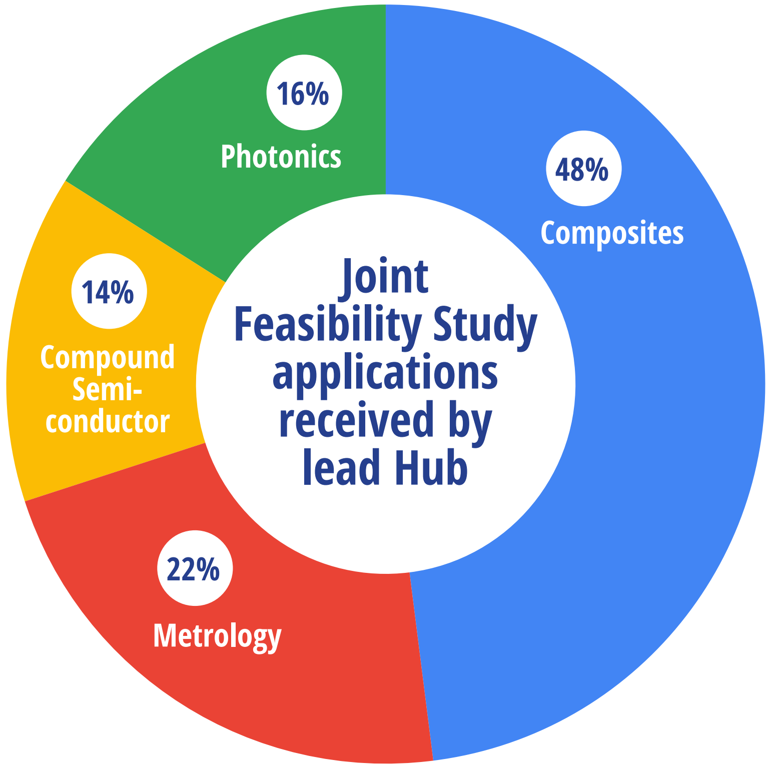
A further Keyword analysis was performed to identify process-specific challenges (e.g. edge of ply stability in multi-ply preforming) vs. potentially cross-cutting research themes (e.g. need for high rate binder application). The full dataset is available on the CIMCOMP website and further work to condense the outputs is underway. Hub effort has been shown to be well aligned with the most critical process areas (Automated Deposition and Forming / preforming), and work continues to assess Hub effort and spend against these priority areas.

A large number of challenges (almost 40%) could be categorised into a general research theme area and the graph below shows that Process Modelling, Automation Hardware, Tooling, DFM and Future Automation are the top 5. This has allowed detailed analysis of the TRL1-3 and 4-6 challenges requiring solution for individual processes as well as areas for investigation grouped by thematic area. It is clear that there are some key areas which, if addressed, could unlock potential across the whole of composite manufacturing.



6.2.2 Joint Hub Feasibility Studies

The Hub's most recent call for feasibility studies in November 2019 was conducted in collaboration with three other EPSRC Future Manufacturing Research Hubs: Compound Semiconductors, Metrology and Photonics, and represented a total of up to £1 million funding to support investigation at TRL 1 to 3.



The Hub was instrumental in administering the call, with a number of our processes utilised in the assessment and awarding of projects.

Applicants were encouraged to apply for projects which spanned Hub disciplines, with each Hub committing to support cross-cutting projects. In total, 63 proposals were received from 33 institutions, with just under half submitted to the Composites Hub.

In addition to the four proposals funded by the Hub, three proposals funded by the Future Metrology Hub are aligned to the Future Composites Hub and receive mentoring from Hub academics and access to facilities. These are:

- Investigation of fibre content and fibre orientation distributions in compression moulded carbon fibre SMC – Dr Connie Qian, University of Warwick
- In addition to the four proposals funded by the Hub, three proposals funded by the Future Metrology Hub are aligned to the Future Composites Hub and receive mentoring from Hub academics and access to facilities. Contactless Dielectric Process Monitoring (CDPM) of Composites Manufacturing – Dr Hamed Yazdani Nezhad, Cranfield University/City, University of London
- Fast Instrumented Laser Cutting of Industrial Fibre Reinforced Composites – Dr Katy Voisey, University of Nottingham

6.2.3 Future strategy

The composites sector is facing an unprecedented period of uncertainty and the need for focus in research activities is clearer than ever. The research landscape exercise has given some clear areas for future research to further unlock the potential of composite materials.

Lobbying policymakers - Through the SDC, the Hub has engaged with the Department of Business, Energy and Industrial Strategy to promote the role of the Hub in the UK composites landscape, and the research being undertaken to deliver our grand challenges. This was especially relevant as the decision to update the UK Composites Strategy was taken.

Creating cohesion between universities – A key aspect to delivering the Hub's Grand Challenges is ensuring that our Core Projects, Feasibility Studies and Fellowships are able to work towards the same goals of meeting the Hub core objectives. In order to do this, we have held two Hub Synergy workshops which allowed researchers and postgraduates to hear about other projects, identify areas of potential cooperation and develop new projects.

Understanding national strategy - In addition to our UK Composites Research Landscape (CiRCL), the Hub has also conducted an analysis of the academic landscape. This identified UK institutions with research interests in composites will enable us to track academic engagement with the Hub and differentiate between institutions with a manufacturing focus, and those with a material science focus.

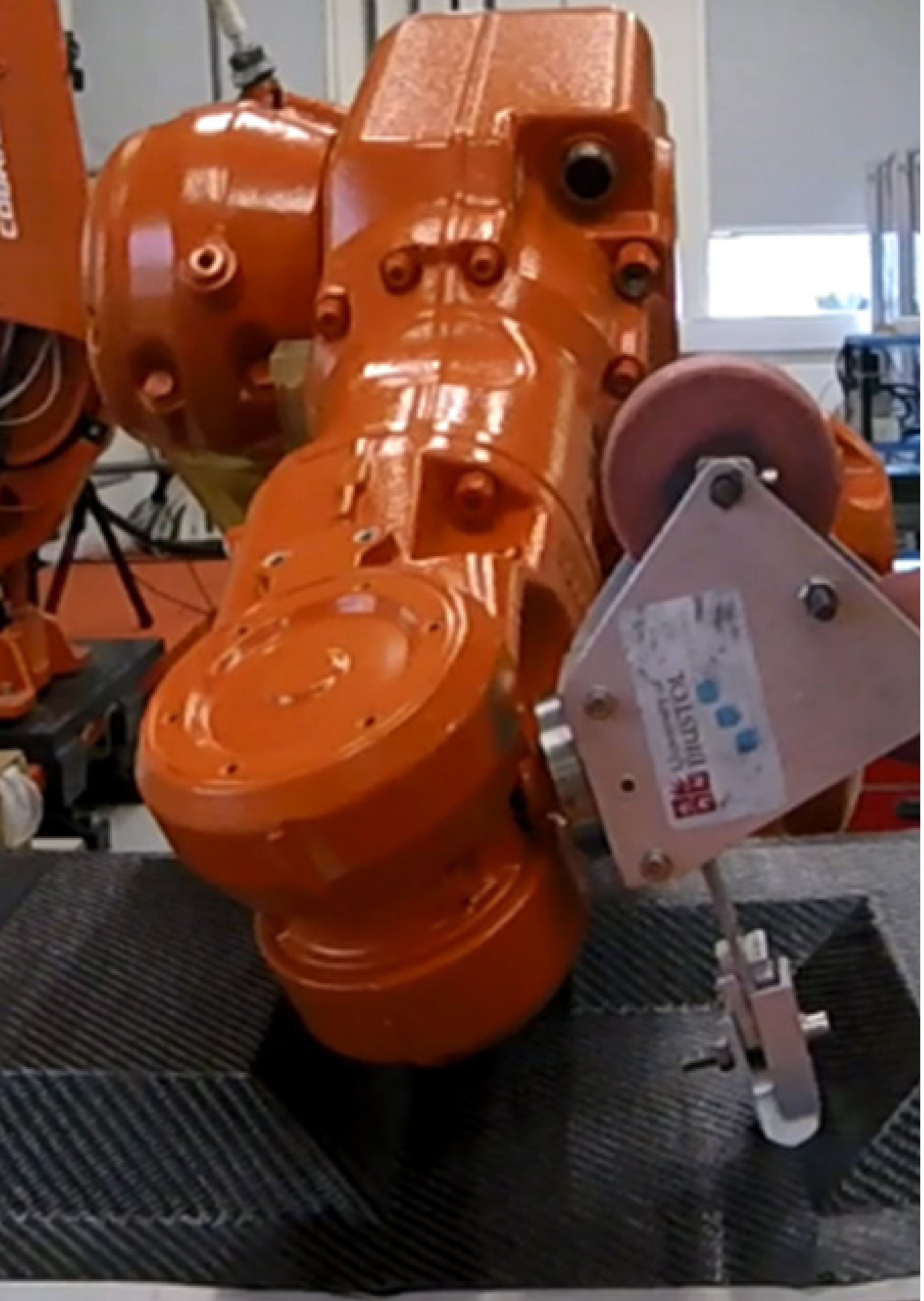
This has found that of the 82 active composites research groups in the UK, just under half (46% have engaged with the Hub). However, of the 32 composites manufacturing focused groups, 75% have engaged with the Hub.

COVID-19 and changes to the research agenda - The recent COVID-19 pandemic has led to significant changes in many of the manufacturing sectors relevant to composites. As budgets are tightened it becomes even more important to conduct research strategically and with a focus on maximising benefits to industry.

