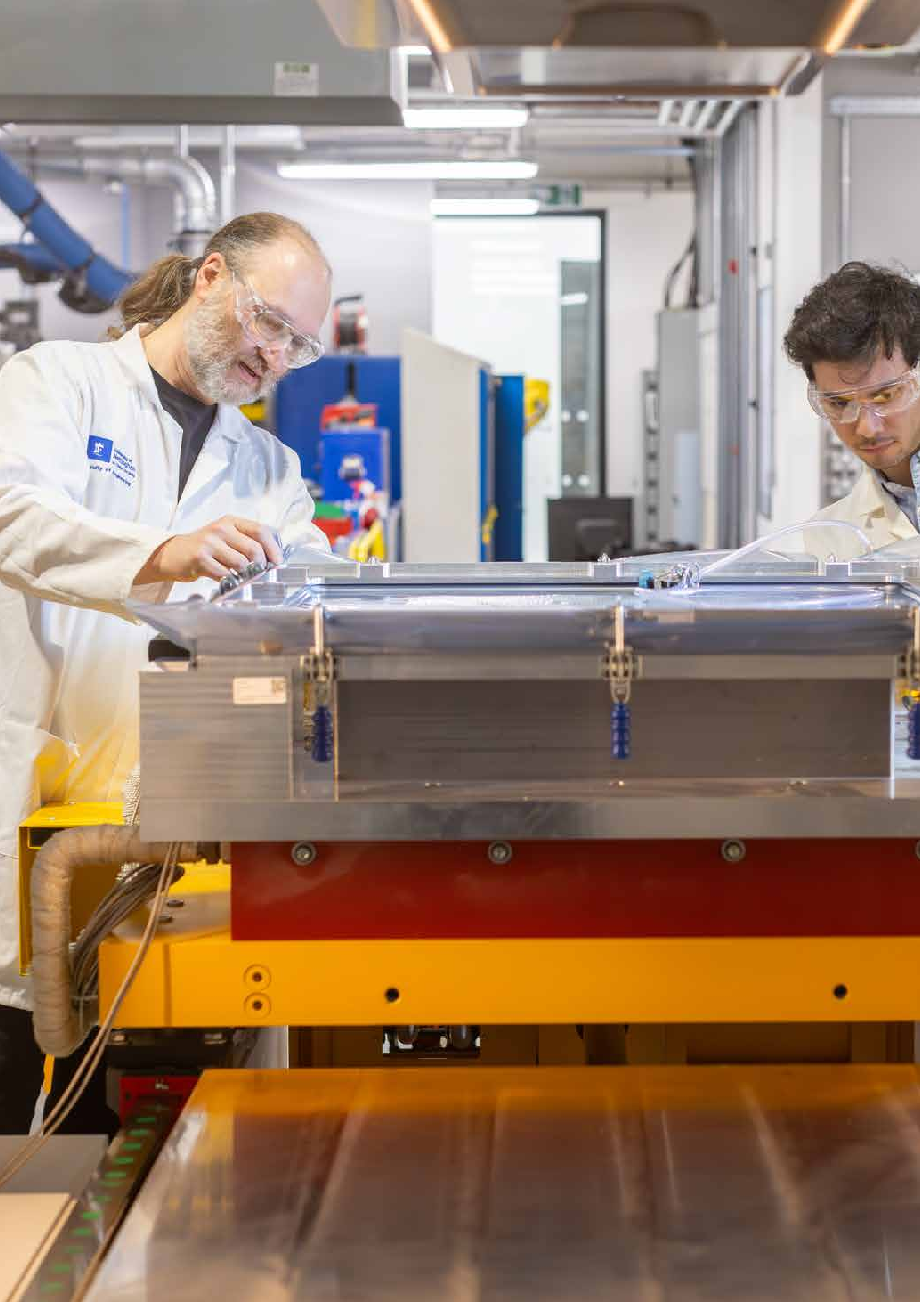
CIMComp EPSRC Future Composites Manufacturing Research Hub

2023/2024

Annual Report

Underpinning the development of next generation composites manufacturing processes for exploitation by industry.

Engineering and Physical Sciences Research Council



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Executive Summary

Nick Warrior, Hub Director

Welcome to the Future Composites Manufacturing Research Hub's final Annual Report which contains highlights from another busy and successful year. Over the course of the programme fundamental scientific research into new technologies and processes has been conducted to improve quality, rate and sustainability in composites manufacturing.

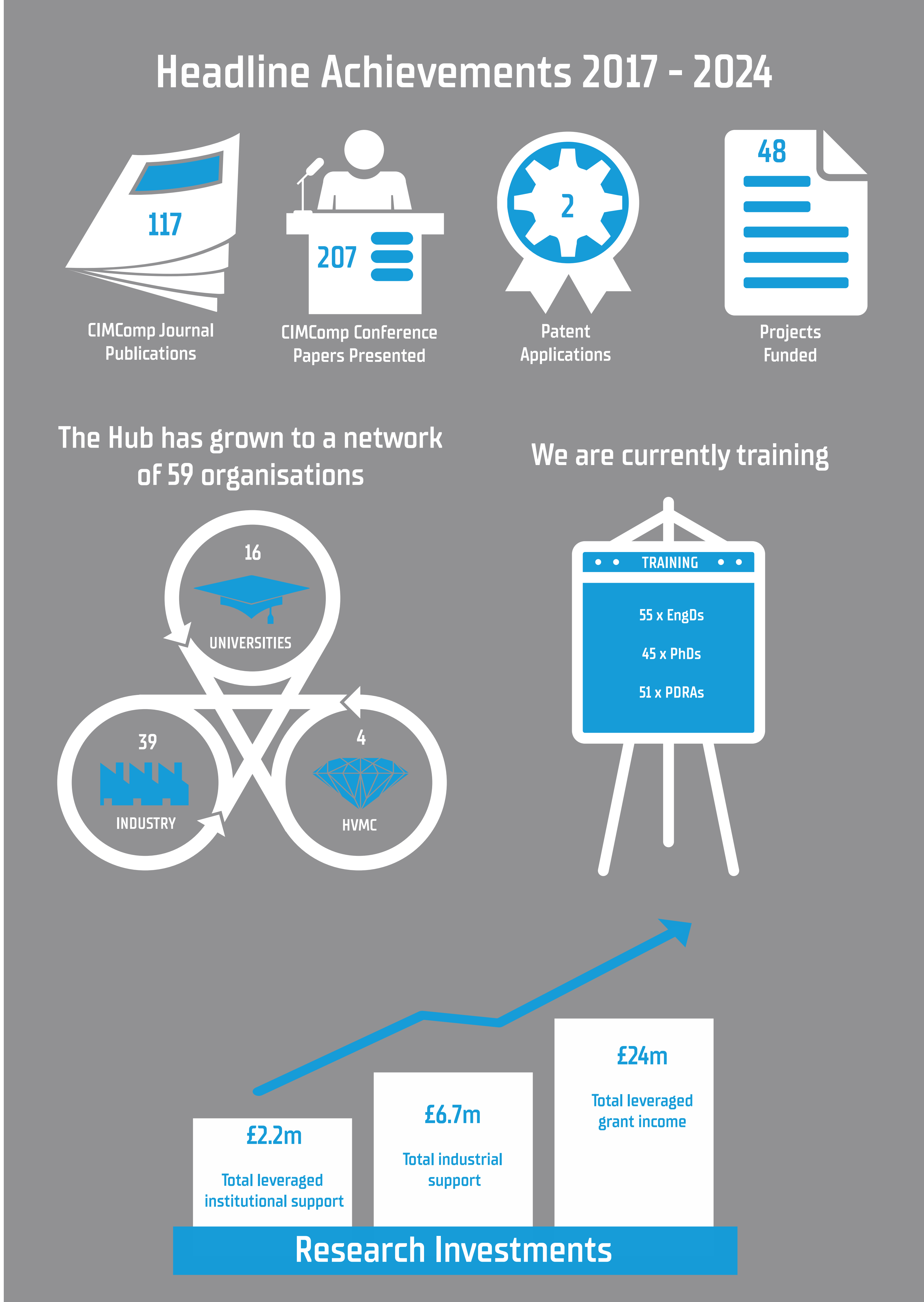
The project teams have to date delivered some innovative experimental and numerical solutions at low TRL, contributing to improved performance and knowledge of composite products, reduced energy use, manufacturing waste and design costs. We have seen several new projects emerge from our earlier investments and predict this trend will increase as our remaining projects end and look to continue their research. Members of the Hub have been successful in securing £24m of leveraged grant funding since the start of the Hub in 2017. Progress on our active projects can be found in this report.

As technologies developed within the Hub have matured, there has been increased activity with industry and the High Value Manufacturing Centres (HVMC) and in particular with the National Composites Centre (NCC), and amongst the Hub network which has grown considerably since the start of the programme. Instrumental to this network, are the connections made by our early career researchers who share their research and experience via the Hub platform to foster future collaborations and enhance job prospects.

Several outreach activities have taken place this year. The Hub was well represented at the International Conference on Composite Materials (ICCM23) in Belfast. Our annual Hub Open Day was held alongside the International Composites Summit (ICS), and we exhibited at the Advanced Engineering Show (AES) and JEC World which provided invaluable access to the composites manufacturing community and the opportunity for us to showcase our research to a wider audience.

I take this opportunity to thank everyone for their dedication to the Hub, especially our industry partners and Advisory Board for their invaluable contributions, and to the EPSRC for the opportunities created.

I hope you enjoy reading our final annual report, and I look forward to working with you all in the future.



1 Hub Vision and Objectives

The Hub vision is founded on two industry inspired Grand Challenges:

- Improving existing composites manufacturing processes
- Developing new composites manufacturing technologies

Since 2017, the Hub has built on the success of the EPSRC Centre for Innovative Manufacturing in Composites (CIMComp; EP/I033513/1), with a vision to develop a national centre of excellence in fundamental research for composites manufacturing – delivering research advances in cost reduction and production rate increase, whilst improving quality and sustainability.

Our aim is to underpin the growth potential of the UK composite sector by developing the underlying manufacturing process science and technology needed by industry, whilst enabling rapid dissemination of that knowledge into the UK industrial base.

Composites manufacturing research is the key to further exploitation of composites in existing sectors (aerospace, automotive, energy and defence) and more widespread adoption in emerging sectors such as infrastructure, rail and marine.

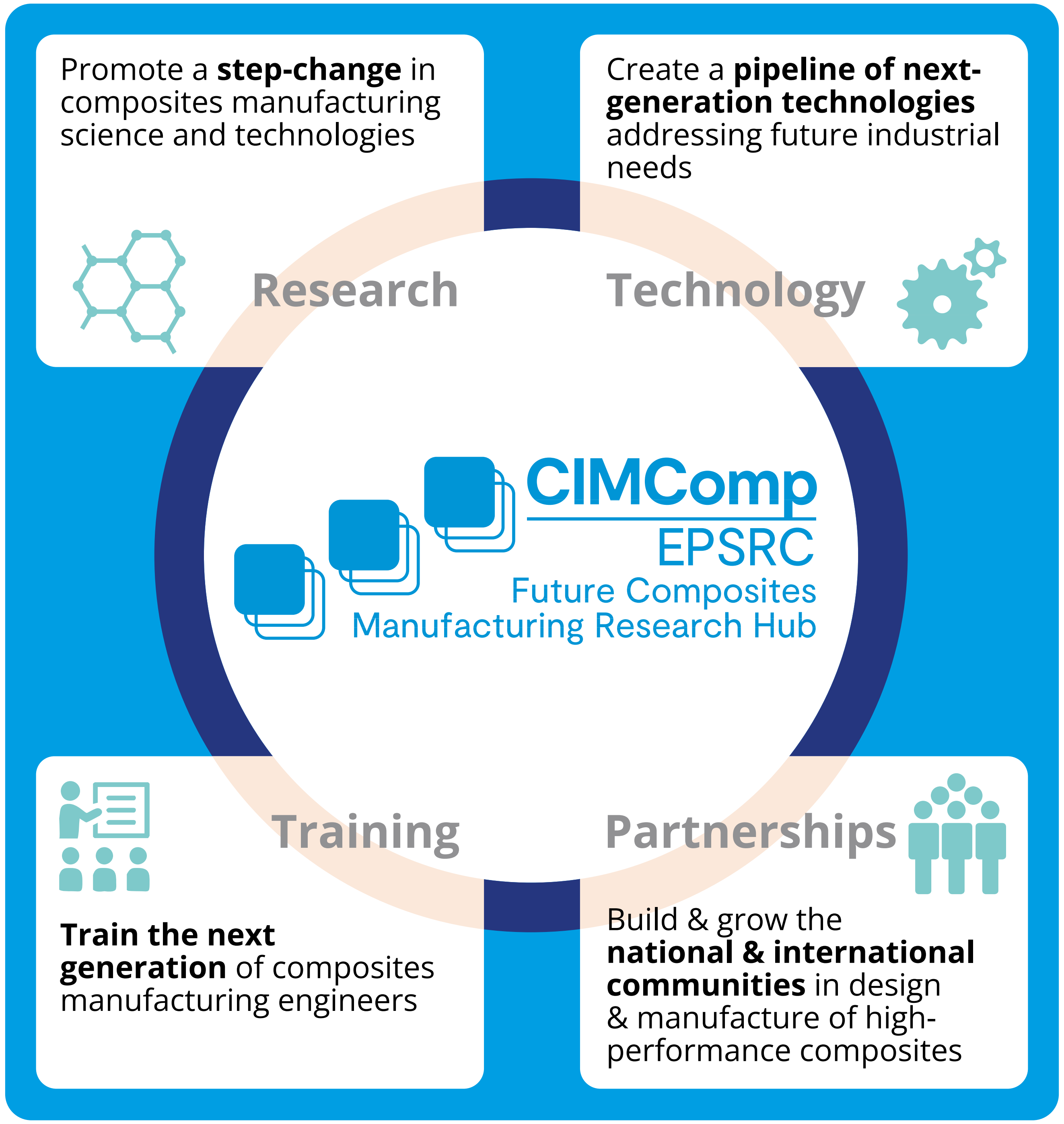
To achieve this vision, the Hub aims to deliver against core objectives in four key areas:

- Research excellence
- Technology transfer
- Network building
- Training

Hub Funding Model

Hub funding model: Academic Institutions and Industry have committed to a further £12.6m in support of the £10.3m EPSRC investment.

Hub Core Objectives

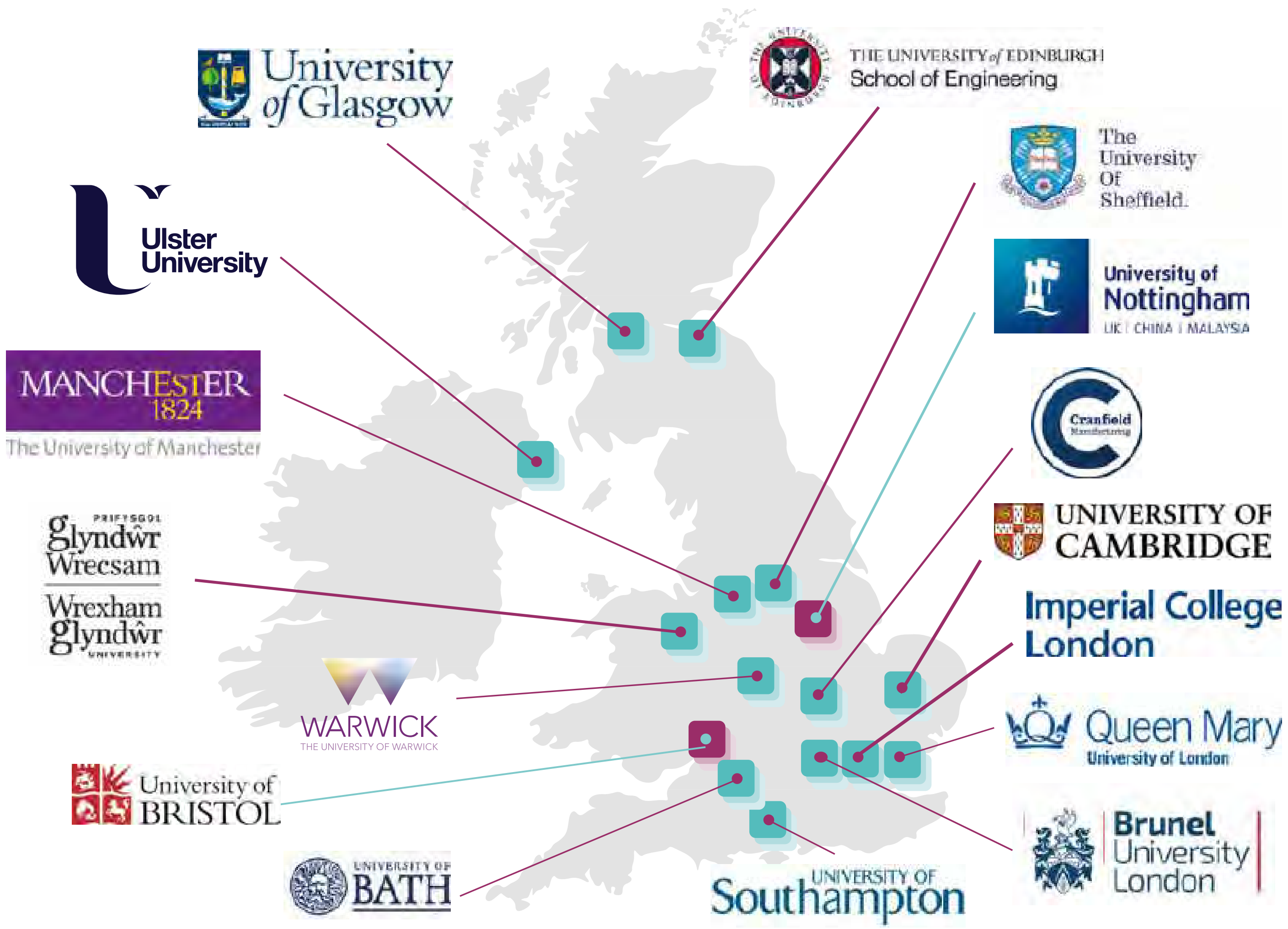


2 Hub Network

The key to sustaining the Hub is in developing the national and international communities to establish important ongoing partnerships for future research programmes.

Academic Partners

The Hub engages with the national academic network in composites manufacturing research through active collaboration with UK research groups. Engagement beyond the original Hub membership of Nottingham and Bristol and four Spokes (Manchester, Imperial, Southampton and Cranfield), has primarily been through Feasibility Study calls. Successful applicants are invited to become Spokes and we currently have 16 academic members participating in the Hub.



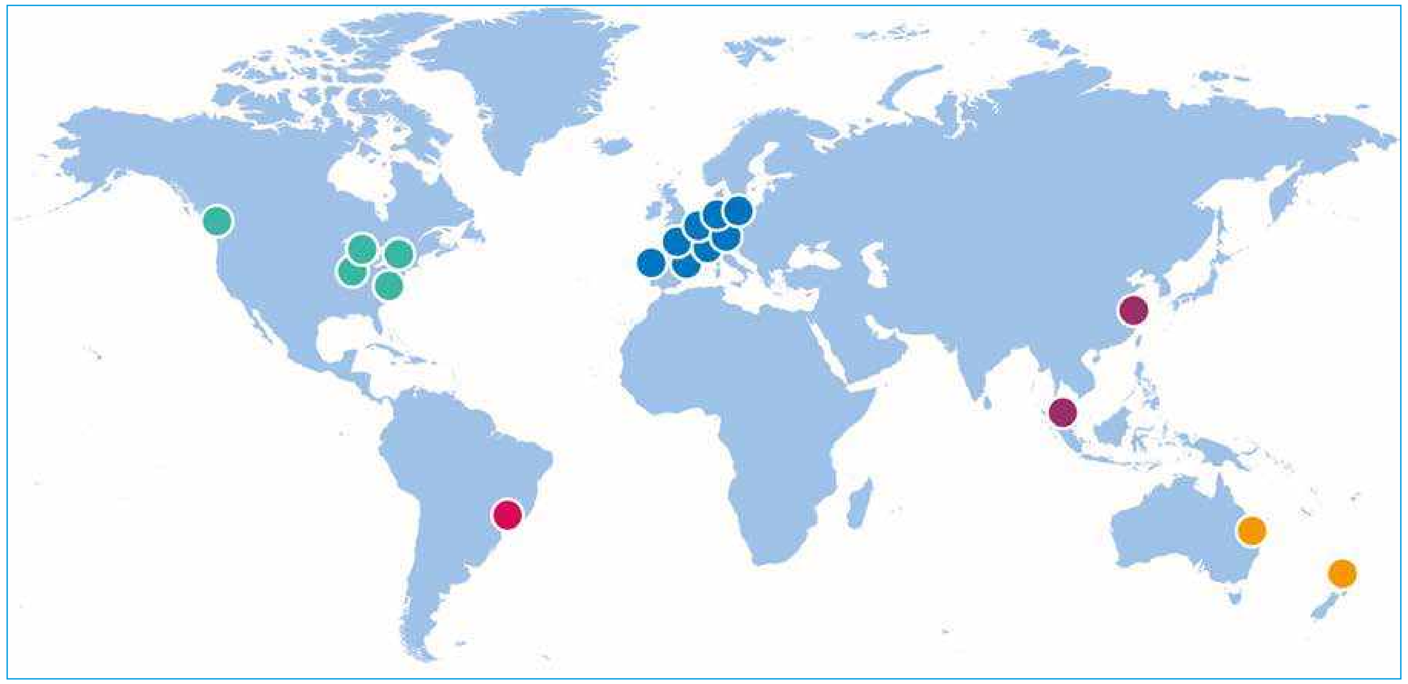
International Network

Developing both domestic and international communities in composites manufacturing is of critical importance to the Hub. The Hub's international network partners are an important component of our network and offer opportunities for collaboration, cooperation and postgraduate and researcher development.

The Hub has developed a network of 23 leading institutions across 11 countries. This is important not only for sharing information and developments in composites manufacturing, but also in our training aspirations, as Hub postgraduate students will have the opportunity to spend a three month secondment at one of the linked institutions, accessing new expertise and facilities and developing their personal networks.

We have successfully funded seven Study Placements within our international partner network, helping students to foster independence.

- Aachen
- Dresden
- École Centrale de Nantes
- EPFL
- Federal Univeristy of Toulouse
- Fraunhofer ICT
- Institut Clement Ader
- Kaiserslauten
- Leuven
- Munich
- Porto
- Stuttgart
- Twente
- UNNC
- UNMC
- British Columbia
- Concordia
- Delaware
- McGill University
- Michigan State
- Purdue
- LEL-IPT
- Auckland
- Southern Queensland



- 23 leading institutions across 11 countries
- Share information and developments in the field
- Facilitate visits and exchange of people
- Establish informal or formal partnerships in research programmes
- All have agreed to host visits from staff and students for 3 months

Industrial Engagement

Support from our Industry Partners helps to ensure our research is industrially relevant and that outputs progress towards commercialisation. This occurs through two mechanisms: support from the Hub's Advisory Board and hosting regular technical project review meetings with our Industry Partners. All project leads are appointed a mentor from the Advisory Board to help identify opportunities for exploitation. This insight helps to coordinate project-level technical meetings for each Work Stream, where specific partners are invited biannually to engage in comprehensive reviews of the projects and offer guidance.

We have endeavoured to create a balanced portfolio of partners, including material suppliers, Tier One Suppliers and OEMs, supporting aerospace, automotive and energy (including high pressure gas storage) sectors equally, and emerging industry sectors such as rail and construction, marine and renewables. We actively encourage our industrial partners to put forward ideas for academia to adopt, ensuring the research is industrially relevant and also ambitious and high-risk. Mechanisms for interaction with new and existing partners are outlined in the Hub's Industrial Engagement Strategy. This provides a framework for engagement and supports our aim to create a collaborative environment where fundamental research can be developed with the support and involvement of industry.

Industrial support has grown strongly over the life of the Hub. Research projects are supported by a network of 37 industrial partners and four Centres within the HVM Catapult, providing £6.7m of leveraged support in the form of studentships, supervision, materials and access to equipment. We have successfully engaged with 17 of the original 22 proposal supporters, with the largest contribution (£1.4m) coming from the HVM Catapult National Composites Centre (NCC).

There are still a number of significant opportunities across the sector and our Business Development Manager will be actively working with other composite partners to realise these and leverage additional support. In addition to our Industry Partners, a further 45 companies (who did not provide letters of support in the Hub proposal) have actively supported or contributed to our research projects.

