CIMComp
EPSRC
Future Composites
Manufacturing Research Hub

2022/2023
Annual Report

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

Engineering and Physical Sciences Research Council

Contents

Executive Summary

Nick Warrior, Hub Director

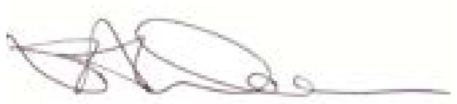
Welcome to the Future Composites Manufacturing Research Hub's sixth Annual Report. In this final year of the Programme, we continue to address our original objectives concerning the challenges facing the composites manufacturing industry, and in particular the new challenges around Sustainability and meeting the 2050 Net Zero targets. Hub research projects have delivered some excellent results and our academic members have been active in showcasing their work at national and international conferences. We endeavour to push proven research outcomes through to the High Value Manufacturing Catapult Centres for exploitation by industry.

The Hub currently has five active Core Projects, and our last round of Feasibility Studies finished in late 2022. Progress on these projects can be found further on in this report. In the summer of 2022, we launched our second and final Synergy Promotion call, and were delighted to receive so many high quality proposals. Funding was allocated to four projects addressing one or more of the Hub's priority research themes with emphasis on the need to reduce environmental impact and connect to the existing research within the Hub. I look forward to seeing the results of these projects at the end of 2023.

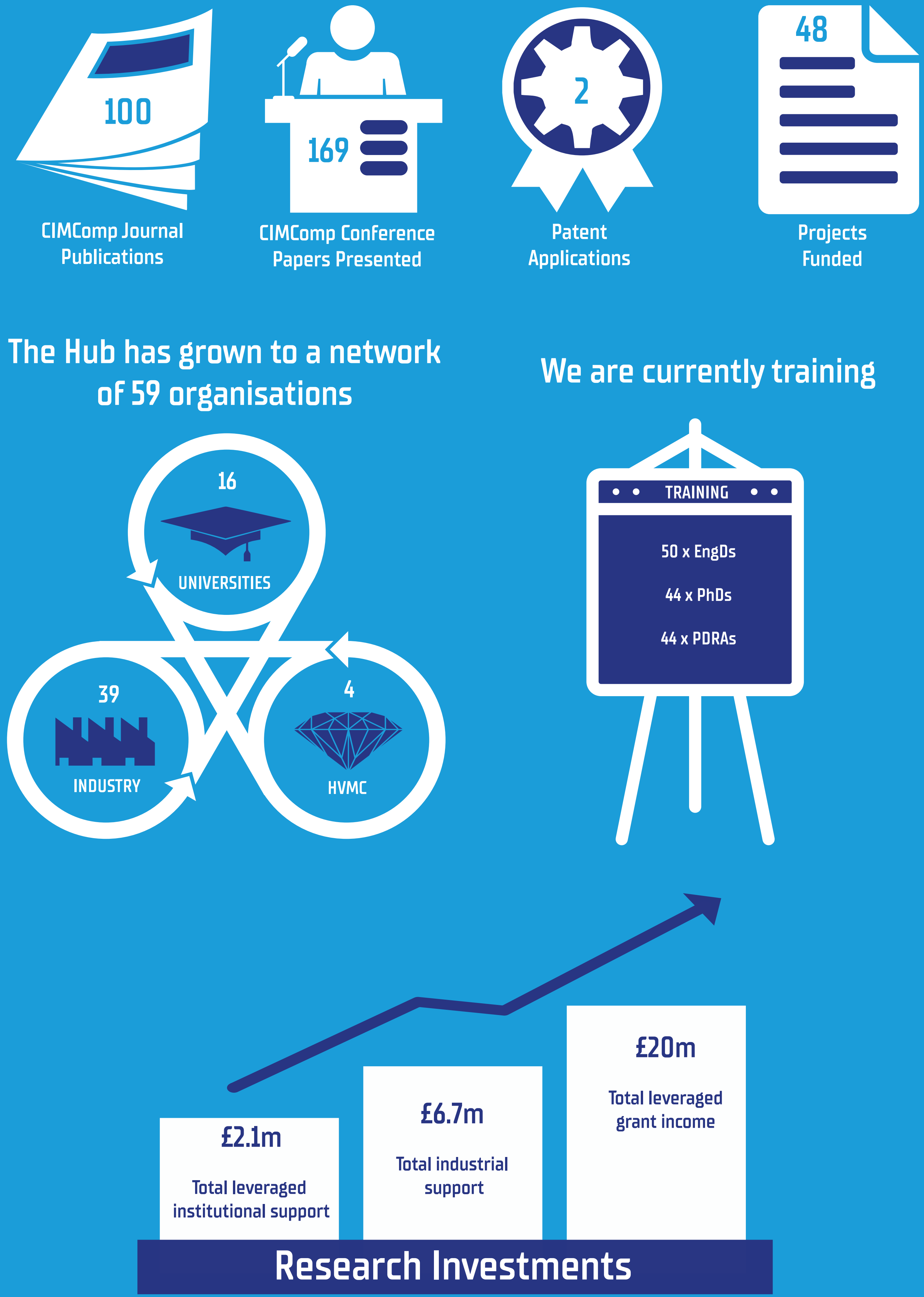
Since the lifting of COVID restrictions, we have made the most of engaging with the composites community by attending and organising a number of outreach activities. It was a pleasure to see so many known and new faces at the events, in particular the Hub Open Day which attracted a large diverse crowd and showcased the interesting research being done by the Hub's academics, researchers and students. These events are crucial to maintaining and expanding our network of composites experts, and highlighting the excellent research funded within the Hub. Furthermore, the events present the opportunity to strengthen our links with industry, and I am thankful for the time our industry partners provide to the Hub, not only in participating in our events but for their contributions to the Hub's projects.

This year we welcomed a new Chair to the Researchers Network, Dr Oriol Gavalda Diaz. Along with the Post Graduate Development Committee, the Researchers Network has been an effective delivery mechanism for developing skills and providing training to our students and researchers. We have developed a series of training schemes under the current Hub and will continue to address these needs over the course of the year.

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



Headline Achievements 2017 - 2023



1 Hub Vision and Objectives

The Hub vision is founded on two industry inspired Grand Challenges:
- Improving existing composites manufacturing processes
- Developing new technologies

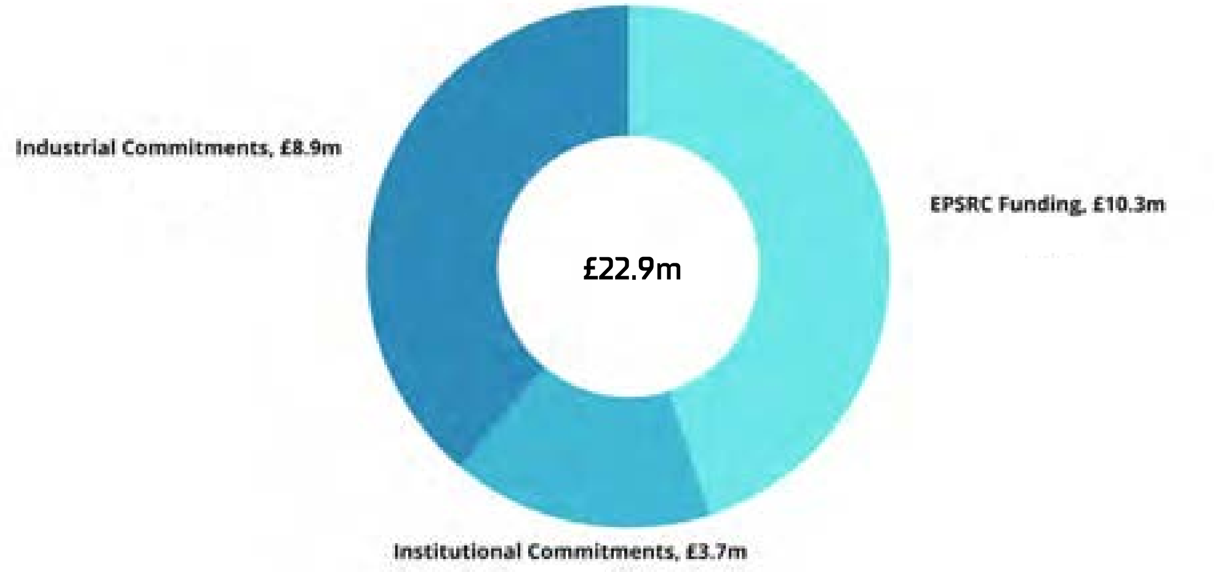
Since 2017, the Hub has built on the success of the EPSRC Centre for Innovative Manufacturing in Composites (CIMComp; EP/I033513/1), with a vision to develop a national centre of excellence in fundamental research for composites manufacturing – delivering research advances in cost reduction and production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

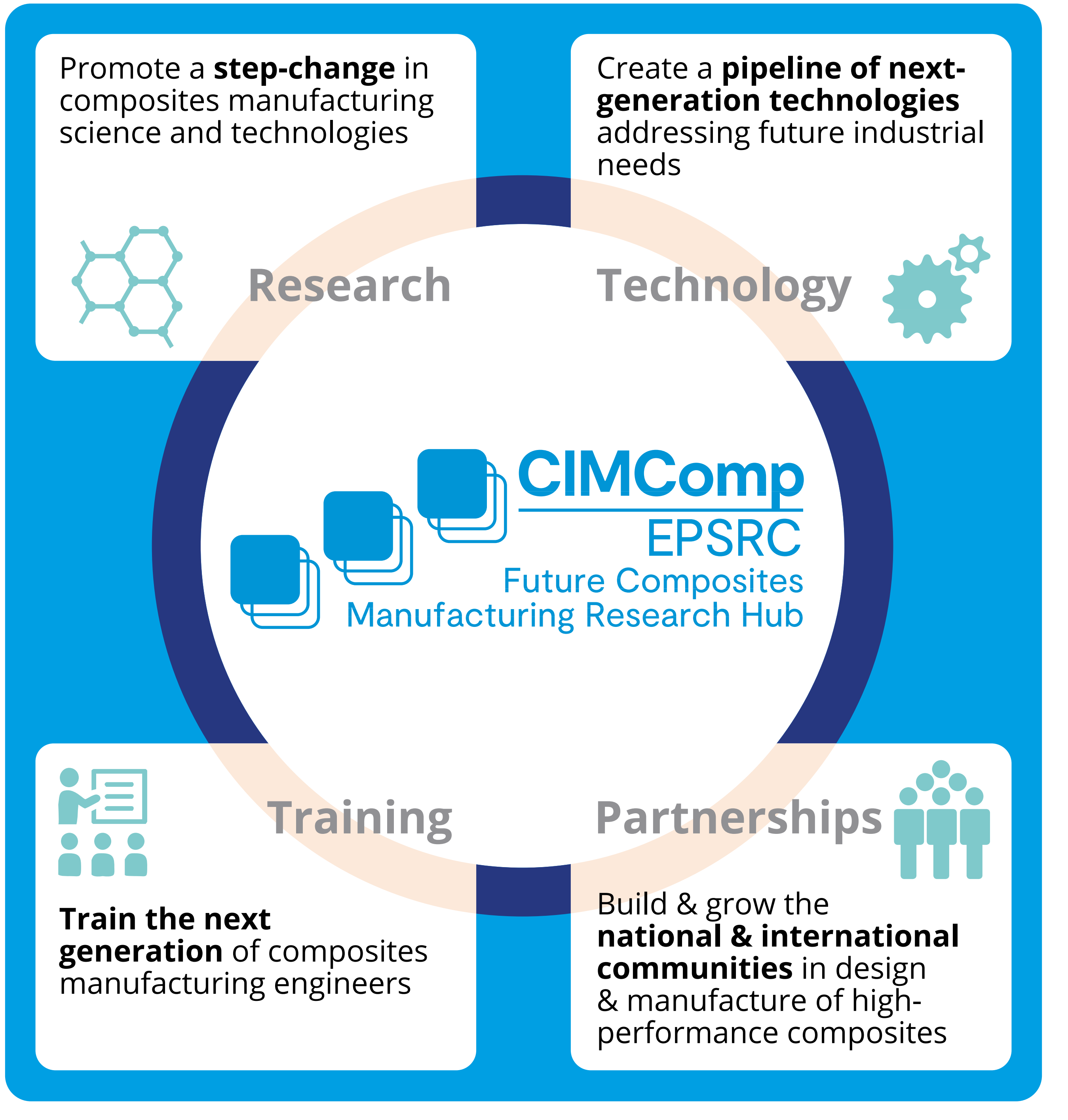
To achieve this vision, the Hub aims to deliver against core objectives in four key areas:
- Research excellence
- Technology transfer
- Network building
- Training

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 months secondment at one of the linked institutions, accessing new expertise and facilities and developing their personal networks. We have successfully funded five 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

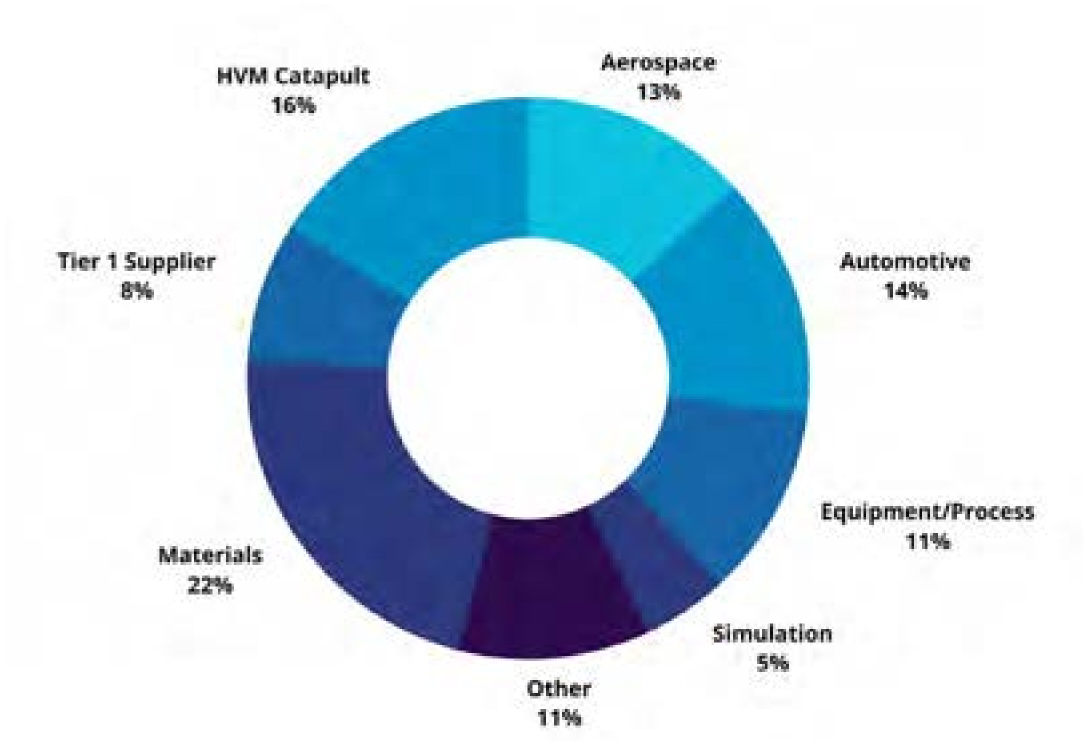
- 23 leading institutions across 11 countries
- Share information and developments in the field
- Facilitate visits and exchange of people
- Establish informal or formal partnerships in research programmes
- All have agreed to host visits from staff and students for 3 months

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.