An important application of the Hub's UK Composites Landscape is its role in helping academics and researchers to provide justification and context to research proposals. We are delighted that this is already evident from our last call for Feasibility Studies where of the 30 proposals submitted, over 70% of the proposals focused on research challenges included in the CiRCL. In total, 72 individual challenges were addressed, with 65% scored as a severity eight or above and therefore considered urgent.

In our last call for Feasibility Studies, 27% of the 30 proposals submitted cited specific challenges within the Hub's UK Composites Landscape as a rationale for their project and justification for funding. However, a further 47% proposed research that directly addressed one or more challenges within the Landscape. The severity score of these challenges averaged eight, suggesting that the proposed research has the potential to be impactful to a number of stakeholders. A number of challenges were also cited multiple times, allowing us to identify key areas of interest. In total, five challenges were mentioned in more than one proposal, three of which had severity scores of between eight and ten.

As the Hub enters the next phase of work the SDC will support the management group in promoting the areas of research challenge that have been identified in the roadmapping activities as well as seeking to transition existing research out to the catapults (in collaboration with the KEC) and wider industry.



6.3 International Visits

International missions form an important part of the Hub's outreach and collaboration agendas so that we engage with and learn from experts outside of the UK. These visits provide the opportunity not only to capability map these regions, but also to grow the Hub's International Research Network, providing increased opportunity for researcher exchange, collaborative research programmes and industry engagement.

6.3.1 Ireland Mission

In June 2019, Hub representatives from the Universities of Nottingham and Bristol visited Northern Ireland to promote the activities of CIMComp and to learn more about the composites manufacturing landscape in the region. Over 2 days, the group visited a mix of industrial and academic institutions, including new Hub member Ulster University, whose feasibility study 'Controlled Micro Integration of Through-Thickness Polymeric Yarns' was funded and commenced in April 2019. The group also had a tour around Queen's University Belfast, led by Prof. Brian Falzon and Prof Stephen Hawkins, where they are manufacturing carbon nanotubes to produce heating elements for anti-icing/de-icing applications. Finally the tour concluded at CCP Gransden, an SME specialising in the design, development and manufacture of advanced composites. Here the group discussed automated manufacturing and saw a demonstration of prepreg compression moulding using their Engel press.

A tour of the Advanced Composites facilities at CCP Gransden, Belfast, Northern Ireland.

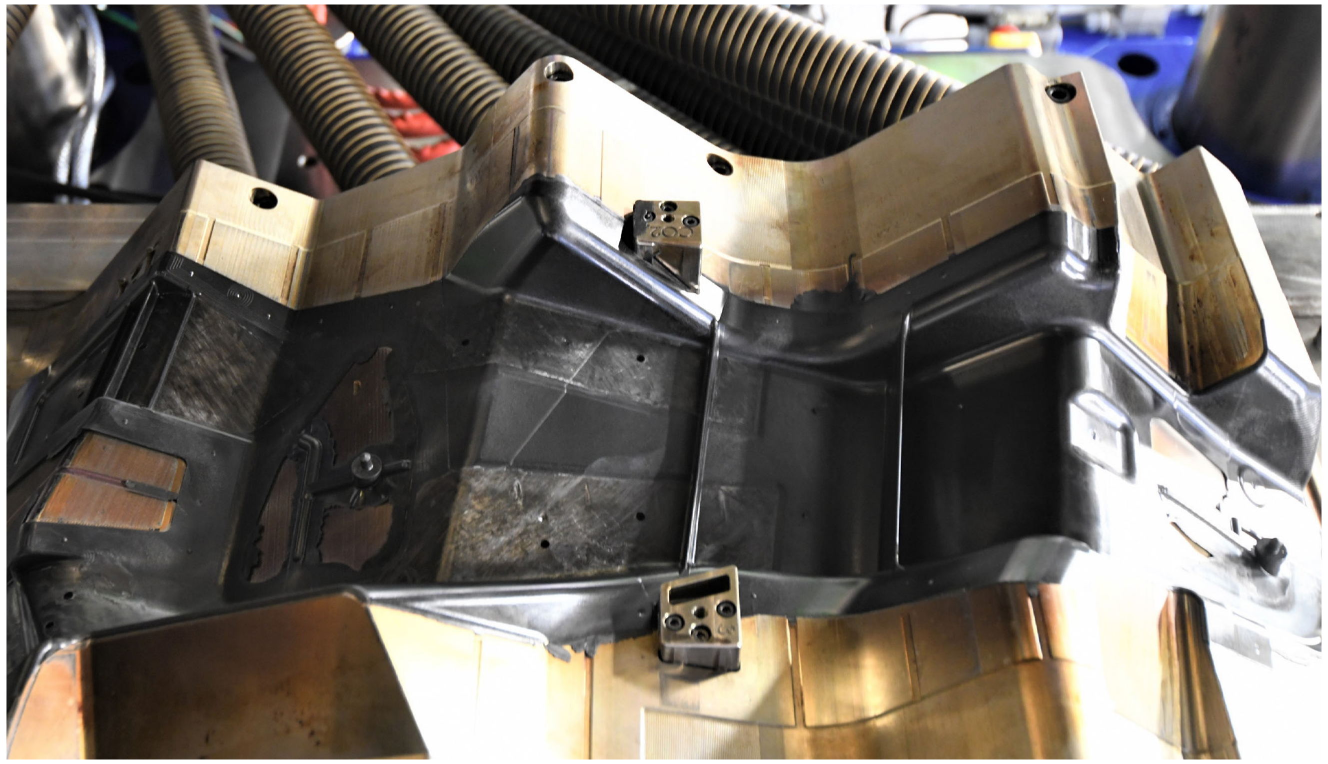
Left to Right: Dr Tommaso Scalici, Dr Zafer Kazanci (QUB), Dr Tom Turner (UoN), Dr Ali Aravand (QUB), Dr Lee Harper, Dr Andy Parsons (UoN), Dr Michael Elkington (UoB), Prof. Brian Falzon, Dr Giuseppe Catalanotti, Prof Stephen Hawkins (QUB), Dr Richard Gravelle, Dr Adam Joesbury (UoN)

6.3.2 USA Mission

In October 2018, Nick Warrior was invited to participate in the Innovate UK KTN Composites Global Expert Mission to the USA. The purpose of the mission was to gain a greater understanding of the US composites materials landscape as part of the UK's National Composites Materials Centre addition to the National Composites Centre and High Value Manufacturing Catapult. Nick represented the UK academic community alongside industry experts, members of the HVMC, Innovate UK and BEIS. The group spent two days in Dallas at CAMX, the largest composites focused exhibition in the US, before travelling to the Oakridge National Laboratory, NASA and the Institute for Advanced Composites Manufacturing Innovation (IACMI).

A major outcome of the mission was the announcement of a joint InnovateUK/Institute for Advanced Composites Manufacturing Innovation (IACMI) call to establish new international links in composites manufacturing. Hub members successfully secured funding for two out of the seven projects awarded in this round.

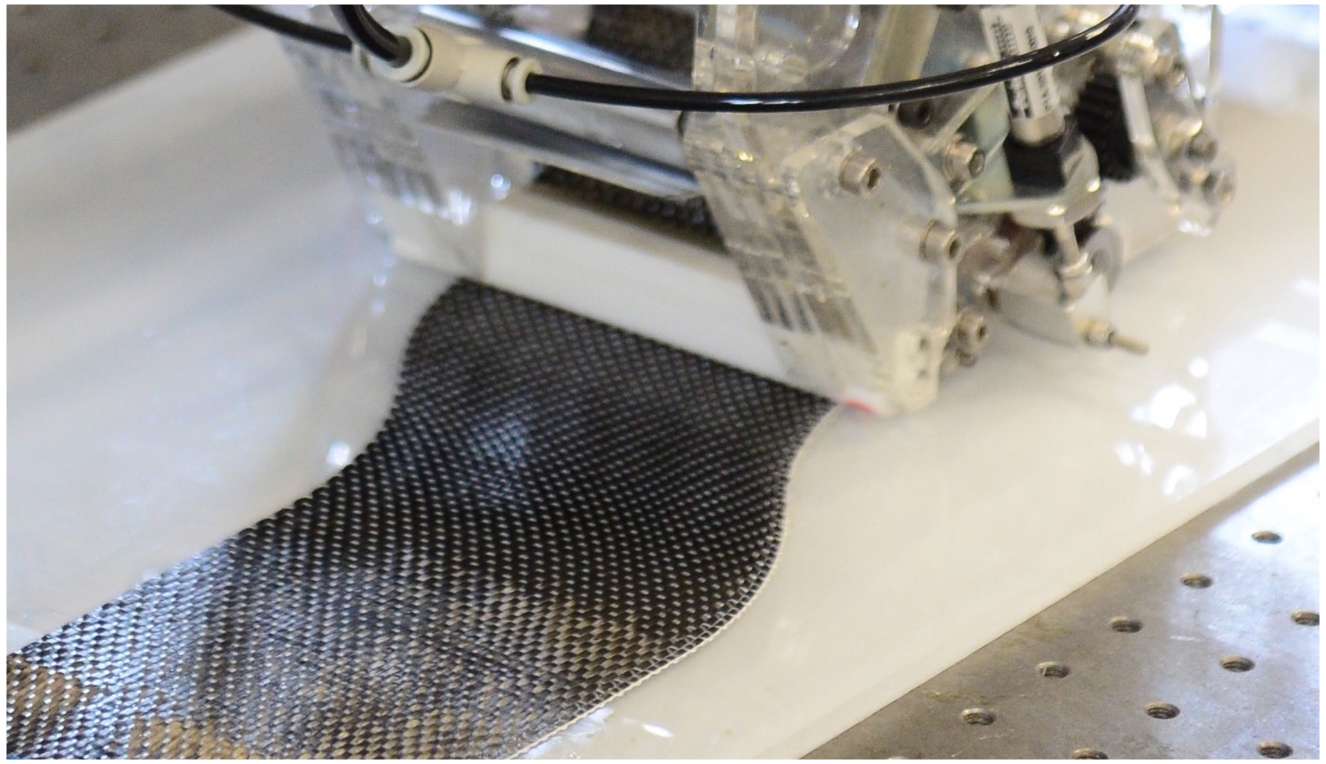
Platform Fellow at the University of Nottingham, Dr Andrew Parsons, was awarded a project in collaboration with Surface Generation, Rutland and Michigan State University (MSU) in the category of Hybrid Injection moulding (injection overmoulding) for structural components. The project entitled "Enhanced Characterisation and Simulation Methods for Thermoplastic Overmoulding" (ENACT), will focus on design-specific understanding of the manufacturing process. The project builds on complementary experience and capabilities to create a new US-UK collaboration, with significant opportunity to develop into a long-term association delivering impact to both nations. ENACT will deliver the necessary understanding that automotive OEMs and Tier-1 suppliers need to select optimum material combinations and provide greater confidence in existing computer aided engineering (CAE) tools.