Additional Industry Partners

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

Industry Partners

3 Hub Research

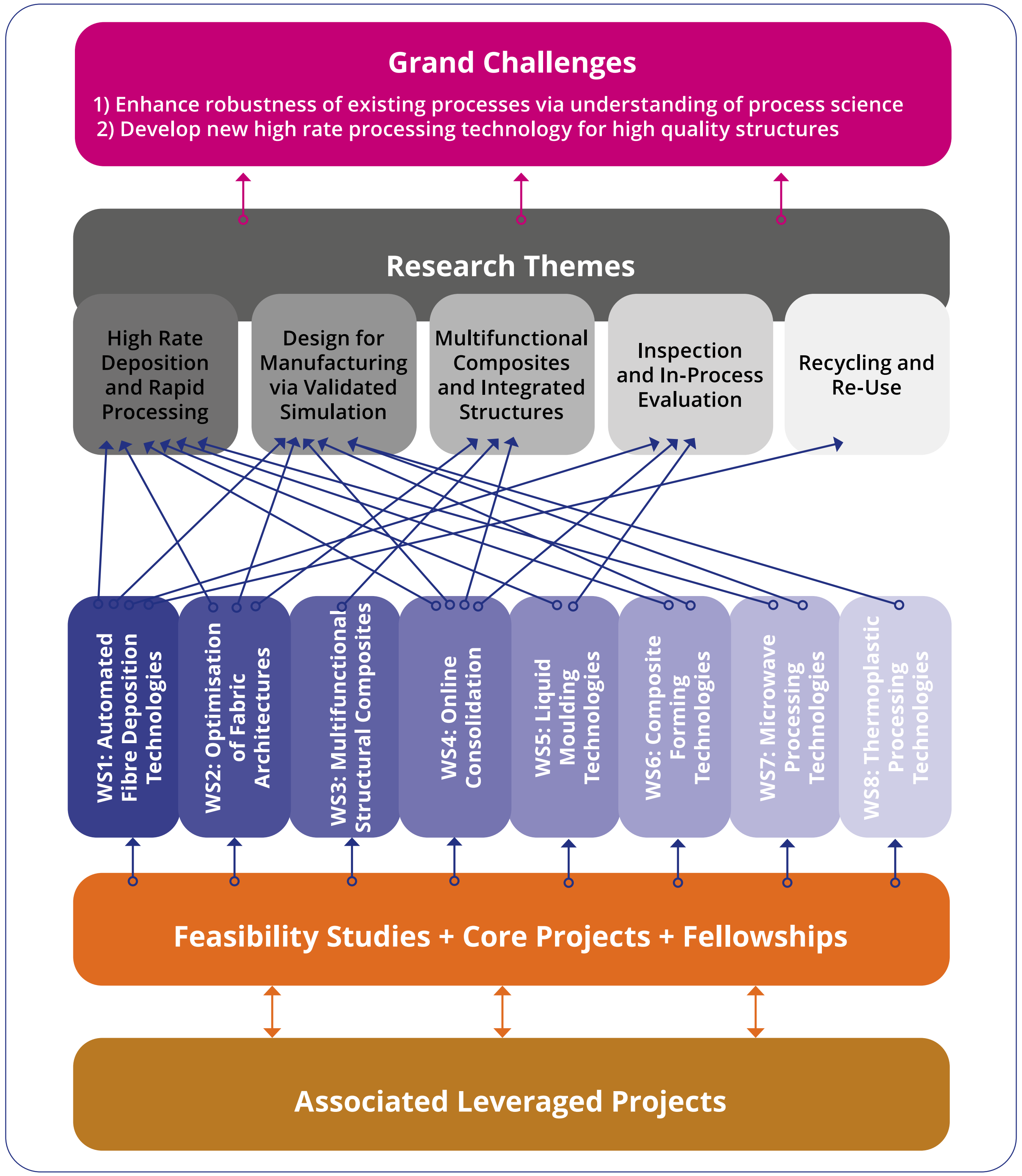
Since 2017 the Hub has funded six Core Projects, 24 Feasibility Studies, three Innovation Fellowships, eight Synergy Promotion projects, and seven Researcher Network Awards. In addition, £24m has been leveraged in associated leveraged projects which has enabled us to build a wider network and further develop key skills.

The Hub project portfolio aims to accelerate the uptake of composite materials by reducing the costs of engineered products whilst increasing quality, increasing functionality, and striving to meet the 2050 Net Zero targets. As legislative support for recycling and the circular economy continues to grow, it becomes even more important to conduct research strategically and with a focus on maximising benefits to industry.

Our Grand Challenges are addressed by five Research Themes identified with the help of industry partners and the broader composites community. The challenges in each Research Theme are met by relevant technologies from across eight Work Streams (WS). All Hub projects and leveraged studentships are linked to a Work Stream, which is led by the principal investigator of a Core Project or one of the Hub's Platform Fellows. The aim is to increase research excellence by ensuring that each Work Stream is driven by national leaders in that technology area, adopting best practices in experimental and modelling manufacturing science across all associated projects.

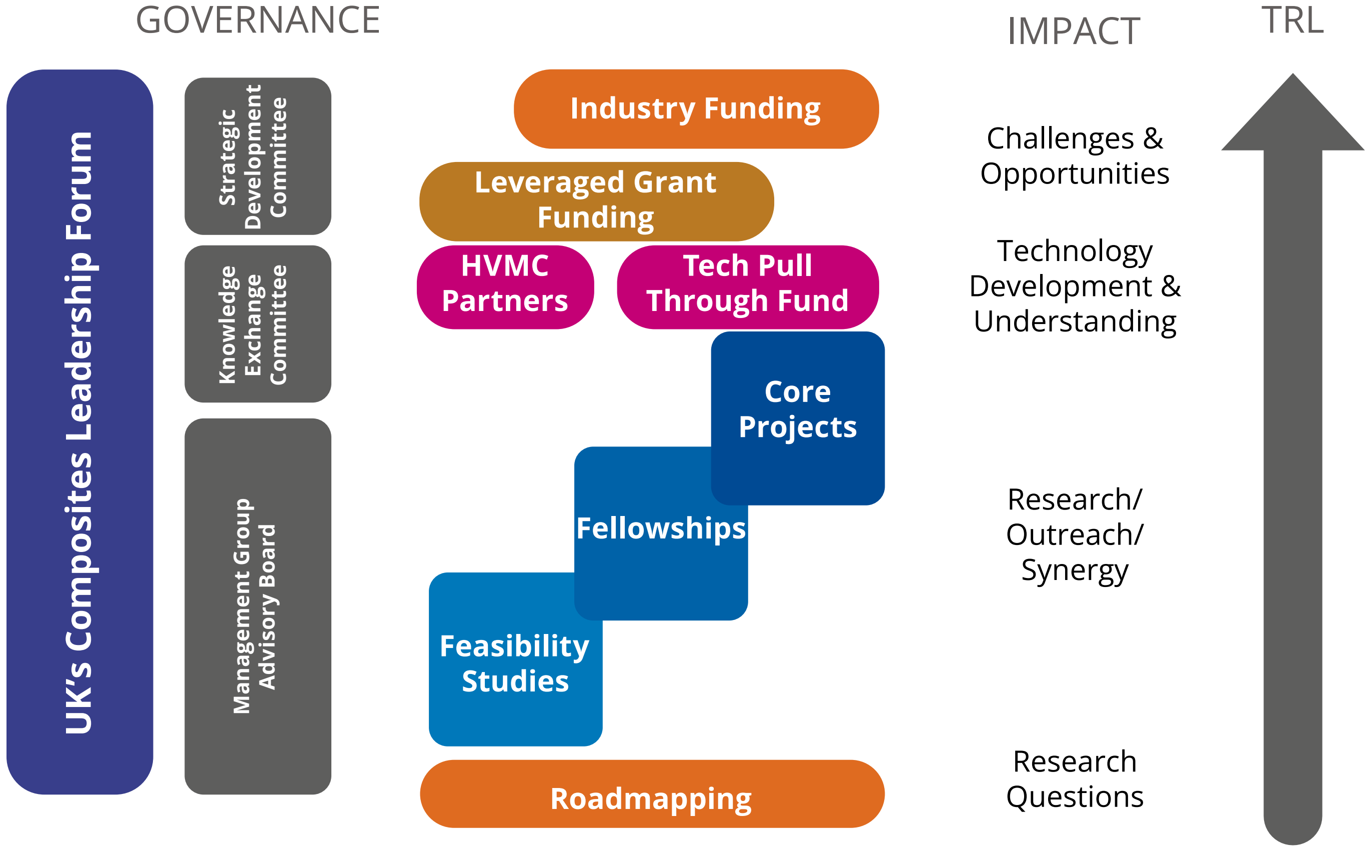
Our Feasibility Study programme offers up to £50k for novel, ambitious six-month projects, which are encouraged, where appropriate, to be developed into proposals for Core Projects (36-month collaborations), of values between £375k and £700k. In 2019, after consultation with the Hub Knowledge Exchange Committee (KEC), we launched the Synergy Promotion Fund to run alongside our Core Projects and Feasibility Studies. The Synergy Projects enable development of synergies between past and ongoing Hub research activity and new academic contributors and promote collaborative activity for emerging and novel research. This ensures our portfolio of projects can work towards the same goals of meeting the Hub core objectives and Grand Challenges. The relationship between individual researchers, their projects and Work Stream can be viewed using the SharpCloud data visualisation platform.

In the summer of 2023, we were granted a six-month extension to the programme and a further six-month extension was granted in April 2024 enabling us to continue project research and impact activities beyond the original Hub end date of December 2023. The aftereffects of COVID-19 combined with recruitment issues for some of our projects meant some deliverables could not be completed by the planned programme end date. During the extension period we will be seeking to transition proven research out to the Catapult Centres in collaboration with the Knowledge Exchange Committee (KEC), wider industry and the Advisory Board (AB). The latest results from our remaining three Core Projects, Innovation Fellowship and four remaining Synergy Projects can be found in this report.



Pathways to Impact

The Hub plays a key role in the composite manufacturing technology pipeline, pushing proven research outcomes through to the HVM Catapult Centres (National Composites Centre (NCC), Advanced Manufacturing Research Centre (AMRC), Warwick Manufacturing Group (WMG) and Manufacturing Technology Centre (MTC) so that they mature through the Technology and Manufacturing Readiness Levels (TRL, MRL) into successful products and manufacturing activity, to be exploited by UK industry.



Many projects have had impact beyond the Hub, advancing fundamental research through the Technology Readiness Levels (TRL's), largely through leveraged funding. Five Hub technologies have been selected for this report, all developed beyond TRL 3 (early proof of concept demonstrated in the laboratory), through translational development, and in four of the five cases, on the journey to adoption through industry funded projects.

The five Hub technologies developed:

- **Composite Forming:** modelling and simulation of multi-ply preforms in composite manufacture.
- **Continuous Tow Shearing:** novel fibre steered composite manufacturing technique for complex components.
- **Fan Blade Compaction:** development of simulation tools for composite manufacturing with application to aerospace (specific example to aircraft engine fan blades), energy and automotive industries.
- **Layer by Layer:** utilisation of layer-by-layer curing to reduce the processing time in comparison to conventional autoclave composite manufacture.
- **Optimise:** multi-scale modelling of multi-material and multi-architecture composite preforms and new manufacturing techniques.

Composite Forming

Principal Investigators: Professor Michael Sutcliffe, University of Cambridge; Dr Lee Harper, University of Nottingham; Professor Richard Butler, University of Bath.

The Composite Forming technology began as a £50k Feasibility Study in the CIMComp Centre in April 2013, with the forming code shared with industrial partners in the first of four Innovate UK projects within two years. Further Hub investment in the form of two Feasibility Studies in the CIMComp Hub from January 2018 led to further leveraged funding from both the EPSRC for equipment, Innovate UK, and industry before funding for a Core Project in the Hub began in May 2020. This has led to both Technology Pull Through funding from the NCC and direct industry funding, with strands of further low TRL work still being funded by the Hub in the form of a Synergy Project, to reflect the fact that technology development is rarely linear. The R&D of this technology has had interactions with 19 industrial partners and RTO's.

Continuous Tow Shearing

Principal Investigator: Dr ByungChul (Eric) Kim, University of Bristol.

The Continuous Tow Shearing (CTS) technology was invented in a ~£650k EPSRC standard research grant that began in June 2010. It was progressed in the CIMComp Centre in January 2013, through a Platform Fellowship, before being further matured through a subsequent EPSRC funded project in May 2018. Further aspects of the technology were developed in the CIMComp Hub, firstly to demonstrate the feasibility (Jan 2019) of a lay-flat and forming process as a cost-effective alternative to direct AFP deposition on complex 3D shapes, and then in a Core Project (Dec 2019) to develop numerical tools and manufacturing processes for complex parts made from fibre-steered sustainable highly aligned short-fibre materials. The technology was spun-out as iCOMAT in January 2019 to pursue industrial end to end solutions from product design to delivery of production components. iCOMAT has been a partner in a subsequent industry funded EngD project (Jan 2020) to develop solutions for large-scale complex components employing novel fibre-steered designs and in an NCC Core Project (Sept 2022) to demonstrate the feasibility of using the CTS with highly aligned recycled carbon fibre materials on an industrial scale, beyond that demonstrated in CIMComp. iCOMAT has achieved remarkable success since 2019 and is now a limited company with >30 employees and has attracted > £8M of investment/ funding. The R&D of this technology has had interactions with nine industrial partners and RTO's.

Fan Blade Compaction

Principal Investigator: Professor Stephen Hallett, University of Bristol.

The first technology brick of Fan Blade Compaction came to the CIMComp Centre in a Core Project that started in July 2013, simulating the compaction behaviour during composite processing of uncured prepreg. These simulation tools were extended in further EPSRC funded work (May 2017), primarily to reduce run time, and in an EngD to apply the tools to industry relevant geometry (Aug 2017). External grant funding in July 2020 enabled the development of an efficient workflow for the modelling of composite manufacturing capabilities at the mid-TRL's, before direct application to optimise the tool for an industrial component in August 2022. The R&D of this technology has had interactions with nine industrial partners and RTO's.

Layer by Layer

Principal Investigators: Dr Alex Skordos, Cranfield University; Dr James Kratz, University of Bristol.

This technology started in parallel projects funded in November 2013, in an external EPSRC project to optimise robustness performance in automated composites manufacture and a CIMComp Centre Core Project to develop experimental techniques to characterise the Layer by Layer (LbL) material/process. The sensing methodology was matured in an EU funded project (Jan 2016), before further CIMComp Hub investment in the form of a Feasibility Project (Nov 2017). Other elements of the technology, such as the control method, were progressed in parallel through further leveraged funding from the EU, the NCC's Technology Pull Through funding and industry sponsored EngD projects before a Core Project was funded by the Hub in June 2020. There has been further EU and EPSRC Impact Acceleration Account (IAA) funding in 2022 to increase the production rate whilst reducing the energy demands and hybridising the sensing system for in-line process monitoring as the technology gets closer to industrial adoption. As a direct continuation of the LbL project, an Innovate UK project merging LbL with Rapid Tow Shearing (RTS) started in December 2023. The R&D of this technology has had interactions with 21 industrial partners and RTO's.

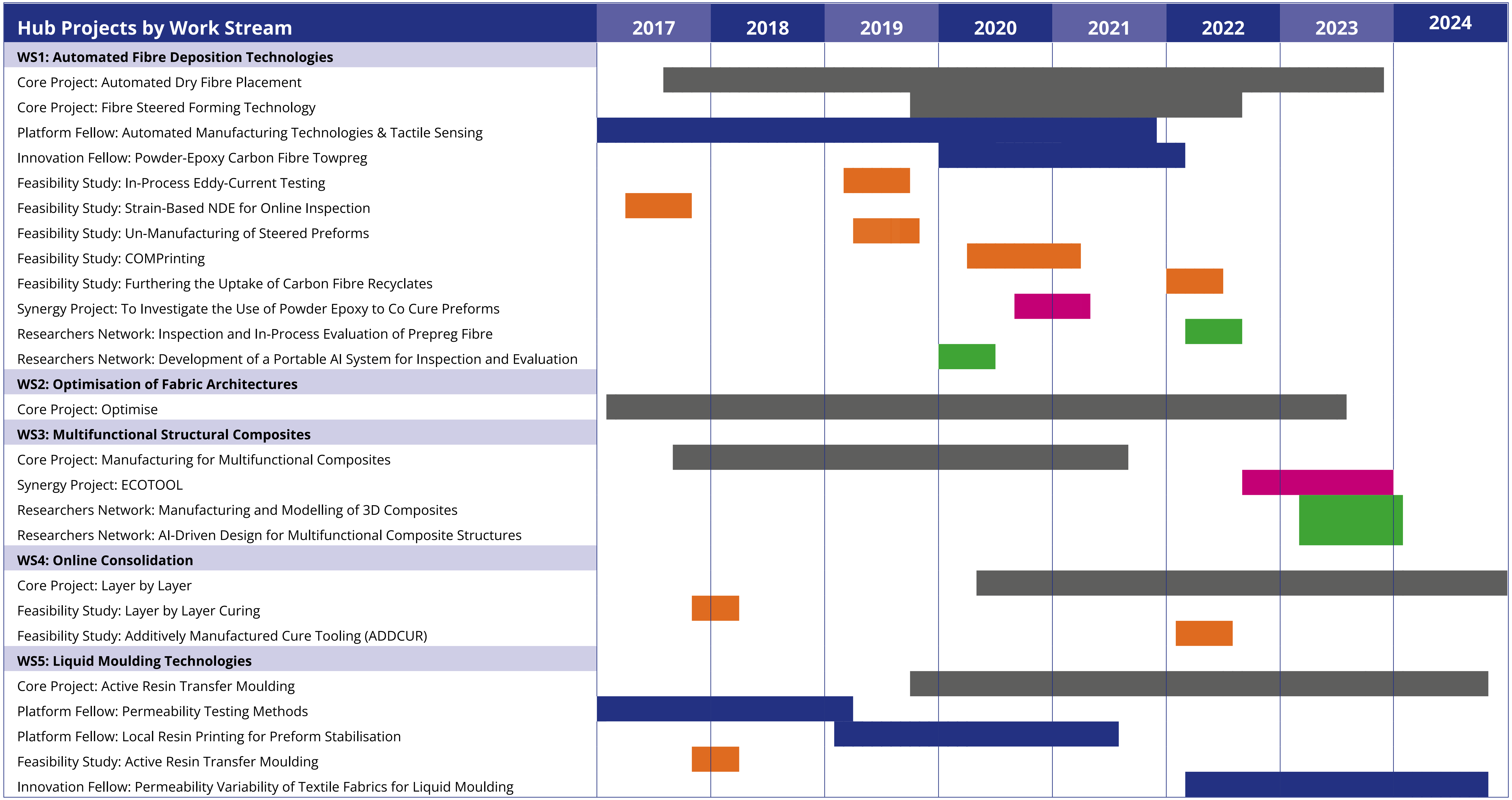
Optimise

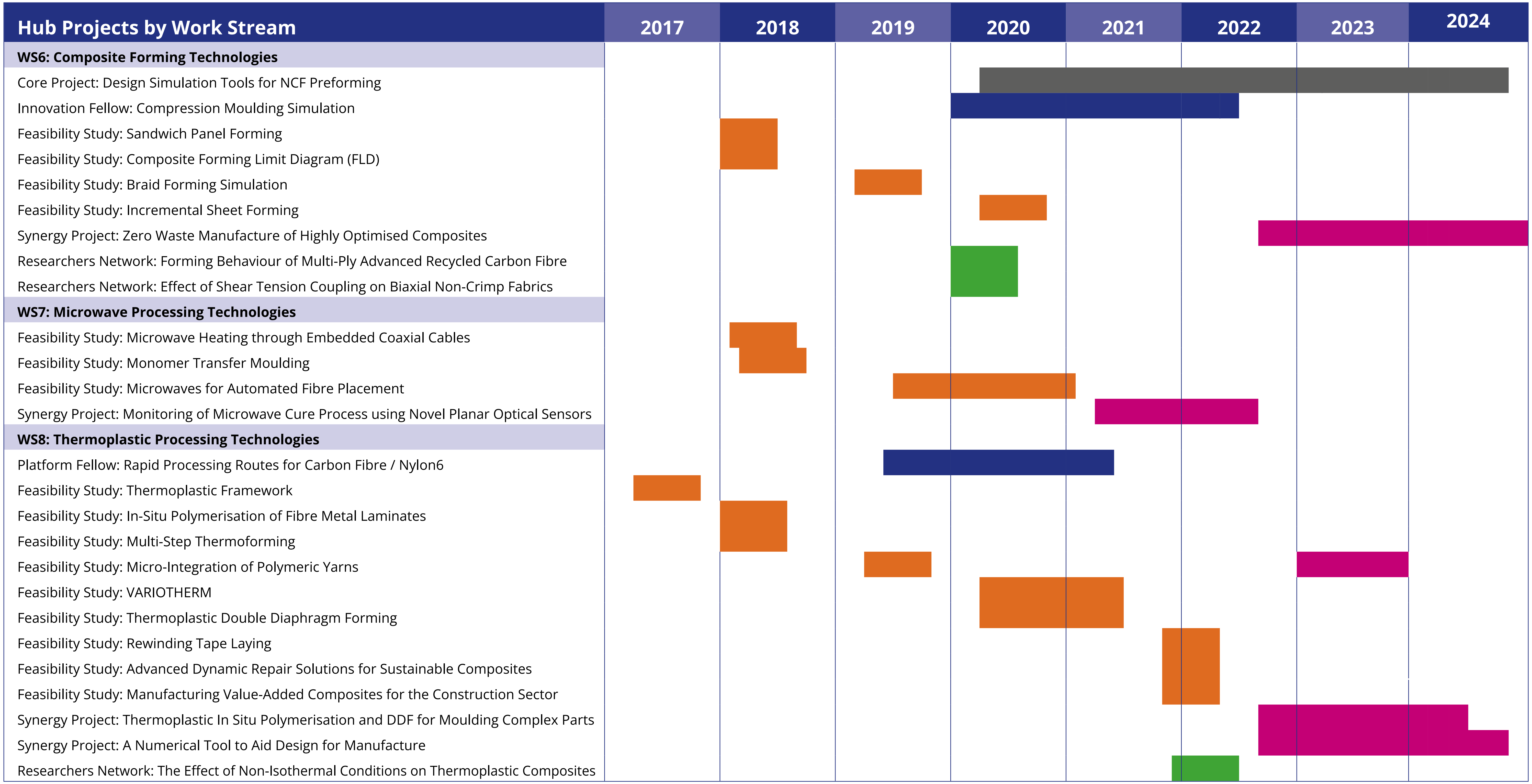
Principal Investigators: Professor Andrew Long/Dr Louise Brown, University of Nottingham; Professor Prasad Potluri, University of Manchester.

The multi-scale modelling of multi-material and multi-architecture composite preforms was the topic of several streams of funding in the CIMComp Centre, as Feasibility and Core Projects, as well as Platform funded research from April 2012. A Core Project (Feb 2017) in the CIMComp Hub considered new manufacturing techniques for the optimised material architectures. This Hub funded investment has been leveraged by other external grants from the EPSRC, Innovate UK and the NCC's Technology Pull-Through programme to further develop braid winding concepts for both the Automotive and Aerospace industries, as well as forming part of a project to develop an interdisciplinary circular economy centre for textiles, in the period from June 2018 to January 2021. The R&D of this technology has had interactions with 35 industrial partners and RTO's.

A full report on Hub impact will be provided at the end of the programme demonstrating how Hub research can influence industrial design thinking. According to feedback from the Hub's industrial partners, the majority of Hub research is of interest, and it is evident industry useable tools are getting closer to application as a result of research funded by the Hub.

Hub Projects by Work Stream




Hub Projects by Work Stream
2017
2018
2019
2020
2021
2022
2023
2024
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
Synergy Project: Zero Waste Manufacture of Highly Optimised Composites
Researchers Network: Forming Behaviour of Multi-Ply Advanced Recycled Carbon Fibre
Researchers Network: Effect of Shear Tension Coupling on Biaxial Non-Crimp Fabrics
WS7: Microwave Processing Technologies
Feasibility Study: Microwave Heating through Embedded Coaxial Cables
Feasibility Study: Monomer Transfer Moulding
Feasibility Study: Microwaves for Automated Fibre Placement
Synergy Project: Monitoring of Microwave Cure Process using Novel Planar Optical Sensors
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
Feasibility Study: Rewinding Tape Laying
Feasibility Study: Advanced Dynamic Repair Solutions for Sustainable Composites
Feasibility Study: Manufacturing Value-Added Composites for the Construction Sector
Synergy Project: Thermoplastic In Situ Polymerisation and DDF for Moulding Complex Parts
Synergy Project: A Numerical Tool to Aid Design for Manufacture
Researchers Network: The Effect of Non-Isothermal Conditions on Thermoplastic Composites

Design Simulation Tools and Process Improvements for NCF Preforming

Core Project Team

Principal Investigators: Prof Michael Sutcliffe, University of Cambridge; Dr Lee Harper, University of Nottingham; Prof Richard Butler, University of Bath; Dr Andrew Rhead, University of Bath; Dr Evros Loukaides, University of Bath.

Research Team: Dr Shuai Chen, University of Nottingham; Dr Adam Joesbury, University of Nottingham; Dr Andrea Codolini, University of Cambridge; Dr Chrysoula Aza, University of Bath; Mr Fei Yu, University of Nottingham; Mr Guy Lawrence, University of Nottingham; Dr Johan Viisainen, University of Cambridge; Mr Rajan Jagpal, University of Bath; Mr Yilong Li, University of Cambridge; Mr Salem Erouel, University of Nottingham.

Industry Partners: Hexcel Reinforcements UK, Gordon Murray Design, GKN Aerospace, Dassault Systèmes.

Grant Award: £698,561 **Start:** 01/05/2020 **End:** 31/05/2024

Executive Summary

This Core Project addresses the scientific and industrial challenges to efficiently design and manufacture dry fabric preforms. To improve the quality of preforms produced by Double Diaphragm Forming (DDF) while reducing the manufacturing costs, the formation of process defects such as wrinkling (i.e. the buckling of fibres) need to be sufficiently understood. The wrinkling mechanism is being investigated for uniaxial and biaxial NCF materials using coupon tests and forming trials.

To date, two process improvements have successfully improved the formability of biaxial NCFs: the modification of inter-ply friction by local lubrication and the removal of intra-ply stitches to minimise the local shear angle across the surface of the ply.

In addition, numerical tools have been developed to enable the design and forming of large industrial structures with greater confidence. A multi-scale finite element model was designed to efficiently identify critical small defects developed in large structures during forming. The experimentally-validated numerical results were used to validate novel analytical and optimisation methods that facilitate rapid design changes.

Developing design simulation tools and process improvements will provide a step-change in the manufacturing of NCF preforms which fits with the Hub research theme: Design for manufacturing via validated simulation. Improving the quality of NCF preforms minimises the amount of waste raw material and resources generated during the development and production of composites parts.

Lightweighting provides an opportunity to reduce in-service energy consumption for components manufactured from fibre reinforced composites. The outcomes from this project enable more robust component design and wider use of composites for new applications and sectors. These aspects of the project match key sustainability drivers identified by partner companies.

Aims and Objectives

The aim of the project was 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 in their performance. High-volume production had been identified to be one of the main solutions to reduce the manufacturing costs of high-performance composites structures. Hence the decision was made to focus specifically on dry fabrics and double diaphragm forming, guided by industrial interest in producing large-scale composites structures using automated out-of-autoclave processes.

The research aims will be achieved by the following objectives:

- Further the fundamental science of fabric deformation to improve the formability of unidirectional and biaxial NCFs during automated manufacture.
- Develop practical process changes to improve the effectiveness of DDF of NCFs.
- Develop practical simulation tools in which this science will be implemented to improve rate and robustness for creating large composite structures via automated manufacture.
- Developing testing methodologies to characterise material properties, friction and the robustness of the solutions in terms of component quality and mechanical performance.

Progress

The project deliverables were subdivided among three work packages: Underpinning Science, Component Design Tools, and Process Improvements.

Underpinning Science

The fundamental science of fabric deformation during forming processes was advanced for uniaxial and biaxial NCF materials applied to automotive and aerospace components.