Hub Partners by Sector



Industry Partners

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 Managers 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

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 £20m 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.

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 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.

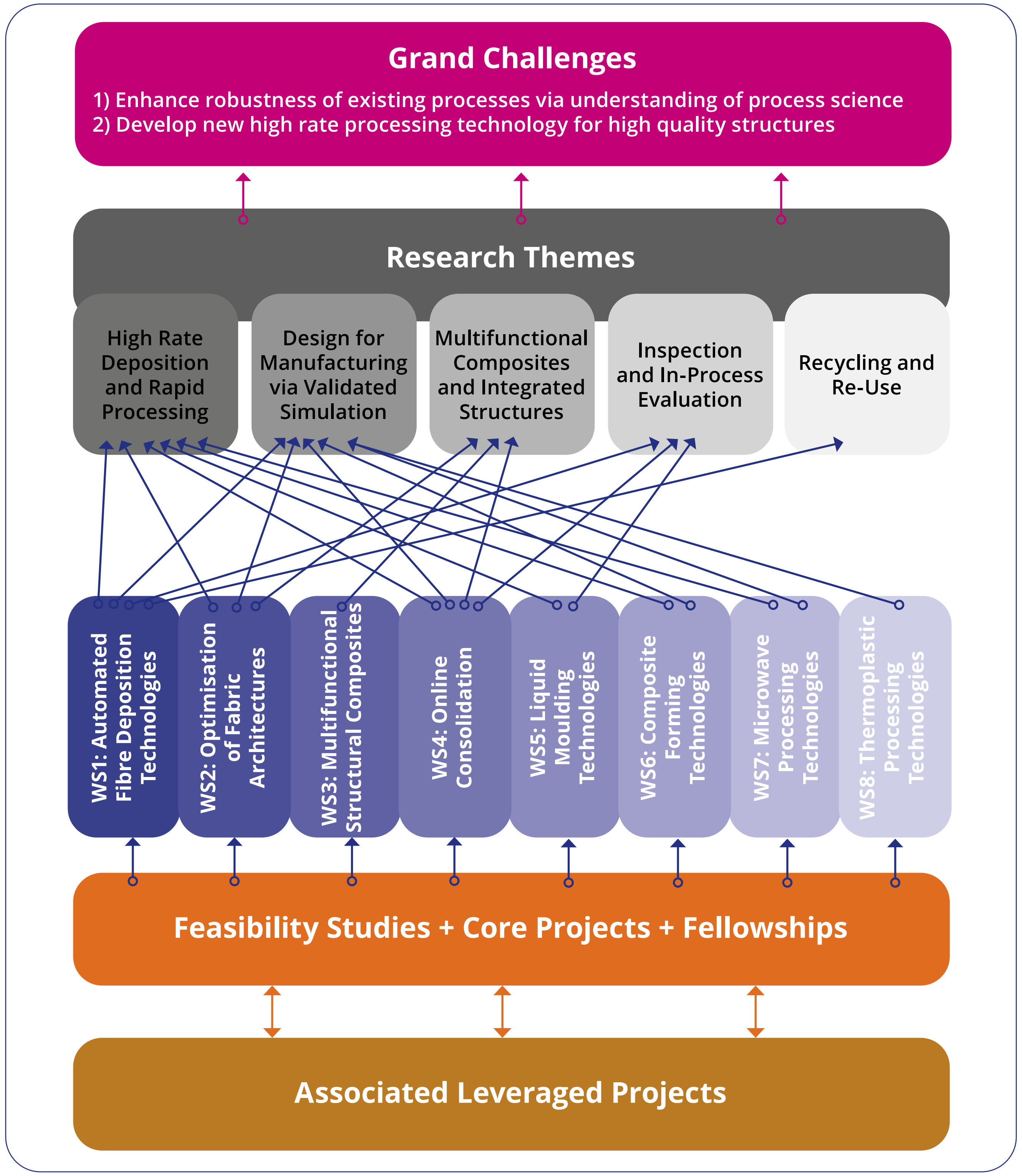
Our Feasibility Study programme offers up to £50k for novel, ambitious six month projects, which are encouraged, where appropriate, to be developed into proposals for Core Projects (36 month collaborations), of values between £375k and £700k. In 2019, after consultation with the Hub Knowledge Exchange Committee (KEC), we launched the Synergy Promotion Fund to run alongside our Core Projects and Feasibility Studies. This ensures our portfolio of projects is able to work towards the same goals of meeting the Hub core objectives and Grand Challenges.

The Synergy Promotion Fund provides funding to enable development of synergies between past and ongoing Hub research activity and new academic contributors and promotes collaborative activity for emerging and novel research. In February 2022 we launched a second Synergy Promotion call with a budget to the order of £100k per academic partner. After a review process consisting of international and UK independent reviewers, four new Synergy Projects were awarded and started in September 2022. We look forward to seeing the results of these projects at the end of 2023.

As the Hub enters the final phase of this programme and looks to the future of composites manufacturing, the Strategic Development Committee (SDC) will support the Management Group in identifying and promoting areas of emerging research, particularly in the areas of sustainability as well as seeking to transition existing research out to the catapults in collaboration with the Knowledge Exchange Committee (KEC), wider industry and the Advisory Board (AB).

The **Grand Challenges** are addressed by five **Research Themes**, with sustainability underpinning all of the Themes. This includes considering life cycle assessment, energy use and environmental impact measures across the research portfolio. The challenges in each Research Theme are met by relevant technologies from across the eight Work Streams.

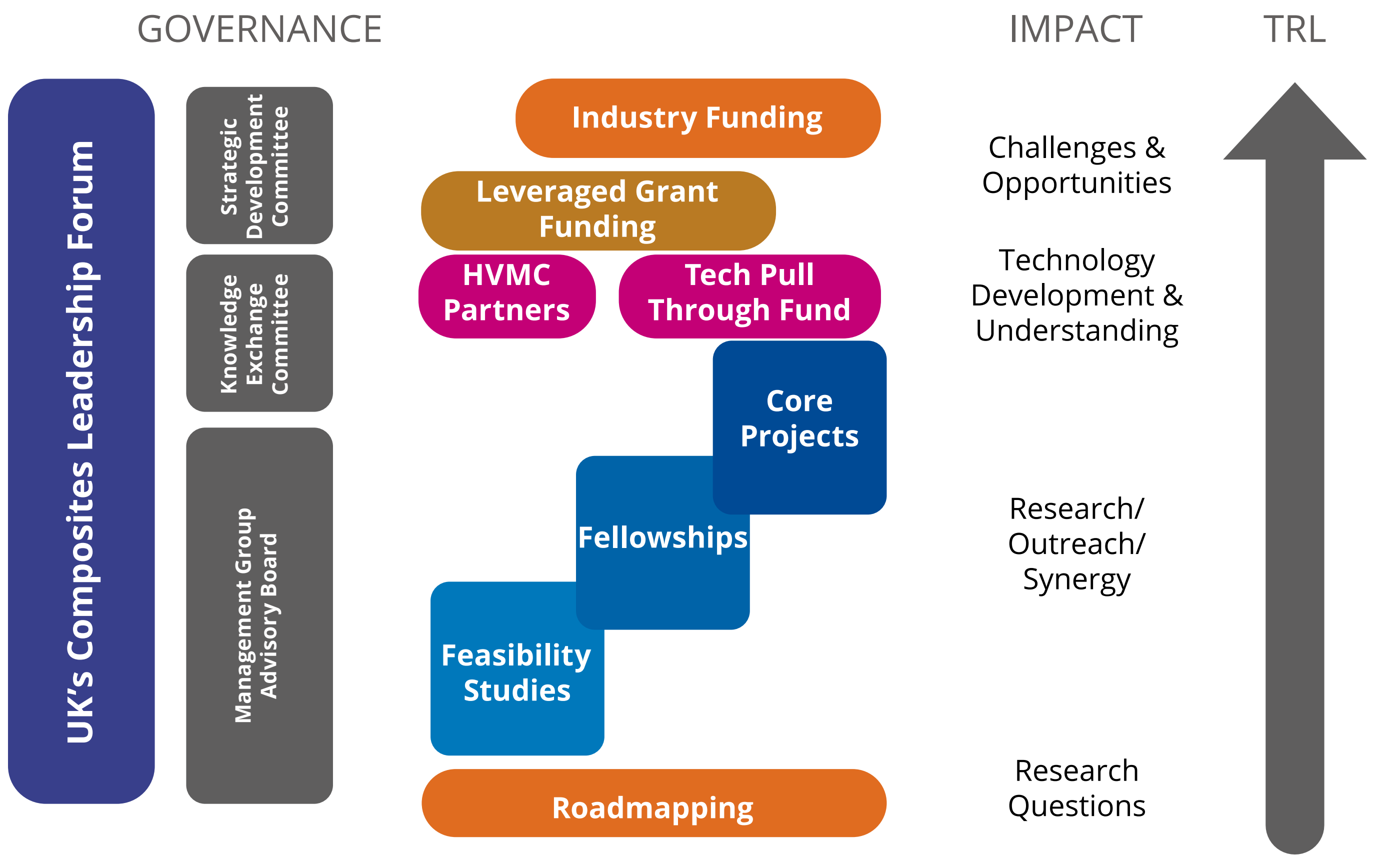
The relationship between individual researchers, their projects and the Work Stream can be viewed using the SharpCloud data visualisation platform.