Alasdair Ryder from Surface Generation said:

"We're delighted to be working with both the University of Nottingham and IACMI on the ENACT project. We look forward to strengthening our understanding of the science that underpins thermoplastic overmoulding and to explore the value of SG's PtFS technology in this field."

The second project was awarded to iComat, a University of Bristol spin out company, in collaboration with the National Composites Centre (NCC), Airbus UK, Airbus Americas and the University of Dayton Research Institute. The project entitled "Fibre Shaping for Stronger Aerospace Components" (FibreSteer), is based on iCOMAT's patented manufacturing process for Continuous Tow Shearing (CTS). CTS was the outcome from a CIMComp Feasibility Study led by Dr BC Eric Kim in 2014, which was the world's first automated composites manufacturing process to place carbon fibre tapes along curved paths without generating defects. Dr Kim currently leads the Core Project "Automated Fibre Steered Forming Technology", part of the Hub's Automated Fibre Placement Technologies Workstream.



6.3.3 TexGen Workshop

Dr Louise Brown, a Senior Research Fellow in the Faculty of Engineering from the University of Nottingham visited one of the Hub's international partners, Purdue University and delivered a workshop on textile unit cell modelling. Louise is the co- investigator on the Hub's core project New Preforming Technologies for Optimised Fibre Architectures, and supervisor on two PhD projects funded by the Hub. Louise also holds an EPSRC Research Software Engineering Fellowship and is responsible for the continued development of TexGen. TexGen is an open source software developed at the University of Nottingham for modelling textile composite structures (www.texgen.sourceforge.net).

The interactive workshop, attended by 18 delegates from academia and industry, demonstrated the use of the TexGen graphical user interface (GUI) to create 2D and 3D woven structures, and gave an outline of the modelling theory used in the software. Python scripting for TexGen was demonstrated both for editing models within the GUI, and for creating custom scripts for maximum control over the textile structures. An overview was given on the use of TexGen as a pre-processor for generating textile models and its use in the multiscale modelling process. Export options were also discussed which allow TexGen models to be easily exported to third-party software such as ABAQUS, which can then be used in simulations for prediction of material properties.

TexGen has a large number of users worldwide and underpins a significant number of research publications. To date there has been 43,517 download from 121 countries. Users can join an online forum to raise queries with the developers of the software and share their views with others. The forum promotes greater engagement and enables the University to connect with users to truly understand their needs, gather feedback, answer questions and build relationships.

Attendees of the workshop titled "A Practical Introduction to Creating Textile Models", which took place on 15th November 2019 at the Composites Manufacturing and Simulation Centre, Purdue University, Indiana, USA

6.4 Centre of Excellence in Rolling Stock

The Hub has joined as a partner of the UKRRIN Centre of Excellence in Rolling Stock (CERS) https://www.ukrrin.org.uk/centres-of-excellence/centre-of-excellence-in-rolling-stock/.

The UK Rail Research and Innovation Network (UKRRIN) is designed to create powerful collaborations between academia and industry, aiming to provide innovation in the sector and accelerate new technologies and products from research into market applications globally. UKRRIN is funded by the UK government and leading industrial partners with £92M of committed funding. The initiative is underpinned by four Centres of Excellence in; Digital systems, Rolling Stock, Infrastructure and Testing. The Centres are formed by a consortium of universities, in collaboration with existing industry testing and trialling facilities.

The Centre of Excellence in Rolling Stock (CERS) aims to meet the current and future demands of the GB rail industry for research and innovation to support the next generation of railway vehicles. The CERS is led by the Institute of Railway Research (IRR) at the University of Huddersfield in collaboration with several other partner institutions of unrivalled capabilities in railway research with a worldwide reach, making it the largest such facility in Europe dedicated to promoting innovation in rolling stock. The CERS is focussed on the major themes of Reduced Whole Life Cost vehicles and Future Low Energy vehicles.

The addition of CIMComp to the CERS combines a breadth of composite design and manufacturing expertises with a strong understanding of railway vehicle dynamics which aims to deliver a step-change in performance to the rail industry. Our current association with UKRRIN stems from Nottingham's involvement in the NEXTGEAR Shift2Rail Project (http://nextgear-project.eu/home.aspx). Moving forward, we look to collaborate more closely with CERS on projects focussed on the use of Composites for Rolling Stock.

UKRRIN
UK RAIL RESEARCH AND INNOVATION NETWORK

Centre of Excellence in Rolling Stock

6.5 Associated Projects

In addition to projects funded through the Hub, we have an ambitious target to secure an additional £20m in grant funding by the end of 2023. This section outlines funding awarded to Hub members over the last year, and how these projects fit within our vision to enhance composites manufacturing robustness.

High-Value Composites Manufacturing Cell with Digital Twinning Capability (HV-COMMAND)

(Strategic equipment grant – access for Hub partners.)
EP/T006420/1
Principal Investigator: Prof. Nick Warrior (Nottingham)
Value: £454,736

The HV-COMMAND project aims to deliver an end-to-end replication of industrial automated composites manufacturing. Comprising four components, the cell will facilitate research into each stage of the manufacturing process: design, handling, forming and inspection. The data-rich combination of stages within the cell will ultimately deliver a virtual duplication of the manufacturing process - a 'digital twin' capturing the effect of material and process variabilities during forming. The cell will be located in the Advanced Manufacturing Building at the University of Nottingham, but will be accessible by Hub spokes and industrial partners through the Hub's equipment sharing agreement.

To date, two elements of the cell have been procured and are awaiting installation and commissioning:

- A 300 T press with a platen area of 750 cm2. This is being produced by Langzauner, a leading manufacturer of hydraulic presses based in Austria.
- An Apodius 2D & 3D Vision System with Romer Arm – Apodius are a division of Hexagon, the World's leading manufacturer of metrology products.

Further elements include a robot, press tooling and a laser projection system and we aim to complete procurement by Q4 2020.

Structures 2025

(Strategic equipment grant – access for Hub partners)
EP/T006420/1
Principal Investigator: Prof. Janice Barton (Bristol)
Value: £1,143,860

The aim of Structures 2025, which is supported by 16 industry partners across different sectors, is to develop a facility for the testing and evaluating of large structures. Structures 2025 will provide a novel integrated imaging and loading system that is flexible, and will be used for the testing and assessment of a wide range of structures across industry sectors. The unique feature of Structures 2025 is that it will, for the first time, enable data-rich studies of the behaviour of large components and structures subjected to realistic loading scenarios mimicking the behaviour of a structure in service. Structures 2025 links to and supports the Hub in that it facilitates performance assessment of composite structures, with particular links to development of imaging based NDE methodologies that are also used in the context of specific Hub activities related to identification and performance assessment of manufacturing induced defects.

CERTEST

(Programme Grant – complementary activity to Hub with strong focus on manufacturing and performance of composite aerostructures)
EP/S017038/1
Principal Investigator: Prof. Ole Thybo Thomsen (Bristol)
Value: £6,924,663

The programme Grant CerTest (Certification for Design: Reshaping the Testing Pyramid) with academic partners University of Bristol, University of Bath, University of Exeter and University of Southampton, represents a decisive step towards virtual testing and reduction of empiricism in validation and certification processes. CerTest will enable lighter, more cost and fuel efficient composite aero-structures through developing the scientific foundations for a new approach for integrated high-fidelity structural testing and multi-scale modelling and 3D product quantification based on Bayesian learning and statistical Design of Experiments (DoE), incorporating understanding of design features at structural lengths scales. CerTest provides a route for lessening regulatory constraints, moving towards a more cost/performance optimised philosophy in a new culture of virtual design and certification focusing on the higher levels of the testing pyramid. CerTest is linked and aligned with the Hub through a strong research workstream of uncertainty quantification and variability of manufacturing processes in terms of their impact on structural performance and safety. complete procurement by Q4 2020.

Real-time AFP

New Investigator Award
Real-time Material Measurements and Process Control in Automated Fibre Placement Composites Manufacture
EP/S032533/1
Principal Investigator: Dr James Kratz (Bristol)
Value: £332,965

This project will build an instrumented test bench combining process sensing and modelling to demonstrate active process control in composites manufacture. The rig will be controlled by new software that acquires material data from sensors, feeds these data to process models to predict the manufacturing outcomes, and adjusts the process to deliver the desired quality. Linking real-time material data to decisions and actions during the production process will replace trial-and-error approaches to complex composite component manufacturing, developing robust manufacturing processes for high-performance structures in shorter development cycles and reduced scrap rates.