The draping mechanism of a biaxial NCF (FCIM359) with carbon fibre tows at ±45° to the stitch direction and a polyester pillar stitch was characterised using 3D digital image correlation. Two wrinkling mechanisms were discovered: via shear lockup and via compression. The macroscale shear wrinkling was triggered by the in-plane compressive forces generated from the pressure between adjacent parallel tows. The macroscale non-shear wrinkling, observed in the area of positive shear strains, was instead generated by lateral compression.

The draping characterisation test was also conducted for a uniaxial NCF (FCIM356) with carbon fibre tows stitched together with glass fibre tows at ±45° and 90° to the carbon fibres by polyester yarns in a tricot pattern. For geometries with sharp corners, the shear strains dominated the deformation mechanism and macroscopic wrinkles were observed on the deformed fabric. Geometries with round features did not exhibit macroscopic wrinkles. However, gapping defects were detected.

To simulate the forming deformations of uniaxial NCFs, a new non-orthogonal constitutive model was developed with a discrete meshing technique. A shell-connector element mesh was introduced in the FE model to simulate the null bending stiffness along the fibre transverse direction and the gapping defect. The transverse tensile and picture frame tests were used to characterise the non-linear behaviour of uniaxial NCFs.

The quality of NCF preforms are also influenced by the repeatability of the DDF process. The variability in wrinkling severity and location during the preforming of biaxial NCF was experimentally investigated. Hemispherical draping tests showed that variations in sample mass and irregular fibre tow orientations produced significant changes in wrinkle amplitude. Numerical DDF tests confirmed that a small perturbation (<10%) in the orientation of the ply stack with respect to the tool influenced the wrinkle severity by 15%.

The inter-ply frictional behaviour of biaxial and unidirectional NCFs has been characterised using the overlap friction test. The static and dynamic coefficients of friction were measured over a range of applied normal loads, up to a maximum of 100kPa. Results from the test demonstrated that the inter-ply friction exhibited strong pressure dependency. Additionally, a fibre orientation dependency was observed, where sliding at fabric interfaces with parallel fibres produced higher coefficients than those with perpendicular fibres.

The static and dynamic inter-ply interactions in biaxial NCF multilayer forming were characterised for different fibre directions using the overlap test. The coefficient of friction was calculated from the force-displacement curves generated by the relative sliding of clamped fabric strips while vacuum was applied. The orientation of stitches between different fabrics influenced the oscillations of the experimental results.

Component Design Tools

Three numerical forming tools were developed to efficiently predict the manufacturing defects generated during the DDF of dry fabrics.

A multi-scale finite element (FE) forming tool was designed to efficiently identify small critical defects (out-of-plane wrinkles magnitude of 1 mm) in large industrial components, i.e. +10m wing spars. The FE results from a global membrane-only model were used to identify the regions where defects could potentially occur using in-plane shear criteria. A refined shell-based model was then run in the critical regions to accurately capture the formation of small wrinkling defects observed during DDF experiments. For the optimisation of the component geometry, a less computationally demanding tool was created. A machine learning-based model was developed to provide rapid predictions of the location and severity of wrinkling defects during the DDF of NCF preforms. Geometry-induced wrinkle patterns were extracted from FE simulations, mapped onto 2D surfaces, and transformed into images to train the machine learning model. A fully convolutional neural network was trained using as inputs the tool geometry and ply layup, and outputs the surface plot of the wrinkle amplitudes.

An analytical tool based on the eigenvectors of lamina stiffness matrices was developed to rapidly calculate the ply compatibility in complex NCF multi-layer layups. A compatibility index was defined from the comparison of minimum energy modes of adjacent plies to rapidly identify the stacking sequences that enhance forming of defect-free parts.

In ongoing work, an analytical model, accounting for vacuum forming and consolidation, to predict the critical ply-by-ply wrinkling force, is being developed. The aim is to compare this force with inter-layer frictional forces to determine when wrinkles cannot dissipate.

Process Improvements

To improve the quality of NCF preforms and to reduce the forming forces during the DDF process, a range of process developments were proposed to industrial partners.

A local intra-ply stitch removal method showed improvement in the formability of pillar-stitched biaxial NCFs. A genetic algorithm coupled with a finite element model was implemented to identify the optimised stitch pattern that can reduce the local shear angle while minimising the total stitch removal area. In addition to eliminating macro-scale wrinkling, the optimum local stitch removal pattern produced a more balanced global material draw-in. Therefore, the stitch removal was not limited to the over-sheared regions, suggesting the optimum pattern to be non-intuitive.

The formability of biaxial NCF during DDF could also be improved by reducing the friction coefficient between the ply stack and the diaphragms. Forming trials on ramped aircraft spar with complex double curvatures showed that applying liquid resin lubrication on the entire fabric eliminated wrinkles generated during forming. The friction modification methodology was also successfully applied to an automotive seatback geometry. Although all the out-of-plane wrinkles could be eliminated, in-plane waviness could not be mitigated.

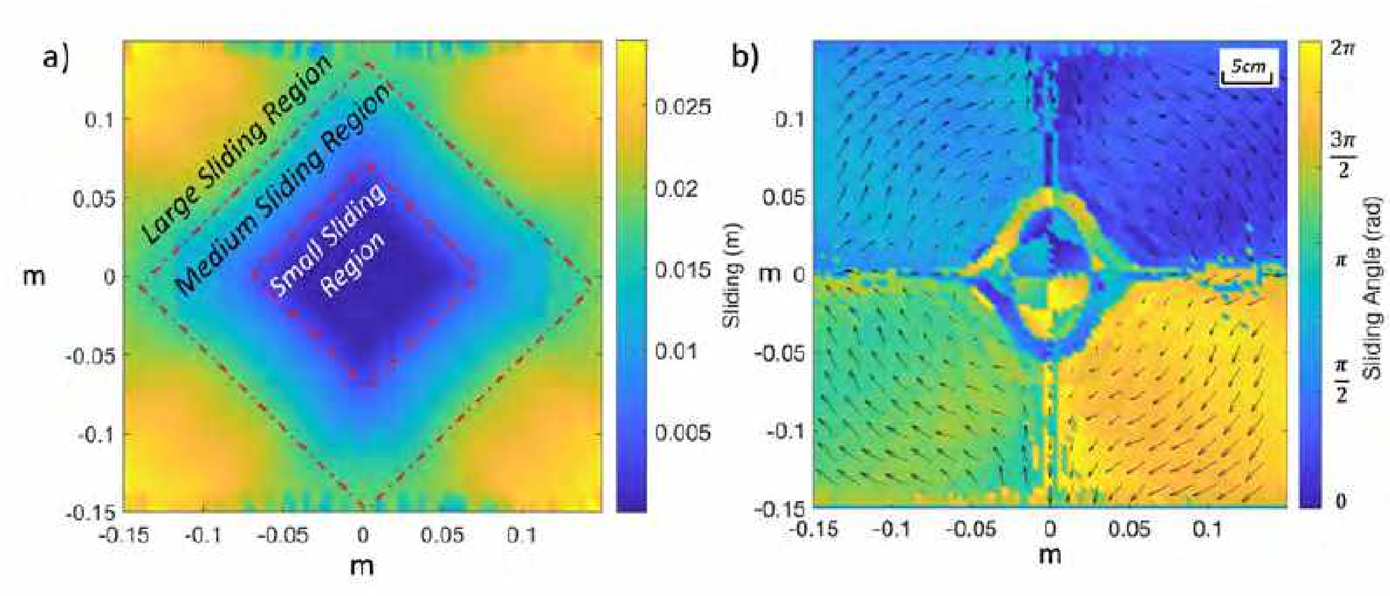


Figure 1. Inter-ply sliding during simulation of single diaphragm forming of a hemisphere: a) sliding distance and b) relative sliding direction.

Future Direction and Impact

The aim of the project was to develop improved process routes and design tools, within the EPSRC lower-level TRL remit, for use by industry. It is expected that the underpinning science will inform future research projects and industrial developments in NCF forming. For example, a better understanding of the role of inter-ply slip can inform development of new ply layups. While understanding of what governs wrinkle formation can inform improved modelling of the effect of material deformation and geometry on avoiding wrinkling.

The design tools provide an opportunity to predict and design for wrinkling at three levels, using a simpler ply compatibility criterion, using a machine-learning algorithm, or using a sophisticated local-global FE approach. All three approaches have potential to be adopted by industry in different phases of design. Specifically for the ML approach, we have developed a demonstrator software tool which can be used to help engage with industrial colleagues in the next stage of development.

The experimental and modelling approaches developed in the project can also be applied to pressing problems in composites, for example understanding how changes in material architecture and behaviour associated with recycled fibres will affect formability and variability in performance.

The research has resulted in the publication of 13 journal papers and 10 conference papers to date, with presentations at major international conferences on composites.

New collaborations have arisen between Cambridge and Bristol Universities on recycled woven composites, resulting in a joint publication; and between Nottingham and Bath Universities on forming optimisation using magnetic clamping, resulting in a joint EPSRC project application. Further funding applied for or received associated with the project has totalled £1,555k from grant awarding bodies and £60k of additional industrial leveraged support.

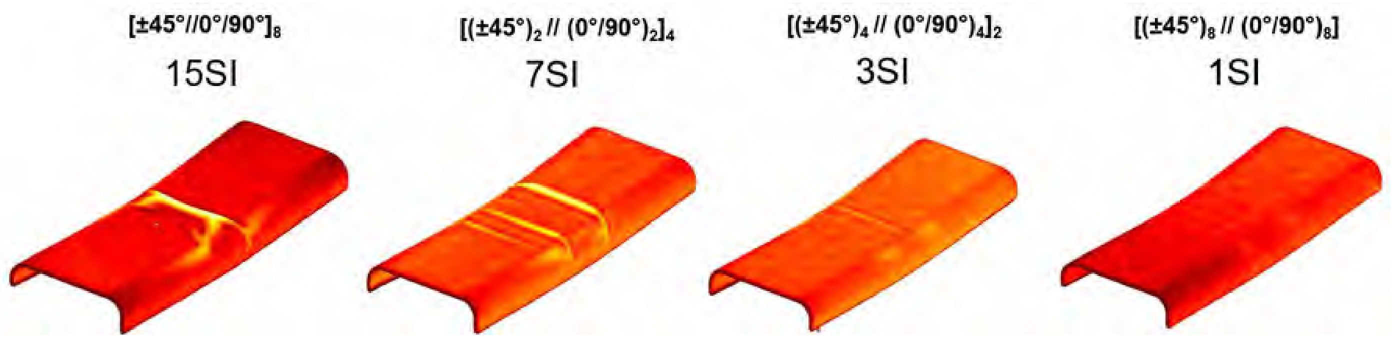


Figure 2. Scan data showing wrinkle evolution with changing slip interfaces (SI) in a thick preform.

Publications

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- 'Process Simulation: Fabric Forming', S Chen and F Yu, in 'Design and Manufacture of Structural Composites', edited by L T Harper, M J Clifford (2022), Woodhead Publishing, ISBN: 9780128191606

Resin Injection into Reinforcement with Uncertain Heterogeneous Properties (Active RTM)

Core Project Team

Principal Investigators: Prof Michael Tretyakov, University of Nottingham; Prof Andy Long, University of Nottingham.

Research Team: Dr Andreas Endruweit, University of Nottingham; Dr Mikhail Matveev, University of Nottingham; Dr Marco Iglesias, University of Nottingham; Dr Andrew Parsons, University of Nottingham; Ms Gwladys Popo, University of Nottingham; Mr Michael Causon, University of Nottingham.

Industry Partners: ESI, LMAT, National Composites Centre (NCC).

Grant Award: £502,760 **Start:** 01/11/2019 **End:** 31/12/2024

Executive Summary

Resin Transfer Moulding (RTM) has great potential for reducing costs and increasing rate in composites manufacturing and is often used for manufacturing of high-value high-performance composite components in aerospace and automotive industries. Uncertainties in material and process parameters may results in dry spots and other defects detrimental to the mechanical properties. This leads to manufacturers selecting more conservative designs with larger safety factors. Online process monitoring with a subsequent process control can be used to keep the process close to the design despite the uncertainties.

This project has developed a range of algorithms and approaches for using in-process data for detecting and mapping locally varying material properties which can be used in process control. This will help to deliver more robust composites manufacturing processes and reduce scrap rates.

Aims and Objectives

A key requirement of the composites industry is the repeatability of production cycles, i.e. the minimisation of the probability for production of defective components and the consistency in the mechanical properties of the components. For the RTM process to be used for high-value components, appearance of defects (specifically, dry spots) needs to be prevented. Incomplete impregnation of the fibre reinforcement with the liquid polymer system and deviations from the designed process cycle time are caused by uncertainties in the material and process parameters, which cannot be realistically fully eliminated. To accommodate the effect of the deviations, manufacturers use more conservative component designs with larger safety factors. These conservative designs increase the total manufacturing and life-cycle costs of the product. Furthermore, defects occurring in a component because of uncertainties in manufacturing can lead to costly rework or higher scrap rate, which again increases the costs. The ability to quantify and control these uncertainties is of great importance for further advances in composites manufacturing. Currently, NDE and rework can take 10% to 30% of the overall manufacturing time in the aerospace industry. Finding new solutions for reducing this time is of the highest significance.

The project vision is to use in-process information acquired using a sensing system during resin injection as a means of reliable and quick NDE of composite parts and to implement an active control system to counteract deviations from the design. Utilisation of in-process data will capture and estimate local deviations from the design for each manufactured part which will create a digital twin for each specific part. This significant advancement will deliver a major step-change in composites manufacturing by increasing the robustness of the manufacturing process, improving the confidence in the part quality, and reducing the effective cost per part. The project's objectives are to:

- Develop, improve, and validate innovative Bayesian inversion algorithms to restore the local permeability of fibre preforms based on data collected from sensors during resin injection into the preforms.
- Develop and validate an active control system based on information from sensors and on physical models together with on-line parameter estimation algorithms to improve the resin injection process. This control system will minimise occurrence of defects and ensure the process robustness.

Progress

Current capabilities on sensors for the RTM industry were reviewed. While in-mould pressure transducers remain a standard tool, several new emerging technologies were identified as suitable for industrial and research environments.

A novel Bayesian inversion algorithm was developed that can capture the material non-uniformity and edge effects such as "race-tracking" using in-process data. The algorithm was validated using virtual and lab experiments. A purpose-built neural surrogate model for simulating resin flow was built so that the algorithm can detect within a second without significantly reducing the accuracy of the detection.

A novel Regularising Ensemble Kalman filter Algorithm (REnKA) based on the Bayesian paradigm was applied to RTM processes to estimate local porosity and permeability of fibrous reinforcements using values of local resin pressure and flow front positions during resin injection measured by sensors. REnKA requires a smaller number of samples than a straightforward Monte Carlo algorithm. It can perform computations on each of the samples in parallel, which makes this algorithm faster and more scalable than the inversion methods based on non-linear optimisation. The inversion algorithm can be used either for characterisation of the fibre material or preform or for detection of defects in the component to estimate the manufacturing process and product quality.

REnKA exploits a novel three-level parametrisation, which is important in modelling complex random fields appearing in RTM. In particular, the parametrisation enabled to describe random fields with two (possibly unconnected) regions with different properties, characterised, e.g. by different mean values and different length scales. The ensemble of samples obtained by REnKA makes it possible to estimate the local values of material parameters. REnKA also allows to quantify uncertainties of estimated permeability and porosity by providing confidence intervals for the predictions. Furthermore, the probability for the presence of defects can be computed, which is valuable for analysis of the process. This is not possible in deterministic inversion algorithms. REnKA was tested using both simulated and experimental in-process data. It was demonstrated that REnKA can detect the non-uniformity in the porosity and permeability of fibre preforms with high precision in terms of local distributions and the corresponding values. It was shown that REnKA is capable of detecting irregularities in which the two length scales differ by an order of magnitude (e.g. such as thin and long race-tracking defect and a defect inside the preform close to a circle). REnKA was validated using experimental data obtained from RTM experiments where preforms had two inclusions with defined properties. Both inclusions were detected with good precision in terms of shape and position. The study showed that in-process data can be successfully used to infer local porosity and permeability distributions. Additional studies were carried out on finding the optimal sensor density for the detection of inclusions.

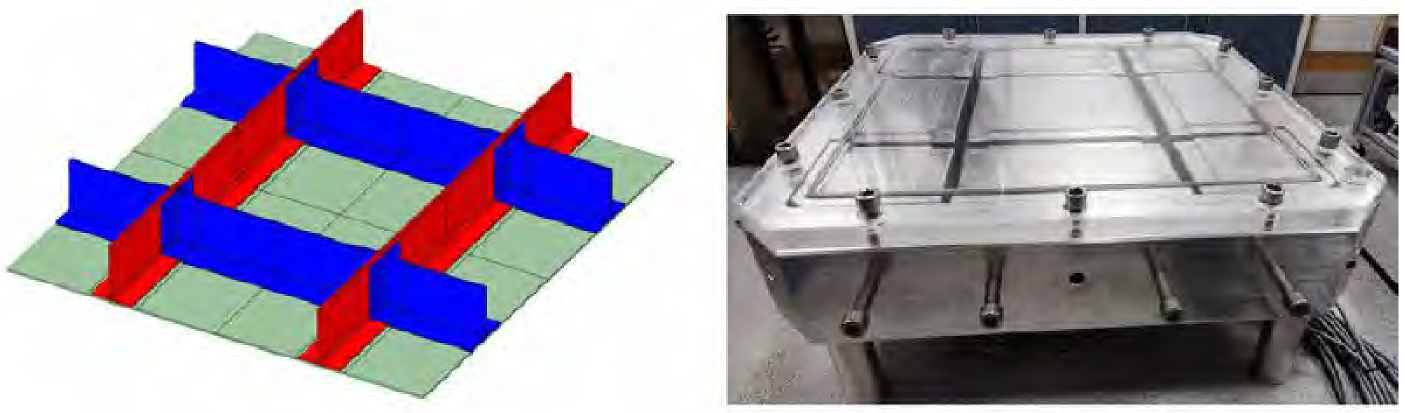

Figure 1. Model of an aerospace integrated stiffened panel (left); Instrumented tooling for the integrated stiffened panel (right).

A neural network framework was developed to speed up the algorithm by creating a surrogate model for resin flow. This led to the detection of inclusions taking less than 1 second without significantly reducing the accuracy of the detection. This allows the algorithm to be applied for real-time process active control.

Further testing of the algorithm in virtual and lab settings is also of substantial interest with the ultimate objective to use it in active control systems in an industrial environment. To this end, a new demonstrator, a tool for a stiffened panel equipped with sensors, has been designed and manufactured. Inversion algorithms will be tested in their ability to detect race tracking as well as layup and material non-uniformity within this new demonstrator. This work is currently in progress.

Control of resin flow in Liquid Composite Moulding processes through localized irradiation with ultraviolet light was successfully demonstrated as an alternative or supplement to control of the flow through changing pressure gradients in the injection tool. A vacuum infusion process was implemented to produce composite specimens from a random glass filament mat and a resin system curable upon irradiation with ultraviolet (UV) light. Through localized irradiation with UV light during the reinforcement impregnation, the viscosity of the flowing resin was increased selectively. This allowed converging–diverging flow patterns with defined inclusions to be realized and racetracking along reinforcement edges to be suppressed. So far, the feasibility of this approach has been proven. Its practical applications could be in process control, that is, compensation for local variations in fibre volume fraction and permeability of fibrous reinforcements. Optimisation of the combination of resin system and UV light source may help to adapt the approach for use in a production environment.

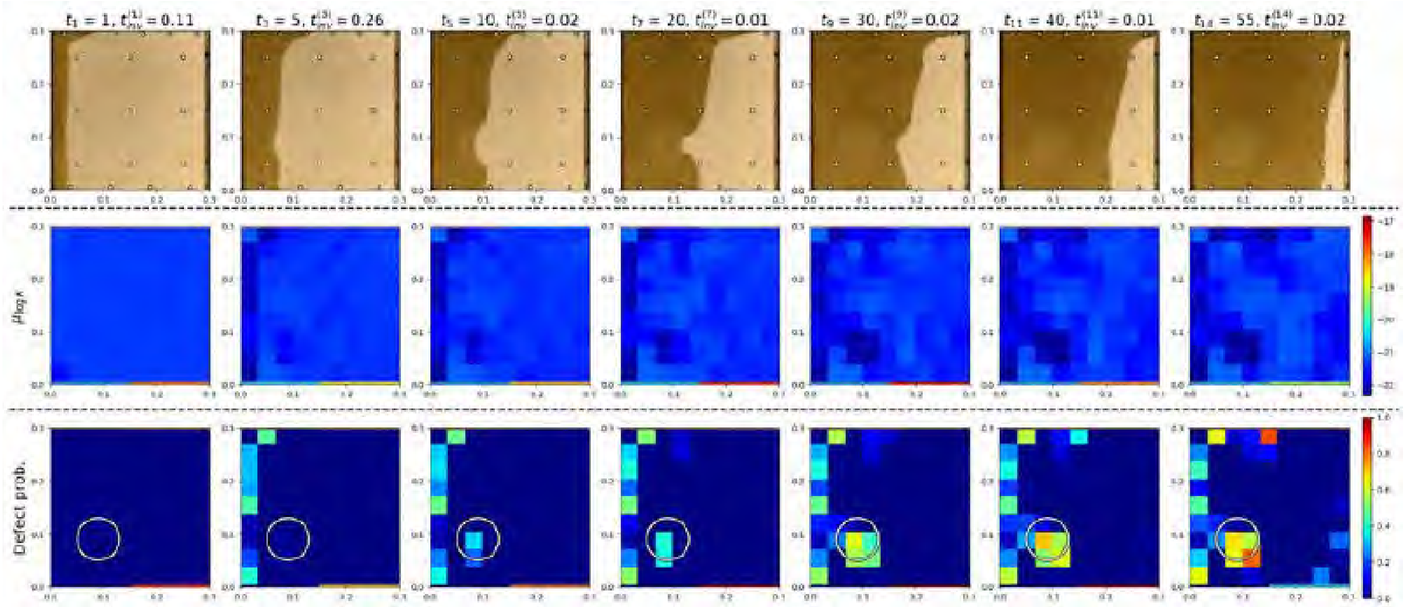

Figure 2. Detection of race-tracking and inclusions using neural network surrogates: experiment (top); detected mean permeability (middle); probability of detection (bottom).

Future Direction and Impact

The Active RTM project aims to reduce the scrap rate in the Resin Transfer Moulding (RTM) process. The project has developed an algorithm that can robustly detect local variations in porosity and permeability of fibre preforms. Coupled with neural networks, the algorithm can detect and map local variations in properties in less than one second, which makes it suitable for use in process control systems. Process monitoring and control of RTM is taken further in a Researcher in Residence project, awarded to Dr Matveev, in collaboration with Sheffield's Advanced Manufacturing Research Centre (AMRC).

An EPSRC responsive mode grant has been identified for further funding in the area of the use of deep learning for purposes of defect detection and active control. We will also explore whether Innovate UK funding can provide further support with moving the developed algorithms to a higher TLR. The Researcher in Residence grant at AMRC will carry on taking the developed technologies to higher TRL levels.

There is synergy between this project and previous work done by Dr Andreas Endruweit (as Hub Platform Fellow) in a worldwide joint effort on standardisation of permeability measurement methods (which culminated in formulation of the standard ISO/DIS 4410). A collaboration with Hub Innovation Fellow Dr Yang Chen is currently underway.

The research has resulted in the publication of 6 journal papers and 10 conference papers to date, with presentations at major international conferences on composites. Further funding applied for or received associated with the project has totalled £90k from grant awarding bodies and with the help of our industry partners, we aim to bring the developed methodology for use of in-process data into an industrial setting.

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Layer-by-Layer (LbL) Curing

Core Project Team

Principal Investigators: Dr Alex Skordos, Cranfield University; Dr James Kratz, University of Bristol.

Research Team: Dr Gabriele Voto, Cranfied University; Dr Arjun Radhakrishnan, University of Bristol; Dr Robin Hartley, University of Bristol; Mr Mehdi Asareh, Cranfield University; Mr Anastasios Danezis (Heraeus) (EngD), Cranfield University; Mr Michael O'Leary (CDT-PhD-Airbus), University of Bristol; Mr Axel Wowogno (CDT-PhD - Rolls-Royce), University of Bristol; Mr Adam Fisher, University of Bristol (University of Nantes cotutelle).

MSc Students: Mr Adrien Gilbert, Cranfield University; Mr Asish Kumar Patra, Cranfield University; Mr Tawfik Al-Qas, Cranfield University; Mr Alexis Aguado Arias, Cranfield University; Ms Anushka Sunil Bhalerao, Cranfield University.

Industry Partners: Airbus, Rolls-Royce, Heraeus, National Composites Centre, Exel Composites.

Grant Award: £675,687 **Start:** 01/06/2020 **End:** 31/03/2024

Executive Summary

The central concept of the Layer by Layer (LbL) curing process is the merging of the deposition, consolidation and curing stages into a single high temperature manufacturing step that is repeated additively as the structure is built up gradually. This strategy aims to improve the current state of the art in composites manufacturing in which the stages of placement/forming, consolidation/flow and curing are carried out separately and sequentially. In the LbL process the physical stages of the manufacturing process are merged and the process becomes sequential in terms of addition of the material. In addition to the intensification benefits due to merging the stages of manufacturing, material additive provides an opportunity to utilise more aggressive processing conditions without increasing the risk of defect generation.

The starting point of the Core Project was the outcomes established in the LbL curing Feasibility Study, which demonstrated the benefits of the process for planar geometries and established a strategy to overcome the challenge of maintaining interfacial toughness while partially curing the sides of the interface. The Core Project work to date has addressed the project objectives addressing the coupled process simulation for complex 3D geometries, material model development for fast processing resins, interfacial toughness development during the process and process design optimisation, whilst made process on the development of manufacturing technology concepts for transfer of the LbL concept to bag based processes and AFP. Use of the coupled model of the cure process developed has shown that the benefits identified in the Feasibility Study for a planar geometry are translated to a positive outcome for more complex components, maintaining benefits of 40-60% reduction in cure time. The characterisation efforts have shown that the methodologies used can be adapted to fast curing systems, whilst the results from the investigation of interfacial toughness development have generalised the findings regarding the partial cure toughness threshold identified in the feasibility to three new resin systems. The optimisation activities have shown that the LbL process can be performed in a region of the landscape in which optimal process parameters (temperature, step duration) in terms of efficiency also result in optimal performance at interfacial level. The LbL concept has been expanded to a combination with 3D printing of continuous fibre thermosetting composites, where the coupled simulation demonstrated the significant benefits of this process variant. Overall, the outcomes have been positive with respect to the main research question of whether the LbL curing process can be applied successfully to complex components for rate intensification, whilst additional potential of the process has been established.