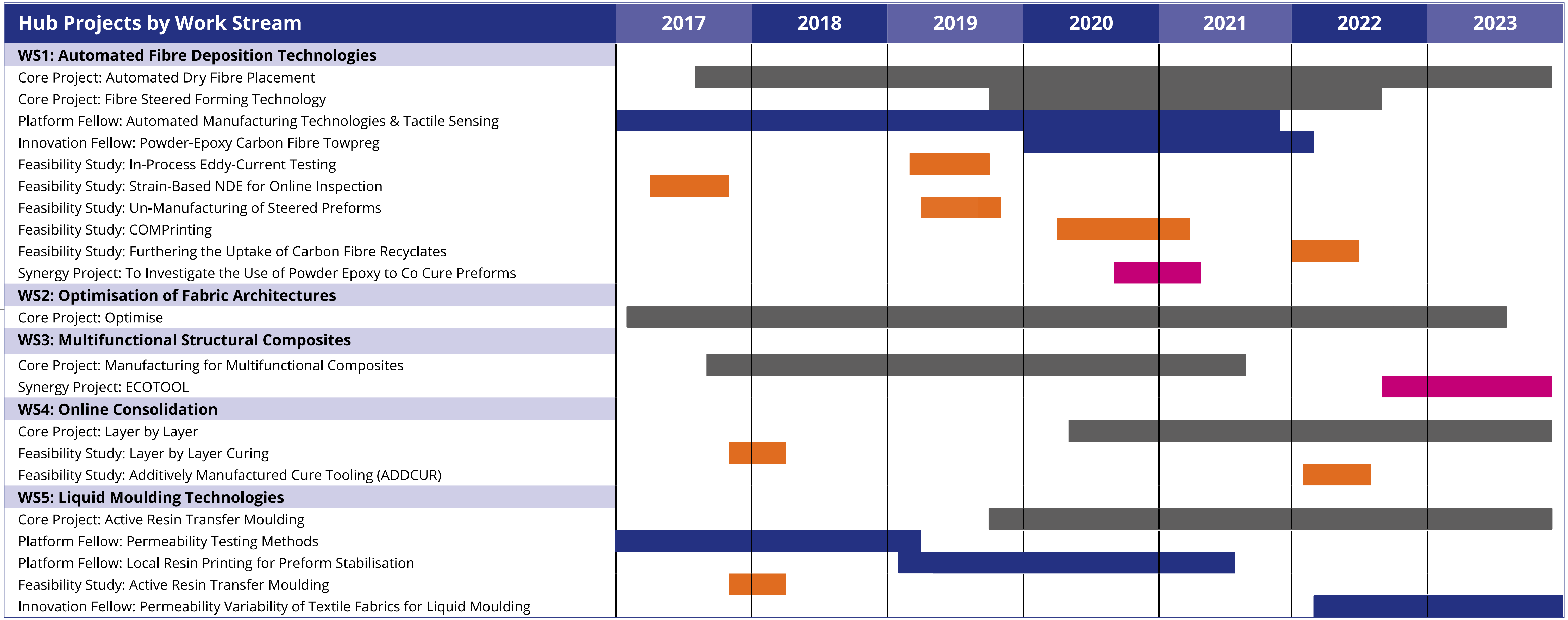
Pathways to Impact

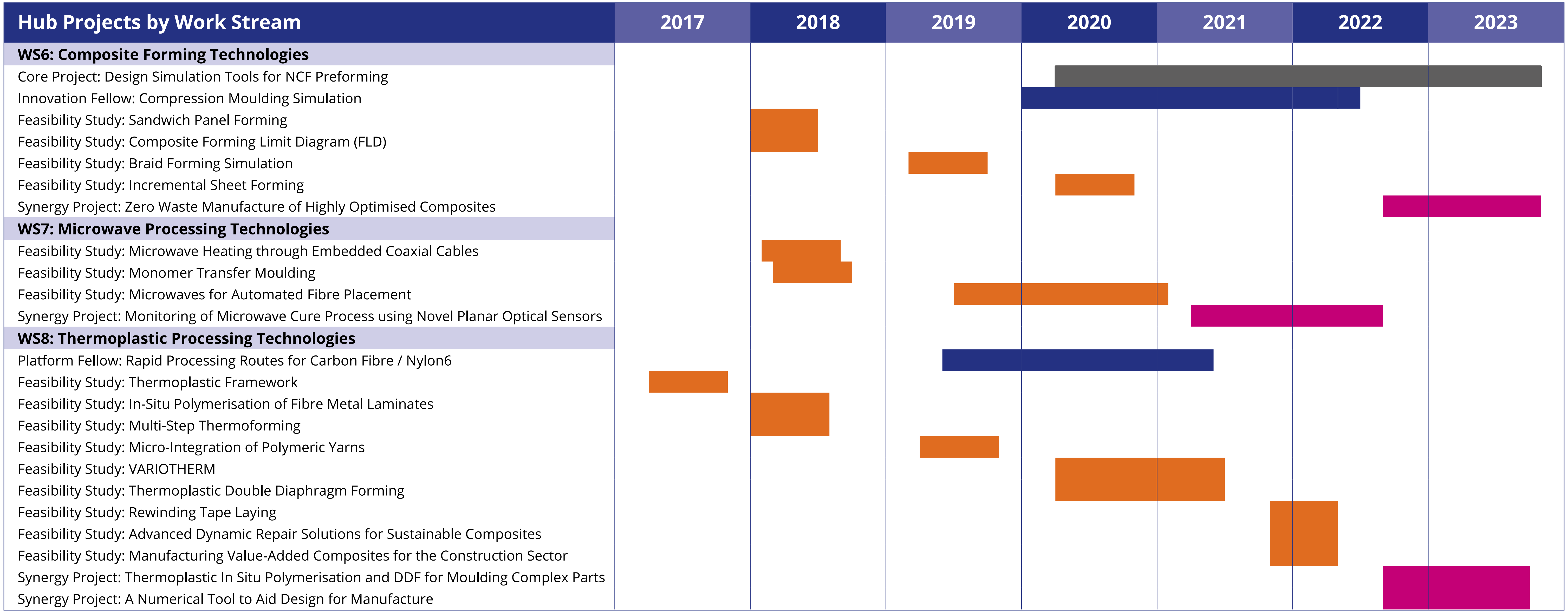
The Hub plays a key role in the composite manufacturing technology pipeline, pushing proven research outcomes through to the HVM Catapult Centres (National Composites Centre (NCC), Advanced Manufacturing Research Centre (AMRC), Warwick Manufacturing Group (WMG) and Manufacturing Technology Centre (MTC) 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.

Following on from Hub funded research at the University of Nottingham, a proposal entitled 'Global to Local Modelling for Forming Related Defect Detection in Aerospace Parts' received funding from the NCC's Technology Pull-Through Programme. The project seeks to further validate a sub-modelling approach developed by the Nottingham team using an established explicit Finite Element (FE) framework, to predict small critical wrinkling defects for large components, and will focus specifically on dry fabrics and double diaphragm forming (DDF) to create high-performance preforms suitable for liquid moulding.



Hub Projects by Work Stream




Hub Projects by Work Stream
2017
2018
2019
2020
2021
2022
2023
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
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

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; Mr Verner 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:** 31/10/2023

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.

Aims and Objectives

High-volume production brings unique and additional challenges in the manufacturing of high-performance composites structures. The Core Project aims to resolve design and manufacturing inefficiencies to create high-performance preforms suitable for liquid moulding. The decision to focus specifically on dry fabrics and double diaphragm forming have been guided by the recent 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. From the analysis of the fabric strains, 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 as shearing was restricted to a minimum by the stitching.

The draping characterisation test was also conducted for a uniaxial NCF (FCIM356) with carbon fibres tows stitched together with glass fibre threads (<10% of the fabric areal weight) 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 (i.e. hemispherical dome) did not exhibit macroscopic wrinkles. However, gapping defects were detected due to the large transverse strains measured on the fabric surface.

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%. IIn addition, pretensioning the diaphragms prior to forming resulted in a reduction of 30% of out-of-plane wrinkle severity, demonstrating its potential in achieving high quality NCF preforms.

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. The larger the relative stitch angle, the higher the amplitude of the oscillations in the force-displacement results used to derive the dynamic friction coefficient.

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 (representative of a double diaphragm forming process). Results from the test demonstrated that the inter-ply friction exhibited strong pressure dependency – as the fabric plies deform the frictional forces between them increased by up to 43%. Additionally, a fibre orientation dependency was observed where sliding at fabric interfaces with parallel fibres produced higher coefficients than those with perpendicular fibres. Ongoing work aims to further explore the relationship between applied normal load and inter-ply friction, and to understand the effect high levels of friction have on the formability of DDF parts.

Challenges: Material supply - now resolved.

<u>Component Design Tools</u>

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 large NCF preforms. Geometry-induced wrinkle patterns were extracted from accurate FE simulations, mapped onto 2D surfaces, and transformed into gray-scale 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 projected onto the undeformed fabric.

In addition, 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. The method will be combined with ply compatibility to enable design of formable laminates.

Challenges: identifying appropriate ranges of geometry to consider in case studies; developing tools and ideas which can be applied to a range of NCF materials.

<u>Process Improvements</u>

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. To minimise the amount of resin added to the forming process, compressive strains extracted from experimentally-validated FE simulations were used to identify the regions where local liquid resin should be apply. 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.

Challenges: developing improvements which could be applied by industry. The close involvement of our industrial partners will help with this.

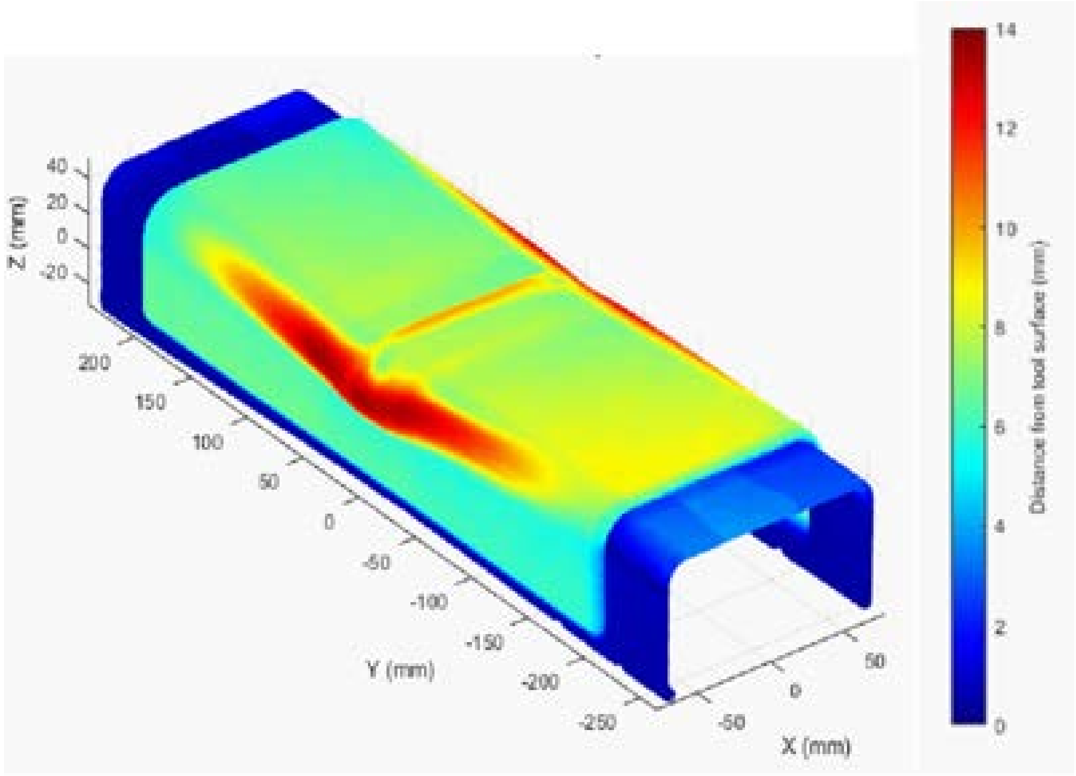


Figure 1. A concave section of a C-spar, produced from 16 plies of biaxial NCF using double diaphragm forming. Large longitudinal wrinkles are apparent along the corner radii.

Publications

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- Yu F., Chen S., Lawrence G.D., Warrior N.A., Harper L.T. A Global-to-Local Sub Modelling Approach to Investigate the Effect of Lubrication during Double Diaphragm Forming of Multi-ply Biaxial Non-Crimp Fabric Preforms. Composites Part B: Engineering, (2023), 110590.
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- Jagpal, R., Evangelou E., Butler R., Loukaides E.G. Multiple Ply Preforming of Non-Crimp Fabrics with Distributed Magnetic Clamping. Composites Communications, Volume 31, (2022), 101107.
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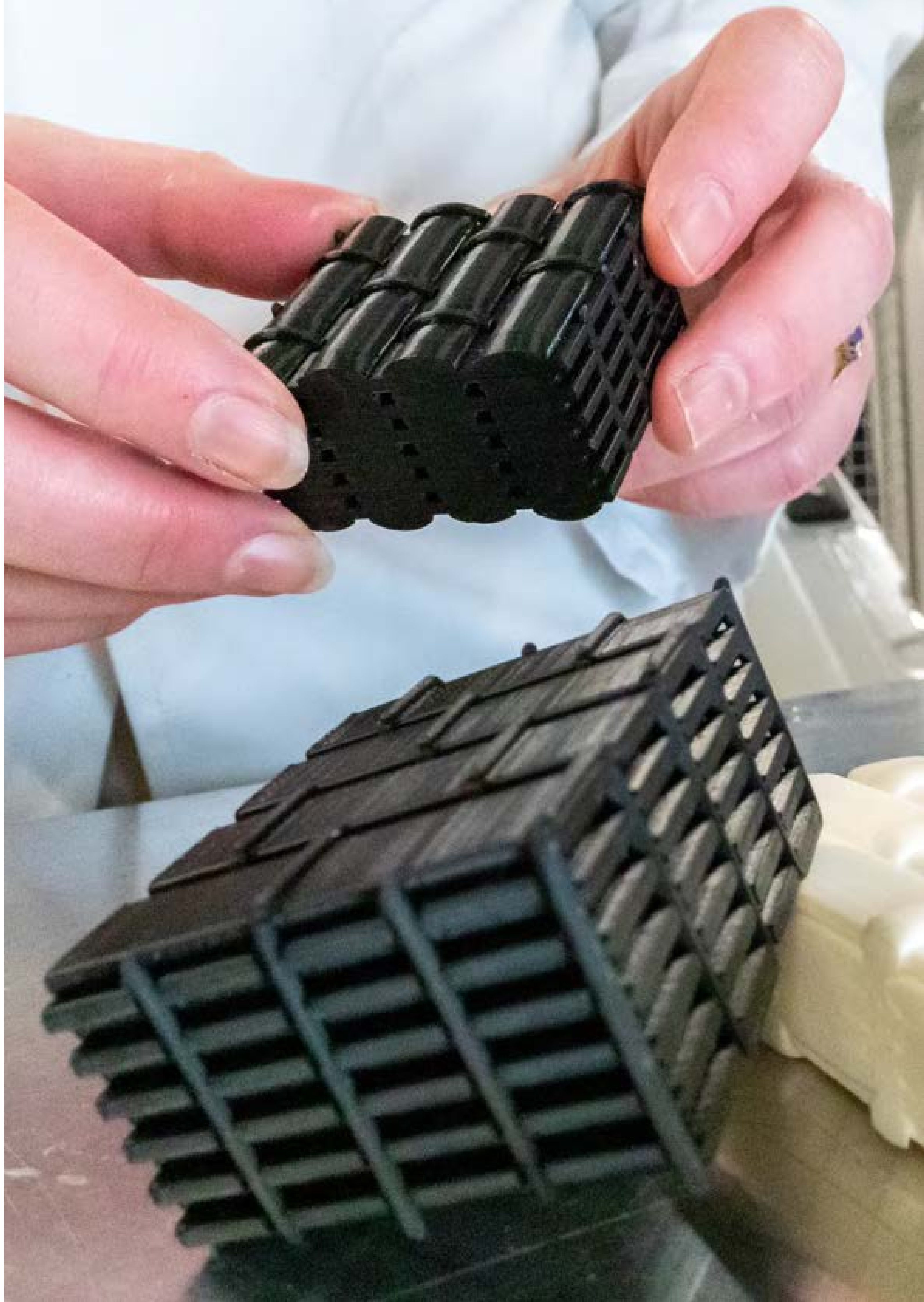
- Yu F., Chen S., Viisainen J.V., Sutcliffe M.P.F., Harper L.T., Warrior N.A. A Macroscale Finite Element Approach for Simulating the Bending Behaviour of Biaxial Fabrics. Composites Science and Technology Volume 191 (2020), 108078.



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:** 31/12/2023

Executive Summary

Resin Transfer Moulding (RTM) 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 will improve understanding of the RTM process and effect of defects on the process. The project aims to develop a range of algorithms that will use in-process data for detecting defects and process control. This will help to deliver more robust composites manufacturing, and reduce scrap rates and need for rework.