SIMPROCS

(Platform grant – aligned with and supporting Hub activities)
EP/P027350/1
Principal Investigator: Prof. Stephen Hallett (Bristol)
Value: £1,115,704

The SIMPROCS platform grant (SIMulation of new manufacturing PROcesses for Composite Structures) aims at developing and supporting simulation capability for composites manufacturing processes. It has developed novel numerical tools in several of the active technologies within the CIMComp hub: braiding, AFP, weaving (including 3D woven) and forming. Specifically, SIMPROCS is providing the technology for the modelling aspects of the Fibre Steered Forming Technology project and has recently launched an EngD project on NCF forming simulation with Airbus.

Other Associated Projects

	Lead Institution	Value (£)	Funder	Description / Title	Start Date
1	Nottingham	£131,000	Innovate UK	40546 - Enhanced Characterisation and Simulation Methods for Thermoplastic Overmoulding - ENACT	Jan-20
2	Nottingham	£8,000	EPSRC	EPSRC Impact Accelerator grant (Active RTM)	Oct-19
3	Bristol	£97,840	EPSRC	EPSRC Impact Accelerator grant (Layer By Layer)	Oct-19
4	Nottingham	£116,000	H2020-EU	Project reference 881803 - NEXT generation methods, concepts and solutions for the design of robust and sustainable running GEAR	Dec-19
5	Bristol	£938,436	EPSRC	EP/S016996/1 - Investigation of fine-scale flows in composites processing	Feb-19
6	Manchester	£23,000	HVMC	Technology Pull Through funding for braid-winding (NCC)	Nov-18
7	Nottingham	£164,998	Innovate UK	Innovate UK Innovate UK: 103362 - Composite Hybrid Automotive Suspension System Innovative Structures	Jun-18
8	Manchester	£210,000	EPSRC	EPSRC Impact Accelerator grant with Axon Automotive	Jun-18
9	Bristol	£518,000	EPSRC	EP/R023247 - Advanced Continuous Tow Shearing in 3D (ACTS3D): Advanced Fibre Placement Technology for Manufacturing Defect-free Complex 3D Composite Structures	May-18
10	Bristol	£101,082	EPSRC	EP/R021597/1 - Achieving a predictive design for manufacture capability in composites by intergating manufacturing knowledge and design intent	May-18
11	Bristol	£200,000	HEFCE	HEFCE: Composites Curriculum Development project	Jan-18
12	Bristol	£1,036,426	EPSRC	EP/P027393/1 - High Performance Discontinuous Fibre Composites - a sustainable route to the next generation of composites	Dec-17
13	Bristol	£383,000	EPSRC	EP/P021379/1 -D forming of low cost steered fibre laminates	Oct-17
14	Imperial College	£393,000	EOARD	EOARD European Office of Aerospace Research and Development (EOARD), Damage Tolerance and Durability of Structural Power Composites	Sep-17
15	Bristol	£101,000	EPSRC	EP/P027288/1 - Novel Tow termination technology for high quality AFP production of composite structures with blended ply drop-offs	Jul-17
16	Nottingham	£591,000	H2020 - CS2	Project reference 754581 - Clean Sky2 Multiscale Analysis of Airframe Structures and Quantification of Uncertainties System (MARQUESS)	Jun-17
17	Imperial College	£1,046,000	EPSRC	EP/P007465/1 - Beyond structural; multifunctional composites that store electrical energy	Feb-17
18	Imperial College	£511,000	H2020 - CS2	Project reference 738085- Structural pOweR Composites foR futurE civil aiRcraft - SORCERER	Feb-17

6.6 Outreach

Wider dissemination of Hub output has been delivered through a series of industrially focused annual events. The Hub has exhibited manufacturing demonstrators at the Advanced Engineering Show, Birmingham NEC, every year since 2017. Alongside our exhibition stand we also coordinate the Composites Engineering Forum to highlight case studies of the latest innovations and technologies in action. These include guest speakers from the Hub's industrial partner network to promote ongoing collaborative research. Hub activities have also been promoted at sector-focused events such as the Farnborough Air Show, and members of the team have presented at Composites UK events, aimed at the SME community. The annual Hub Open Day has been aligned with the IoM3 International Conference on Manufacturing of Advanced Composites (ICMAC), which was successfully relaunched by CIMComp in 2015, ensuring access to the widest community possible. The Hub website is also a central pillar for UK composites information, including a UK capability map and equipment register covering all active universities, the Hub Research Challenge Map and the Industrial Engagement Strategy.

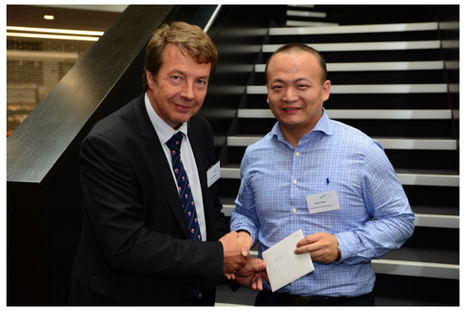
2019 Open Day

The Hub hosted its second annual Open Day in September 2019. Over 130 delegates from the UK and international academic institutions, and industry, attended the event. The Open Day is an opportunity for the composites community to hear first-hand about all of the research progress to date from all of the students and researchers working on projects within the Hub.

The Hub were delighted to welcome keynote speaker Dr Nuno Lourenco from Jaguar, Land Rover, to give the keynote presentation on composite structures for future electric vehicles. Dr Lourenco graduated with his PhD from the Composites Group at Nottingham in 2002, so it was a pleasure to show him around the University of Nottingham's Advanced Manufacturing Facility and update him on our current research.

Project leads were each invited to deliver a ten minute presentation to showcase their work, which presented opportunities for them to meet other members of the Hub community and extended partners, and further develop their network within the Hub.

The Open Day captured the work of 21 quick- fire presentations from EngD, PhD and Post Doc Hub members. These two minute summary presentations were accompanied with a poster competition. The posters were judged by delegates at the day and prizes were awarded to the two highest scored posters:



Dr Shuai Chen "An innovative approach to manufacturing closed-section composite profiles"

Jinseong Park, "Development of Stable Hybrid yarns for 3D woven Thermoset Composites"

Towering above the rest

The Hub held its first annual Composite Design and Make competition at the annual Open Day in September 2019, in conjunction with the Society for the Advancement of Material and Process Engineering (SAMPE UKIC). Six teams competed to build the tallest freestanding tower to support a mass of 1kg. Entries had to use either glass fibre or carbon fibre, with no metallic fasteners, with an overall limit on the total mass set at 250g.

There was a clear winner at just over 6.7 metres, which presented a real challenge for the judges during the testing. The winning team from the University of Bristol were presented a trophy and a cash prize by the SAMPE UKIC Chairman, Tim Wybrow. Tim commented that "our first Design and Make completion for Young Engineers and Students (YES) has been a huge success. It has created a real buzz and I'm so pleased to see so many new young and enthusiastic people engaging with SAMPE".

2019 Advanced Engineering Show

The Hub attended the Advanced Engineering Show 2019, held on 30th – 31st October at the NEC, Birmingham. This event is the UK's largest annual engineering and manufacturing event that connects OEMS, Tier 1 manufacturers and supply chain partners. It is also the primary networking and showcasing opportunity for CIMComp to engage with the industrial community within the UK.

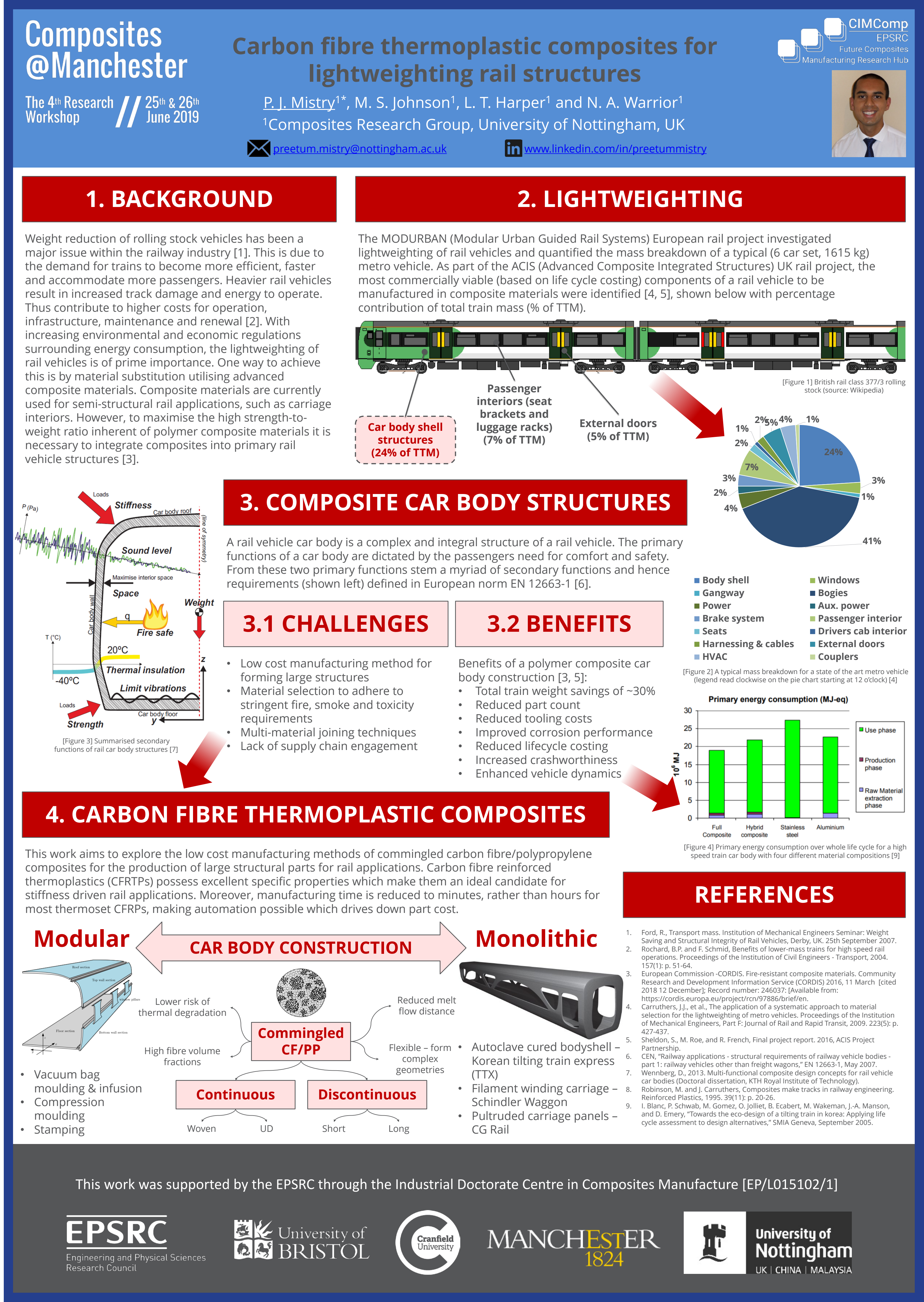
With an attendance of 15,000 visitors over the two days, the Hub was pleased to exhibit the most recent developments during the one-hour open forum session, where project leads, researchers and postgraduates delivered their research to a full auditorium.