The ability to process thicker, larger structures through elimination of intense exothermic effects as well as through a 3D printing/LbL processing route is in line with the Hub Vision of exponentially increasing production capability and the Grand Challenges of combining high rate processing with high quality and of understanding process science to improve manufacturing robustness. The LbL process lends itself to the concept of uninterrupted tow composites established as a future direction during the Core Project, with the potential of critical benefits in the area of Sustainability of thermosetting matrix/continuous fibre composites.

Aims and Objectives

The aim of the project is the development of the LbL curing process at the level of complexity required for application to advanced composite structures. The overall aim of the project is achieved by addressing the following objectives:

- Development of fully coupled (thermal-consolidation-thermomechanical) 3D simulation of the LbL process combining appropriate mutli-physics modelling tools for each physical process in an open-source interface.
- Development of constitutive models and associated characterisation campaigns addressing conventional and snap curing systems under the aggressive processing conditions of LbL curing.
- Process optimisation to achieve maximum interfacial toughness, minimum process duration and control of residual stresses.
- Development of tailored process setups, including an end effector and zonally heated reusable bagging, allowing implementation of the LbL process in complex geometries/components.
- Optimisation of LbL process implementation within the whole process chain to minimise defect generation due to ultralow viscosity, ply drop offs, gaps and curvature.
- Demonstration of applicability based on lab/pilot scale LbL implementations of AFP/ATL, pultrusion and filament winding.
- Demonstration of LbL process capabilities through the development of hybrid thermoset/thermoplastic components, stabilised preforms and laminates with tailored residual stress state. The developments in LbL target applications of thermosetting and hybrid continuous fibre composite in the transport and energy sectors, where currently autoclaving, filament winding, pultrusion and AFP processing strategies are utilised. The nature of the LbL process provides significant advantages in structural applications involving thick laminates. Primary aerospace structural components involving stiffening elements, high pressure vessels for gas storage and containment casings present the primary opportunities for application of the process.

Progress

- Reduction of cure time by 40-60% resulting in lower costs and overall process intensification.
- Ability to manufacture ultra-thick structures using conventional and fast curing materials under conditions and in duration not accessible currently due to exothermic effects.
- Ability to combine material with incompatible processing temperature within hybrid structures due to the possibility of altering thermal profiles as the component is built up.
- Layerwise processing compatibility with un-manufacturing for recycling/re-use purposes.

The project has established the process benefits of the LbL process which for a typical aerospace part (skin with stiffener) reach 40% reduction in cure time and 70% reduction in temperature overshoot. These represent a corresponding reduction in equipment, energy and salary costs per part and improved process quality and robustness which can results in direct benefits for industry.

The benefits are leveraged by two aspects of the process: (i) its additive character, which delivers linear scaling in contrast to the highly non-linear effects observed with increased size of composite components; (ii) its operation away from the steep regions of the process design space, which enable optimised implementations to be delivered without the loss of process robustness conventionally associated with adopting optimal conditions. The process maturity was enhanced by two proof of concept implementations: one using Automated Fibre Placement (AFP) and one using a re-usable flexible bag. Furthermore, these implementations were carried out using a fast-curing prepreg, pushing further the envelope in terms of minimising process durations.

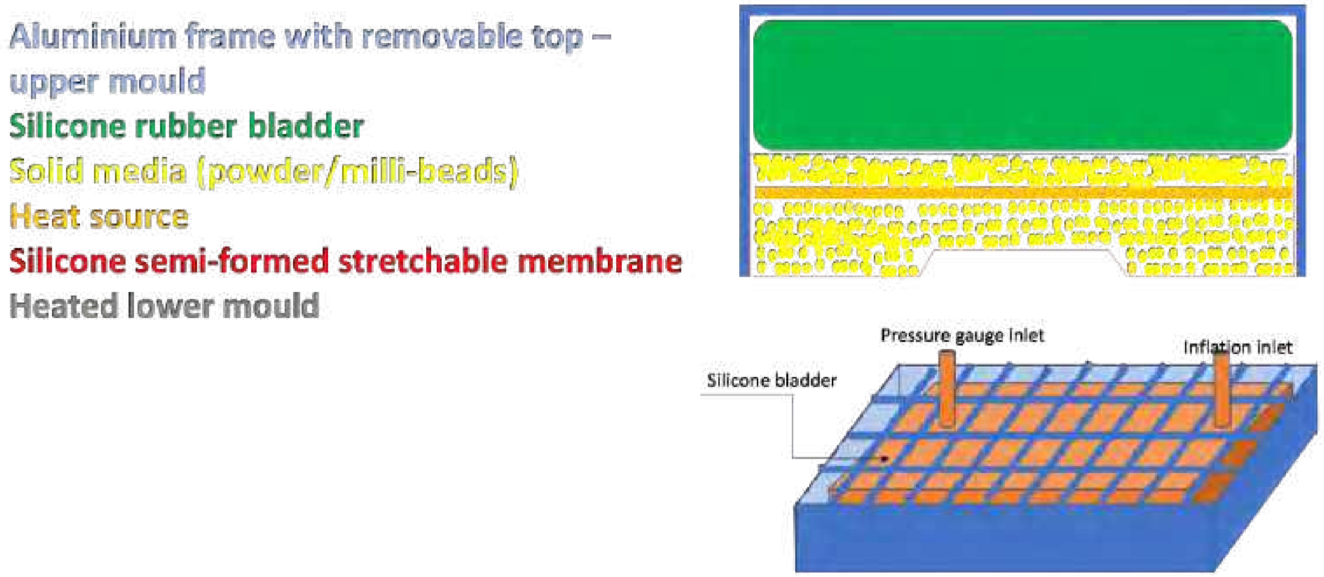
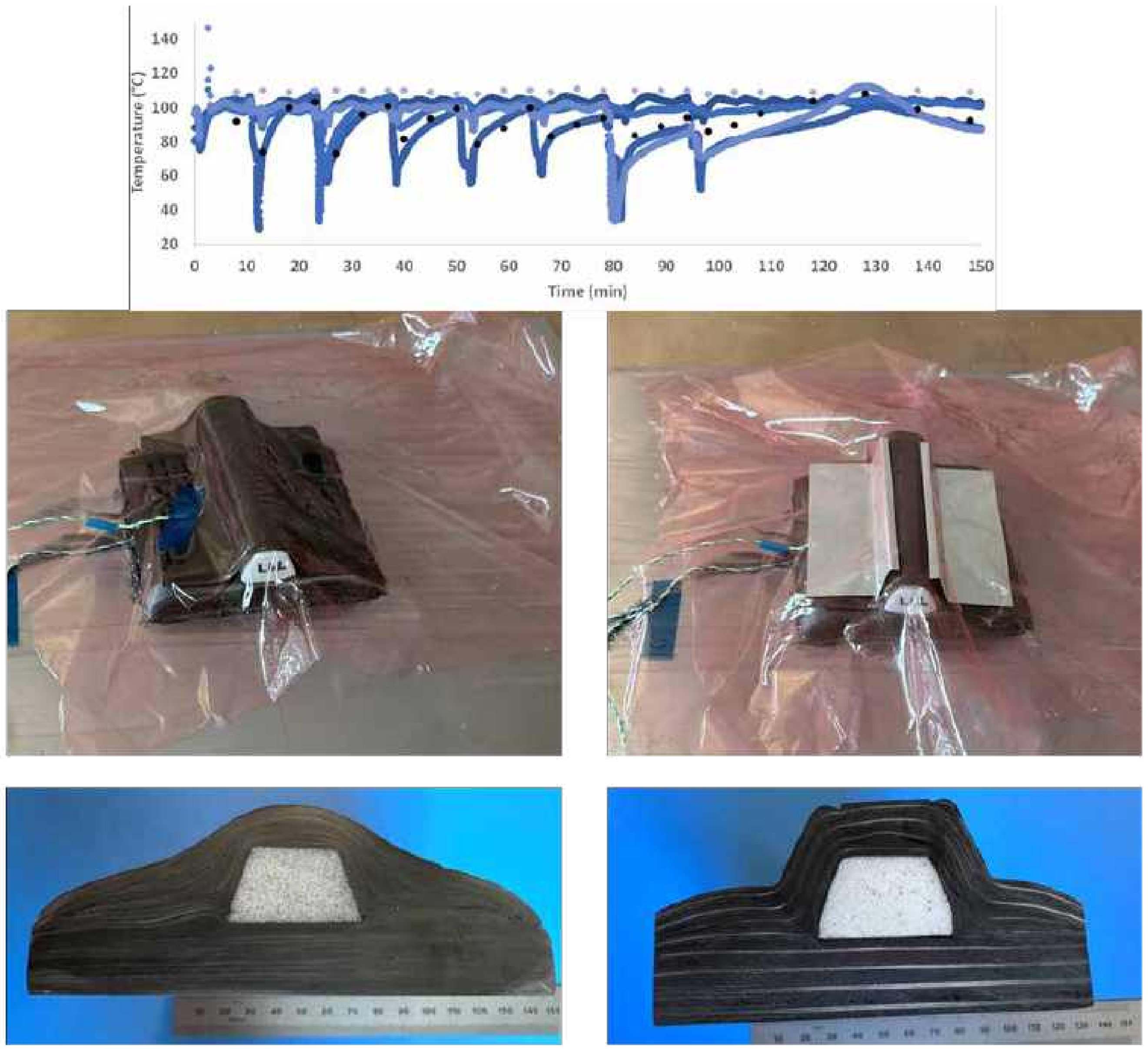


Figure 1. LbL manufacturing with reusable bag: top – process setup design. Page right, top – temperature evolution in trial of stiffened part in 8 layers; middle. Page right, middle – processing of stiffened part without intensifiers. Page right, bottom - processing of stiffened part with intensifiers.

Exploitable IP has been generated from these two implementations around the solutions for heating the re-usable flexible bag and controlling the material state before placing the next layer in the process. The design of the reusable bag LbL process setup is illustrated in Figure 1, comprising a metallic frame utilised to constrain a silicone bag filled with solid particles and incorporating heating elements. The setup is placed on a heated mould that also incorporates attachment points for the frame. The system allows application of positive pressure on the LbL stack and has the capability to conform within the limits of the change of geometry during the placement of successive sublaminates. Trials based on a manual implementation using an air press, with pressure differential of up to 1 bar have been carried out (Figure 1). These have demonstrated the practical applicability of the process as well as the elimination of overshoots in the omega stiffener-skin part. The utilisation of intensifiers improves the net shape of the part; while the presence of fibre misalignment is observed. The implementation of the design using the design represented in Figure 1 will achieve maturation of the LbL flexible bag process.

Activities in the next period of the project focus on implementation of manufacturing technologies (LbL-AFP and reusable flexible bag) and integration of the tools developed to implement the LbL process within selected industrial applications.



Future Direction and Impact

The LbL technology will need further funding upon completion of the project both to extend the opportunities and to increase TRL. Innovate UK and EU funding is envisaged in the future for direct extension of LbL maturity, alongside EPSRC funding for the developments of research strands of LbL.

Previous efforts on continuation funding (2 EU, 2 Innovate UK and 2 Hub/EPSRC) resulted in acceptance of one proposal focusing on the integration of LbL with Rapid Tow Shear AFP, which aims to progress the implementation of the process and explore the concept of minimising tape cutting to enable recycling the reuse of carbon fibre material. This development is also relevant with the concept of recyclable vitrimetric matrix composites in a concept that was development jointly by Cranfield and Bristol and will be a major driver of future funding applications.

Future proposals planned around the LbL concept are:

- EPSRC proposal on uninterrupted tow LbL processing and remanufacturing using vitrimeric matrices between Cranfield, Bristol and Northumbria.
- EU including maturation of the LbL concept, also including AFP and process monitoring as part of HORIZON-CL4-2024-TWIN-TRANSITION-01 call.

The total funding generated in direct relation to the project is £770k, with £500k supporting the integration of LbL with AFP through the ADIMAC Innovate UK project.

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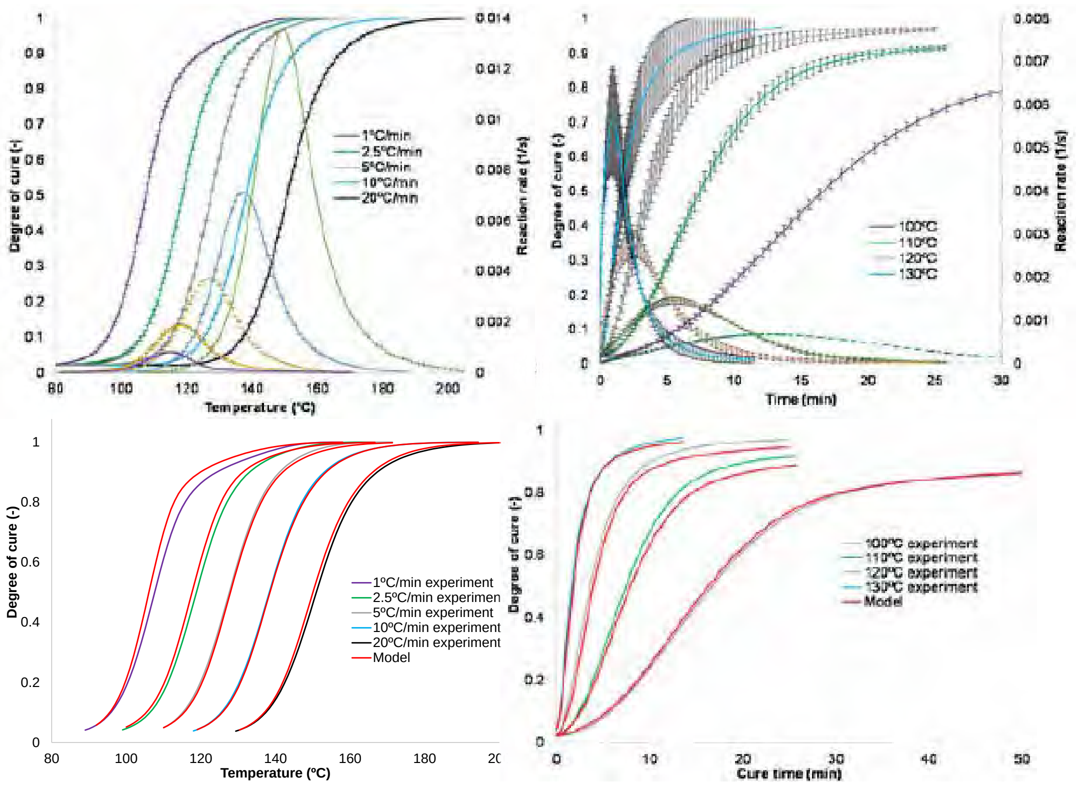


Figure 2. Cure kinetics of fast-curing prepreg (M78.1): top left – dynamic DSC experiments; top right – isothermal DSC experiments; lower left – kinetics model fitting for dynamic cure; lower right – kinetics model fitting for isothermal cure.

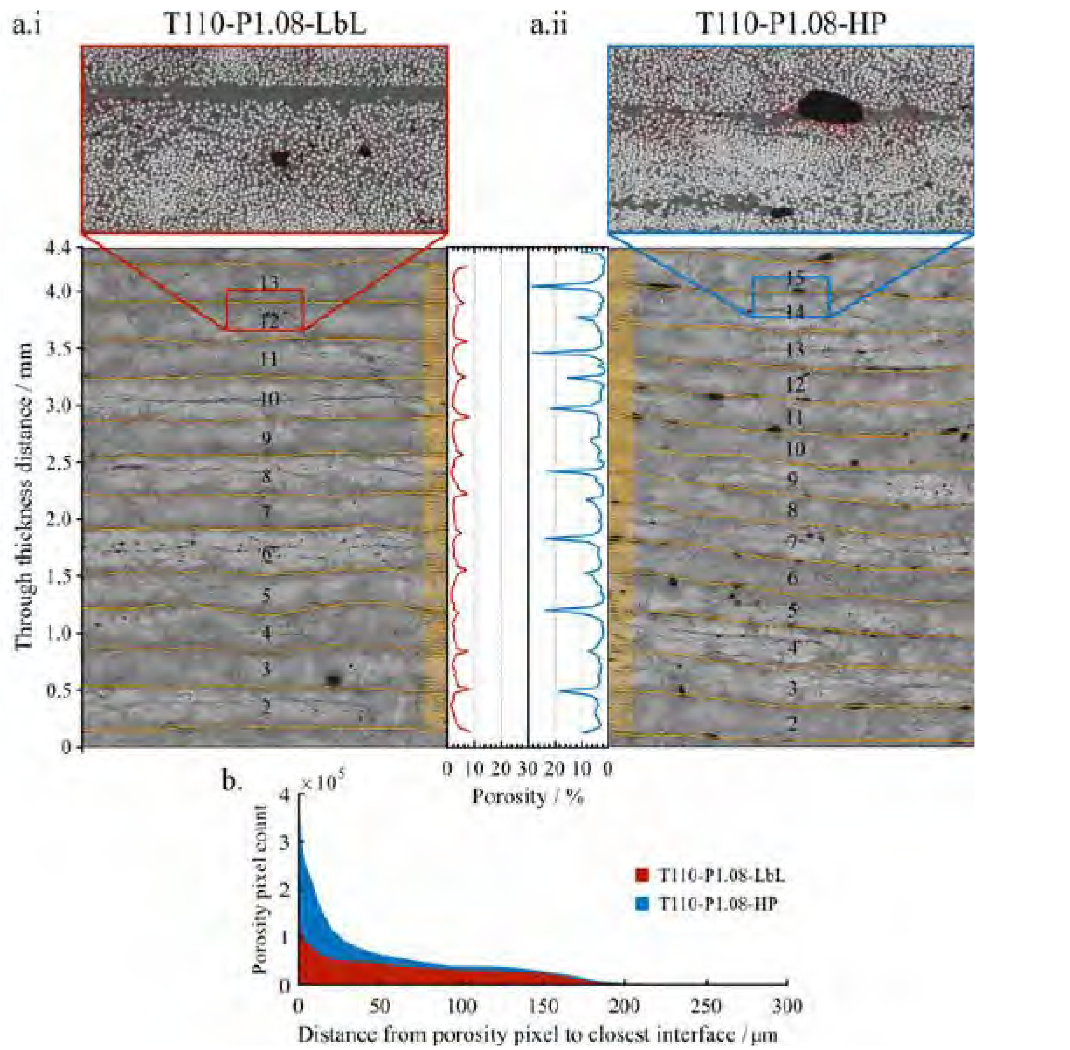


Figure 3. The images in a.i) and a.ii) show the polished cross sections of LbL and hot press samples respectively. The longer yellow splines represent the ply interfaces. Inset is a plot of porosity through the thickness of the laminate. In b) the resulting porosity from the LbL and hot press methods are compared by plotting pixel count against the distance between each segmented porosity pixel and the closest ply interface.

Permeability Variability of Textile Fabrics for Liquid Moulding

Project Team

Principal Investigator: Dr Yang Chen, University of Bath.

Grant Award: £214,027 **Start:** 01/03/2022 **End:** 30/06/2024

Executive Summary

The vision of this project is to harness the recent development in computational methods, X-ray imaging and machine learning techniques to investigate the variability in textile permeability. The research is structured around three questions: developing an efficient numerical solver for dual-scale flow problems; applying cutting-edge machine learning techniques for resin-flow simulation and permeability prediction; correlating permeability uncertainty to microstructural variability.

Permeability is a key parameter for resin flow simulation tools and for optimising the liquid moulding process. By providing new insights into this parameter, the project has the potential of proposing new techniques for improving the resin injection/infusion process by reducing the time and porosity defects. This will eventually help reduce manufacturing costs and improve the performance of composite products.

This project has developed an efficient numerical solver for dual-scale porous media flow problems. Leveraging the full potential of supercomputers, the method enables massively parallelised computations using high resolution 3D images of textile fabrics. Combined with an in-house image processing code dedicated for textile composites, the method offers an important building block for accurate calculations of permeability of fibre reinforcements. The developed method has the potential of being integrated into other software environments to create a seamless permeability calculation framework, such as AVIZO (using realistic microstructures) and TexGen (using virtual microstructures).

A large amount of 3D image data has been collected with X-ray computed tomography using both laboratory and synchrotron facilities. This rich dataset reveals the statistical variability of the textile microstructures under different compaction levels, which helps understand the source of uncertainty of the permeability in such dual-scale porous media.

The machine learning techniques explored in this project stand for the state of the art for surrogate models of dual-scale flow problems. It offers step-changing capabilities in predicting permeability of complex bi-porous structures, in terms of speed and accuracy.

Aims and Objectives

The simulation of the resin injection process can help optimise the process parameters and minimise the possibility of defects. However, the usefulness of these simulations highly depends on the quality of the permeability inputs. Local variations in permeability can dramatically change the flow front progression and hence the void formation.

To explore robust processing conditions, the statistics of permeability have to be inputed into the resin flow simulations. The uncertainty of local permeability is not only affected by the geometrical variations in virgin fabrics (i.e. not deformed), but also by the deformation (e.g. fibre distortions and shearing) that are created during the preforming step. Therefore, it is a long-standing challenge to determine the permeability of fibre reinforcements.

Experimental measurement is time and labour-intensive and difficult to be reproduced due to the uncontrolled variations in material and experimental condition. Analytical models have been successful in predicting permeability in simplified situations (e.g. uniformly dispersed fibres), yet they fail to provide faithful values for complex textile reinforcements in which fibres and fibre tows exhibit more random features. Numerical models can explicitly take into account the geometrical variations, whose accuracy relies on the accuracy of the microstructural description. The latter requires fine meshes and hence limits most of the current existing numerical approaches.

Recent advances in large-scale simulations and data-driven techniques offer new opportunities to push this limit for the application of permeability prediction.

This project is focused on accomplishing three primary objectives:

1. Develop multiscale numerical models for predicting permeability;
2. Create stochastic surrogate models that can accurately represent the inherent variability in material properties; and
3. Establish a correlation between microstructural variability and permeability uncertainty.

These objectives aim to address the longstanding challenges in accurately modelling and predicting permeability, thereby enabling more precise control over the resin injection process and improving the overall quality of composite materials.

Progress

Table 1 outlines the project's objectives and their respective progress and deliverables. The first objective has been successfully met, with an efficient FFT method proposed and implemented in both Python (for fast prototyping) and Fortran (for solving real-world problems). The second objective is near completion, marked by the development of a physics-informed neural network for predicting Darcy flow with heterogeneous permeability distributions, and a Fourier neural operator model for solving the dual-scale flow problem and estimating overall permeability. Progress on the third objective is ongoing, with a substantial dataset acquired from laboratory and synchrotron XCT experiments. Data processing is time consuming, but progress is being made. Current focus is to finalise the analysis of the in-situ experimental data and to conduct permeability calculations using real textile microstructures derived from the XCT images. This will enable a clearer understanding of the relationship between microstructural variability and permeability uncertainty.

Objectives	Progress	Deliverables	Current Work
Numerical solver	100%	• Efficient FFT solver implemented with Python for fast prototyping and Fortran for solving real-world problems (Paper published); • A workflow of image-based permeability calculation: Matlab code for image processing + FFT solver for permeability calculation (open-source code available on GitHub).	None
Surrogate models	75%	• CNN model with self-attention mechanisms implemented for a 2D problem of micro-composite damage behaviour (Paper published); • PINN model for injection flow experiments with heterogeneous permeability distributions (Paper in preparation); • FNO model for bi-porous media flow (Paper in preparation).	• Fine-tune the PINN model parameters to achieve potential improvement; Apply the PINN model to inverse problem. • Combine the FNO model with the physics-based FFT solver to have a control on the accuracy of model prediction. • Apply the FNO model to realistic textile microstructures obtained from XCT images or TexGen.
Structure-property correlation	50%	• XCT data on various textile microstructures (complete). • Variability analyses of the textile microstructures (ongoing). • Correlation between microstructural variability and permeability uncertainty (ongoing).	• Analyse the microstructural variability of the NCF samples tested by in-situ experiments. • Conduct permeability calculations of the various textile microstructures.

Table 1. Summary of objectives, progress, deliverables, and current work of the project.

In its first year, the project achieved the first objective of developing a numerical solver with its efficiency in large-scale simulations demonstrated and started the collection of XCT data. The focus of the second year then shifted towards developing machine learning techniques, finalising the XCT data collection, and analysing the experimental data.

The researcher conducted a one-month visit to the Centre for Composite Materials at the University of Delaware, supported by the Hub's International Exchange Programme. This visit initiated a collaboration on developing physics-informed neural networks for solving forward and inverse problems in resin infusion experiments. Access to the Liquid Injection Moulding Simulation (LIMS) software, obtained during this visit, facilitated the generation of data necessary for training the machine learning model. Preliminary results were presented during the Hub Open Day, and more elaborated results will be presented at the ECCM21 in Nantes.

A Fourier Neural Operator (FNO) model has been developed as a surrogate to the numerical solver for predicting permeability in bi-porous media. Promising initial results suggest that the FNO model offers the potential of real-time prediction of permeability using large image datasets with high accuracy. It also breaks the limitation of image resolution due to its zero-shot super-resolution capability.

In summary, progress has been made through multiple channels towards the end goal of understanding the microstructure-permeability relationship. The XCT images provide essential data of real microstructures for both the numerical solver and the FNO model. The main achievements of the project include not only the findings on microstructure-permeability relationships, but also the methodologies developed, which can be used to a broader application even beyond composites manufacturing.