Aims and Objectives

The key requirements of the composite industry are to have repeatable mechanical properties of composite components, to minimise possibility of defects, and to have repeatable production cycles. For the RTM process to be used for high-value components, appearance of dry spots (i.e., defects) should be prevented. Appearance of voids and deviations from the designed filling time are caused by uncertainties in the material and process parameters, which cannot be realistically fully eliminated. To counteract the effect of the deviations, manufacturers use more conservative designs with larger safety factors. These conservative designs increase the total manufacturing and life-cycle costs. Furthermore, defects occurring because of uncertainties can lead to costly rework or higher scrap rate, which again increase 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.

Our vision is to use in-process information from sensors during resin injection for reliable and quick NDE of composite parts and for an active control system to counteract random deviations from the design. Utilisation of in-process data will capture and estimate local deviations from the design for any manufactured part which will create a digital twin for this part. This significant advancement will deliver a major step-change in composites manufacturing by reducing the cost and increasing the robustness of the manufacturing process, thus improving confidence in the quality of the part. The project will develop, improve and test innovative Bayesian inversion algorithms to restore permeability of composites components based on data collected from sensors during resin injection into reinforcement. It will also develop and test an active control system based on information from sensors and on physical models together with online parameter estimation algorithms to improve resin injection. This control system will minimise occurrence of defects and ensure the process robustness.

Figure 1. a. An instrumented tool for experiments with different sensors' densities. b. Data acquisition system for the instrumented tool.

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.

An algorithm for analysis of in-process data has been developed and validated in the virtual and lab experiments. This was shown to accurately capture both race tracking and other defects. Work on process control is in progress. 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.

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 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 including those based on Machine Learning. REnKA was tested using both simulated and experimental in-process data. It was demonstrated that REnKA can detect defects with high precision in terms of shape and position, as well as values of porosity and permeability. It was shown that REnKA is capable of detecting defects such as race-tracking in 3D components for which the two length scales differ by an order of magnitude. REnKA was validated using experimental data obtained from RTM experiments with two intentionally induced defects. Both defects were detected with a 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. The inversion algorithm can be used either for characterisation of material or for defect detection to estimate the manufacturing process and product quality.
Additional studies on finding optimum numbers and positions of sensors used for generating in-process data needed for REnKA are required based on the theory of optimal experimental design. A special tool to verify predictions based on virtual experiments for optimal number and position of sensors has been designed and manufactured. This work is currently in progress.

Speeding up the algorithm is another area for future work, which is a topic for one of the PhD students affiliated with the project. Preliminary results indicate that new algorithms can potentially be 10 times or more faster than the existing ones. This work is currently in progress.

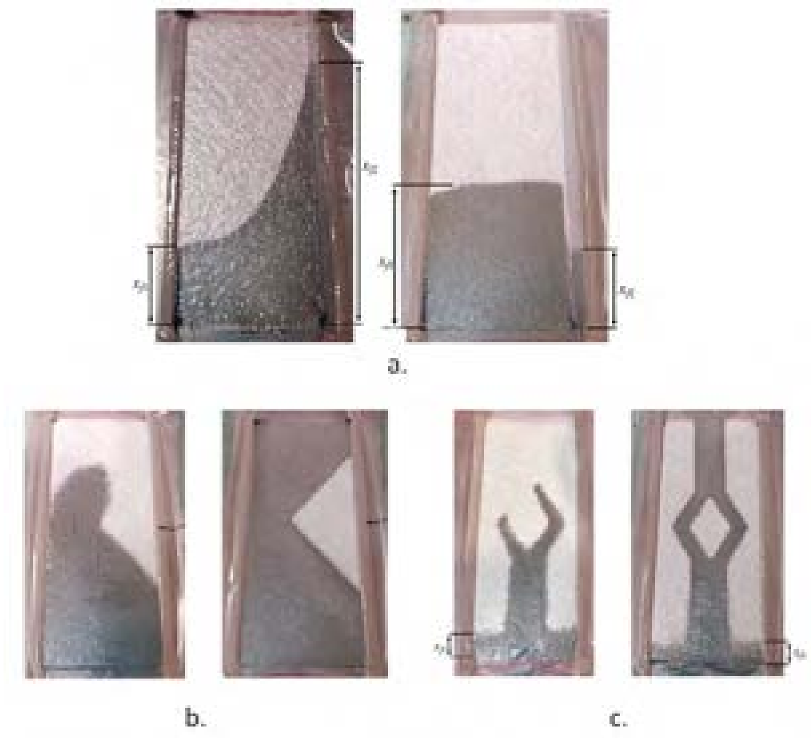


Figure 2. Control of resin infusion with UV-curing resin. a. Suppression of race-tracking; b. Converging-diverging flow; c. Splitting and merging flow fronts.

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Core Projects
Work Stream 4: Online Consolidation
Research Theme: High Rate Deposition and Rapid Processing Technologies

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).

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

Grant Award: £675,687 **Start:** 01/06/2020 **End:** 31/11/2023

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 of 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 modelling tools for each physics 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

The LbL simulation methodology developed in the project incorporates a coupled thermochemo-mechanical solution and a strategy for addition of elements as the process evolves. The implementation of the 3-D model was carried out in the finite element solver MSC Marc. Figure 1 shows the outcome of the simulation for the selected case geometry of an intermediate thickness omega stringer stiffened panel using 8552 epoxy/carbon prepreg. The process outcome has been compared with a conventional scenario in which the monolithic component is cured in autoclave using a standard cure cycle. In the case of the LbL profile, the duration of the cure of each layer was selected to ensure the partial cure does not exceed the gel point of the resin.

In comparison to autoclave processing, the LbL simulation results in a 40% cure time reduction together with a 70% temperature overshoot reduction. The evolution of internal stress and process strain involves some transient spikes upon placement of each new layer, whilst the strain is predominantly in the thickness direction. The transient stress relaxes quickly after placement and the evolution of the strain results in distortion and final residual stress of a magnitude similar to that of conventional processing. The level of residual stress is also consistent with the monolithic process around corner regions and features, indicating the LbL character of process does affect adversely process induced deformation at local level.

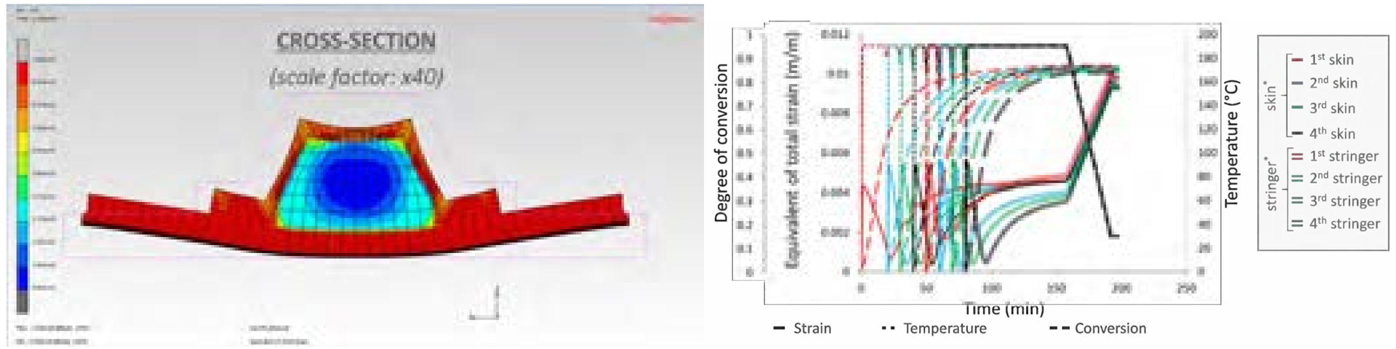

Figure 1. LbL simulation of a stiffened panel: left – total strain distribution and deformed shape (deformation scaled for visualisation) upon placement of the last stringer sublaminate; right – evolution of strain, temperature and degree of cure in the four sublaminates of the skin and of the stringer.

The evolution of the interfacial toughness as a function of conversion of one of the adherends has been quantified for a number of resin systems to establish the universality of the behaviour previously established. The hypothesis tested is that the state of the interface is governed by the degree of cure, with precure below the gel point resulting in interfacial properties equivalent to those of the virgin material.

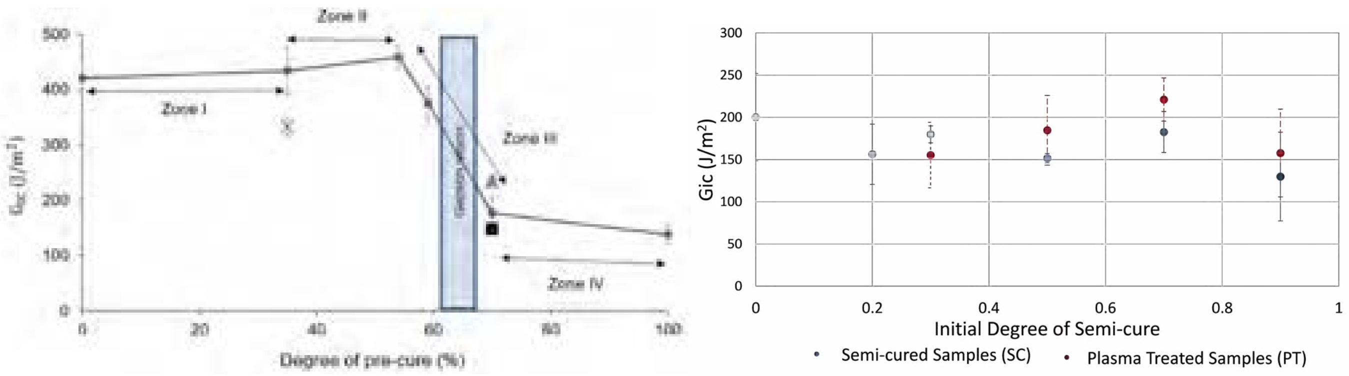

Figure 2. Dependence of toughness on degree of precure: left –epoxy prepreg system; right –epoxy liquid moulding system.

Figure 2 illustrates the dependence of Mode I toughness on the degree of precure of one side of the interface for materials representative of prepregs and liquid moulding epoxy systems. The general behaviour was also observed in a pultrusion system.
Table 1 shows the T-peel toughness for different precure states of both sides of the interface for the XU3508/XB3473 system incorporating PAT-656/B3R release agent. In all cases the behaviour follows previous observations with a value of toughness similar to that of the virgin material up to a degree of cure of 50-60%, which is the range in which gelation is expected in these epoxy systems. This can be explained through observation of the delamination fracture surface, as illustrated in Figure 3.

	Bottom Layer				
Top Layer DoC %	0	40	55	75	100
0	578 ± 112	408 ± 80	-	390 ± 48	248 ± 48
40		360 ± 70	460 ± 110	202 ± 26	-
55			428 ± 100	-	76 ± 78
75				80 ± 118	-
100					0

Table 1: Dependence T-peel toughness of XU3508/XB3473 on degree of pre-cure.

The imprint of the peelply utilised at deposition of the first sublaminate becomes visible once precure levels exceed gelation. Below this level the mobility of the partially crosslinked polymer allows full diffusion of molecular chain across the interface, yielding full bonding. The universality of this observation, which is also reinforced by measurements carried out previously for the RTM6 epoxy system, establishes the main criterion for process design of the LbL process. The results obtained for a two-sided precure for the XU3508/XB3473 system (Table 1) also confirm validity of the criterion for a 3D printing implementation of the process in which the incoming tow can be also partially cured within the printing die.

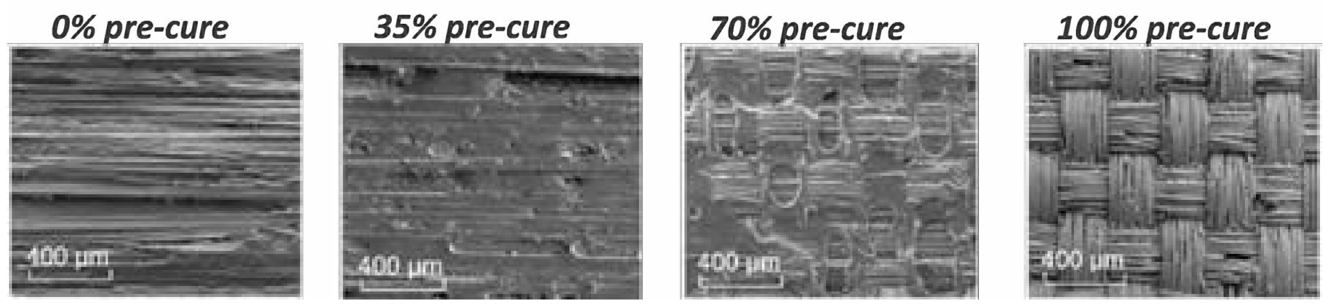

Figure 3. Fracture surface of LbL interfaces of 913 epoxy prepreg for different levels of pre-cure.

Utilisation of the coupled LbL process model for the demonstration component shown in Figure 1 was combined with multi-objective optimisation to identify optimal LbL profiles and link these with processing resulting in control of the interfacial toughness. Optimisation variables include the duration and temperature of LbL steps and minimisation objectives the maximum temperature and total process duration. The LbL process follows the temperature overshoot – cure duration trade-off observed in conventional manufacturing, with high-risk areas combined with fast processing and conservative areas associated with low overshoots, whilst a region combining relatively low risk and moderate process temperature exists along the Pareto front. The critical parameter in exploiting the potential of LbL is the conservation of interfacial properties. As observed in Figure 4, the degree of partial cure range resulting in optimal interfacial behaviour is part of the Pareto front, a result that resolves one of the main research questions of the project regarding the control of properties during LbL. When compared with monolithic processing, it is shown that LbL results in simultaneous reduction of overshoots by 10°C and process duration by 2000 s.