'Composites @ Manchester', June 2019

Members from the EPSRC Future Composites Manufacturing Research Hub were invited to attend the 4th annual workshop "Composites@ Manchester" conference at the University of Manchester in June 2019. Hub Representatives from the University of Nottingham, University of Edinburgh, Manchester University and AMRC attended the 2-day event, sharing their research through a combination of oral presentations and posters. Preetum Mistry, a PhD researcher from the University of Nottingham, won the poster presentation competition for his poster entitled: 'Carbon fibre thermoplastic composites for light-weighting rail structures'. More than 80 students, researchers and academics participated in the event over the two days.

Matthew Collinson, AMRC, said:

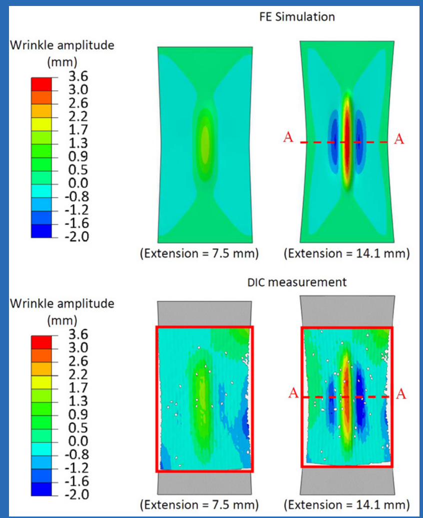
"I experienced a large range of high quality presentations from early researchers, over a wide variety of composite based topics. I also had the opportunity to present my work, which was good experience in itself. It was useful to get feedback from people doing similar research, in particular those facing similar challenges."



7 Journal Publications

2020

41. F. Yu, S. Chen, J.V. Viisainen, M.P.F. Sutcliffe, L.T. Harper, N.A. Warrior. (2020).
A Macroscale Finite Element Approach for Simulating the Bending Behaviour of Biaxial Fabrics.
Composites Science and Technology. 191.
Grant Number: EP/P006701/1
doi.org/10.1016/j.compscitech.2020.108078



This paper presents a macroscale finite element (FE) model to simulate the forming behaviour of biaxial fabrics, incorporating the effects of bending stiffness to predict fabric wrinkling. The dependency of the bending stiffness on the fibre orientation was addressed by extending a non-orthogonal constitutive framework previously developed for biaxial fabric materials. The nonlinear bending behaviour of a biaxial non-crimp fabric (NCF) with pillar stitches was characterised by revised cantilever test using structured light scanning to measure specimen curvature, providing input data for the material model. Simulations were performed to replicate the bias-extension behaviour of the NCF material, showing good agreement with experimental data. Wrinkles were observed within the central area of the specimen at low extension, which consequently affect the uniformity of the shear angle distribution in the region where pure shear is expected.

40. Valkova, M., Anthony, D.B., Kucernak, A., Shaffer, M.S.P., Greenhalgh, E.S. (2020). **Predicting the Compaction of Hybrid Multilayer Woven Composite Reinforcement Stacks.** Composites Part A: Applied Science and Manufacturing. 133.
Grant Number: EP/P006701/1
doi.org/10.1016/j.compositesa.2020.105851

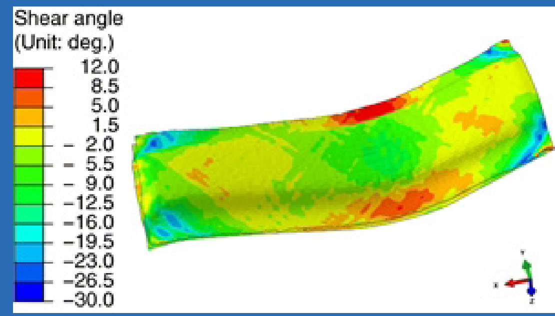
39. Elkington, M., Almas, E., Ward-Cherrier, B., Pestell, N., Lloyd, J., Ward, C., Lepora, N. (2020). **Real Time Defect Detection During Composite Layup via Tactile Shape Sensing.** Journal of Science and Engineering of Composite Materials. Grant Number: EP/P006701/1

38. PJ Mistry P.J., Johnson M.S., Galappaththi, U.I.K. (2020). **Selection and Ranking of Rail Vehicle Components for Optimal Lightweighting using Composite Materials.** Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit. 133. Grant Number: EP/P006701/1

37. Johannisson, W., Nguyen, S., Lindbergh, G., Zenkert, D., Greenhalgh, E., Shaffer, M.S.P., and Kucernak A. (2020). **A Residual Performance Methodology to Evaluate Multifunctional Systems.** Multifunctional Materials.
Grant Number: EP/P006701/1
doi.org/10.1088/2399-7532/ab8e95

2019

36. S. Chen, O. P. L. McGregor, A. Endruweit, L. T. Harper, N. A. Warrior. (2019).
Simulation of the Forming Process for Curved Composite Sandwich Panel.
International Journal of Material Forming.
Grant Number: EP/P006701/1
doi.org/10.1007/s12289-019-01520-4



The work in this publication was completed as part of a Feasibility Study in conjunction with Gordon Murray Design. A finite-element-based process model was developed to simulate to production of affordable, high-volume sandwich panels with complex curvature and varying local thickness. Meso-scale sandwich models, based on measured properties of the honeycomb cell walls, indicate that panels deform primarily in bending if out-of-plane movement of the core is unconstrained, while local through-thickness crushing of the core is more important in the presence of stronger constraints.

As computational costs for meso-scale models are high, a complementary macro-scale model was developed for simulation of larger components. This is based on experimentally determined homogenised properties of the honeycomb core. The macro-scale model was employed to analyse forming of a generic component. Simulations predicted the poor localised conformity of the sandwich to the tool, as observed on a physical component.

35. Veldenz, L., Di Francesco, M., Giddings, P., Kim, B.C., Potter, K. (2019). **Material Selection for Automated Dry Fiber Placement using the Analytical Hierarchy Process.** Advanced Manufacturing: Polymer and Composites Science. Online: 24th January 2019, 83-96. Grant Number: EP/P006701/1 doi.org/10.1080/20550340.2018.1545377

34. May, D., Aktas, A., Advani, S.G., Endruweit, A., Fauster, E., Lomov, S.V., Long, A., Mitschang, P., Abaimov, S., Abliz, D., Akhatov, I., Allen, T.D., Berg, D.C., Bickerton, S., Bodaghi, M., Caglar, B., Caglar, H., Correia, N., Danzi, M., Dittmann, J., Ermanni, P., George, A., Grishaev, V., Kabachi, M.A., Kind, K., Lagardère, M.D., Laspalas, M., Liotier, P.J., Park, C.H., Pipes, R.B., Pucci, M., Raynal, J., Rodriguez, E.S., Schledjewski, R., Schubnel, R., Sharp, N., Sims, G., Sozer, E.M., Umer, R., Willenbacher, B., Yong, A., Zaremba, S., Ziegmann, G. (2019). **In-plane Permeability Characterization of Engineering Textiles Based on Radial Flow Experiments: A Benchmark Exercise.** Composites Part A: Applied Science and Manufacturing. 121, 110 -114. Grant Number: EP/P006701/1. doi.org/10.1016/j.compositesa.2019.03.006

33. Turk, M, Vermes, B, Thompson, A, Belnoue, J. P.H, Hallett, S. R, Ivanov, D. S. (2020). **Mitigation Against Forming Defects by Local Modification of Dry Preforms.** Composites Part A, Special Issue of Euromech 602 congress : Composite manufacturing processes. Analyses, modelling and simulations. Grant Number: EP/P006701/1 doi.org/10.1016/j.compositesa.2019.105643

32. Matveev, M, Endruweit, E, De Focatiis D. S. A., Long A.C, Warrior, N.A. (2019) **A Novel Criterion for the Prediction of Meso-scale Defects in Textile Preforming.** Composite Structures. 226, pp.111263. Grant Number: EP/P006701/1 doi.org/10.1016/j.compstruct.2019.111263