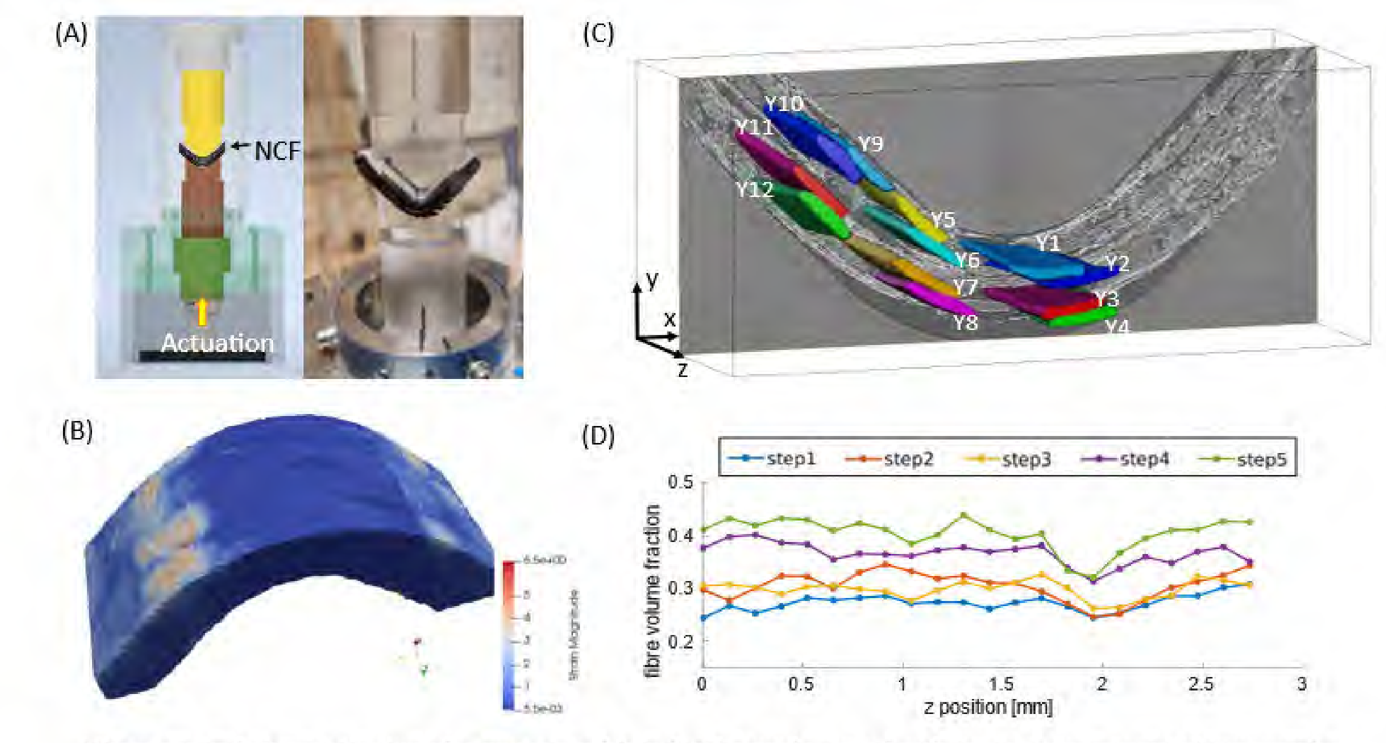


Figure 1. Microstructural characterisation of a non-crimp fabric (NCF) sample, tested with in-situ x-ray computed tomography experiment. (A) Loading rig for the in-situ compaction test. (B) Local deformation measured by Digital Volume Correlation. (C) Manually segmented yarns. (D) The longitudinal profile of fibre volume fraction of an exemplar yarn.

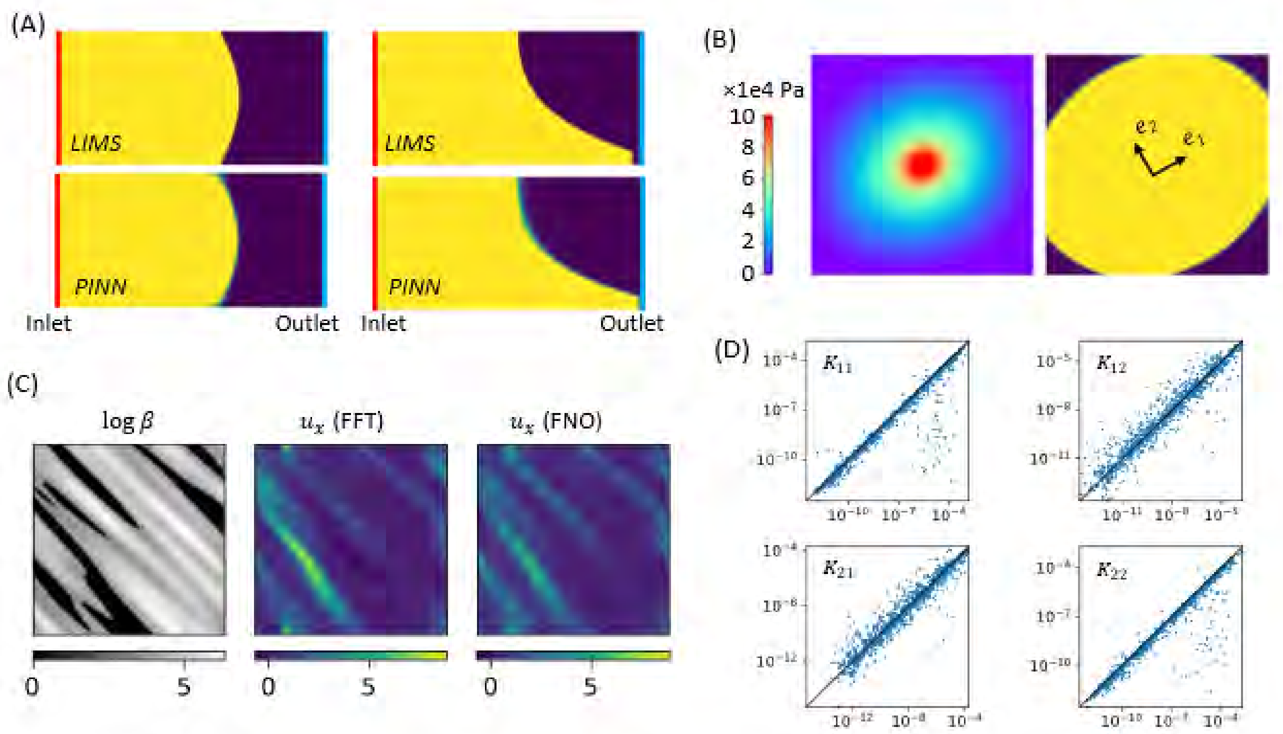


Figure 2. Illustrative results of the machine learning models developed in this project: (A-B) Physics-Informed Neural Networks (PINN) model, predicting linear injection flow with heterogeneous permeability (A) and radial injection flow with anisotropic permeability (B). The linear injection results are compared.

Future Direction and Impact

The project potentially will improve the liquid composite moulding process, which will reduce the process time and prevent defect formation, leading to a positive impact on the sustainability of composites manufacturing.

A proposal has been submitted to the Catapult Network for the Researchers in Residence scheme. If successful, the project will work on manufacturing of thermoplastic composites at the AMRC in Sheffield. Furthermore, a proposal has been submitted to the Royal Society for a travel grant, to aid collaboration with Kyoto University in Japan. This project will work on testing and modelling of ceramic matrix composites.

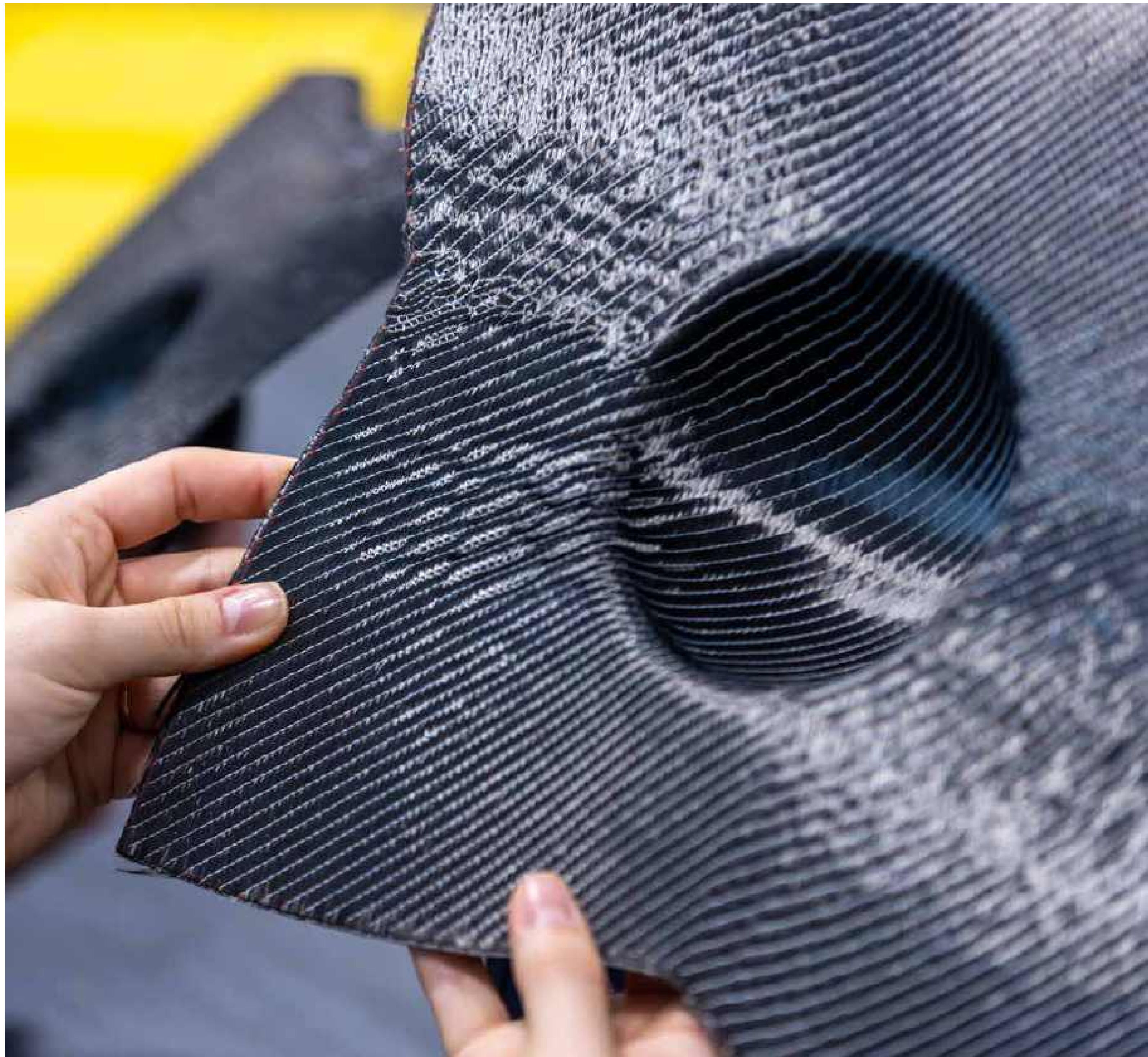
Dr Chen has conducted short-term research visits to Germany with travel funded by the German Humboldt Foundation, for his project 'Full-field characterisation and multiscale modelling of Ceramic Matrix Composites'; and awarded funding from Beamtime at DIAMOND Lightsource for his project 'High speed microtomography of viscous deformation mechanisms in carbon non-crimp fabrics during compaction'.

Publications

- Chen, Yang. High-Performance Computational Homogenization of Stokes–Brinkman Flow with an Anderson-Accelerated FFT Method." International Journal for Numerical Methods in Fluids (2023).
- Chen, Yang, et al. Full-Field Prediction of Stress and Fracture Patterns in Composites using Deep Learning and Self-Attention." Engineering Fracture Mechanics 286 (2023): 109314.

Other Outcomes

- Open-source code for permeability prediction, available on GitHub: https://github.com/yang-chen-2022/fftpermeability-StokesBrinkman .
- Fortran code for permeability prediction with parallel computing capability (available upon request).
- Open-source code for full field prediction of composite mechanical behaviour, available on GitHub: https://github.com/yang-chen-2022/CNN_SelfAttention_CompMat



Synergy Project
Work Stream 3: Multifunctional Structural Composites
Research Themes: Recycling and Re-Use; Manufacturing for Multifunctional Composites and Integrated Structures

Energy Efficient Composite Tooling with Integrated Self-Regulating Heating and Curing Capabilities based on Recycled Composite Waste (ECOTOOL)

Project Team

Principal Investigator: Dr Han Zhang, Queen Mary University London.

Co-Investigators: Dr Thomas Turner, University of Nottingham; Prof Iain Bomphray, University of Strathclyde and National Manufacturing Institute Scotland; Dr Yi Liu, Loughborough University; Dr Zhe Liu, Loughborough University.

Research Team: Dr Qinrong He, Queen Mary University London; Dr Shanshan Huo, Queen Mary University London; Ms Yushen Wang, Queen Mary University London; Mr Lichang Lu, Loughborough University; Mr Sandy Guo, Loughborough University; Mr Georgios Xypolias, University of Nottingham; Mr James Mills, University of Strathclyde.

Industry Partners: Expert Tooling and Automation Ltd; Gen 2 Carbon Ltd; LMK Thermosafe Ltd.

Grant Award: £205,711 **Start:** 01/09/2022 **End:** 31/12/2023

Executive Summary

Compared with traditional metal tooling, composite tooling possesses advantages of closely matched coefficient of thermal expansion and easy fabrications with reduced lead time. The lower thermal mass of composite tooling compared to their metal counterparts can reduce the energy consumption during the curing process. However, most of these composite tools still require the use of a convection oven to provide the heating function, limiting the productivity with long cycle times and low energy efficiency. The key novelty of this research is its capability to achieve an energy efficient integral heating instrument for composite manufacturing based on recycled composite waste without the need of ovens, allowing flexible manufacturing with reduced cycle time for a wide range of materials and applications.

The project demonstrated the upcycling of carbon composite recyclates as a functional heating sources, with pilot scale compounding and assembly of commercially available recyclates towards industrial production rates. Life cycle analysis was performed on the developed sustainable manufacturing instrument to demonstrate the reduction in energy consumption. With developed energy efficient composite tooling based on recycled composite waste, a sustainable and flexible route to produce a wide range of composites has been achieved, enabling energy efficient manufacturing for multifunctional composite and integrated structures.

Aims and Objectives

This proposal aims to overcome the mentioned limitations by developing an extremely energy efficient and safe manufacturing instrument based on recycled composite waste, solving issues from increasing volume of composite waste, high capital investment in manufacturing, long cycle time and lead time (of tooling), efficiency and component size limitations, to safety concerns in workplace. A universal tooling solution with easy fabrication and uniform heating has been developed, achieving high compatibility with existing composite systems and closing the loop of composites with various forms of rCF as an efficient heating source.

Progress

- Demonstrated a feasible route to upcycle reclaimed composite waste (recycled carbon fibres) as functional materials in value added applications.
- Developed an integral heated composites tooling consisting of recycled carbon fibres as the heating layer, with extremely high energy efficiency in composites manufacturing (90% energy consumption reduction compared to oven curing).
- Thermal and mechanical modelling performed to optimise the design with guidelines provided for future composites tooling.
- Life cycle assessment performed to evaluate the environmental impacts of developed tooling, in comparison with traditional tooling.

Future Direction and Impact

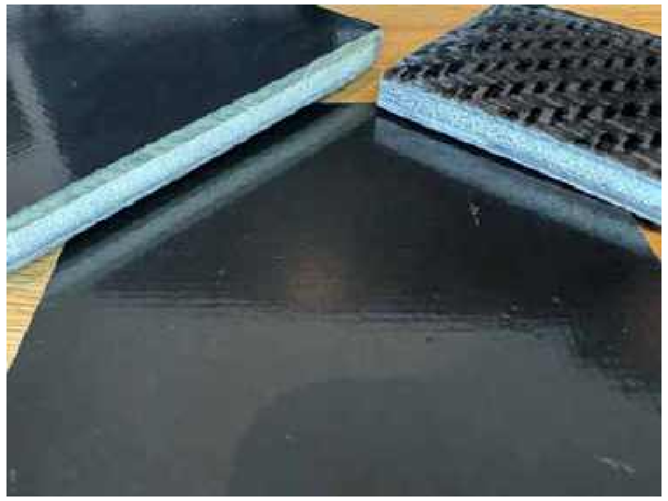
The ECOTOOL project marks a significant advancement in sustainable composite manufacturing, redefining energy efficiency and environmental stewardship in the industry. By pioneering a novel integral heated composites tooling system that utilises recycled composite waste, ECOTOOL has achieved a remarkable 90% reduction in energy consumption compared to conventional oven curing methods. This leap in energy efficiency not only aligns with the EPSRC's commitment to sustainable manufacturing but also demonstrates a feasible route to upcycle composite waste as functional materials, closing the loop for the composite industry's transition towards a circular economy.

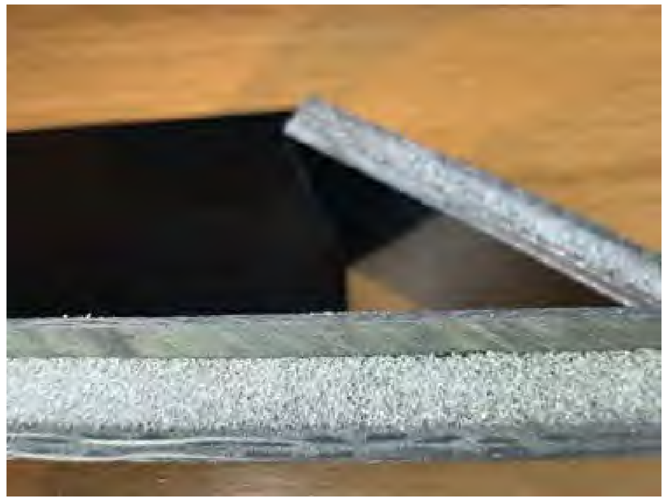
Most importantly, the project draws together complementary expertise from four institutions, joining forces to deliver multiple tasks in parallel with great knowledge exchange and teamwork. The developed knowledge in this innovative tooling system has demonstrated its potential to contribute to composite manufacturing, making it an attractive proposition for industry partners interested in sustainable and energy-efficient manufacturing solutions.

The project has one planned joint publication alongside presentations at international conferences. Additionally, the project has engaged with a wide audience through diverse dissemination activities, ensuring the broad adoption of its findings and technologies.

Future collaborations have been identified in the field of composites tooling and energy efficient manufacturing, with other Hub members including Dr James Kratz (University of Bristol, who successfully completed Hub Feasibility Study ADDCUR) and Professor Ton Peijs (University of Warwick, who successfully completed Hub Feasibility Study VarioTherm).

Further funding routes including the Technology Pull Through (TPT) programme and Knowledge Transfer Partnerships (KTP) have been identified for developing the tooling, while the fundamental research challenge raised in sequential heating in conductive polymer composites will be explored through future EPSRC funding.





Figures 1 and 2. Lab-scale samples showcase the ECOTOOL's energy efficient tooling, upcycling rCF as integral heating layer towards sustainable manufacturing with recycled materials.

Synergy Project
Work Stream 8: Thermoplastic Processing Technologies
Research Themes: High-Rate Deposition and Rapid Processing Technologies; Design for Manufacture via Validated Simulation; Recycling and Re-Use

A Numerical Tool to Aid Design-for-Manufacture of Injection Over-Moulded Composite Parts

Project Team

Principal Investigator: Dr Jonathan Belnoue, University of Bristol.

Co-Investigators: Dr Lee Harper, University of Nottingham; Prof Stephen Hallett, University of Bristol.

Research Team: Dr Shuai Chen, University of Nottingham; Dr Anatoly Koptelov, University of Bristol; Mr Will Darby, National Composites Centre (NCC).

Industry Partners: NCC, Jaguar Land Rover, Surface Generation.

Grant Award: £194,371 **Start:** 01/12/2022 **End:** 30/06/2024

Executive Summary

Injection overmoulding of fibre reinforced composites has the potential to deliver aerospace-quality components with automotive Takt times. Wider adoption of the injection overmoulding process will help reduce the sector's dependency on thermosets and offer a more sustainable thermoplastic-based alternative. This project has developed and validated a new design-for-manufacturing tool to unlock the potential of this method for complex, industrial-scale components. Hence, this tool can help mitigate risks associated with the design and manufacture of prohibitively costly tooling.

Aims and Objectives

Thermoplastic injection overmoulding is being explored for structural applications within the automotive and aerospace sectors. Low-cost fibre-filled injection moulding polymers are typically combined with high stiffness, high strength continuous fibre organosheets (see Figure 1.a). In this way, manufacturing can be simplified such that the continuous fibre material requires only a moderate change in shape during forming, while the discontinuous material is used to generate complex geometrical features via injection moulding.

Overmoulded parts have several design and manufacturing challenges. An abrupt transition from insert to overmoulding material results in stress concentrations at the interface due to the mismatch in stiffness, therefore the efficiency of the insert is low. This transition must be managed through a combination of laminate design rules and geometrical solutions. Discrete inserts also cause potential problems in terms of manufacturing, such as fibre wash, as it is difficult to constrain them when subjected to considerable pressure during the overmoulding process. Injection moulded parts also tend to have heterogeneous fibre architectures due to flow-induced alignment, which can have a significant effect on the variability of the bond strength for overmoulded parts.

The aim of this project is to find a practical and efficient way to combine thermoforming and injection moulding simulation tools to model the temperature and rate dependency effects encountered during thermoplastic injection overmoulding. A particular emphasis of the project will be to capture the deformation of the organosheet throughout the process, starting with the initial thermoforming phase and including the influence of the injection overmoulding phase.

Objectives include:

- To understand the influence of tool temperature and injection pressure during overmoulding on the integrity of a UD organosheet insert.
- To investigate strategies to constrain a UD organosheet insert to maintain integrity during injection overmoulding.

Progress

This project has enabled the development of a numerical tool that can efficiently support the design and manufacture of thermoplastic overmoulded parts of industrial scale. The tool is set to predict process induced fibre angle deviation in the continuous fibre insert, caused by a pressure differential across the surface as the mould tool closes. This work builds on the physics-based DefGen material model developed at the Bristol Composites Institute. Whilst the model was originally developed to capture the visco-elastic response of thermoset composites, it is also appropriate to model the compaction response of thermoplastics. The main restriction for the analysis of full-size models is the large computational cost of traditional ply-by-ply modelling. To tackle this, a previously developed homogenisation scheme has been used for the analysis. A series of compaction tests have been performed to extract adequate material properties for PA66.

Model validation was then performed on feature components tested in a lab environment and then on an industrial scale overmoulded panel. The results show the potential of the proposed approach for rapidly predicting the deformation in the organosheet during the overmoulding process. This work can potentially improve the Design for Manufacturing processes in industry and the suppression of many of the costly physical trials currently required to optimise the manufacturing conditions of injection overmoulded components.

Future Direction and Impact

The tools developed have reached a good level of maturity and it is thought that further TRL elevation can only be done in partnership with industry. Two conference abstracts have been accepted and two journal papers are in preparation. The project has allowed further development of the University of Bristol's software tool for compaction defects predictions so that it is now applicable to thermoplastic organosheets. The software is computationally efficient enough to predict defects in industry-size parts >1 m. Joint publications between the Universities of Bristol and Nottingham, and the National Composites Centre are planned.

The success of this project is, in part, due to the connections that have been realised early on within the Hub. Links between Nottingham and Bristol Platform Fellows and an EngD student sponsored by the National Composites Centre have provided experimental validation that goes way beyond what was originally planned. This has also enabled the problem to be considered in a holistic way, covering modelling, experiments, part manufacture and structural performance all at the same time.

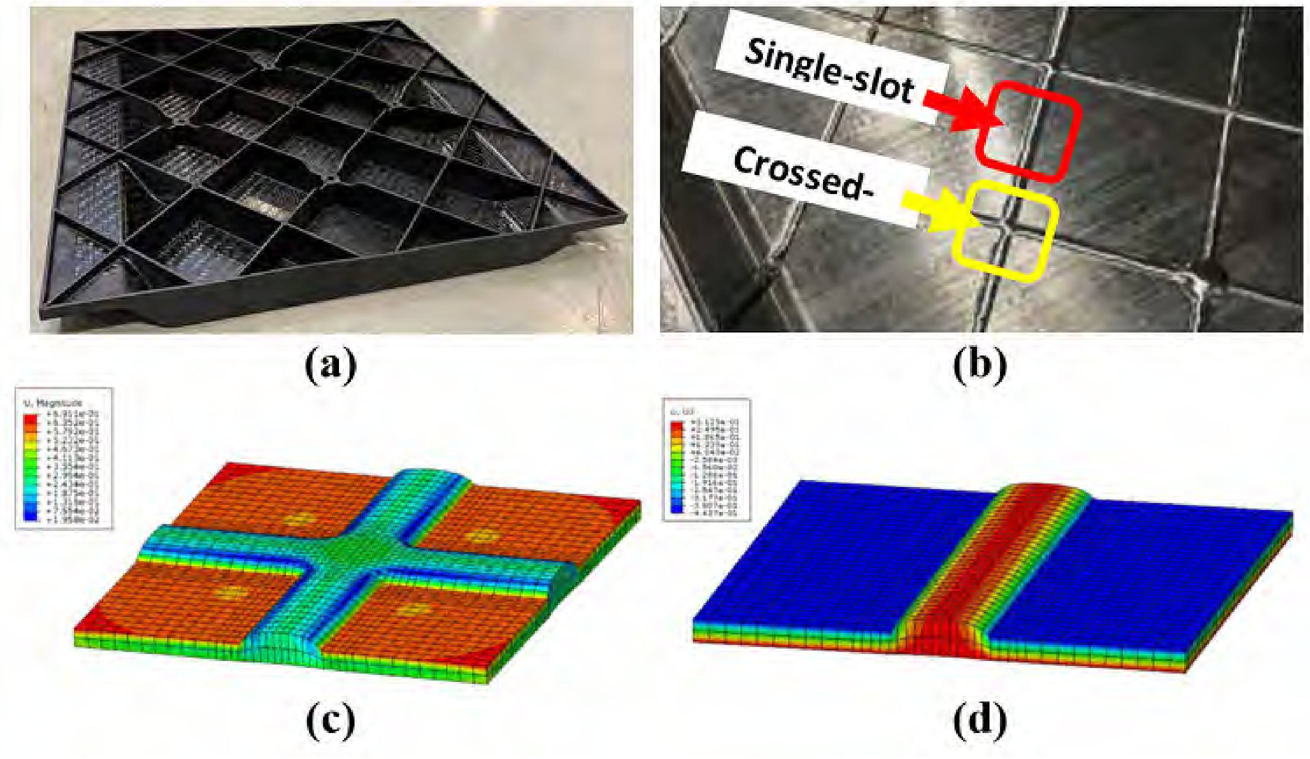


Figure 1. (a) An overmoulded panel; (b) Modelled sections of a panel (no ribs); (c) Compacted geometry of a crossed slot organosheet, (d) Compacted geometry of a single slot organosheet.