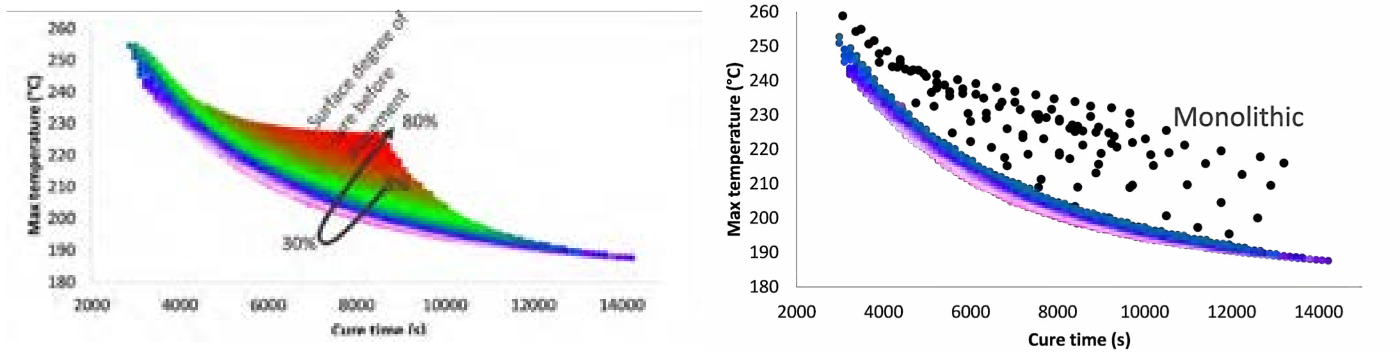

Figure 4. LbL multi-objective design/optimisation: left – population of solutions in the max temperature -process duration space with colour coding showing the maximum interfacial degree of partial cure during; right – Pareto front and comparison with conventional processing solutions.

The constitutive models and associated characterisation currently available for the 913 and 8552 systems have been extended to the fast cure M78.1 epoxy prepreg. Figure 5 illustrates the results of isothermal and dynamic differential scanning calorimetry (DSC) experiments and the corresponding cure kinetics model fitting. The results show that the epoxy of the prepreg undergoes an autocatalytic reaction, with the cure becoming very fast (below 3 min) over 130°C. The total heat of reaction is consistent across isothermal and dynamic conditions as well as across different rates, which is indicative of lack of thermal history dependence of cure kinetics. The reaction can be modelled using an autocatalytic model:

$$\frac{d\alpha}{dt} = k\,(1-\alpha)^n\,\alpha^m$$

where k is a rate constant including an Arrhenius chemically controlled reaction term and n and m are reaction orders. The evolution of glass transition temperature of the snap curing system as a function of degree of cure was investigated, establishing that the DiBenedetto equation, which is valid for conventional epoxies, is also applicable to the M78.1 prepreg system.

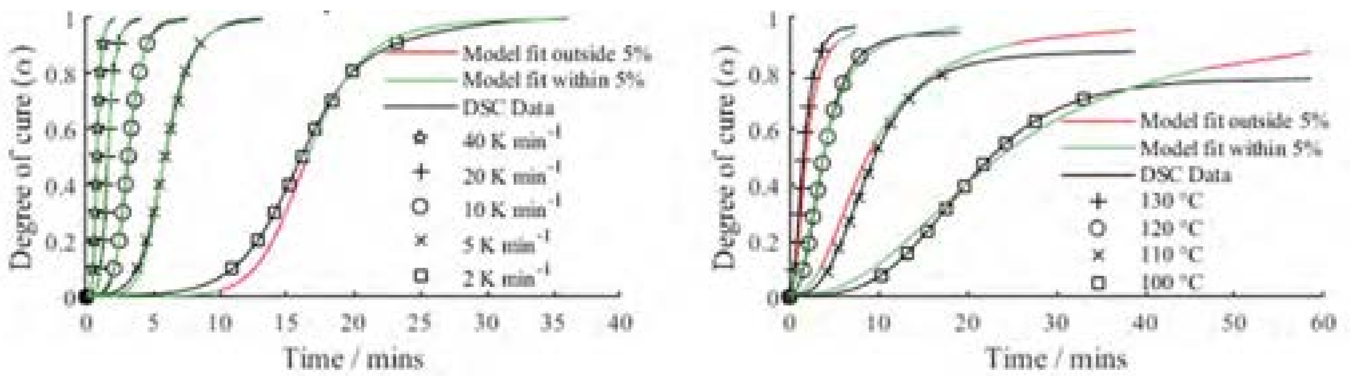

Figure 5. Cure kinetics of M78.1 system: left – dynamic DSC experiments; right – isothermal DSC experiments.

The criticality of establishing the degree of precure achieved on LbL deposition highlights the importance of cure kinetics modelling accuracy for process design. This challenge which can be overcome by the use of dense, high-quality datasets in terms of characterisation accuracy also involves consideration of inherent variability of the cure behaviour. Characterisation of uncertainty in kinetics was carried out for the EP2410 aerospace system and the results were linked to heat transfer model sensitivity to identify the range of tolerance necessary to take into account in process design. Table 2 summarises the results of the sensitivity analysis which shows that tool temperate plays the most significant role in propagating variability to the results of the heat transfer calculation.

			Sensitivity	
Parameter	HTC	Tool	Peak Cure Time	Peak Overshoot
Temperature	50	Invar	44.3%	3.6%
	120	Invar	47.4%	3.9%
	50	Composite	47.7%	4.1%
	120	Composite	50.1%	4.2%
HTC	50	Invar	0.2%	0.1%
	120	Invar	3.1%	1.0%
	50	Composite	0.8%	0.1%
	120	Composite	10.5%	2.1%

Table 2: Heat transfer calculation sensitivity to model input parameters.

Manufacturing technology development focus on two process variants. LbL-AFP and reusable flexible bag processing. Current progress on these is on development of concepts and design. A successful implementation of LbL-AFP requires controlled partial cure of each deposited layer, ensuring that there is enough residual reactivity within the matrix to bond with the subsequent ply. It has been demonstrated that if the degree of cure of a precured layer is below a degree of cure near gelation, the interfacial properties are equivalent to bonding two virgin layers. Based on this finding the LbL-AFP process will be realised using the bench top real time AFP (RT-AFP) rig at UoB. This system has a heated tool plate, allowing bottom-up heating during the LbL manufacturing process (Figure 6). As the thickness of the laminate is built up, the temperature of the tool is increased as determined by the coupled process model to maintain the chosen isothermal temperature of the upper ply, while also advancing the cure of already deposited plies. The potential use of a heated roller is also included in the concept. The reusable flexible concept (Figure 6) is based on simultaneous application of vacuum and positive pressure to deal with both concave and convex geometries. The design includes a recessed arrangement for effective sealing of the rubber membrane and two-stage actuation for tool removal. A combination of contact and radiative heating will be utilised. Part of the current design are being tested with an air press system.

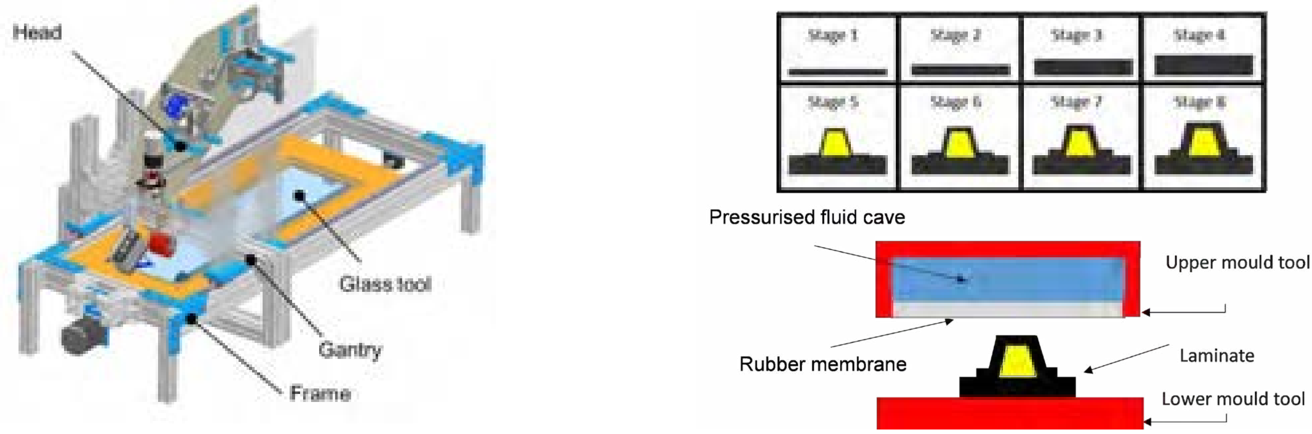

Figure 6. LbL manufacturing technology: left – LbL AFP system at UoB; right – reusable bag concept at CU.

The transfer of the LbL process from conventional prepreg to snap cure systems involves additional challenges manufactured with respect to defect generation addressed earlier. The evolution of the main LbL-AFP parameters (pressure, temperature and time) was analysed to assess impact on quality of the deposited material. Although the snap cure system (M78.1) shows high reactivity allowing LbL processing at low temperatures such as 100°C, it can present additional challenges in terms of simultaneous cure-consolidation, as the evolving degree of cure can inhibit the consolidation process (Figure 7). The low viscosity and cure rate shown by the material at lower temperatures (100-130°C) improve the bonding between the plies in comparison to greater temperatures (140-160°C) at which lower levels of adhesion are achieved. Ongoing work will define the optimal window with respect to defect generation based on cure kinetics modelling, the coupled process simulation and CT scanning.

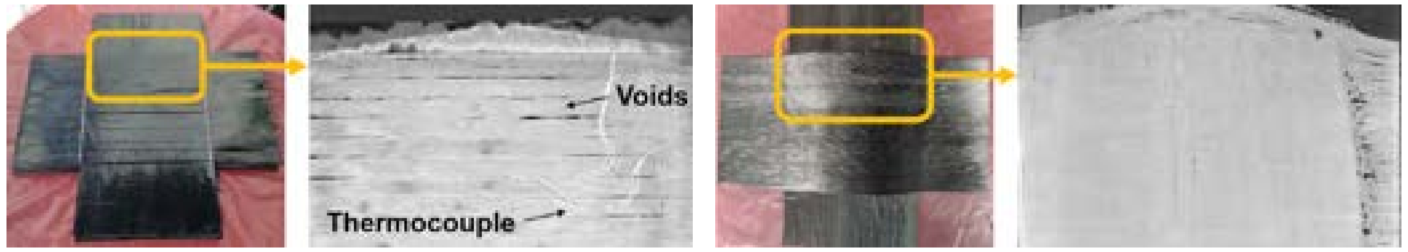

Figure 7. Defect generation during simultaneous cure/consolidation: left - conventional prepreg; right - snap-cure system.

The envelope of applicability of LbL based AFP – in the form of 3D printing of continuous fibre thermosetting materials - has been established through the application of simulation and optimisation to demonstrate the benefits with respect to both process time and temperature overshoot compared to monolithic curing. Similarly to the whole layer by layer process, partial cure of the tow upon deposition renders the process time-temperature overshoot trade-off surface of optimal processing conditions insensitive to thickness and establishes benefits that approach 50% with respect to both objectives. Furthermore, the nature of the LbL process is subject to simplified modelling that allows estimation of processing time and temperature overshoot through straightforward regression relationships to explore the process envelope. Figure 8 illustrates the dependence of processing time on component size for an epoxy prepreg. 3D printing/LbL can reduce the temperature overshoot to small values, whilst also enabling processing of small to intermediate components with a benefit in process duration. For very large components, where duration reach 100 s of hours the 3D printing/LbL strategy has the potential of intensification though its scalability via use of multiple heads and thick tows.

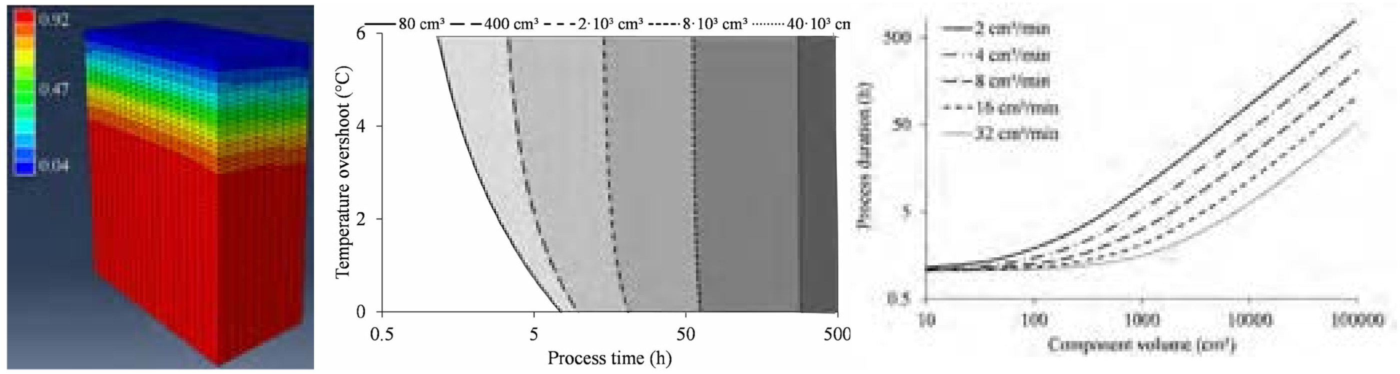

Figure 8. 3D printing/LbL process: left – degree of cure distribution; middle: envelope of applicability of 3D printing/ LbL for the M21 epoxy/carbon prepreg; right – process duration as a function of component volume.

In the future implementation of LbL-AFP, accurate knowledge of the temperature of deposited material is necessary for controlling the degree of precure within the acceptable limits for producing an interface with the right levels of toughness. An inverse solution of heat transfer in AFP was developed and used to estimate the actual irradiance acting on the surface using tool temperature data. Figure 9 illustrates the setup and the results of estimation, which is carried out through an analytical solution of the steady state heat transfer problem and function specification of the irradiance distribution. The model was further developed to extrapolate tool temperature data to nip point temperatures, setting up the necessary background for control of the process in the future.