31. Mistry, P, J., Johnson, M. S. (2019). **Lightweighting of Railway Axles for the Reduction of Unsprung Mass and Track Access Charges.** Part F: Journal of Rail and Rapid Transit. Grant Number: EP/P006701/1 journals.sagepub.com/doi/

30. Herring, R, Dyer, K, Macleod, A, Ward, C. (2019). **Computational Fluid Dynamics Methodology for Characterisation of Leading Edge Erosion in Whirling Arm Test Rigs.** Journal of Physics: Conference Series. Grant Number: EP/P006701/1 doi.org/10.1088/1742-6596/1222/1/012011

29. Herring, R, Dyer, K, Macleod, A, Martin, F, Ward, C. (2019). **The Increasing Importance of Leading Edge Erosion and a Review of Existing Protection Solutions.** Renewable and Sustainable Energy Reviews. Grant Number: EP/P006701/1 doi.org/10.1016/j.rser.2019.109382

28. Yan, S., Zeng, X., Long, A.C. (2019). **Meso-scale Modelling of 3D Woven Composite T-joints with Weave Variations.** Composites Science and Technology. 171,171-179. Grant Number: EP/IO33513/1. doi.org/10.1016/j.compscitech.2018.12.024

27. Matveev, M.Y., Belnoue, J.P-H., Nixon-Pearson, O.J., Ivanov, D.S., Long, A.C., Hallett, S.R., Jones, I.A. (2019). **A Numerical Study of Variability in the Manufacturing Process of Thick Composite Parts.** Composite Structures. 208, 23-32. Grant Number: EP/IO33513/1 doi.org/10.1016/j.compstruct.2018.09.092

2018

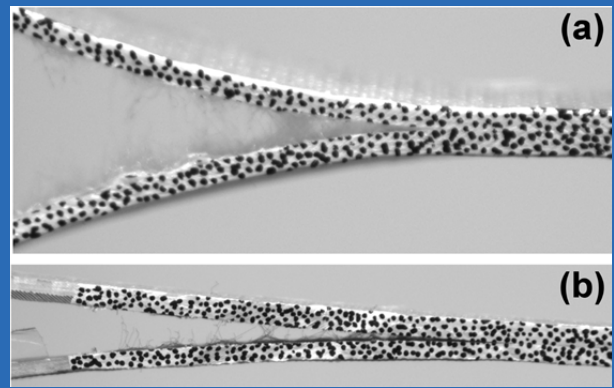
26.Endruweit, A., Zeng, X., Matveev, M., Long. A.C. (2018). **Effect of Yarn Cross-sectional Shape on Resin Flow Through Inter-yarn Gaps in Textile Reinforcements.** Composites Part A: Applied Science and Manufacturing. 104 (1),139-150. Grant Number: EP/I033513/1. doi: 10.1016/j.compositesa.2017.10.020

25.Mesogitis, T.,Kratz, J., & Skordos, A.A. (2018). **Heat Transfer Simulation of the Cure of Thermoplastic Particle Interleaf Carbon Fibre Epoxy Prepregs.** Journal of Composite Materials. 53 (15), 2053-2064. Grant Number: EP/IO33513/1 doi./10.1177/0021998318818245

24.Yan, S., Zeng, X., Brown, L.P., Long, A.C. (2018). **Geometric Modeling of 3D Woven Preforms in Composite T-joints.** Textile Research Journal. 88 (16), 1862-1875. Grant Number: EP/IO33513/1. doi.org/10.1177/0040517517712098

23.Yan, S., Zeng, X., Long, A.C., (2018). **Experimental Assessment of the Mechanical Behaviour of 3D woven Composite T-joints.** Composites Part B. 154,108-113. Grant Number: EP/IO33513/1 doi.org/10.1016/j.compositesb.2018.08.007

22.Mamalis, D., Obande, W., Koutsos, V., Blackford, J., Ó Brádaigh, C.M., Ray, D. (2018).
Novel Thermo-plastic Fibre-metal Laminates Manufactured by Vacuum Resin Infusion: The Effect of Surface Treatments on Interfacial Bonding.
Materials & Design. 162, 331 -344.
Grant Number: EP/P006701/1
doi.org/10.1016/j.matdes.2018.11.048

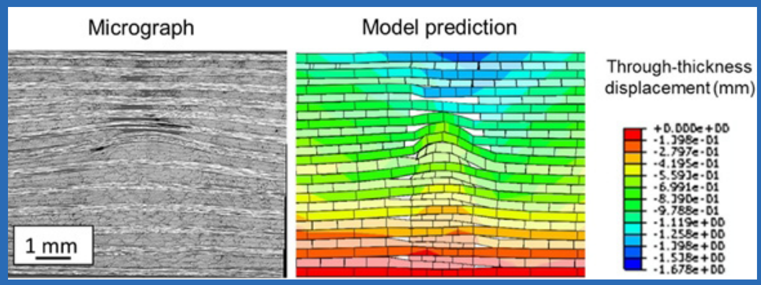


High-speed images of the crack tip zone for the (a) GF-Elium® and (b) TP-FMLs.

A vacuum assisted resin infusion method was used to produce hybrid laminates to study the effect of various chemical and physical treatments on the surface morphology of the aluminium (Al) alloy sheets and on the bond strength at the metal-composite interface. The wettability, topography and chemical composition of the treated Al alloy sheets were studied by employing contact-angle goniometry, coher-ence scanning interferometry, profilometry and X-ray photoelectron spectroscopy. The results showed that the applied treatments on the Al alloy sheet changed the surface morphology and surface energy in a different degree, which in turn effectively enhanced the interfacial bond strength between the constit-uents. In addition, the flexural, interlaminar shear strength and interlaminar fracture toughness of the manufactured TP-FMLs with the optimum metal surface treatment were evaluated. The experimental results of the TP-FMLs were compared to an equivalent thermoplastic composite. The composite-metal interface and the fracture surface characteristics were examined under scanning electron microscopy. In-situ polymerisation was found to play a key role in bonding the treated Al alloy with the composite layer during manufacturing.

2017

21. Belnoue, J., Tassos, M., Nixon-Pearson, O.J., Kratz, J., Ivanov, D.S., Partridge. I.K., Potter. K.D., Hallett, S.R. (2017). **Understanding and predicting defect formation in automated fibre placement pre-preg laminates.** Composites Part A: Applied Science and Manufacturing. 102. 195-206. Grant Number: EP/I033513/1 doi: 10.1016/j.compositesa.2017.08.008



Gaps and overlaps coupled solution (a) Thickness evolution (b) Model prediction comparison with sample micrographs for the internal ply geometry around the central wrinkle.

The focus of this paper is to understand how out-of-plane wrinkles form during debulking and autoclave curing of laminates with embedded gaps and overlaps between tapes deposited by automated fibre placement. Predictions are made using a novel modelling framework and validated against micro-scale geometry characterisation of artificially manufactured samples. The paper demonstrates the model's ability to predict consolidation defects for the latest generation of toughened pre-pregs.

20. Akonda, M., Stefanova, M., Potluri, P., & Shah, D. (2017). **Mechanical Properties of recycled carbon fibre/polyester thermoplastic tape composites.** Journal of Composite Materials. 51 (18), 2655-2663. Grant Number: Not acknowledged. Doi.org/10.1177/0021998316672091

19. Atas, A., Gautam, M., Soutis, C., Potluri, P. (2017) **Bolted Joints in Three Axially Braided Carbon Fibre /Epoxy Composites with Moulded-in and Drilled Fastener Holes.** Applied Composites Materials. 24(2), 449-460. Grant Number: Not acknowledged.

18. Corbridge, D.M., Harper, L.T., de Focatiis, D.S.A., Warrior, N. (2017). **Compression moulding of composites with hybrid fibre architectures.** Composites Part A: Applied Science and Manufacturing. 95 (1): 87-99. Grant Number: EP/I033513/1. doi: 10.1016/j.compositesa.2016.12.018

17. Gautam, M., Katnam, K., Potluri, P., Jha, V., Latto, J., Dodds, N. (2017). **Hybrid Composite Tensile Armour Wires in Flexible Risers: A Multi-scale Model.** Composites Structures. 162, 13-27. Grant Number: Not acknowledged. doi.org/10.1016/j.compstruct.2016.11.090

16. Goktas, D., Kennon, W., Potluri, P. (2017). **Improvement of Model Interlaminar Fracture Toughness of Stitched Glass/ Epoxy Composites.** Applied Composites Materials 24 (2), 351-375. Grant Number: Not acknowledged. doi.org/10.1007/s10443-016-9560-x

15. Hartley, J.W., Kratz, J., Ward, C., Partridge, I.K., (2017). **Effect of tufting density and loop length on the crushing behaviour of tufted sandwich specimens.** Composites Part B: Engineering. 112 (1): 49-56. Grant Number: EP/I033513/1. doi: 10.1016/j.compositesb.2016.12.037

14. Jones, H., Roudaut, A., Chatzimichali, A., Potter, K., Ward, C. (2017). **The Dibber: Designing a standardised handheld tool for lay-up tasks.** Applied Ergonomics. 65 (1), 240-254. Grant Number: EP/I033513/1. doi: 10.1016/j.apergo.2017.05.014