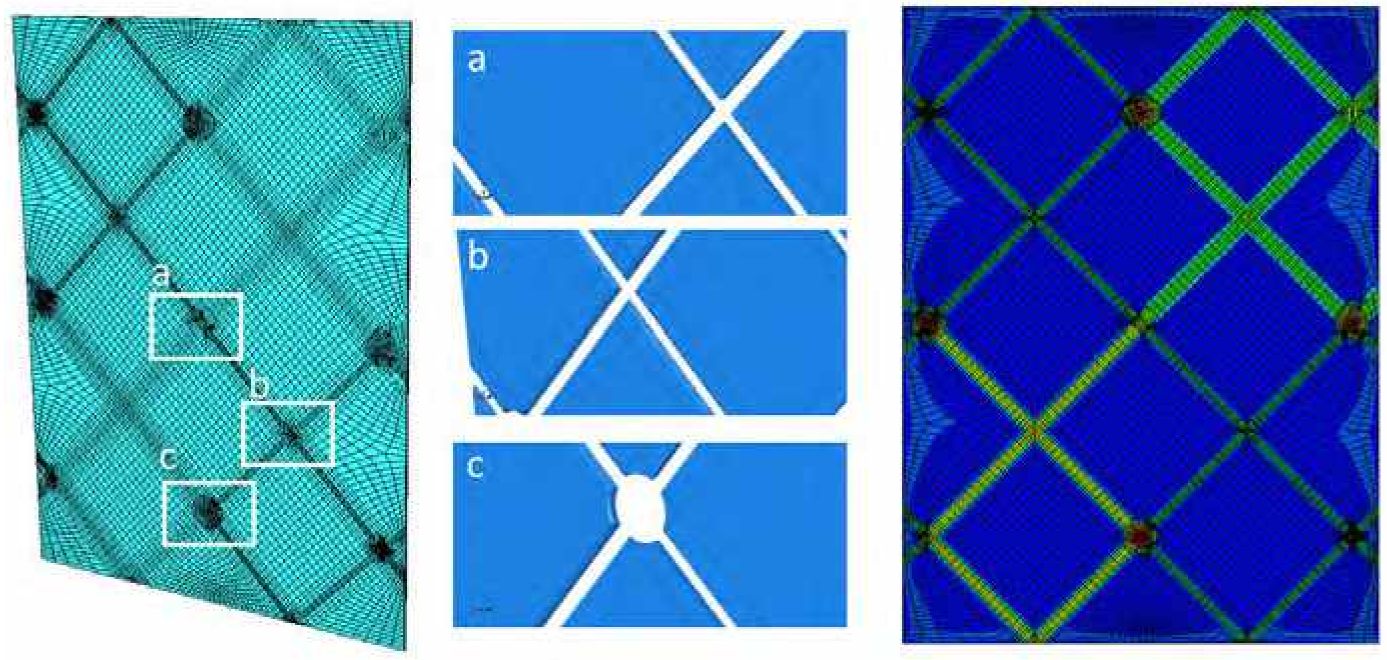


Figure 2: A design for manufacturing tool able to predict consolidation-induced defects of organosheets in full-size overmoulded thermoplastic parts was developed.

Synergy Project
Work Stream 8: Thermoplastic Processing Technologies
Research Themes: High-Rate Deposition and Rapid Processing Technologies

Thermoplastic In Situ Polymerisation (TPIP) and Double Diaphragm Forming (DDF) for Moulding of Complex Parts at Scale

Project Team

Principal Investigator: Dr Edward McCarthy, University of Edinburgh; Dr Andrew Parsons, University of Nottingham.

Co-Investigators: Prof Conchúr Ó Brádaigh, University of Edinburgh; Dr Lee Harper, University of Nottingham; Dr Adam Joesbury, University of Nottingham.

Research Team: Mr James Mortimer, University of Nottingham; Dr James Davidson, University of Edinburgh; Dr Gabrielis Cernauskis, University of Edinburgh .

Industry Partners: Johns Manville, Bruggemann, Pentaxia, AMRC, ESI.

Grant Award: £199,865 **Start:** 01/09/2022 **End:** 31/03/2024

Executive Summary

This project will establish thermoplastic composite manufacturing via in-situ polymerisation of polyamide in double diaphragm forming (DDF), demonstrating the capability using a realistic geometry tool and supporting the process with a forming model. It brings together expertise in in-situ moulding at the University of Edinburgh (UoE) with expertise in forming at the University of Nottingham (UoN) and builds on a previous Hub Feasibility Study.

The project aligns well with the AMRC Catapult, utilising similar development tooling to facilitate transition. It also ties in with software development at ESI, working through an existing collaboration at the UoN. The in-situ polymerisation technique could be employed using a similar approach to the double diaphragm forming of thermoset components utilised by Solvay and the AMRC to achieve a sub five-minute Takt time for compression moulding.

The project is complementary to multiple existing and prior projects funded by the Hub including:

- Additively Manufactured Cure Tooling (2022).
- Permeability variability of textile fabrics for liquid moulding (2022).
- Incorporation of thermoplastic in situ polymerisation in double diaphragm forming (2020).
- Active control of the RTM process under uncertainty using fast algorithms (2019).
- Acceleration of monomer transfer moulding using microwaves (2018).
- Manufacturing TP fibre metal laminates by the in-situ polymerisation route (2018).
- Modelling forming of multi-ply preforms (2011).
- Multi-scale modelling to predict defect formation during resin infusion (2011).

Very low viscosity (~10 cP) monomers combined with double diaphragm forming (DDF) presents a novel opportunity to create huge (multi-metre e.g. wind turbine, train body panels) thermoplastic structures. DDF facilitates filling before forming; the initially flat reinforcement is easier to infuse due to more consistent permeability and the presence of the liquid provides lubrication to reduce inter-ply friction during forming. Furthermore, pot life can be extended through thermal control (Infusion can be undertaken at temperatures at which polymerisation rates are minimal) and no temperature cycling is required – polymerisation occurs below the final polymer melt temperature so the component is immediately solid and no cooling step is needed.

With increasingly pressing sustainability goals in all sectors, thermoplastic composite manufacturing developments are timely. Low cost, low emission processes are needed to create recyclable components that meet stringent regulations. The process also enables the introduction of re-mouldable resins, thus facilitating the transformation of composite manufacture into a circular economy and reducing disposal to landfill.

Aims and Objectives

- **Assemble low-viscosity diaphragm forming system**
  In conjunction with AMRC (in an advisory role), develop the existing double diaphragm tooling at UoN to incorporate a bespoke frame suitable for a low viscosity resin system. Integrate with the UoE mixing system. Specific clamp design elements will be required to ensure minimal bridging at the edge so as to prevent racetracking during fill.
- **Establish forming model**
  In conjunction with ESI, build on a basic model of the fill-form process using the PAM software suite to represent the tea tray geometry. Demonstrate virtually the benefits of the low viscosity (fast fill, lubrication) or waxy (high tack, resistance to corner thinning) resin on shear behaviour during forming in terms of fibre angle, wrinkling and corner thinning, and validate experimentally.
- **Establish processing method**
  Produce tea tray component in double diaphragm tool utilising one-stage fill and form, and two-stage quench and form. Ensure reproducibility and establish appropriate processing window.
- **Quality assessment and validation of model**
  Use metrology-grade 3D laser scanner (Creaform) and Apodius Vision System facilities to capture forming behaviour, distortion, fibre angle and wrinkles and correlate with model (Objective 2). Assess quality of the parts in terms of thermomechanical behaviour and microstructure.

Progress

The project is still running, and the technology is still in its early stages.

The assembly of a low-viscosity diaphragm forming system was completed by mixing systems at both sites. There was successful infusion of DDF frame without significant race-tracking issues. Small modifications are planned to mixer/frame integration to make this more robust. PDI control is planned for the heater system on the mixer by the end of the project.

A forming model has been established. The majority of experimental materials characterisation are complete. A basic forming model was developed with ESI. A full model has not yet been achieved due to lack of software resource and lack of personnel resource for an alternative Abaqus approach.

Final testing is in progress in order to establish a processing method. Extreme geometry on part of the tooling is proving challenging to bagging survival at reaction temperatures but mitigation has been identified.

The Apodius system is being used for assessment of parts and model validation.

Future Direction and Impact

There is a strong pathway to potential impact through the AMRC and its partners, through Pentaxia, and with a clear potential for interaction with other Hub activities. Johns Manville's expansion into intermediate materials (Neomera) targeted at automotive and motorsport markets, plus Teijin's expansion into engineering thermoplastic pre-pregs illustrates the opportunities for low-cost manufacturing in the thermoplastic composites field.

The project partners have already established regular exchange of ideas with the AMRC on how to progress and scale-up the proposed fill-then-form processing approach, so that it can be presented as a higher TRL proposition to AMRC industrial partners and thus enable trials at a low-risk pre-commercial level. Specifically, successor trials after this project would transfer our approach firstly onto an AMRC double diaphragm with shuttle heating capability, and then onto a 3 x 1.8 m DDF single-sided tooling system. A follow-on consortium featuring AMRC, its partners, and these two university partners would then seek further maturation and commercialisation of the technology.

There is potential to draw on the outcomes of Dr Chen's Hub Innovation Fellowship on Permeability Variability of Textile Fabrics for Liquid Moulding, particularly with regard to understanding the challenging permeability conditions of double diaphragm dry fabric infusion.

Figure 1. Caprolactam mixing and delivery system connected to double diaphragm frame, with infra-red heating.

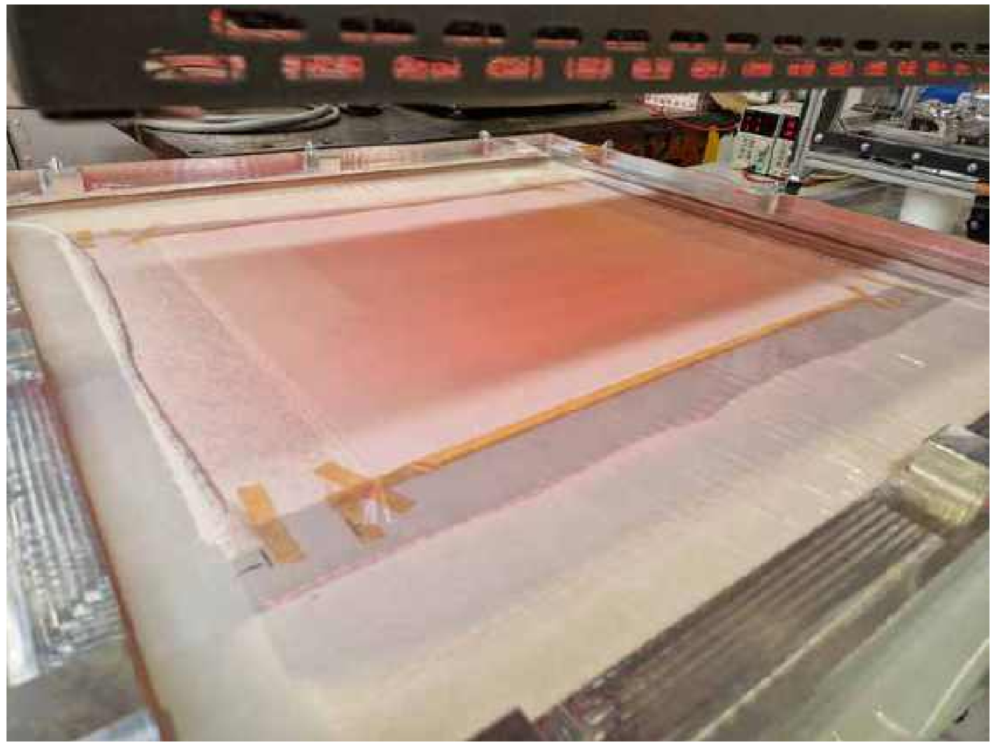


Figure 2. Double diaphragm frame heated using an infra-red lamp, ready for infusion.

Synergy Project
Work Stream 6: Composite Forming Technologies
Research Themes: High-Rate Deposition and Rapid Processing Technologies; Recycling and Re-Use

Zero Waste Manufacturing of Highly Optimised Composites with Hybrid Architectures

Project Team

Principal Investigator: Dr Connie Qian, University of Warwick.

Co-Investigator: Dr Lee Harper, University of Nottingham.

Research Team: Dr Hasina Begum, University of Warwick; Dr Adam Joesbury, University of Nottingham; Dr Hao Yuan, University of Warwick; Mr Tom Hill, University of Warwick; Mr Richard Groves, University of Warwick; Mr Hussain Abass, University of Warwick; Mr Jiashu Liao, University of Warwick; Mr Josh Evans, University of Warwick.

Industry Partners: Ford, DowAksa, Gestamp.

Grant Award: £193,278 **Start:** 01/11/2022 **End:** 30/09/2024

Executive Summary

Composites manufacturing using prepreg generates a large proportion of waste (30-40% depending on the geometry) from ply cutting, which usually ends up in landfill, having a negative impact on the environment and resulting in substantial costs. This project aims to develop practical high-value manufacturing solutions for reusing prepreg manufacturing waste, with a particular focus on woven fibre based prepregs. Three routes are investigated to repurpose this material, including:

- Reprocessing waste material into randomly distributed and randomly orientated chips which can be compression moulded like Sheet Moulding Compounds (SMCs).
- Reprocessing waste material into carefully arranged patches which can be compression moulded as patchwork laminates.
- Combining the new material formats developed with continuous, virgin prepreg to form hybrid architecture composites. Experimental and numerical simulation studies are conducted to investigate the processing behaviour and mechanical properties of the materials manufactured through these three different routes.

An automated process for rapidly manufacturing components from hybrid fibre architectures (continuous and discontinuous) will significantly improve the manufacturability of complicated geometries and will promote the utilisation of waste materials to create zero-waste manufacturing of highly optimised structures. This approach will increase production rate, reduce material wastage, save cost, and reduce harmful CO_2 emissions.

To date it has been demonstrated that the materials manufactured through the chip-SMC route exhibit similar levels of processibility (squeeze flow behaviour) compared to conventional SMCs, but the main challenge is to improve the strength of these materials by optimising the meso-scale fibre architecture. An automotive demonstrator geometry has been successfully manufactured using both chip-SMC and chip-SMC/continuous prepreg hybrid architecture composite.

Aims and Objectives

This project aims to create a practical solution for prepreg waste, by reprocessing prepreg waste into discontinuous formats (chip-SMC and patchwork laminate) that can also be co-moulded with continuous fibre prepreg to form a hybrid material.

The main objectives are:

- Develop a lab-scale reprocessing method for manufacturing prepreg chip-SMCs.
- Determine the effects of chip size on the processibility and mechanical properties of chip-SMC through in-plane squeeze flow tests and tensile tests.
- Explore different layup strategies for improving the strength of patchwork laminates using a combine experimental and numerical simulation approach.
- Perform process characterisation for hybrid architecture composites using in-plane squeeze flow tests.
- Manufacture demonstrator components to further evaluate the processibility of the materials using real-life geometries and manufacturing processes.

As the research focuses on compression moulding and discontinuous fibre composites, potential industrial applications are likely to be seen in high-volume manufacturing automotive and aerospace parts. With the chip-SMC route initial applications might be non-structural due to the limited strength of such materials, but semi-structural and structural applications will be possible if the mechanical properties can be improved in this project. Patchwork laminates are likely to be adopted in semi-structural to structural applications.

Progress

Lab-scale manufacturing of chip-SMCs

Manufacturing prepreg chip-SMCs requires two main steps: cutting and laminating of the chips. Two cutting methods and two laminating methods have been investigated in this project. The first cutting method utilises a cutting table where loose chips can be produced through a grid-like cutting pattern, and the chip sizes can be freely adjusted by changing the intervals of the gridlines. The second cutting method utilises a clicker press containing arrays of removeable blades of which the intervals can be adjusted using spacers. The cutting table provides greater levels of flexibility in terms of cutting different chip sizes but cannot easily process material offcuts of irregular shapes and sizes with the existing CNC software.

The two different laminating methods were required due to the different tack levels for the two different prepregs. For the low tack DowAksa material the chips do not agglomerate at room temperature, making it easy to distribute them but difficult to stop the chips from moving during handling. The high tack resin in the Mitsubishi material causes the chips to agglomerate at room temperature, making it harder to distribute the chips evenly, but the tack enables the chips to remain in place once deposited. The DowAksa chips were laminated by shuffling the chips in a sealed envelope at room temperature until the distribution of the chips was visually uniform, and then compacting the envelop of chips at an elevated temperature (50°C) to bind the chips together. The Mitsubishi chips were laminated at room temperature by manually positioning each individual chip to achieve a visually uniform distribution, but no subsequent compaction step was performed.

Experimental Characterisation for Chip-SMCs

Experimental characterisation of the chip-SMCs consists of processibility characterisation and mechanical properties characterisation, where both have been conducted using the DowAksa material. Processibility characterisation is performed using the squeeze flow method developed through the PI's Innovation Fellowship project. Chip-SMCs consisting of chip sizes of 12.5mm, 17.5mm and 25mm with nominal areal masses of 3000gsm, 6000gsm and 8000gsm have been studied and benchmarked against a baseline commercial SMC. The squeeze flow results have shown that materials with smaller chip sizes experience more area increase during squeeze flow, but the chip-SMCs generally experience less area increase compared to the baseline SMC as the fibre interlacing (woven fibres) prohibit fibre dispersion. Higher numbers of interlaced tows have been observed in samples consisting of larger chip sizes after squeeze flow testing, which have resulted in surface bumps in the sample. Analysis of the compressive stress-strain relationship has suggested that the material's resistance to compression stresses decreases with increasing areal mass, but chip size has little influence on the compressive stress-strain response.

Flat plaques have been compression moulded using the 17.5mm chip-SMC with 80% and 100% initial tool coverage. All plaques have been fully filled with no visible surface defects. Tensile test data from the plaques has shown that there is no fibre directionality, and the fibre volume fraction is uniform.

The next steps will involve studying different chip aspect ratios and characterising chip-SMCs manufactured using the Mitsubishi material.

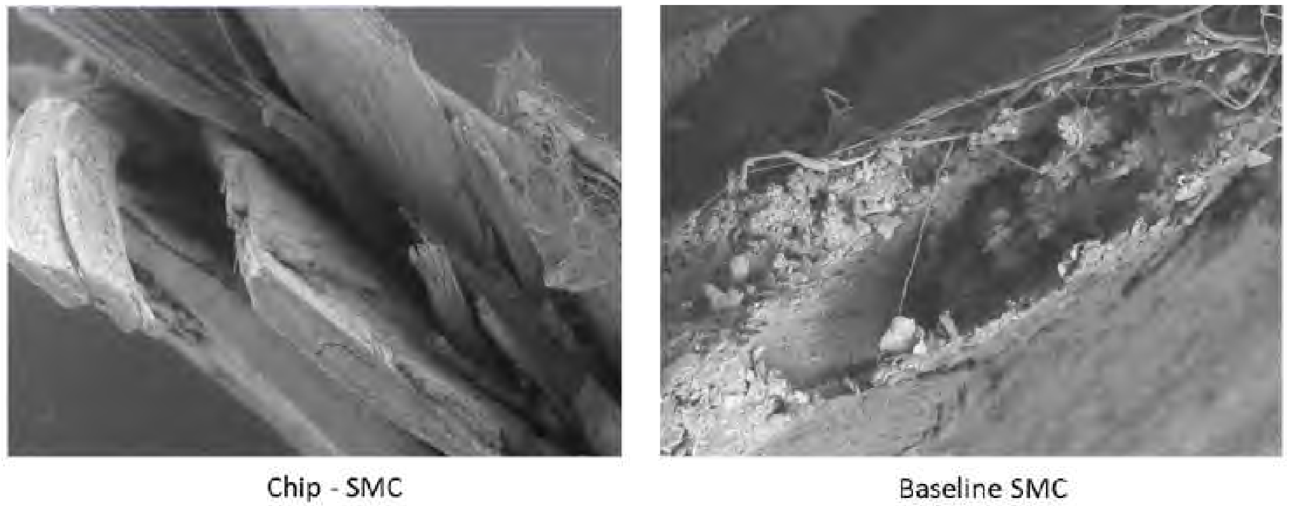


Figure 1. Comparison of typical failure mode between chip-SMC and baseline SMC.

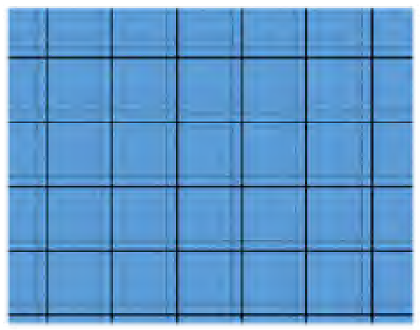
Prepreg Patchwork Development

This work package investigates the use of medium-sized patches of prepreg that are tessellated to form patchwork plies with controlled fibre orientation. Two patch sizes have been investigated, 70 x 70 mm and 100 x 100 mm, having 0/90° fibre directions aligned with the edges of the patch. Literature has shown that the greatest mechanical performance is achieved when ply gaps are staggered through the laminate thickness in a scarf pattern. Therefore, the patchwork laminate study also investigates stagger offset distances in addition to patch sizes. Stagger offsets of 10 mm and 30 mm were investigated for both patch sizes, with an additional stagger offset of 50 mm investigated for the 100 mm patch size, thus forming a 'brickwork stretcher-bond' pattern.

The same out-of-life Mitsubishi Rayon PYROFIL TRK501 368GMP prepreg was used in the patchwork laminate study. The condition of the out-of-life prepreg was assessed by moulding plaques that could be mechanically tested for comparison with datasheet values. It was found that measured tensile strength and interlaminar shear strength agreed with datasheet values, however, measured laminate modulus was 22% greater than the datasheet value. This can be attributed to the open edge press moulding process, which was common for all panels manufactured in this work package. Further tests need to be performed to determine the laminate volume fractions. Patchwork laminates were manufactured in accordance with the technical data sheet, using a flat tooled heated platen press to compression mould for a minimum of 5 minutes at 140°C with 4.0 MPa pressure.

Mechanical test results show the strength of patchwork laminates are dependent on both patch size and stagger offset. Of the laminate configurations described in Figure 2, a 100 mm patch size with 30 mm offset (Si100-St30) has the greatest strength properties, having 63% retained strength compared with a continuous ply laminate. Stiffness properties of patchwork laminates are shown to be much less sensitive to laminate configuration, ranging between 73% and 78% retained stiffness compared with the continuous ply laminate. FE simulations are planned to study this effect further, enabling the effect of certain variables to be isolated in order to clearly identify optimised patchwork laminate configurations.

Plan view (transparency)



Patchwork laminate configuration

Tile Size (Si.)	Stagger offset (St.)					
	Short		Medium		Long (brick bond)	
mm	mm	Code	mm	Code	mm	Code
70	**10.0**	Si70-St10	**30.0**	Si70-St30	-	-
100	**10.0**	Si100-St10	**30.0**	Si100-St30	**50.0**	Si100-St50
Total number of patchwork laminate configurations = 5						

Cross-section view

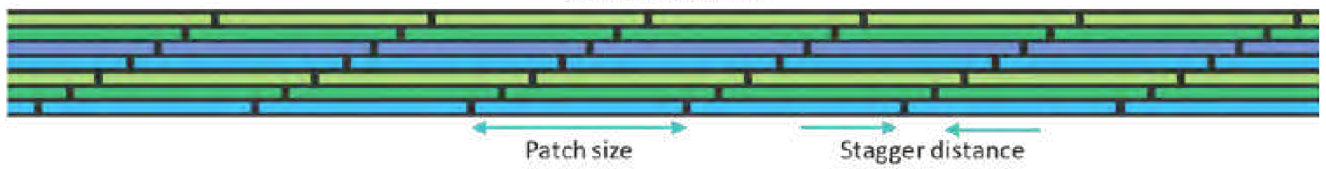


Figure 2. Patchwork laminate configurations.

An additional patchwork configuration was trialled, taking the Si100-St30 configuration and replacing the outer patchwork plies with continuous plies. The retained strength of this configuration was 70%, which is lower than what is expected from a Rule of Mixtures calculation, confirming that stress concentrations at the patch edges are driving failure initiation. The next stage will investigate strategies to reduce the effect of stress concentrations and increase interlaminar fracture toughness, to increase the retained strength of patchwork laminates.

Experimental Characterisation for Hybrid Architecture Composites

All hybrid architecture samples were manufactured using the Mitsubishi material and characterised using the squeeze flow method. Two studies have been conducted in this WP where the first study investigates different hybridisation hierarchies, and the second study seeks practical approaches for minimising the distortion in continuous fibres during hybrid moulding processes.

In the first study, hybrid architecture samples with two different hierarchies have been investigated: one consists of only chip-SMC and continuous prepreg, and the other one consists of chip-SMC, prepreg patches and continuous prepreg. Results from both hierarchies have shown that the flow of chip-SMC introduces tow spreading in the area underneath the SMC, and tow compaction in the area ahead of the flow front of the SMC. Furthermore, in the sample with patches, while no significant effects are observed on the level of distortions in the continuous prepreg ply, the patches experience large distortion and the flow of SMC is restricted, suggesting reduced formability and reduced mechanical properties compared to the hybridisation of chip-SMC and continuous prepreg only. Higher levels of tow spreading, and internal cracks tend to appear in areas where interlaced tows remain in the chip-SMC.

The primary focus for the second study was to investigate the effects of staging on the flow of chip-SMCs and the distortion in the continuous prepreg. To date, experimental characterisation has been performed for samples consisting of chip-SMC and continuous prepreg, where the prepreg has been staged to different levels. Rheology tests have been performed on prepreg samples (with fibres) at 80°C to investigate the change in the apparent complex viscosity as a function of staging time. Staging for continuous prepreg has then been performed using three different staging times prior to squeeze flow tests for hybrid architecture samples. Increasing the level of staging in the continuous prepreg reduces the flow length of the chip-SMC, possibly because of higher friction at the chip-SMC/prepreg interface caused by the higher resin viscosities. On the other hand, the distortion in continuous prepreg reduces as the level of staging increases, as the increased resin viscosities cause the overall stiffness of the material to increase. Furthermore, the distortion in the continuous prepreg shows highly non-uniform distributions, especially in the samples with lower levels of staging, which indicates non-uniform flow fields in the chip-SMC. Image based grid strain analysis (GSA) methods are currently being developed to quantify the deformations in the continuous prepreg and the heterogeneity of fibre architecture in the chip-SMC. In addition, effects of staging the chip-SMC will also be investigated in future work.