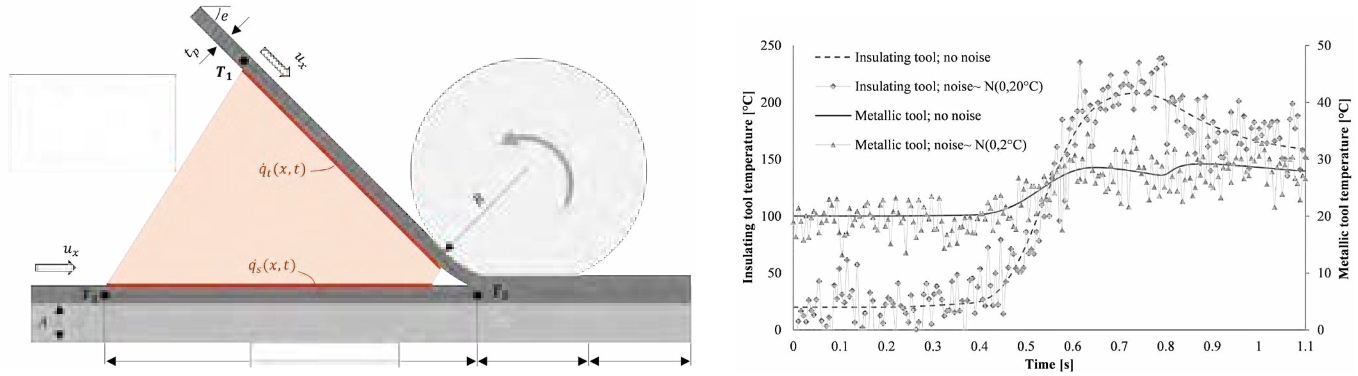

Figure 9. Inverse solution for irradiance estimation in AFP based on tool temperature measurements: left – model setup; right – estimation of irradiance subject to significant level of Gaussian noise.

The need for active control that will potentially arise due to the tight tolerances of the LbL-AFP process necessitates the development of simulation tools that can be executed iteratively in real time. In this context, an 1D model of AFP was established based on the high Peclet number of heat transfer effects during the process and the concept of dividing the modelling into three sub-domains: (i) incoming tow; (ii) deposited material and; (ii) consolidation zone. Figure 10 provides a comparison of 2D and 1D results demonstrating the excellent accuracy of the 1D model, which is achieved in solution times that are about 100 times shorter than the full simulation. The capability of the 1D model was demonstrated by applying it to the multi-objective optimisation of conventional AFP addressing the simultaneous minimisation of process time and degradation, whilst maximising bonding between layers (Figure 10). The results show that the strong trade-off between degradation and bonding shifts to a moderate dependence when the process uses high power and speed, whilst at the same increasing efficiency. This result acts as a guideline for the implementation of LbL-AFP, where fast, intense processing is expected to lead to efficient manufacturing, whilst achieving an appropriate level of surface precure without risking degradation.

Activities in the next period of the project will 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 (filament winding, pultrusion, hybrid material processing).

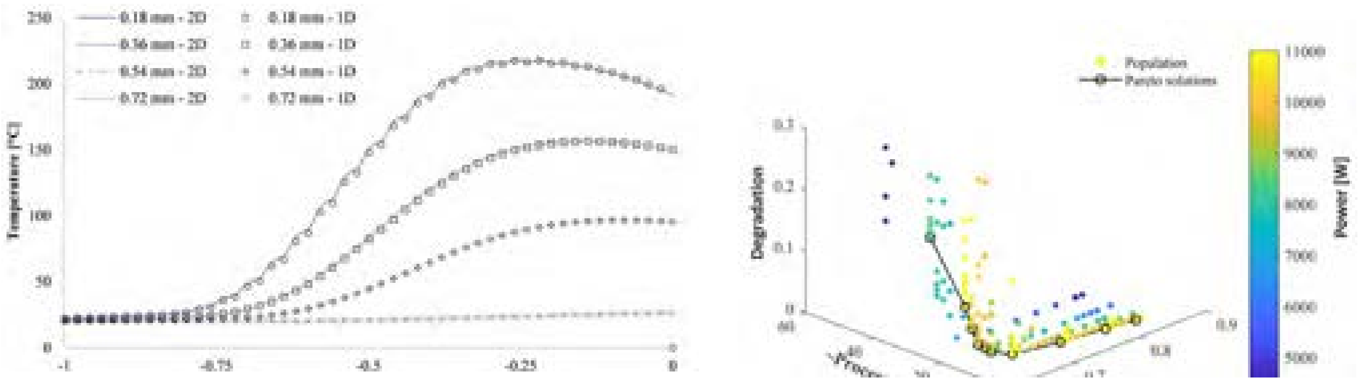

Figure 10. 1D modelling of AFP: left – comparison of 1D and full model results at different positions along the deposited thickens (time 0 denotes the nip point); right – multi-objective optimisation results based on the 1D model.

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- Danezis A., Williams D., Skordos A.A. One-Dimensional Approximation of Heat Transfer in Flashlamp-Assisted Automated Tape Placement. Journal of Thermoplastic Composite Materials, (2023).
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- Danezis A., Williams D., Edwards M., Skordos A.A. Heat Transfer Modelling of Flashlamp Heating for Automated Tape Placement of Thermoplastic Composites. Composites Part A: Applied Science and Manufacturing, (2021), 106381.

Technologies Framework for Automated Dry Fibre Placement & Fibre-Steered Forming Technology

Core Project Team

Principal Investigators: Dr Thomas Turner, University of Nottingham; Dr Byung Chul (Eric) Kim, University of Bristol; Prof Stephen Hallett, University of Bristol; Prof Ian Hamerton, University of Bristol; Dr Jonathan Belnoue, University of Bristol; Dr Marco Longana, University of Bristol.

Research Team: Dr Ric Sun, University of Bristol; Dr Bohao Zhang, University of Bristol; Dr David Brigido, University of Bristol; Dr Tharan Gordon, University of Bristol; Mr Usman Shafique, University of Nottingham; Mr Shimin Lu, University of Nottingham.

Industry Partners: ESI, Coriolis, GKN Aerospace, AMRC, NCC, WMG, Airbus, Rolls-Royce, Hexcel, Composites Integration, Solvay, JLR, BAE Systems, iCOMAT, ATI.

Grant Award: £649,269 **Start:** 01/04/2017 **End:** 30/11/2023

This Core Project is well aligned with the Hub goals of improving rate and quality. It focusses on barriers to increased uptake of this deposition technology. These include Digitalisation of the process, sustainability and the ability to produce complex fibre architectures. The team at Nottingham have developed a novel programming and data storage paradigm to advance the state of the art in automated composites manufacture by creating a true digital twin. A digital twin of the process will allow bi-directional communication between designed part and manufactured part to facilitate real-time process control, online in-process quality control and seamless connection to resin flow and structural simulations. In the longer term machine learning approaches can be adopted to refine the behaviour of the processes.

A novel automated manufacturing process named 'Fibre-steered forming technology (FSF)' was developed by the team at the University of Bristol, for high-volume production of small and highly complex composite parts, which are not manufacturable using the current AFP processes. The FSF was developed by combining three cutting-edge technologies (material, manufacturing, simulation) developed in the Bristol Composites Institute: Virtual unforming simulation, HiPerDiF (High Performance Discontinuous Fibre) process, and CTS (Continuous Tow Shearing). The new approach allowed for designing a 2D fibre-steered preform that can be formed into the 3D target shape and fibre trajectories through the unforming simulation and producing the 2D fibre-steered preform using the CTS defect-free fibre steering process. The FSF process can be used with HiPerDiF highly-aligned short-fibre prepregs as well as conventional continuous fibre prepregs, which allows for more sustainable high-volume manufacturing and more effective use of high-value materials for small and complex composite parts.

Since the last Annual Report, the team at Bristol have been focusing on experimentally validating the unforming simulation results and carrying out forming tests with multi-ply fibre-steered preforms (both continuous fibre and HiPerDiF prepreg preforms), to enhance the industrial applicability of the FSF process. Multi-ply preform forming trials were carried out on a rugby-ball shape (positive Gaussian curvature) and a twisted plate shape (negative Gaussian curvature) in an in-house double diaphragm forming rig. The test results successfully demonstrated the superior formability of the HiPerDiF preforms and its steerability using the CTS process. It was also demonstrated that multi-ply fibre steered preforms could have dual advantages of eliminating forming defects and optimally distribute the reinforcement fibres, which enables production of ultra-lightweight small and complex composites parts.

Aims and Objectives

Automated Fibre Placement (AFP) technology has been adopted within the aerospace industry for the manufacture of carbon fibre reinforced components, such as wing spars, wing box covers and fuselage barrel segments. AFP has the ability to control fibre orientation as a result of its fibre steering capabilities by directing fibres onto a complex geometry or curved surface. The robustness, low wastage and repeatability through automation result in a desirable process for high quality high volume manufacture. AFP eliminates the labour intensive hand layup methodology that significantly increases production times. However, for small and complex parts, the advantages it offers cannot be realised. Furthermore, the current AFP processes can only use continuous fibre tapes, limiting the sustainability of the process. Traditionally, AFP uses thermoset or thermoplastic prepreg slit tapes, using the tack of the matrix material to adhere the fibres into position. However, these materials are expensive, require accurate temperature control during storage and deposition, to ensure sufficient adhesive properties are not affected by aging, and require further consolidation processing, such as by autoclave. The latter further increases initial equipment cost and operation cost as well as cycle times in comparison to liquid composite moulding (LCM) processes. Therefore, automated dry fibre placement (ADFP) has become of particular interest with the aim of reducing cost and cycle times whilst maintaining the high quality and low wastage of fibre placement technologies.

The team at the University of Bristol aim to develop a rapid manufacturing process, using sustainable materials for complex composite parts, which are not manufacturable using current AFP technologies. They have developed and validated a new manufacturing framework to achieve optimal fibre paths to maximise a part's mechanical performance. Their work consists of four work packages:

- Fast numerical tools that derive the ideal fibre paths of a flat preform from the "as-designed" geometry and fibre orientation of a given part will be developed.
- A sustainable material production method will be used to produce highly-aligned discontinuous fibre (HiPerDiF) tapes suitable for automated process, and the material configuration will be optimised to provide maximum drapability in the forming process.
- Defect-free fibre steering (CTS, Continuous Tow Shearing) process will be modified to feed the HiPerDiF tapes with high stretchability and produce high-quality fibre steered preforms.
- The overall workflow will be demonstrated to show how the technologies developed in WPs 1-3 can be integrated in a coherent, combined workflow to produce a novel, as designed, manufacturable, sustainable "part" at increased rate, with reduced defects.

The team at the University of Nottingham aim to understand the rate and quality limiting effects in the ADFP process and develop models to increase understanding of the critical factors. Their work consists of five work packages:

- Process design to determine hardware effects and control of the deposition apparatus whilst developing lab scale equipment to demonstrate these.
- Material design to investigate the fundamental tow/tape/NCF structure, optimising the binder content (type and volume) for tack and the prevention of fibre fuzzing during deposition.
- Deposition process to quantify the tack properties with respects to rate and temperature of dry fibre systems as well as the studying the compaction and topology to predict behaviour of single tows or ply stacks and their interactions with the deposition roller.
- Infusion process to quantify the permeability effects of the fibre architecture post deposition.
- Part design to part geometric effects in terms of processing rate and quality of the preforms.

Progress

Developments at the University of Nottingham
One Hub PhD student has successfully defended his thesis entitled "A rapid flow assessment tool for automated dry fibre preforms – a numerical and experimental study". The second student is due to submit in August 2023. The PDRA working on the project has left for a job in industry. Nottingham continue to work on the functionality of the rig in the following main areas:

1. Realtime pressure control: The team has developed an approach for machine control which is well suited to the highly compliant dry fibre substrates and able to operate at high speed. We continue to develop this approach using the physical machine hardware and are working on a variety of test geometries to assess the efficacy of this method at high speeds and for challenging geometry. Feedforward control through knowledge of the underlying tool geometry at any location may lead to enhanced control.
2. Joule heating: There is interest in the idea of heating dry fibre reinforcements using the Joule effect since it seems uniquely applicable to this process and has key advantages over competing technologies. We are continuing to develop a model-based control strategy and characterise performance of various carbon fibre reinforcements.
3. Materials characterisation & modelling: Detailed characterisation of the compaction and thermal properties of the input materials are required to allow model-based control of the process. After a successful collaboration with Francois Robitaille at the University of Ottawa we have obtained thermal properties which will be used in the developed model. We are in the process of commissioning a highly accurate mixed-mode compaction test rig to deliver improved data.

The Digital Twin / Data Repository aspects of the project are now being worked on as part of the Materials Made Smarter Centre. A PDRA has been recruited for this project and he is working closely with the ADFP team. We continue to benefit from materials supplied by Solvay and we have also hosted a visit from a team from Dassault Systemes who were interested in development tools for Digital Twins.

A key output from the project will be to demonstrate the core technology developed – that of a synchronous bi-directional digital twin for the control of the layup. A key part of this which is not fully developed is the data streaming over the ADS transport layer within the EtherCAT network. This will be demonstrated before the end of the project. Other aspects under development include the integration of machine vision sensing alongside the other sensors on the deposition head.

We hope to complete construction of our fibre compaction test rig which will be used to get force/displacement data at a much higher resolution than is currently available from our LVDT-equipped Instron test rig. This will include cyclic compaction data which will be fed into our FE models. We should also be able to produce data for mixed-mode through-thickness thermal conductivity/compaction which will contribute to knowledge in this area.

Work continues on recycled tape development and we hope to trial the deposition of short lengths of recovered fibre based aligned 3mm fibres produced on our alignment test rig. This is overlapping work with the recent Hub Feasibility Study in this area.