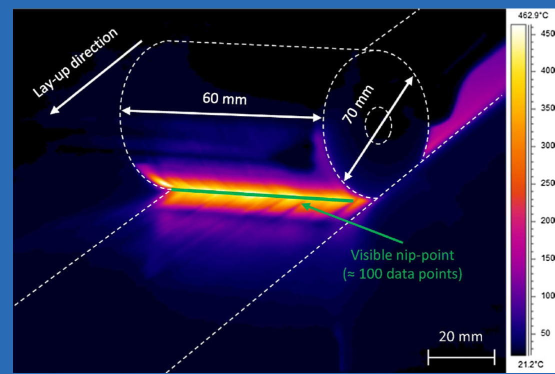
13. Koncherry, V., Potluri, P., Fernando, A. (2017). **Multifunctional Carbon Fibre Tapes for Automotive Composites.** Applied Composite Materials. 24 (2), 477-493. Grant Number: Not acknowledged. doi.org/10.1007/s10443-016-9550-z

132. Matveev, M.Y., Long, A.C., Brown, L.P., Jones, I.A. (2017). **Effects of layer shift and yarn path variability on mechanical properties of a twill weave composite.** Journal of Composite Materials. 51 (7), 913-925. Grant Number: EP/I033513/1. doi: 10.1177/0021998316655870

11. Mesogitis, T., Skordos, A., Long, A. (2017). **Stochastic Simulation of the Influence of Fibre Path Variability on the Formation of Residual Stress and Shape Distortion.** Polymer Composites. 38 (12), 2642-2652. Grant Number: Not acknowledged. doi.org/10.1002/pc.23856

10. Nixon-Pearson, O.J., Belnoue, J.P-H., Ivanov, D.S., Potter, K., Hallett, S. (2017). **An experimental investigation of the consolidation behaviour of uncured prepregs under processing conditions.** Journal of Composite Materials. 51 (13), 1911-1924. Grant Number: EP/I033513/1. doi: 10.1177/0021998316665681

9. Di Francesco, M., Veldenz, L., Dell'Anno,G., Potter, K. (2017). **Heater power control for multi-material, variable speed Automated Fibre Placement.** Composites Part A: Applied Science and Manufacturing. 101, 408-421. Grant Number: EP/P006701/1 doi.org/10.1016/j.compositesa.2017.06.015



This paper presents a simple semi-empirical thermal model for the Automated Fibre Placement process, which correlates the heater power and the layup speed with the substrate surface temperature. The deposition temperature was measured over a range of heater powers and layup speeds. The experimental data is used to define and validate a semi-empirical thermal model for two classes of materials used in conjunction with a diode laser: carbon fibre reinforced thermoplastics and bindered dry fibres. This enables open-loop, speed dependent heater power control, based on defining and programming the speed dependent heater power function in the machine controls.

8. Pavlopoulou, S., Roy, S., Gautam, M., Bradshaw, L., Potluri P. (2017). **Numerical and Experimental Investigation of the Hydrostatic Performance of Fibre Reinforced Tubes.** Applied Composite Materials. 24 (2), 417-448. Grant Number: Not acknowledged. doi.org/10.1007/s10443-016-9563-7

7. Prabhu, V.A., Elkington, M., Crowley, D., Tiwari, A., Ward, C., (2017). **Digitisation of manual composite layup task knowledge using gaming technology,** Composites Part B: Engineering. 112 (1), 314-326. Grant Number: EP/I033513/1. doi: 10.1016/j.compositesb.2016.12.050

6. Thompson, A.J., El Said, B., Ivanov, D., Belnoue, J.P-H., Hallett, S.R. (2017). **High fidelity modelling of the compression behaviour of 2D woven fabrics.** International Journal of Solids and Structures. 154, 104-113. Grant Number: EP/I033513/1. doi: 10.1016/j.ijsolstr.2017.06.027

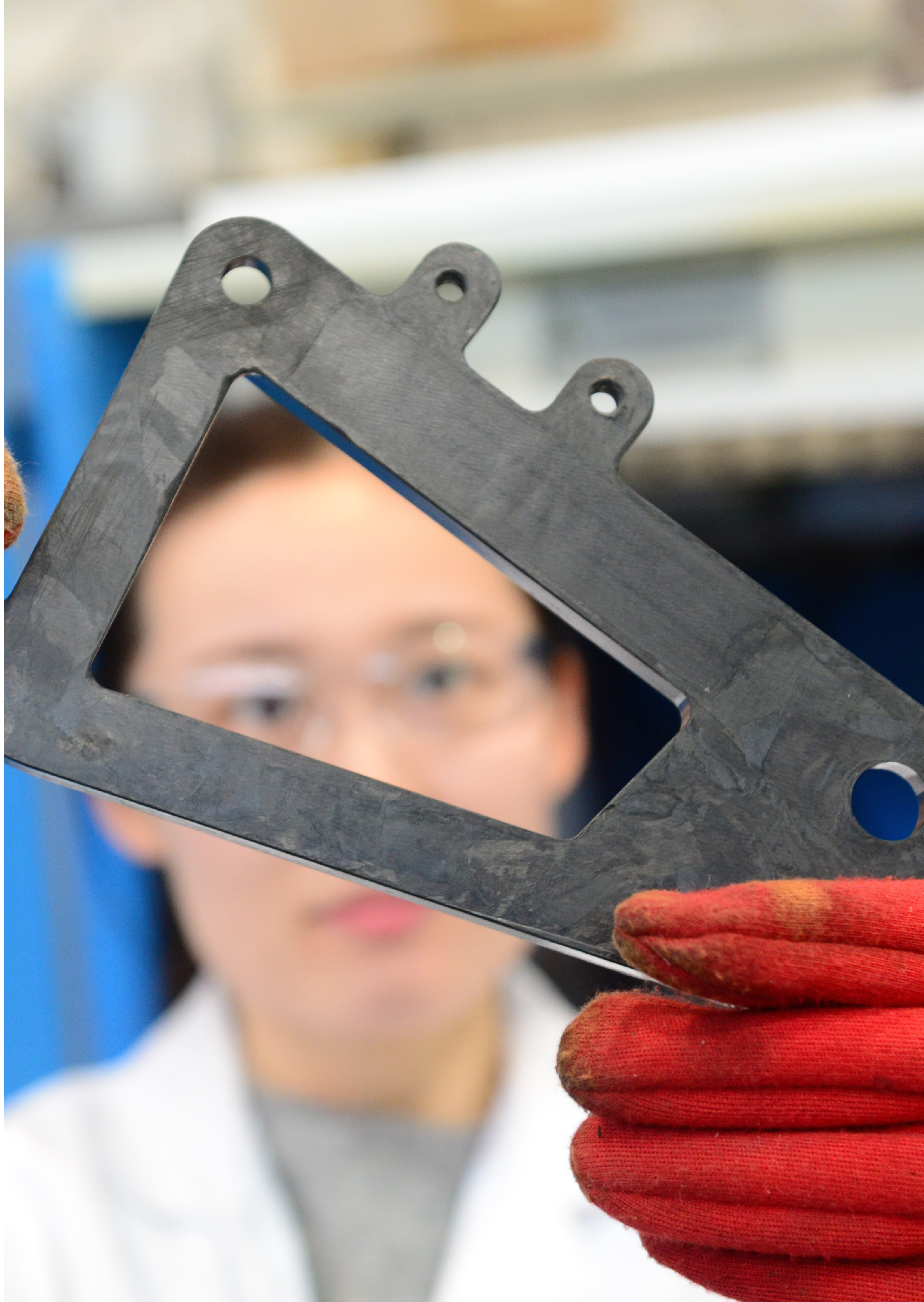
5. Gommer, F., Endruweit, A., Long, A.C. (2017). **Influence of the micro-structure on saturated transverse flow in fibre arrays.** Journal of Composite Materials. 52 (18), 2463-2475. Grant Number: EP/IO33513/1. doi.org/10.1177/0021998317747954

4. Roy, S., Potluri, P, Soutis, C. (2017). **Tensile Response of Hoop Reinforced Multiaxial Braided Thin Wall Composite Tubes.** Applied Composite Materials. 24 (2), 397-416. Grant Number: Not acknowledged. doi.org/10.1007/s10443-016-9570-8

3. 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. Grant Number: Not acknowledged. doi.org/10.1007/s10443-016-9529-9