Demonstrator Manufacturing

An automotive beam geometry has been selected as the demonstrator component for this project. Compression moulding trials have been performed using the Engel press at Warwick Manufacturing Group and all parts have been manufactured using the Mitsubishi material. Two different fibre architectures have been used, including a chip-SMC only version and a hybrid architecture version combining chip-SMC and continuous prepreg. Figure 3 shows the layout of the initial charge and preform in the mould cavity, along with the finished parts. In both type of fibre architectures, the chip-SMCs have fully filled the mould cavity including the ribs. Further work will be performed to investigate the fibre architecture in the ribs through XCT scanning or microsection, providing benchmarks to evaluate future process improvements. More demonstrator parts will be manufactured at the end of the project once the chip-SMC characterisation has been concluded, in order to understand potential strategies to improve the quality and mechanical performance of this 3D part.

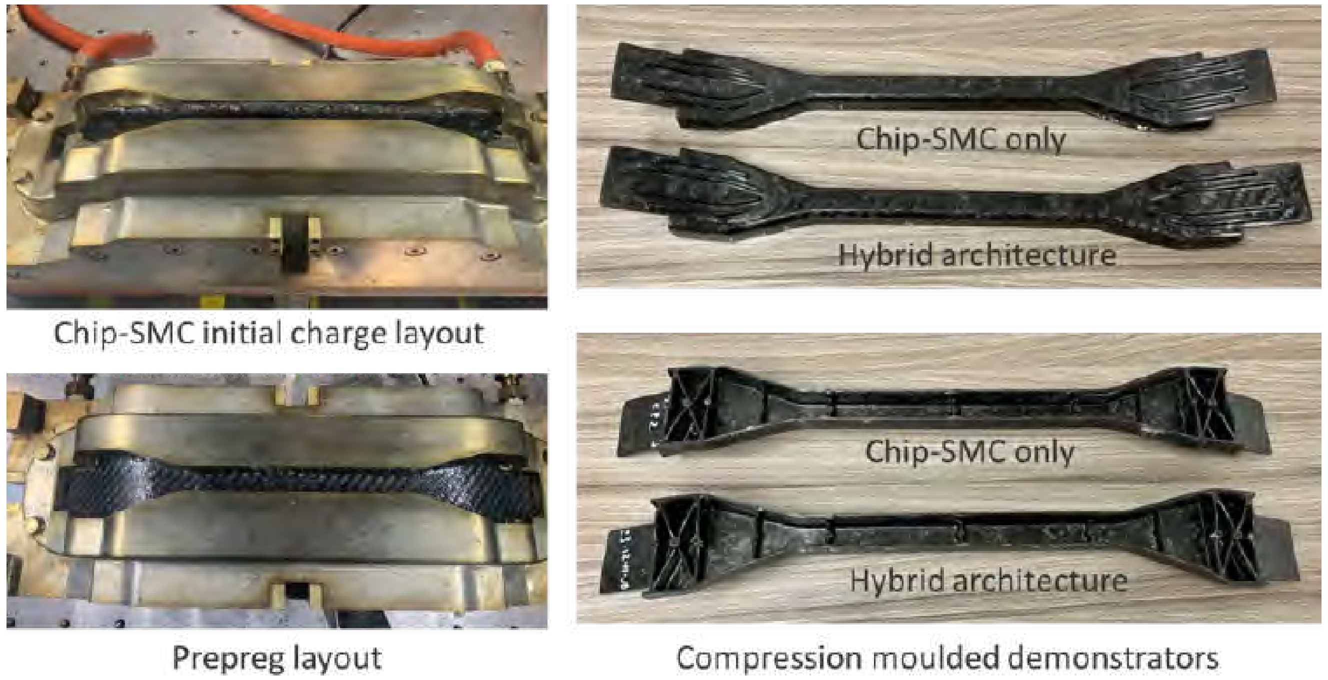


Figure 3. Demonstrator parts manufactured in this project.

Future Direction and Impact

This project seeks practical solutions for reprocessing prepreg manufacturing waste into suitable material formats for high-value manufacturing processes, and subsequently mix and match different reprocessed material formats to create hybrid architecture composites. Composites with hybrid architectures take advantage of both continuous and discontinuous fibres to produce load-bearing parts using efficient out-of-autoclave processing such as compression moulding. This idea can benefit a wide range of industries.

The outcomes from this project will enable OEMs to increase their uptake of sustainable lightweight materials, by advancing the use of trim waste into high-value products, ensuring no waste materials are sent to landfill. It will also enable Tier-1 component manufacturers to expand their capabilities and for material suppliers to identify new applications for existing prepreg products. Experimental and numerical simulation studies are performed to investigate the processing behaviour and mechanical properties of the reprocessed material, and the outcomes of the research will lead to several journal publications and conference presentations.

Several follow-on projects have been identified through the current projects. There have been ongoing discussions with GKN Aerospace and FAIRMAT on potential scaling up for the chip-SMC process and the prepreg patchwork process. In addition, several challenges identified in this project need to be further investigated at the fundamental levels. For instance, how to control the fibre architecture in chip-SMCs to improve the strengths of these materials; how to characterise the out-of-plane flow behaviour of chip-SMCs; how to design the prepreg patchwork when forming non-planer geometries. These challenges will be addressed through EPSRC grants or a PhD studentship.

4 Hub Training

We are currently training 45 PhD students, 55 EngDs and 51 postdoctoral researchers.

The Hub continues to assess the training needs of our students by conducting surveys and responding to feedback in order to provide appropriate professional development opportunities.

We are committed to training 150 researchers over the lifetime of the Hub to help support the anticipated growth in the UK composites sector over the next ten years. The flexibility of our funding model offers an effective way for early-career researchers to develop and express their own ideas. Under our training remit, all Hub Spokes are eligible to study the taught EngD modules within the EPSRC Industrial Doctoral Centre in Composites Manufacturing (IDC), encouraging the Spoke members to continue to engage with the Hub beyond their initial project, widening their expertise and skills.

Our Staff Development Policy outlines a culture where postgraduate students, researchers and academics are supported throughout their affiliation with the Hub. The policy aims to provide Hub members with opportunities to support their career progression above and beyond those typically on offer by their home institution. The policy is built around a network of senior academics and members of the Advisory Board, who focus on giving support to junior members of the team. We actively encourage researchers to engage with the Management Group and Advisory Board, requiring them to present technical project summaries at the quarterly meetings to help build their independence.

Training with Pentaxia

The Hub has worked closely with its industrial partner Pentaxia to create a bespoke course delivered at their premises in Derby. The course is an intensive three-day practical programme covering mould design, CNC tool programming, kit templating and nesting, and laminating and inspection. The course has received positive feedback from all attendees and four sessions were held between 2023 and 2024.

Vitae Researcher Development Framework (RDF)

The Hub became a member of the Vitae Researcher Development Framework (RDF) in 2021. The Framework is designed to enhance and develop the necessary skills for individuals in academia. To date, 11 PhDs and researchers have enrolled and participated in a half day training course to help use the tools developed under the Framework, for managing their own professional development.

International Exchange Programme (IEP)

The programme is intended to foster collaborations and expand knowledge, exposing students to the latest technologies championed by leading academic and research institutes. Funding is available to support visits of up to 3 months. To date, seven exchanges have taken place and we continue to encourage our students to participate.

In April 2023, Hub Innovation Fellow Dr Yang Chen, University of Bath, visited the Centre for Composites Materials (CCM) at the University of Delaware, USA, under the supervision of Professor Suresh Advani and Dr Pavel Simacek. Prof Advani and Dr Simacek are experts in composites manufacturing, with interests in liquid composites moulding and related numerical modelling. They have developed an advanced software (LIMS) for resin flow simulations. During his visit, Dr Chen was trained on the LIMS software, and was provided with two licenses. The aim of the visit was to develop a numerical framework for analysing the variability of textile permeability, using radial injection experiments, and empowered by physics-informed neural networks.

Dr Yang Chen with Dr Pavel Simacek at the University of Delaware, USA.

At the end of the visit, Dr Chen was invited to give a seminar, providing him with the opportunity to present his research and promote the Hub. The collaboration initiated during his visit will continue, with the current focus being the development of a PINN model. They will incorporate the PINN model to solve inverse problems identifying textile permeability, for which interactions are expected with the Nottingham team, Dr Mikhail Matveev, Dr Andreas Endruweit, and Prof Michael Tretyakov, principal investigator on the Hub funded Active RTM project.

This year the Hub also supported PhD researcher Aidan Hawkins, Queens University Belfast, on an exchange to the USA. Aidan embarked on an informative composites trip starting with a visit to meet his external PhD supervisor Professor Stephen Tsai to discuss his work on Double-Double (DD) laminates, a new layup design approach which seeks to address the limitations of quad laminates. Aidan also had opportunities to present his work at the American Society for Composites Conference (ACS) in Boston Massachusetts and visit the NASA Jet Propulsion Laboratory (JPL) where he hosted a seminar on DD laminates with supervisors Professor Tsai and Dr Ali Aravand. The trip was concluded with a visit to Northrop Grumman and California Institute of Technology (Caltech) which led to discussions about future collaborations.

Aidan Hawkins at the NASA Jet Propulsion Laboratory (Los Angeles, CA).

Researcher Network

The Hub's Researcher Network has been an effective delivery mechanism for developing skills and providing training. This network administers our Early-Career Feasibility Studies (£5k - £10k), which give younger Hub members the opportunity to express their independent ideas and experience the peer-review process. The researchers organise their own workshops to develop composite manufacturing skills. These offer practical experience to all students, who might otherwise only be involved in simulation-based projects.

In 2024, Angela Lendinez Torres from the University of Nottingham was appointed as the new chair following Dr Oriol Gavalda Diaz's promotion to lecturer at Imperial College London. The Committee welcomed three new members:

- Joseph Humphries, University of Nottingham
- Bj Shah, University of Bath
- Hao Yuan, University of Warwick

Researchers Network Event, Belfast - 1st August 2023

The Researchers Network organised a tour of the Northern Ireland Advanced Composite and Engineering Centre (NIACE), a regional Centre of Excellence for innovative composites manufacturing Research and Technology. The tour showcased the centre's 3D weaving Facility, Thermoplastic Manufacturing, Spirit Aerospace SPAR and RTI, training and Digital RTM Cell. A dinner was organised after the tour and provided further opportunity to socialise with other researchers from the Hub and Industrial Doctorate Centre (IDC).

The Researchers Network tour of Northern Ireland Advanced Composite and Engineering Centre facilities (NIACE)

The Researchers Network dinner held in Belfast in August 2023.

Researchers Network Event, Bristol – 20–21 September 2023

The Researchers Network hosted a careers event in Bristol in partnership with SAMPE and the IDC. Hub researchers from the Universities of Ulster, Nottingham, Cranfield, and Queen Mary University London presented results from their Early-Career Feasibility Projects (£5k - £10k) awarded last year under the Researchers Network Awards. There were also presentations from the National Composites Centre (NCC), Lineat, GKN and Leonardo. It was a great opportunity for researchers and students to get an insight into people working in Catapult Centres, startups and large companies in composites manufacturing. The event was followed by a tour of the Leonardo facilities. We are grateful for the time taken by everyone involved to help make the event such a success.

Researcher Network Committee

Dr Oriol Gavalda Diaz (Chair to end 2023)	University of Nottingham
Ms Ángela Lendínez Torres (Chair from 2024)	University of Nottingham
Mr Raul Andres Gomez Quinones	University of Bristol
Dr Monali Dahale	National Composites Centre
Mr Patrick Sullican	University of Bristol
Dr Yang Chen	University of Bath
Mr Joseph Humphries	University of Nottingham
Dr Bj Shah	University of Bath
Mr Hao Yuan	University of Warwick

Fellowships

Fellowships are an effective first step for researchers looking to establish an independent career. To date, we have funded 3 Platform Fellows and 3 Innovation Fellows across 5 Hub institutions. The final Innovation Fellowship call was launched in the summer of 2021 and an appointment was made for the new recruit from the University of Bath to start in March 2022. A Transitional Fellow was also recruited enabling an additional senior postdoctoral researcher to progress over a 3-year period to a permanent academic position.

Industrial Doctoral Centre in Composites Manufacturing (IDC)

The IDC in Composites Manufacturing aims to provide the UK composites manufacturing industry with Research Engineers equipped with the necessary advanced technical and leadership skills required for effective adoption of new knowledge and technologies in composites manufacturing.

The IDC has reached its 10th year with a total of 31 students graduating with an EngD in Composites Manufacturing. The transition to a new structure for the taught component for the Engineering Doctorate started in September 2023. It is delivered over three years and is designed to engage students with a cross disciplinary view of composites, from material chemistry to physics of imaging and NDE, combining analytical techniques with modelling and practical application in a manufacturing context. A holistic examination of the impact of the industry is provided, including future strategies for adopting composite materials in a framework of NetZero. The units do not have pre or co-requisites therefore students can take up studies at any time during the academic year. This maintains flexibility for the industrial interaction according to their needs and enables suitable candidates to be identified throughout the year. Furthermore, the start-up of the industrially based research is not dependent on the material in the units. The final unit taken in year 3 is Technology Transfer in Practice, replacing the Study Tour, and is focused on personal development. It comprises a secondment to another organisation within a business area related to the student's research and offers an opportunity to reflect on their research experience and its wider ranging impact on society. Students are encouraged to use a variety of media tools in their final report to effectively communicate their findings.

In 2023 the National Composites Centre (NCC) provided full sponsorship of the students on the new IDC. The research projects are related to NCC's core research programme, which involves their members and other collaborators. The students are exposed to industry practice and collaboration throughout as well as being embedded into industrial research and development practices. Five new EngD students have been hired this year and we envisage hiring 9 students next year, when the IDC changes to the CDT in Innovation for Sustainable Composites Engineering. The new CDT is led by the University of Bristol in partnership with the University of Nottingham. The CDT has 28 partners representing OEMs to SMEs committed to supporting the CDT, with the NCC providing a substantial part of the industrial funding. There are four integrated and intertwined threads of the programme:

- A doctoral research project that includes industrial and academic mentoring.
- Personal development that includes peer-to-peer mentoring as well as team building and outreach, enabling students to build a portfolio of skills tailored to their needs.
- A flexible programme of credit-bearing taught units in the first three years of study, described above.
- Innovation-driven cross-cohort professional development to enhance technical and entrepreneurial competencies and build cohort interaction.

IDC New Starters 2023/2024

- Jenny Banks, University of Bristol, Project title: Reducing Waste and Cost in Large Scale Infusions through Adaptive Process Control.
- Erica Barnes, University of Bristol, Project title: Through-Life Damage and Environmental Assessment.
- Matthew Miller, University of Bristol, Project title: High-Rate Automated Deposition.
- Kieron Guote, University of Bristol, Project title: Large Scale Rapid Infusion.
- George Holiday, University of Bristol, Project title: Composite Shielding against directed Energy Weapons.

Welcome to Caroline Perkins, who took over from Helen Howard as the IDC Manager in June 2023. Caroline was the IDC Administrator and has skills in project management, strategy, sales and marketing to help shape the future CDT. Peter Selway is the new IDC Administrator with a background in education including working at University of the West of England in admissions for the last 10 years.

IDC Team

Caroline Perkins
IDC Manager

Pete Selway
IDC Administrator

Successful EngD Vivas and Destinations - Graduated Since Last Report

Successful EngD Vivas	Destination
Preetum Mistry, “Lightweighting of railway vehicles”	Director of Growth at STUDIO AZAM
Josh Loughton, “Design for manufacture of high volume carbon fibre composites for automotive”	Composite Design Engineer Dynisma
Nikita Gandhi, “Automated composites inspection and verification”	Research Engineer (Systems) at the National Composites Centre, Bristol
Nikita Budwal, “Advanced 3D woven lightweight composites structures for future automotive high rate programmes”	Advanced Materials Systems Engineer, Boeing
Owen Taylor, “Design for manufacture principles for the Automated Fibre Placement manufacturing method”	Advanced Materials Systems Engineer, Lamborghini
Tasos Deneziz, “Enhanced heating strategies for composites manufacture”	Applications Development Engineer, Aerospace
Claudia Jimenez Martin, “Forming and infusion of next-generation composite aerostructures”	Industrial Architect, Airbus
Maria Onoufriou, “Virtual manufacturing: validation of laminate deformation processes in automated composite material deposition and moulding”	Post Doctorate, KTH (Royal Institute of Technology) Stockholm
Phil Druiff, “Data-driven manufacturing in the automated lay-up of composites”	Adavanced Research Engineer, Automated Lay-up, National Composite Centre
Zoe Fieldon Steward, “Matrix Formulation optimisation and processing parameters for high-temperature resins suitable for filament winding and resin transfer moulding”	Composite Materials Engineer, Rolls-Royce Electrical

Jack Holyoak presents his work at the IDC Annual Showcase event on 19 September 2023.

Equality Diversity and Inclusion (EDI)

The long-term strength of the UK composites research base depends on harnessing all available talent. The Hub is committed to ensuring that equality, diversity and inclusion is embedded at all levels and in all aspects of research practice and funding policy. We are committed to ensuring that fairness is fully reflected in all our funding processes.

The Hub's EDI Committee chaired by Dr Connie Qian from the University of Warwick, helps deliver our strategic aim of creating a fully inclusive culture that is pro-active in initiating change and driving forwards best practice in EDI matters. Several training activities have been organised by the Committee and have been well attended.

EDI Committee

Dr Adam Joesbury	University of Nottingham
Prof Alistair McIlhagger	Ulster University
Dr Alex Skordos	Cranfield University
Ms Ángela Lendínez Torres	University of Nottingham
Dr Connie Qian	University of Warwick
Mrs Joanne Eaves	University of Nottingham
Dr Michael Johnson	University of Nottingham
Dr Oriol Gavalda Diaz	Imperial College London
Dr Xun Wu	University of Bristol
Dr Yang Chen	University of Bath

The Equality, Diversity and Inclusion policy is available if you click here.

5 Hub Outreach

JEC World 2023 – 25 to 27 April 2023

Hub Business Development Managers, James Whyman and Simon Quinn, attended JEC World 2023 in Paris, France, on 25 to 27 April. The event brought together the international composites community and showcased the latest advancements and innovations in composites materials, their manufacturing technologies, and their applications in industry. A wide range of exhibits, workshops, and conferences featured at the show, covering topics such as automation, materials, and design. One of the key themes of the event was sustainability and with the increasing demand for environmentally friendly products, the composites industry is poised to play a significant role in shaping the future of manufacturing. The Hub stand attracted a number of visitors and several new business relationships were formed.

International Conference on Composite Materials (ICCM23), Belfast – 30 July to 4 August 2023

The 23rd edition of the International Conference on Composite Materials (ICCM23) was held in Belfast from 30 July to 4 August 2023. Approximately 1200 delegates from 57 countries attended the world's largest conference on composite materials, where 900 presentations were delivered over five days. Plenary and keynote presentations were given by preeminent members of the composites community from both industry and academia, in addition to tours to local industrial sites: Spirit AeroSystems, Artemis Technologies and the Northern Ireland Advanced Composites and Engineering Centre (NIACE). ICCM23 was an excellent forum for the Hub to engage and network with the global composite's community in both the technical sessions and the social activity. In total there were 36 presentations from Hub academics and researchers presenting the latest findings from Hub research, as well as the chairing of several sessions, in addition to the organisation of special sessions and workshops. Conference sessions ranged from computational methods, fatigue, fracture and damage, liquid moulding, process modelling, and design and manufacture. There was a noticeable focus on circularity and sustainability with sessions on bio-composites, the circularity of composites, life cycle assessment and recycling.

International Composites Summit and Hub Open Day 2023, Marshall Arena, Milton Keynes – 6 September 2023

The Hub Open Day took place on 6 September 2023 at the Marshall Arena in Milton Keynes, held in parallel with the International Composites Summit (ICS). We were pleased to have Hub academics, researchers and students presenting on their projects, as well as a poster competition and Quick-Fire session. We were grateful for presentations from the National Composites Centre (NCC) and keynote speakers, Professor Ian Lane from Vertical Aerospace Group and Dr. Emer McAleavy from Artemis Technologies. Over 100 delegates registered for the Open Day and over 200 guests from academia and industry attended the delegate dinner following the event.

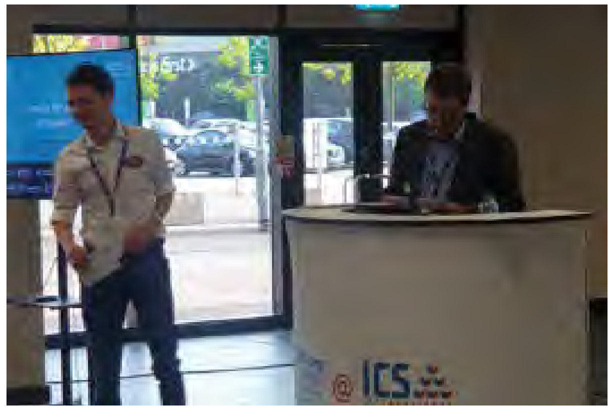
Keynote presentation from Dr. Emer McAleavy, Artemis Technologies.

Delegates enjoying the poster presentation session.

Holding the Open Day alongside the ICS presented an excellent opportunity for industry to hear about Hub research and gave our delegates the chance to strengthen their links with many of the industrial exhibitors on site. Congratulations to the following students and researchers on their achievements:

- Poster Competition 1st Place prize: George Street, University of Nottingham, "The Influence of Laminate Thickness on CFRTP Intra-Ply Shear Behaviour".
- Runner up 1: Guy Lawrence, University of Nottingham, "Measurement of Mesoscale Inter-ply Contact Area using µ-CT and Machine Learning".
- Runner up 2: Ángela Lendinez Torres, University of Nottingham, "How does breather distribution affect drapability during DDF?"
- Quick-Fire Presentation Competition 1st Place prize: Jack Holyoak, SHD/University of Nottingham, "High Rate Production of Automotive Components using Sustainable Composite Prepregs".
- Runner up 1: Laura Pickard, University of Bristol, "NextCOMP: Human Robot Collaborative Manufacture of Hierarchical Composites".
- Runner up 2: George Street, University of Nottingham, "The Influence of Laminate Thickness on CFRTP Intra-Ply Shear Behaviour".

George Street, University of Nottingham, receiving 1st placed poster presentation prize from Prof. Nick Warrior, Director of the Hub, University of Nottingham.



Jack Holyoak, SHD/ University of Nottingham, receiving 1st placed Quick-Fire presentation prize from Prof. Nick Warrior, Director of the Hub, University of Nottingham.

Advanced Engineering Show - National Exhibition Centre, Birmingham, UK 1–2 November 2023

The Advanced Engineering Show (AES) is the UK's largest annual gathering of engineering and manufacturing professionals, attracting more than 9,000 visitors. The Hub joined more than 400 exhibitors at the event, to showcase its activities and capabilities to the visitors and contribute to the Composites Forum conference programme. The CIMComp session was organised on the second day, to introduce the Hub, and provide the findings from four of its research projects. The Forum was well attended and made a good contribution to the innovation theme of the programme. AES 23 was an effective forum for the EPSRC Future Composites Manufacturing Research Hub to engage and network with the UK composites community, both with those with an existing relationship and new contacts. There have already been several follow-up conversations to discuss future engagement with the Hub.

The CIMComp stand at the AES attracting discussions from members of the composite's community.

Dr Andreas Endruweit presenting at the Composites Engineering Forum at the AES, on his research project 'Active RTM: Resin injection into reinforcement with uncertain heterogeneous properties: NDE and control'.

School Open Day - Advanced Manufacturing Building (AMB), University of Nottingham – 19 June 2023

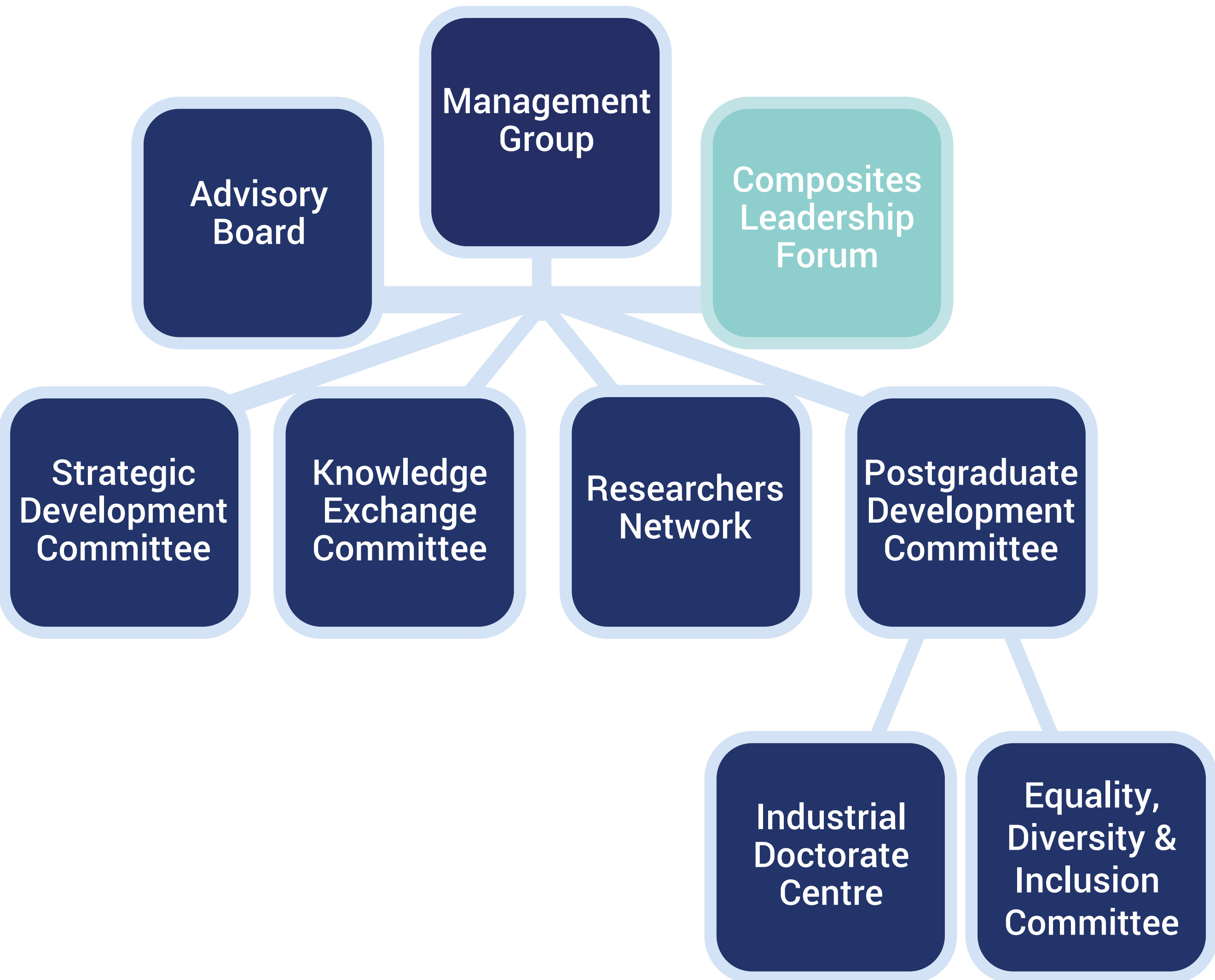
The annual School Open Day took place on 19 June at the AMB, University of Nottingham. Students from three local schools were introduced to the world-class manufacturing equipment in the AMB laboratories. Academics, PhD students and researchers were on hand to discuss their research, answer questions and provide demonstrations of the equipment. These events are important in promoting STEM learning and careers, and feedback received shows the students were really inspired by what they heard and saw so we hope to have contributed to shaping the next generation of engineers.