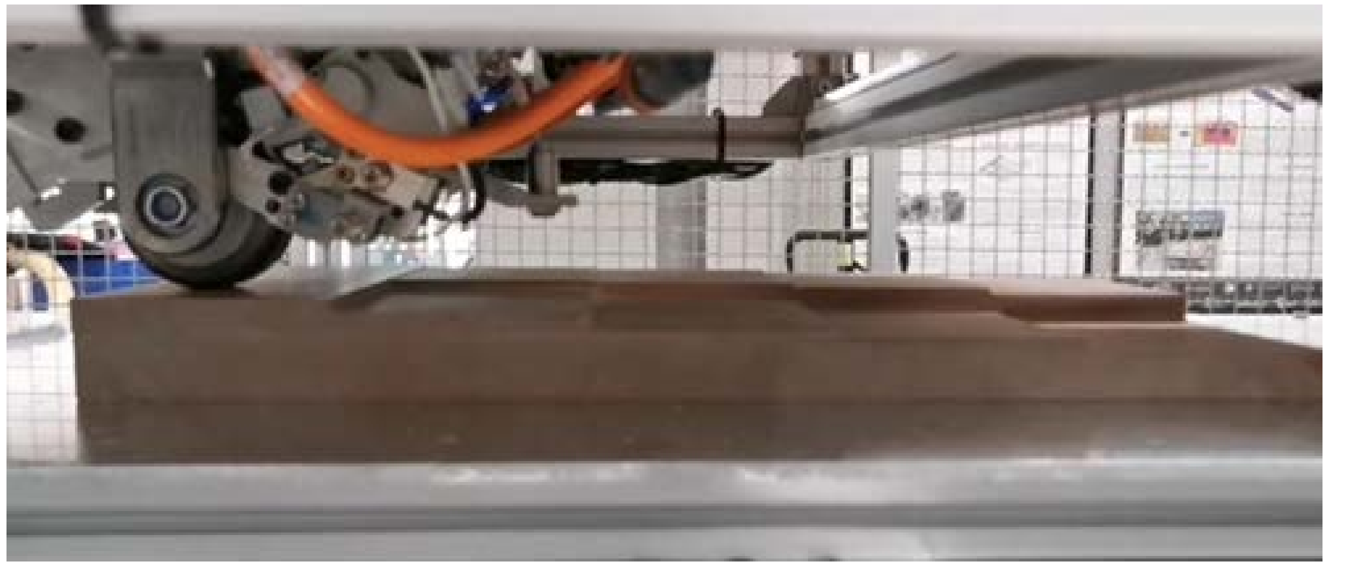


Figure 1. Deposition test on stepped tool to test efficacy of force control strategy.

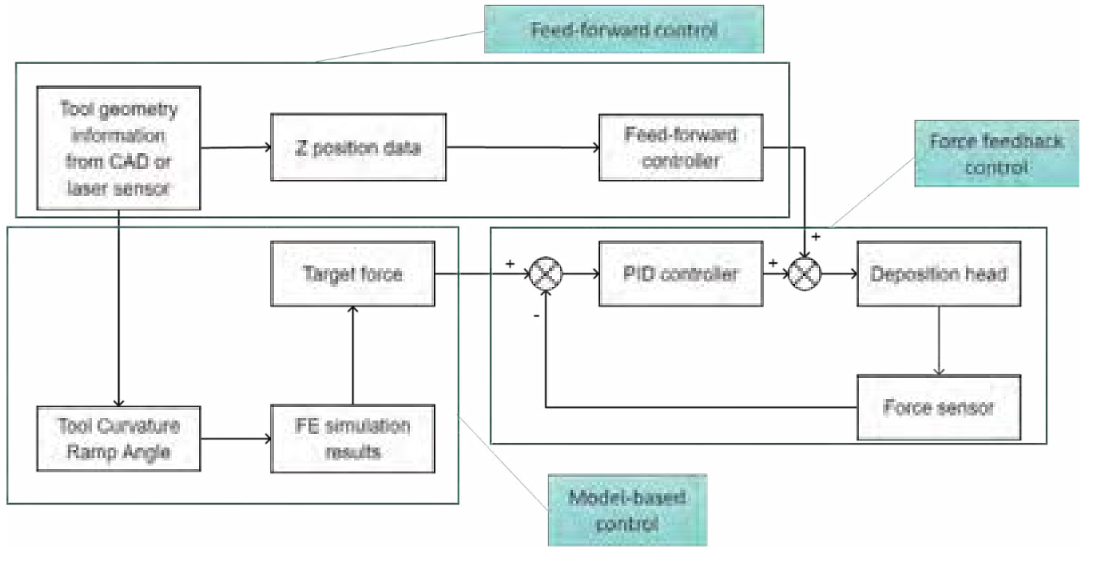


Figure 2. Force Control strategy – Model based control with feed-forward.

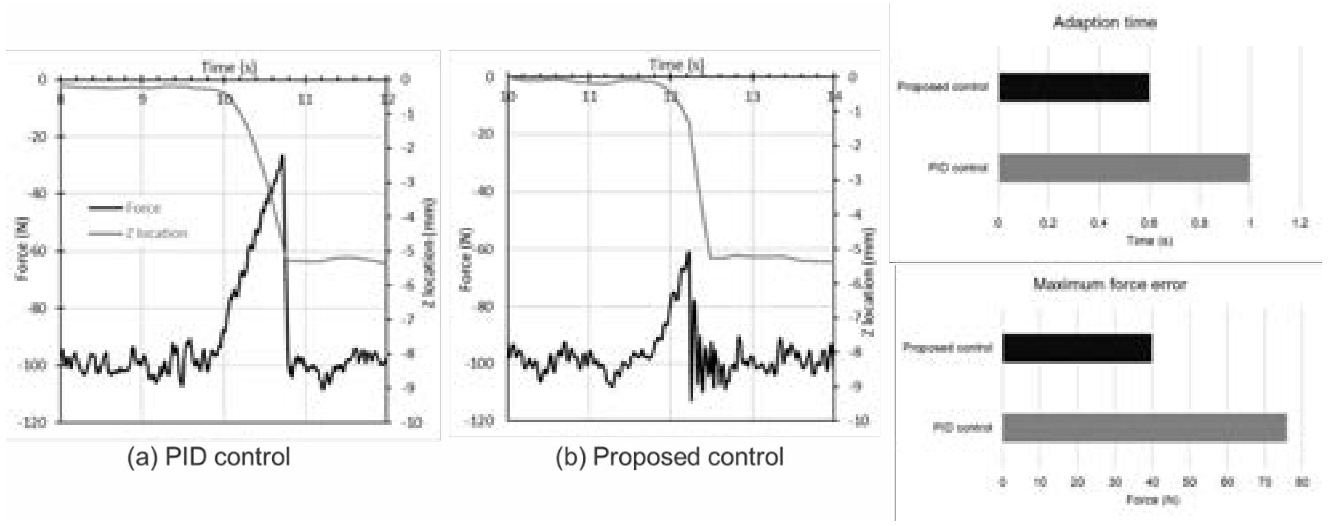


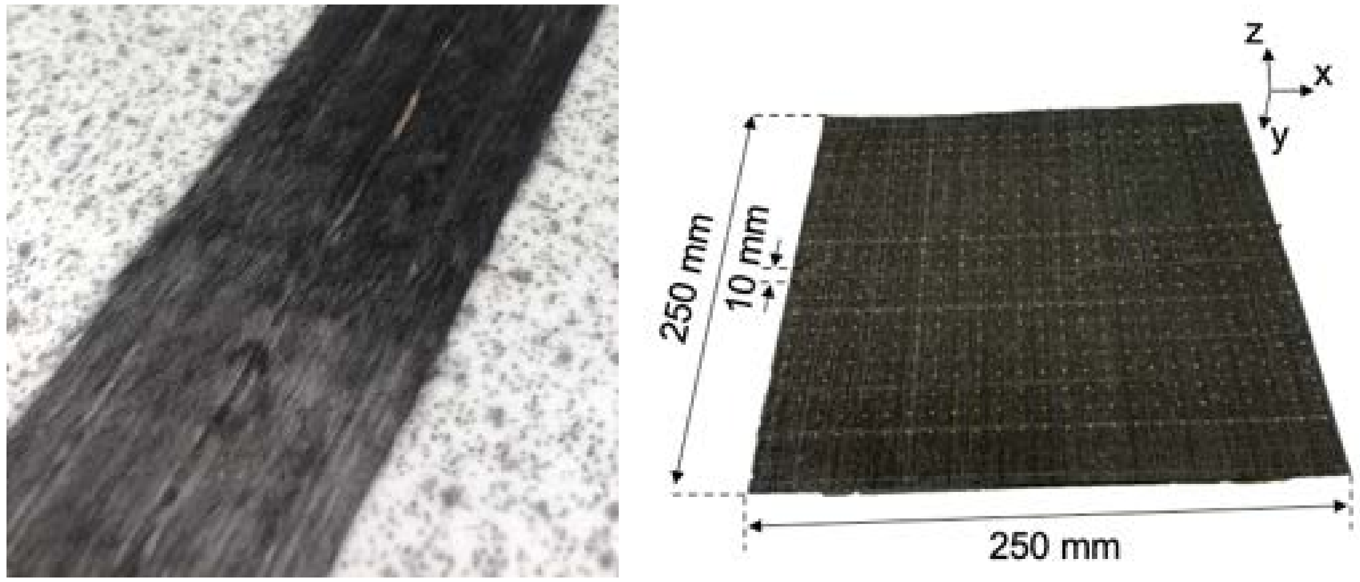
Figure 3. Results from testing showing improved force control with implemented model.

Developments at the University of Bristol

Formability of HiPerDiF Preform

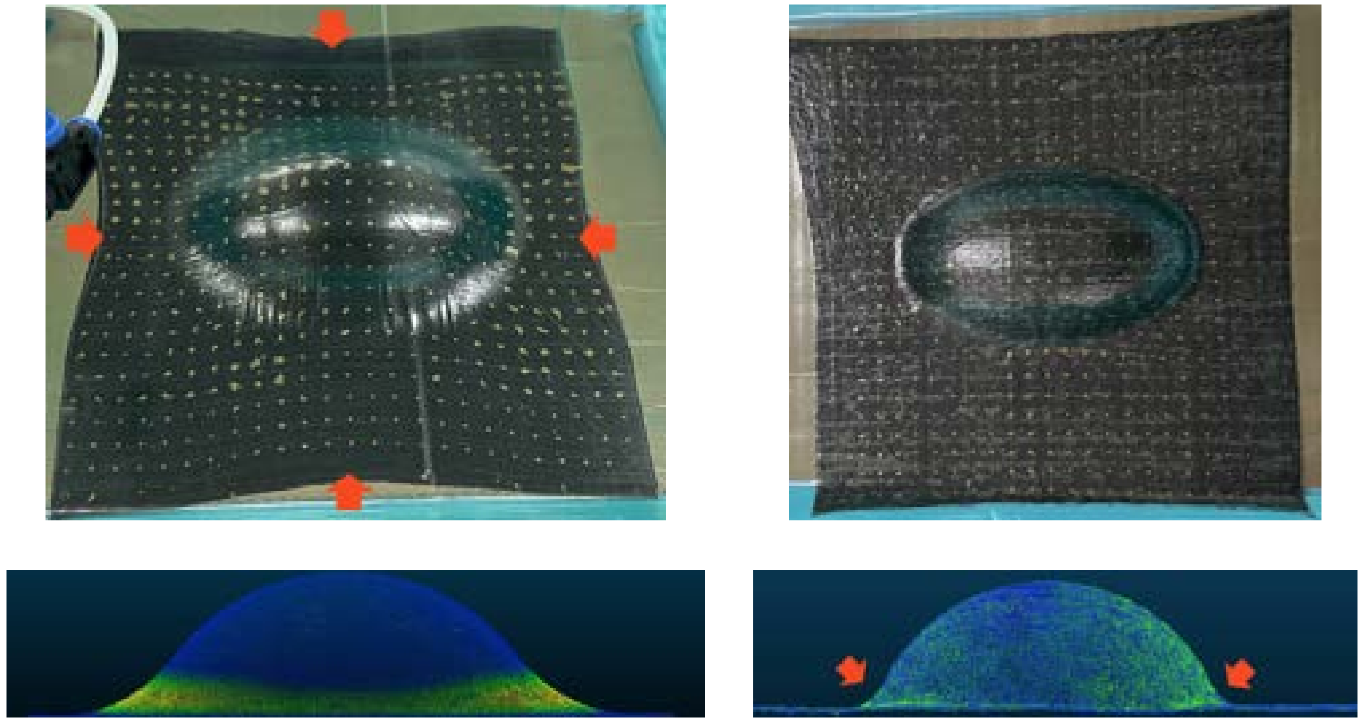
Previously, the formability of a single-ply HiPerDiF prepreg sheet was compared with that of a single-ply continuous fibre prepreg sheet, which limitedly showed its potential for industrial application. Cross-ply preforms were newly fabricated using both material forms and their formability were assessed on the rugby ball shape tooling. First, 25 mm wide HiPerDiF prepreg tapes were produced using the HiPerDiF-3G machine; Dried highly-aligned short carbon fibres (3 mm, Tenax, Teijin) were impregnated with a B-stage epoxy resin film (MTM49-3, Solvay). Then, as shown in Figure 1, the HiPerDiF tapes were manually laid up into unidirectional prepreg sheets with dimensions of 250 mm x 250 mm and a [0/90] preform was prepared. A cross-plied continuous fibre preform was also prepared using a commercial prepreg (MTM49-3/T800, Solvay) for comparison. The average overall thicknesses of those preforms were 0.25 mm and 0.3 mm, respectively. The average total areal weights were 14.1 gsm and 28.2 gsm, respectively.