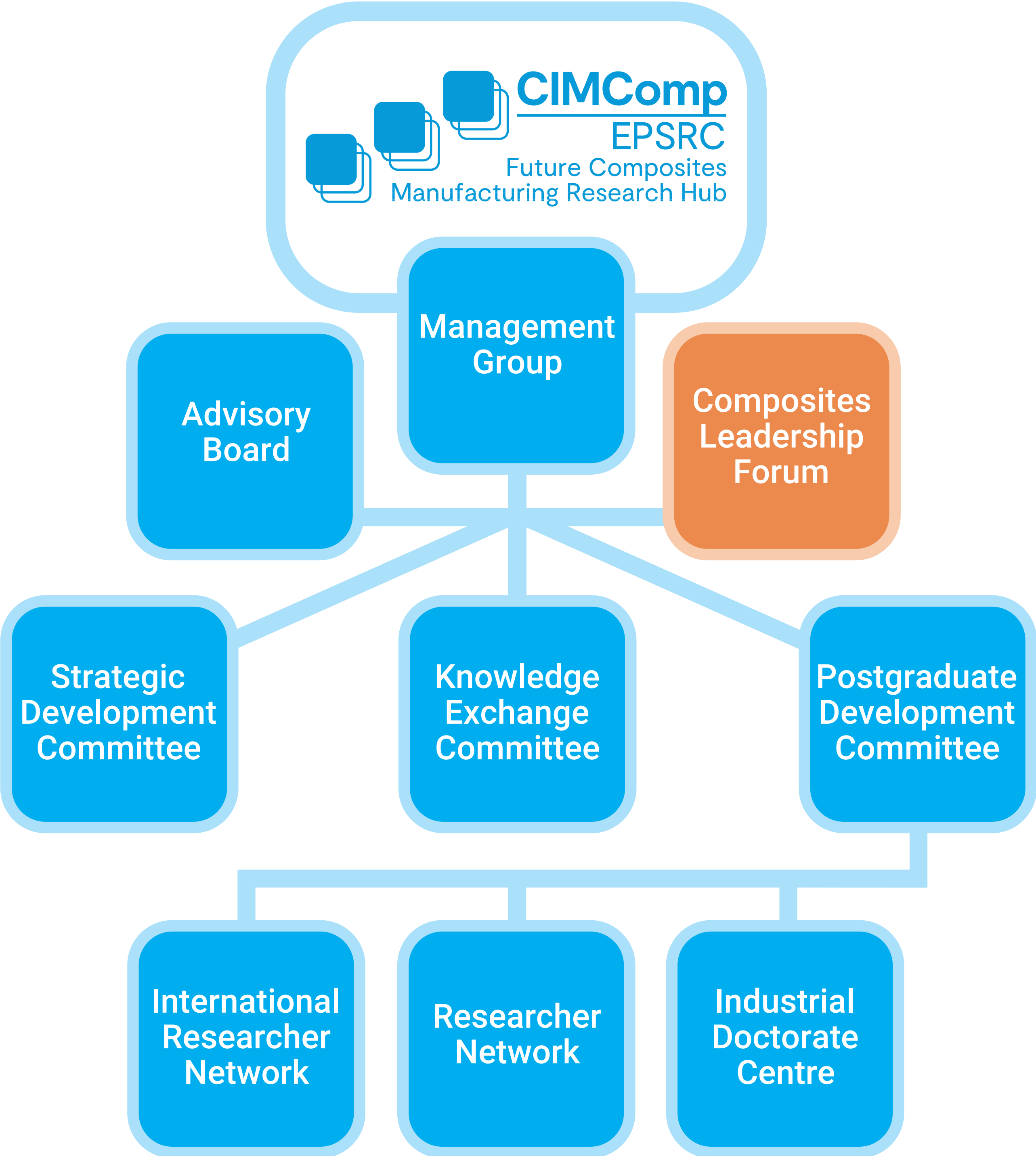
2. Thompson, A., El Said, B., Ivanov, D., Belnoue, J., Hallett, S. (2017). **High Fidelity Modelling of the Compression Behaviour of 2D Woven Fabrics.** International Journal of Solids and Structures. 154, 104-113. Grant Number: EP/L504919/1 doi.org/10.1016/j.ijsolstr.2017.06.027

1. 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. Grant Number: Not acknowledged. doi.org/10.1007/s10443-016-9554-8



8 Meet the Team

The Hub's governance structure is responsive to the need to develop user engagements over the life of the Hub. The Management Group 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 outlined in the figure below.



The **Advisory Board** comprises independent academic and industrial members who take a high level, strategic view of the needs of Hub stakeholders. The Advisory Board 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.

8.1 Management Group

Professor Nick Warrior is the Hub Director and Professor of Mechanical Engineering. He has been in the Faculty of Engineering at the University of Nottingham since 1985 and Head of the Composites Research Group since 2009. His research is on manufacturing processes and design and test methodologies of high performance polymer composites for automotive and aero-space applications. Nick has worked on many EPSRC, TSB and industrial composites projects (portfolio value of over £33 million) and has published more than 200 papers in composites and solid mechanics. He has supervised over 40 successful PhD projects. In his research he has worked with most of the UK automotive manufacturers and collaborated with many leading UK universities. He is a Chartered Engineer and a Fellow of the Institution of Mechanical Engineers and has received the Royal Academy of Engineering Silver Medal Award (2009) for successful industrial exploitation of composite materials.

Prof Ole Thybo Thomsen is the NCC Chair in Composites Design and Manufacturing, Bristol Composites Institute, University of Bristol, and the National Composites Centre (NCC). He has held previous positions at the University of Southampton; Aalborg University, Denmark; European Space Agency, European Space Technology and Research Centre (ESTEC), the Netherlands, the University of Delaware, USA; and Israel Institute of Technology. He was the Chairman of the Research Council for Technology and Production Sciences, Independent Research Fund Denmark between 2012-2014 (equivalent to EPSRC); appointed Fellow of the Danish Academy of Technical Sciences (equivalent to FREng) 2007, and received a Knighthood from Her Royal Majesty Queen Margrethe II of Denmark in 2012. His research interests include design, manufacturing and experimental/computational characterisation/validation of lightweight composite structures. He has led numerous national and international research programmes, most with industry support, with life term research fund earnings in excess of £35M.

Dr Tom Turner is Deputy Director of the Hub and Chair of the Strategic Development Committee. Tom is an Associate Professor in Composites Manufacturing at the University of Nottingham where he teaches Aerospace Design. Since joining the Composites Group at Nottingham in 2000 he has been involved with 14 UK research council / UK Government funded projects as well as 5 large industrially funded programmes. Recently he has acted as Co-Investigator on a multi-million dollar strategic collaboration in composites recycling with Boeing. He has wide-ranging interests in all stages of composites design, manufacture & assembly predominantly in the aerospace and automotive fields, including process modelling and process automation development, methods for whole life cycle cost assessment and the recovery and re-use of carbon fibres.

Dr Lee Harper is the Hub Manager, responsible for the day-to-day operations of the Hub. He is also an Associate Professor in Composites Manufacturing at the University of Nottingham and has worked in the field of composite materials for 20 years. He has established credible expertise in process development and numerical modelling for fibre reinforced polymer composites. His principal research interests focus on developing and modelling automated manufacturing processes for the automotive industry. He developed the Directed Carbon Fibre Preforming (DCFP) process, an automated technology for producing net-shaped non-woven materials. He has authored 50 peer-reviewed publications, co-supervised 12 PhD students and been PI on projects totalling £4.0m. He currently sits on the UK's Composite Leadership Forum, as part of the Technology Working Group and is a committee member for the Society for the Advancement of Materials and Process Engineering (SAMPE).

Dr Mike Johnson is Associate Professor in Engineering Design and Polymer Composites at the University of Nottingham. Mike's principal research is in lightweighting across the transport sectors, but particulary for rail vehicles. As Chair of the Hub Postgraduate Development Committee, he provides coordination of the Industrial Doctorate Centre, the Researcher Network and the Hub Core Projects. Mike oversees the training and progression of research personnel, the development of the IDC taught programme, the management of cohesion between PhD and EngD students along with post-doctoral Researchers and delivery of the International Research Exchange. Mike is currently leading a Hub funded Feasibility study entitled "Incremental sheet forming of fibre reinforced thermoplastic composites" directed at the manufacture of large, low cost structures.

Andrew Mills is Deputy Chair of the Postgraduate Development Committee and Principal Research Fellow in Composites Manufacturing at Cranfield University. He leads the development of technology for the cost effective manufacturing of lightweight composite structures in close partnership with industry. Andrew has led the Airbus UK/Cranfield project AMCAPS, which investigated novel materials and process technology for large composite wing manufacture, some techniques from which have now been qualified for manufacturing the Airbus A380. Currently, he is developing knowledge tools for automotive sector composites design for manufacture within an APC project involving Nissan and GKN, landing gear thermoplastic composite components and integrated carbon fibre composite and titanium structures for next generation defence aircraft.

Dr Mikhail Matveev is Chair of the Researcher Network. He is a Research Fellow at the University of Nottingham working on the core projects "New manufacturing techniques for optimised fibre architectures" and "Resin injection into reinforcement with uncertain heterogeneous properties: NDE and control". His fields of expertise are the mechanics of composites and modelling of composite manufacturing processes.

Professor Ivana Partridge is the Director of the multi-partner EPSRC Industrial Doctorate training Centre in Composites Manufacture. She is Professor in Composites Processing within the Bristol Composites Institute at the University of Bristol. Her long-term research interests include thermoset resin and composite toughening, through-thickness reinforcement of composites, composite process control and polymer-metal-fibre hybridization. Her past research has been funded mainly by EPSRC grants, but also by EU and direct industry programmes. Professor Partridge is Fellow of the Institute of Materials, Minerals and Mining (IoM3) and a member of the EPSRC Peer Review College.

Janice Dulieu-Barton is a Professor of Experimental Mechanics in the Bristol Composites Institute at the University of Bristol in the UK. Prior to this she was at the University of Southampton for 20 years. She received her PhD from the University of Manchester where she started her research on the topic now known as 'Thermoelastic stress analysis'. She has published around 350 papers with 130 in archival journals. Janice's expertise is in imaging for data rich materials characterisations and assessments of structural performance, with a focus on lightweight structural design particularly composite structures. Janice is a Fellow of the institute of Physics, the US Society for Experimental Mechanics and British Society for Strain measurement. Janice is also active in training and mentoring early career researchers; she has supervised over 30 successful PhDs, produced many short courses aimed at graduate students and is Deputy Director of the Industrial Doctorate Centre in Composites Manufacturing.

Dr Dipa Roy is the Spoke Representative for the Hub and a Senior Lecturer in Composite Materials Processing at the University of Edinburgh. Her research focus is in Materials and Structures, in the Institute for Materials and Processes, Mechanical Engineering, within the School of Engineering. Previously Dipa worked with the Irish Composites Centre (IComp), University of Limerick, Ireland, for more than five years participating in many industry-led R&D projects.

Alex Hammond is the Hub Deputy Manager and assists with the day-to-day operations of the Hub. Her background is in corporate governance, finance and project management. She has worked at the University of Nottingham since 2012 and joined the Future Composites Manufacturing Research Hub in May 2020. She has over 10 years' experience of managing large-scale multi-partner research projects funded by the EU and UKRI.

8.2 Advisory Board

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