6 Hub Governance

The Management Group is supported by the Advisory Board and three committees: the Knowledge Exchange Committee, the Strategic Development Committee and the Postgraduate Development Committee.

The Management Group (MG) is chaired by Professor Nick Warrior, the Hub Director, with overall responsibility for developing and delivering the Hub's strategy. He is supported by two Deputy Directors, Professor Ole Thomsen and Dr Thomas Turner, and the Chairs of the KEC, SDC and PDC committees.

The Advisory Board (AB) is chaired by Professor Mike Hinton and takes a high level, strategic view of the needs of all the Hub stakeholders, offering guidance on the delivery and impact of research, ensuring the needs of the UK composites community are addressed. The AB plays a key role in advising the MG on technical progress and relevance to industry needs. The AB membership is a mix of independent academic and industrial members from the UK and abroad. Members represent a broad section of the UK supply chain, including end users from automotive and aerospace, material suppliers and HVM Catapult Centres.



From top left to right: Prof Janice Dulieu- Barton, Director of the IDC; Prof Mike Hinton, Chair of the AB; Dr Mike Johnson, Chair of the PDC; Dr Oriol Gavalda Diaz, Chair of the RN; Prof Ole Thomsen, Chair of the KEC; Dr Thomas Turner, Chair of the SDC; Prof Nick Warrior, Hub Director and Chair of the MG; Ms Ángela Lendínez Torres, Chair of the RN from 2024.

The **Strategic Development Committee (SDC)**, chaired by Dr Tom Turner, engages with funders, industry and government bodies to develop knowledge and strategies to evolve the Hub's priority areas, using the two Hub Business Development Managers to secure additional R&D funding, map capability and influence research priorities.

The **Knowledge Exchange Committee (KEC)**, chaired by Professor Ole Thomsen, is the formal link between the Hub and the HVM Catapult stakeholders and contains representatives from four Centres. The KEC is responsible for identifying and strengthening collaboration opportunities between Hub Spokes, administering funding for synergy promotion and technology pull-through (NCC TPT fund), and managing IP emerging from Hub projects.

The **Postgraduate Development Committee (PDC)**, chaired by Dr Mike Johnson, oversees the training and progression of research students, at doctoral level via the IDC and at postdoctoral level via the **Researcher Network (RN)**, chaired by Dr Oriol Gavalda Diaz. The RN is led by postdoctoral researchers to promote collaboration and enhance the cohort experience, engaging in outreach activities as STEM ambassadors. The PDC also manages an international student exchange scheme through the **International Researcher Network**, establishing partnerships in research programmes across 23 leading institutions in 12 countries.

The Hub is represented within the national **Composites Leadership Forum (CLF)**. The Hub Director sits on the main board and members of the MG and AB are active members of the CLF sub-committees supporting Working Groups in Technology, Sustainability, Automotive, Aerospace, Workforce Development and Regulations. This strong interaction enables a continued alignment of the Hub activities with the UK Composites Strategy, ensuring that the Hub research priorities address evolving long-term sector needs. The CLF has facilitated dissemination of the Hub's CiRCL road mapping activity to an industrial audience and resulted in the Hub's involvement in an Innovate UK International Mission to the USA to develop collaborative research programmes. Prof Pickering's involvement in the CLF Sustainability Working Group also led the Hub's contribution to the UK Vision and Roadmap for Sustainable Composites.

7 The Hub Team

Management Group

Professor Nick Warrior
Hub Director
University of Nottingham

Professor Ole Thomsen
Deputy Hub Director
University of Bristol

Dr Thomas Turner
Deputy Hub Director
University of Nottingham

Dr Lee Harper
Hub Manager
University of Nottingham

Mrs Alex Hammond
Hub Deputy Manager
University of Nottingham

Dr Mike Johnson
Chair of the Postgraduate Development Committee
University of Nottingham

Mr Andrew Mills
Deputy Chair of the Postgraduate Development Committee
Cranfield University

Dr Oriol Gavalda Diaz/ Ms Ángela Lendínez Torres
Chair of the Researcher Network
University of Nottingham

Professor Janice Dulieu-Barton
Director of Industrial Doctorate Training Centre
University of Bristol

Dr Dipa Roy
Hub Spoke Representative
University of Edinburgh

Dr Connie Qian
EDI Champion
University of Warwick

Advisory Board

Dr Rob Backhouse
Industrial Representative
Rolls-Royce

Mr Craig Carr
Industrial Representative
GKN Aerospace

Dr Enrique Garcia
Industrial Representative
National Composites Centre

Mr Stefanos Giannis
Industrial Representative
National Physical Laboratory

Dr Warren Hepples
Industrial Representative
Luxfer

Professor Mike Hinton
Advisory Board Chair
CTO, HMV Catapult

Mr Tom James
Industrial Representative
Hexcel Reinforcements

Dame Professor Jane Jiang
Scientific Expert
University of Huddersfield

Professor Ian Kinloch
Scientific Expert
University of Manchester

Professor Véronique Michaud
Scientific Expert
EPFL

Mr Emmanuel Owobu
EPSRC Representative
EPSRC

Dr Amir Rezai
Industrial Representative
BAE Systems

Mr Andy Smith
Industrial Representative
Gordon Murray Design

Mr Tim Wybrow
Industrial Representative
Composilite Ltd

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8 Publications and Conferences

Publications

Publications support the delivery of the Hub programme and vision, in both high impact factor journals and at international conferences and workshops. Hub investigators have continued to publish research from previous projects initiated by the EPSRC Centre (EP/I033513/1), bringing the total journal paper output for CIMComp to 117 since January 2017.

2024

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192. Lawrence, G.D. 'Preforming of Thick Non-Crimp Fabric Laminates using Double Diaphragm Forming'.

191. Lu, S. 'Application of Joule Heating in Automated Dry Fibre Placement (ADFP)'.

190. Matveev, M.Y., Endruweit, A., Iglesias, M.A., Tretyakov, M.V. 'Detection of race-tracking and other defects in resin transfer moulding'.

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186. Pickard, L. 'Overbraiding of Pultruded Rods for Hierarchical Composites'.

185. Palubiski, D.R. 'Multi-Matrix Continuously-Reinforced Composites for Waste Reduction and Repair Applications'.

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183. Qian, C. '3D Fibre Architecture Characterisation for Discontinuous Carbon Fibre Composite Structures using Computed Tomography Technique'.

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174. Wu, L. 'The Fatigue Damage Evaluation of 3D Woven Hybrid Glass/Carbon Fibre Composites'.

173. Yuan, H. 'Process Characterisation for Compression Moulding of Hybrid-Architecture Composites'.

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171. Zhang, B. 'Pure Shear and Compression-Shear Characterisation of Polymer Matrix for Carbon Fibre Composites'.

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166. Galvez-Hernandez, P. 'In-situ CT of out-of-autoclave composites manufacturing processes'.

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164. Levy, A. 'Development of a lab scale in-situ characterisation bench for deconsolidation of high temperature thermoplastic composites'.

163. Lu S. 'A Model Based Feed-Forward Force Control Strategy for ADFP on Complex Tools'.

162. Luong, M.H. 'Deep learning-based predictions of process parameters for thick composites laminates manufacturing'.

161. Mills A. 'Wet Compression Moulding Process Development for High Rate, Complex Shape Automotive Structures'.

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158. Perrin, H. 'Co-curing process optimisation for hybrid thermoset/ thermoplastic composite joining'.

157. Pickard L.R. 'Manufacturing of Pultruded Rod Based Hierarchical Composite Structural Members'.

156. Potluri P. 'Automatic Feature and Defect Recognition in Carbon Fibre Preforms using Image Processing with Deep Learning'.

155. Radhakrishnan A. 'Semi-Curing of Thermoset Composite Elements for Assembly of Large Composite Structures'.

154. Rao, N.S.N. 'Digital process chain for thermoplastic structural components with local unidirectional reinforcements for aerospace applications'.

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146. Bullock R.C., Laux, T., Dulieu-Barton J.M., Thomsen O.T. 'Ply Orientation Effects in Multidirectional Carbon/Epoxy Open-Hole Specimens Subjected to Shear Loading'.

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135. Jiménez-Fortunato, I., Valverde, M. A., Allegri, G., Hallett, S.R. 'Novel Z-pin Technologies for Through Thickness Reinforcements'.

134. Krajangsawasdi, N., Woods, B.K.S., Hamerton, I., Ivanov, D.S., Longana, M.L. 'Highly Aligned Discontinuous Fibre Composite Filaments for Fused Deposition Modelling: Comparison between printed and lay-up open-hole sample'.

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124. Park, J., Koncherry, V., Lloyd, D., Potluri, P. 'Impact damage tolerance of thermoset composite with hybrid yarns: advanced manufacturing process'.

123. Pickard, L.R., Allegri, G., Wisnom, M.R. 'Manufacturing Advances for Pultruded Rod Based Structural Members and Thick Ply Systems'.

122. Qian, C., Deshpande, A., Simset, P.D., Clarke, J., Sicard, F., Kendall, K. 'Manufacturing Process Simulation for Compression moulding of Sheet Moulding Compound – An Automotive Case Study'.

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114. Tabatabaeian., A, Fotouhi, S., Fotouhi, M., Harrison, P. 'On the optimal design of smart composite sensors for impact damage detection'.

113. Thompson, M., Brown, L., Rengaraj, K., Warrior, N. 'TexGen–Geometrical Modelling of Biaxial Braided Fabrics'.

112. Thomsen, O., Dulieu-Barton, J., Hallett, S., Butler, R. 'Validation of Composite Aerostructures through Integrated Multi-Scale Modelling and High-Fidelity Substructure Testing Facilitated by Design of Experiments and Bayesian learning'.

111. Thorn, T.D.S., Liu, Y., Bilotti, E., Peijs, T., Zhang, H. 'Easy-repairing of high performance fibre reinforced composites with multiple healing cycles and integrated damage sensing'.

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109. Wang, Y., Yao, X., Liu, Y., Bilotti, E., Zhang, H. 'Out-of-Oven manufacturing for natural fibre composites with integrated deformation and degradation sensing'.

108. Whitehouse, A., Medeau, V., Mencattelli, L., Greenhalgh, E., Blackman, B., Pinho, S. 'A novel profiling concept leading to a significant increase in the mechanical performance of metal to composite joints'.

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processing parameters on the consolidation of out-of-autoclave prepreg'.

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103. Yavuz, B.O., Belnoue, J. P.H., Longana, M.L., Hamerton, I. 'Tensile characterisation of HiPerDiF PL A/Carbon fibre tape under processing conditions'.

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Poster Submission

Almousa, H., De Luca, H., Anthony, D.B, Greenhalgh, E., Bismarck, A., Shaffer, M.S.P. 'Robust Continuous Production of Carbon Nanotube-grafted Structural Fibres: A Route to Hierarchical Fibre Reinforced Composites'.

Anthony, D., Garulli, T., Pickard, L., Quino, G., Garguili, J., Pimenta, S., Allegri, G., Pinho, S., Hamerton, I., Greenhalgh, E., Eichhorn, S., Robinson, P., Wisnom, M., Trask, R., Shaffer, M. 'Hierarchical solutions to compressive problems in fibre-reinforced composite'.

He, S., Ward, C., Hamerton, I. 'kinetic studies and its influence on phase transition behaviour of multicomponent amine-cured epoxy blend'.

Jimenez-Martin, C. 'Time Resolved In-situ CT Scanning of Non-Crimp Fabric Forming'.
Shaw, C., Anthony, D., Garguili, J., Hamerton, I., Shaffer, M. 'Designing Bicontinuous Silica-Epoxy Nanocomposites'.

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101. Aza, C., Butler R., Loukaides E G., Rhead A.T., 'Fibre length effect on the design of formable laminates for complex geometries'.

100. Codolini A., Sutcliffe M., 'Influence of tool orientation on the drapeability of unidirectional non-crimp Fabrics'.

99. Devine, M., Bajpai, A., Obande, W., Brádaigh, C.O., Ray, D., 'Recyclable Acrylic-Glass Composites For Marine And Tidal Energy Applications'.

98. Evans, A.D., Turner, T.A., 'Developing a Testbed for Automated Fibre Placement Technologies'.

97. Kim, B.C., Sun, X., Zhang, B., Gordon, T., Brigido, D., Macleod, C., Longana, M., Belnoue, J.P.H., Hamerton, I., Hallett S.R., 'Fibre-Steered Forming Technology for High-Volume Production of Complex Composite Components'.

96. Krajangsawasdi, N., Woods, B.K.S., Hamerton, I., Ivanov, D.S., Longana, M.L., 'Highly Aligned Discontinuous Fibre Composite Filaments For Fused Deposition Modelling: Investigating The Ease Of Printing'.

95. Lawrence G.D., Chen S., Warrior N.A., Harper L.T., 'Characterisation Of Inter-Ply Friction Of A Dry Bi-Axial Non-Crimp Fabric During Automated Preforming'.

94. Macleod, C.P., Zhang, B., Cooper, J., Kim, B.C., 'Fibre-Waviness Characteristics Of Fibre-Steered Laminates Produced By Continuous Tow Shearing Process'.

93. Parsons, A.J., 'Enhanced Characterisation and Simulation Methods for Thermoplastic Overmoulding – ENACT'.

92. Pickard, L.R., 'Manufacturing of novel hierarchical hybridised composites'.

91. Rautmann, M., Gabriel, E.R., Kim, B.C., 'Advanced Continuous Tow Shearing'.

90. Scarth, C., Chen, Y., Rhead, A.T., Butler,R., 'Stacking Sequence Selection For Defect Reduction In Forming Of Long Composite Spars'.

89. Sun, X., Jones, J., Mahadik, Y., Nguyen, D., Tretiak, I., Valverde, M.A., Kratz, J., 'On-the-fly Process Control in Automated Fibre Placement'.

88. Thompson., Grimes, B., Rengaraj, K., Warrior, N.A., 'Effect Of Winding Twist On Multilayer Braided Composites'.

87. Tretiak, I., Koptelov, A., Belnoue, J. P.H., Ivanov, D.,Hallett, S.R., 'Cyclic Compressive loading of Carbon/Epoxy Prepregs: Novel Challenges and Model Requirements'.

86. Wang, Y., Mahapatra, S., Belnoue, J.P.H., Ivanov, D., Hallett, S.R.,' A Simulation Platform For The Influence Of Process Conditions On Steering-Induced Defects In Automated Fibre Placement (AFP)'.

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84. Qian C.C., Yuan, H., Jesri, M., Khan, M.A., Kendall, K.N., 'Flow Behaviour of Carbon Fibre Sheet Moulding Compound'.

83. Sowrov K., Fernando A., Koncherry V., Withers P., Potluri P., 'Damage Evaluation in 3D Woven Composites with Warp-way and Weft-way Binders'.

82. Dhiman S., Potluri P., Katnam K.P., 'Thermally induced residual stresses in orthogonal 3D woven composites: The role of binder architecture and cooling rate'.

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80. Chen S, Yu F., Joesbury A., Harper L.T., Warrior N.A., 'Local intra-ply stitch removal for improved formability of biaxial non-crimp fabrics'.

79. Codolini A., Viisainen J.V., Sutcliffe M.P.M., 'Numerical Assessment of Variability in Double Diaphragm Forming of Non-Crimp Fabric Preforms'.

78. Collinson M., 'Development of integrated electrical self-sensing in aerospace CFRP components'.

77. Endruweit A., 'Time-temperature dependant adhesive tack and contact area development between prepreg carbon fibre tape and rigid substrate'.

76. Fisher A., 'The significance of spatial temperature variations in large volume oven curing'.

75. Grimes B., 'A computational and experimental analysis of the influence of guide ring size on fibre architecture in the braiding process'.

74. Matveev M., 'Defect detection and process control in resin transfer moulding'.

73. Moses W., 'Novel through Thickness Reinforcement Method for Carbon Composite Structures with No Reduction in In-Plane Properties'.

72. Munshi L.C., Codolini A., Viisainen J.V., Ward C., 'Experimental Investigation into the Effect of Localised Tufting on the Behaviour of Biaxial Carbon NCF Fabrics'.

71. Qian C., 'Experimental and Numerical Characterisation of Fibre Orientation Distributions in Compression Moulded Carbon Fibre SMC'.

70. Robert C., 'Powder Epoxy Towpregging Tapeline for Automated Fibre Placement'.

69. Robert C., Celik M., Noble T., McCarthy E.D., Ó Brádaigh C.M., 'Toward Streamlining Towpregging Tapeline and Automated Fibre Placement for Quicker and Cheaper Composite Manufacturing'.

68. Soltan J., 'Modular Infusion: Novel Approaches to Segregation and Control of Flow Fronts within Liquid Resin Moulding'.

67. Sowrov K., 'Analysing the Influence of Binder Architectures on Compressibility and Permeability of 3D Woven Preforms with Warp Way and Weft Way Binders'.

66. Viisainen J., Codolini A., Sutcliffe M.P.F.,'A deep learning surrogate model for rapid prediction of geometry-induced wrinkles in fabric preforming'.

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50. Evans A., Turner T., Endruweit A. 'Development of Automated Dry Fibre Placement for High Rate Deposition'.

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43. Jimenez Fortunato I., Bull D., Dulieu-Barton J., Thomsen O. 'Damage characterisation of composite components using full-field imaging techniques'.

42. Gent I., Mann N.L., Ward C.' Localised inkjet printing of resin additives for selective property enhancement'.

41. Murray J, Gleich K, McCarthy E.D, O'Bradaigh O. 'Properties if Polyamide-6 Composites using Thermoplastic Resin Transfer Moulding'.

40. Pappa E. 'Optimization of Carbon Fibre re-inforced polymer (CFRP) composites with a thin embedded polyurethane film'.
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38. O'Bradaigh C, M, Mamalis D, Flanagan T, Doyle A., 'Tidal turbine blade composite using basalt fibre reinforced powder epoxy'.

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33. Elkington M., Gandhi N., Libby M., Kirby A., Ward C.,' Collaborative Human-Robotic Layup'.

32. Harrison P.,' Multi-step thermoforming of multi-cavity multi-axial advanced thermoplastic composite parts'.

31. Mamalis D., Obande W., Koutsos V., Ó Brádaigh C., Roy D., 'Novel infusible thermoplastic matrix in fibre metal laminates'.

30. Partridge I., Greenhalgh E., Ivanov D., Ward C., Radhakrishnan A., O'Keeffe C., Gent I., Bilge K., Valkova M., Shaffer M., 'Manufacturing for structural applications of multifunctional composites'.

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23. Matveev M., Koncherry V., Roy S.S., Potluri P., Long A., 'Novel textile preforming for optimised fibre architectures', TexComp-13, Milan, Italy, 17-19 September 2018.

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20. Roy D., 'Out of Autoclave Processing of Composites: Challenges and Opportunities', Innovate UK, 15th March 2018, Titanic Belfast, Belfast, United Kingdom.

19. Bull D.J., Dulieu-Barton J.M., Thomsen O.T.,' High-fidelity testing and integrated modelling of composite substructures and components', 18th European Conference on Composite Materials, Athens, Greece, 2018.

18. Dulieu-Barton, J.M., Bull, D.J., Thomsen, O.T.,' Integrating full-field experimental imaging techniques to predict the performance of compression moulded composites', 18th European Conference on Composite Materials, Athens, Greece, 2018.

17. Mamalis D., Obande W., Koutsos V., Ó Brádaigh C.M., Roy D., 'Effects of Surface Treatments on the Bonding and Interlaminar Fracture Toughness of Aluminium/ Fiberglass Thermoplastic Laminates Produced by In-situ Polymerisation Route', European Conference on Composite Materials, Athens, Greece, 2018.

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15. Dulieu-Barton, J.M., Bull, D.J., Thomsen, O.T.,' Integrating full-field experimental imaging techniques to predict the performance of compression moulded composites', 18th European Conference on Composite Materials, Athens, Greece, 2018.

14. Dulieu-Barton J.M., 'Integrating full-field experimental imaging techniques for on-site inspections and stress based non-destructive evaluation', International Conference on Modern Practice in Stress and Vibration Analysis (MPSVA 2018), Cambridge, 2018. (Invited plenary presentation)

13. Jiménez-Fortunato, I., Bull, D.J., Dulieu-Barton, J.M., Thomsen, O.T., 'Towards combining imaging methods to evaluate defect and damage in composite sub-structures', International Conference on Modern Practice in Stress and Vibration Analysis (MPSVA 2018), Cambridge, 2018.

12. Scott, M., Dell'Anno, G., Clegg, H., 'Effect of Process Parameters on the Geometry of Composite Parts Reinforced Through-the-Thickness by Tufting', Proceedings of the 8th World Conference on 3D Fabrics and Their Applications, Manchester, UK, 28-29 March 2018.

11. Scott, M., Dell'Anno, G., Clegg, H., 'Creating intersections in composite structures using Tufting and 3D woven connectors', 7th International Symposium on Aircraft Materials (ACMA2018).

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10. Bull D.J., Dulieu-Barton J.M., Thomsen O.T., Butler R., Rhead A.T., Fletche, T.A., Potter K.D.,' Reshaping the testing pyramid: utilisation of data-rich NDT techniques as a means to develop a 'high fidelity' component and sub-structure testing methodology for composites'.

9. Koncherry V., Pate, D., Yusuf Z., Potluri P.,' Influence of 3d weaving parameters on preform compression and laminate mechanical properties'.

8. Roy S.S., Yang D., Potluri P.,' Influence of Bending on Wrinkle Formation and Potential Method of Mitigation'.

7. Waddington B., Caballero A.S., Roy S. S., Kennon W.R., Potluri P., 'Damage tolerance of carbon/epoxy quasi-interwoven composites subjected to low velocity impacts'.

6. Yan S., Long A.C., Zeng X., 'Design optimization of 3D woven T-joint reinforcements'.

5. Zympeloudis E., Potter K., Weaver P.M., Kim B.C.,' Advanced Automated Tape Laying with Fibre Steering Capability Using Continuous Tow Shearing Mechanism'.

Other Conferences

4. Radhakrishnan A., Hamerton I., Shaffer M., Ivanov D.,' Localised control of composite properties using Liquid Resin Printing', poster presentation at Bristol Composites Institute conference, Bristol, 15 November 2017.

3. Dulieu-Barton J.M., Thomsen O.T., 'Towards a new paradigm for high-fidelity testing and integrated multi-scale modelling of composite substructures and components', International Symposium, Novel Composite Materials and Processes for Offshore Renewable Energy, Cork, September 2017.

2. Di Francesco M., Veldenz L., Atwood S., Giddings P., Dell'Anno G., 'Feature-Based Design for Manufacturing Guidelines for Dry Fibre AFP', International Symposium on Automated Composites Manufacturing Montreal 2017.

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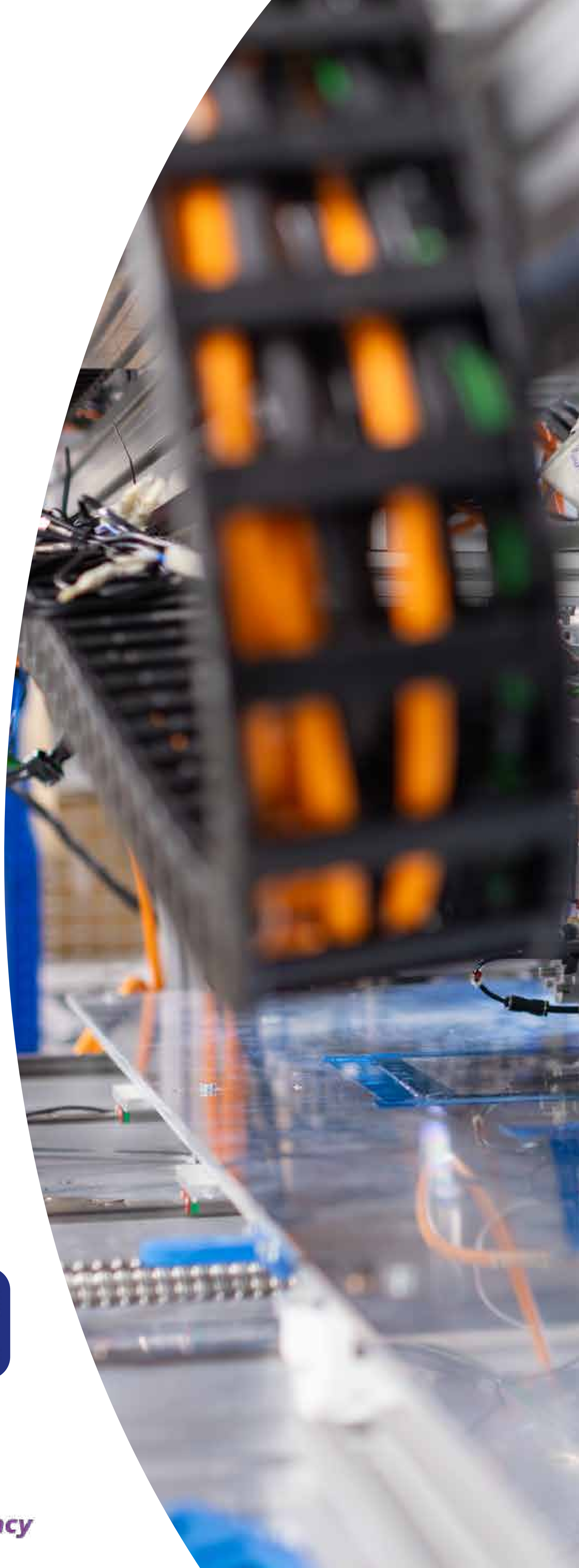

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