The forming was carried out using an in-house double-diaphragm forming rig, and the preform was heated to about 50 °C within the diaphragms using a portable fan heater before and during the forming. The preform temperature was monitored using a thermocouple attached to the diaphragm surface. After the forming was completed (i.e. no further shape change of the preform), the top surface of the diaphragm was scanned using a 3D laser scanner. As shown in Figure 2, the continuous fibre preform could not completely conform to the mould surface due to fibre bridging although the material was drawn into the corner regions between the flat and curved areas of the mould. In contrast, the HiPerDiF preform was able to confirm to the mould without causing any gap and without pulling the material from the flat region, which implies that some localised stretching occurred. To investigate the localised stretching of the preform, the dot pattern imprinted on the preform before forming was captured using the 3D laser scanner (using manual probing mode). Using the 3D coordinates of the dots on the diaphragm after forming, finite element meshes were created for both preforms and then strains along the length and width directions of the prolate spheroid shape were calculated. As shown in Figure 3, there was a significant amount of stretching near the corner area, which was over 60% in maximum. This example clearly demonstrates the advantage of HiPerDiF preforms over continuous fibre preforms in terms of material formability. There must have been some localised thinning caused by the stretching, but it was difficult to measure. This could be considered as a disadvantage. However, this example clearly shows that a challenging geometry non-manufacturable using continuous fibre preforms can be manufactured by using HiPerDiF materials.



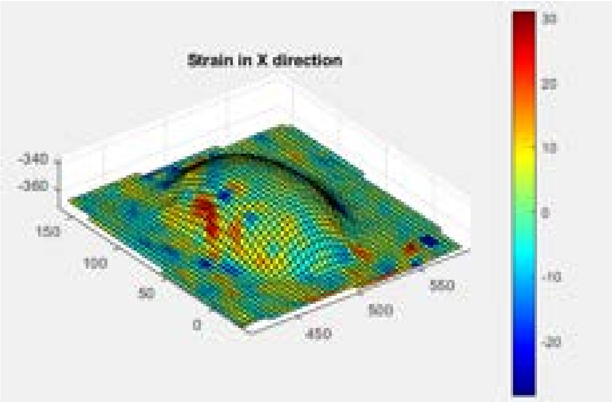
[a] [b]

Figure 1. (a) 25 mm wide HiPerDiF prepreg tape roll, and (b) [0/90] preform manually laid up.

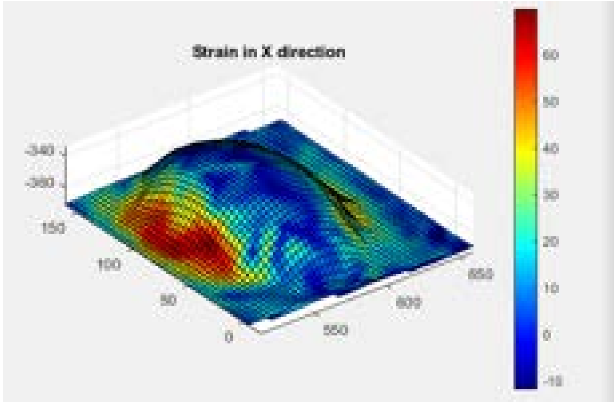


[a] [b]

Figure 2. Diaphragm forming quality comparison (top: photo, bottom: 3D profile scan result): (a) continuous fibre preform, and (b) HiPerDiF preform.



[a]



[b]

Figure 3. [a] Normal strain distribution: continuous fibre preform, and [b] HiPerDiF preform. The mesh presented is an interpolated one from the original mesh captured by the 3D scanner.

Formability of Fibre-steered Continuous Fibre Preform

To experimentally demonstrate the benefit of fibre-steering for enhancing formability, multi-ply preforms made of continuous fibre prepregs (MTM49-3/T800, Solvay) were formed on a twisted plate shape shown in Figure 4 100 mm wide prepreg tapes were steered using the UoB's CTS prototype machine (See Figure 5) and cut into rectangular sheets for manual stacking. Figure 6 shows the non-steered and steered fibre preforms in comparison. As shown in Figure 6(b), for the multi-ply fibre steered preform, the steering angle varied from the left end to the right end.

Figure 7 shows the forming qualities of those two preform types. The same in-house diaphragm forming rig was used, and the forming carried out at about 50 °C. As shown in Figure 7, a few large out-of-plane wrinkles were generated on the non-steered continuous fibre preform. In contrast, the fibre-steered preform was formed without any defect. The out-of-plane wrinkling in the former case could be related to the fibres within the 45° layer on the preform surface increasing the bending stiffness along the principal curvature direction of the twisted plate shape. In the case of the fibre-steered preform, the fibres are slightly offset from the principal curvature direction, which could significantly reduce the bending stiffness along that direction. This resulted in no wrinkling. This result demonstrated that the fibre steering could be used to enhance the formability of the preform as well as to optimally distribute the fibres for structural performance improvement.

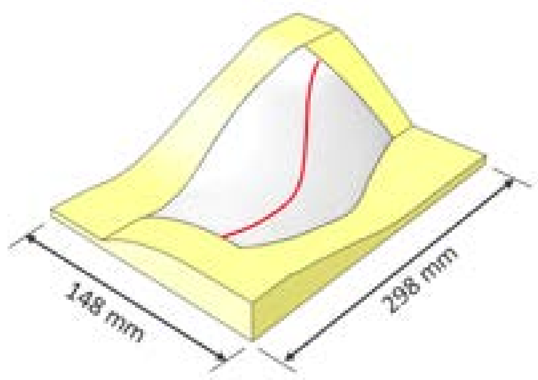
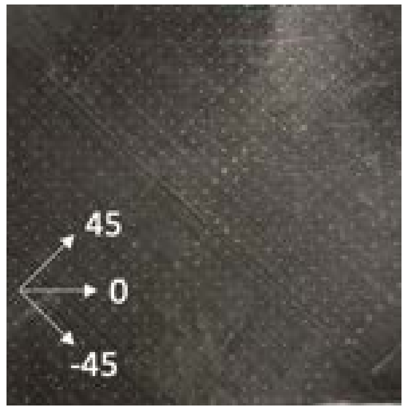
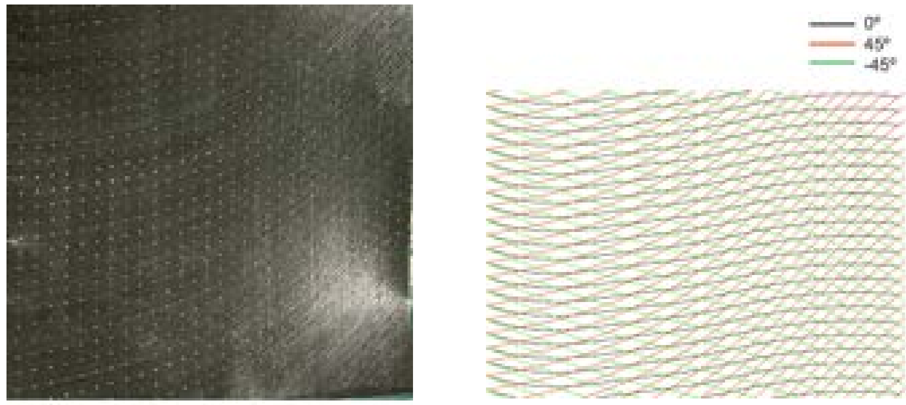


Figure 4. Twisted plate shape used for multi-ply fibre-steered preforms.

Figure 5. Production of fibre-steered prepreg ply using the CTS process.



[a]



[b]

Figure 6. Multi-ply continuous fibre preforms with the stacking sequence of [45/0/−45]: [a] non-steered preform, and [b] fibre-steered preform and the fibre paths used in the CTS process.

[a]

[b]

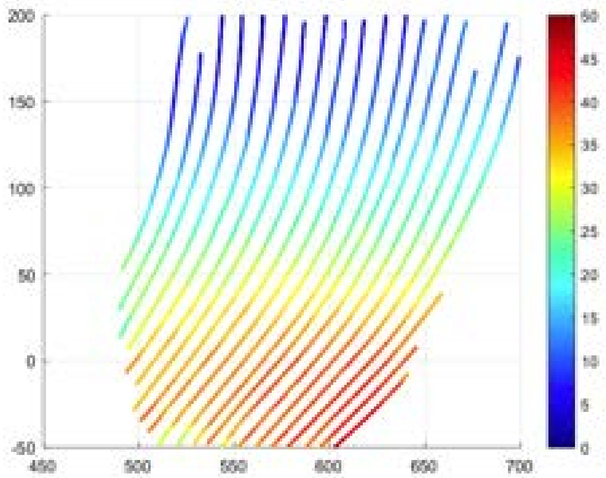
Figure 7. [45/0/−45] preforms formed on the twisted plate shape: [a] straight-fibre preform, and [b] fibre-steered preform.

Formability of Fibre-steered HiPerDiF Preform

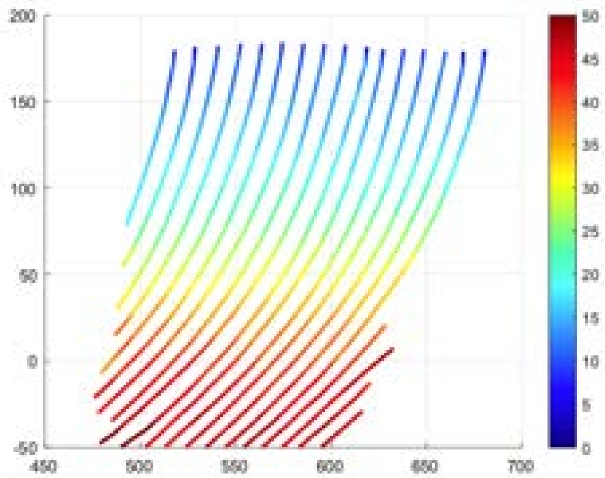
To produce a fibre-steered HiPerDiF preform, 25 mm wide HiPerDiF tapes shown in Figure 1 were staggered to produce a single blocked and 100 mm wide unidirectional tape. Then the tape was steered using the UoB's CTS machine. The steering paths used were the same as those used for continuous fibre prepregs shown in Figure 6(b), and the steered plies were cut into rectangular shapes and stacked manually to produce a preform (See Figure 8(a)). And the forming condition was the same as that used in the test described above. As shown in Figure 8(b), no wrinkling was generated during forming and the overall preform deformation was very close to that of the steered continuous fibre preform shown in Fig. Figure 7(b). For more accurate comparison, the dot points on the top ply were detected using the 3D laser scanner, and their coordinates were displayed in projected views as shown in Figure 8(c, d). Although there was a slight mismatch due to the rotation of the preform during forming, the result showed that fibre angle distribution was well controlled. This test result successfully showed the great advantages of the FSF (Fibre-steered Forming) technology when it was used together with HiPerDiF materials: 1) Improved preform formability, 2) Optimal fibre distribution, 3) Improved sustainability of the process.

(a)

(b)



(c)



(d)

Figure 8. Fibre-steered multi-ply preforms formed on the twisted plate shape: (a) continuous fibre pre-form, (b) HiPerDiF preform, and fibre angle distribution comparison between (c) continuous fibre pre-form and (d) HiperDiF preform.

Publications

- Sun X.C., Belnoue J.P., Wang W.T., Kim B.C., Hallett S.R. "Un-forming" Fibre-Steered Preforms: Towards Fast and Reliable Production of Complex Composites Parts. Composites Science and Technology (2021).

Recently Completed Feasibility Study
Work Stream 8: Thermoplastic Processing Technologies
Research Theme: Inspection and In-Process Evaluation; Recycling and Re-Use

ADvanced Dynamic REpair Solutions for Sustainable Composites (ADDRESS)

Project Team

Principal Investigator: Dr Dmitry Ivanov, University of Bristol.

Co-Investigators: Prof Ian Hamerton, University of Bristol; Prof Janice Barton, University of Bristol; Dr Marco Longana, University of Bristol.

Research Team: Dr Dmitry Ivanov, University of Bristol.

Grant Award: £49,947 **Start:** 22/11/2021 **End:** 21/05/2022

Executive Summary

Composites design offer significant cost savings by reducing parts counts and joining operations. However, when a composite component is damaged it is difficult to replace a part that is co-bonded or co-cured in a larger structure, often resulting in disposal of a large asset. Currently, repairs are cumbersome and time-consuming with low confidence in their efficacy for primary structures. This is a critical barrier to a more sustainable approach to composite asset management.

Adhesive repair strategies rely on the mechanical properties of relatively weak polymers. The problem is exacerbated by the complexity of the repair process. A repair procedure is generally conducted in-field, with limited resources and little opportunity for control of the processing parameters. The result is non uniform curing in complex geometries, with insufficient bonding of the repair to the hosting structure, thermal distortions, voidage, which prevent efficient load transfer across the repair. The difficulties also arise from the intrinsic composite material properties such as low through-thickness thermal conductivity, highly reactive thermosetting matrices, and thermal stresses due to the mismatch of properties. Furthermore, there are many processing problems that occur due to the intrinsic material limitations, e.g. thermal lag in heat transfer, run-away exothermic reactions, inefficient heating methods, and requirements for air extraction at the bonding interfaces.

The ambition of this work was to develop design for repair strategy by means of manufacturing multi-matrix continuously-reinforced composites (MMCRC). The concept, pursued in this Feasibility Study, enables composite structures combining domains of Covalent Adaptive Networks (CANs) and conventional established resins. CAN's can change their topology without decreasing their connectivity and hence present a great potential for repair. On the other hand, CAN's are far less processable and present manufacturing challenges: high viscosity, short processing window, demanding consolidation requirements.

Designing repair with MMCRC at the manufacturing stage allows bringing new and existent resin in an integral material assembly. Instead of relying on the adhesive bonding of repair patches the novel manufacturing concept creates fibre bridged interphases ensuring better structural integrity and reliability of repair. Such concept circumvents both the manufacturability challenges and lack of confidence associated with conventional forms of repair. Moreover, it has been shown that MMCRC structures do not demand excessive processing requirements for repair and can be dealt with tools available in-field. Inductive coil with new architecture has been designed specifically for the non-planar shape and aim at localised targeted and uniform heating.

The project demonstrated successful manufacturing of CAN-epoxy MMCRC for corner geometries and subsequent mechanical testing to generate controlled level of matrix damage. It has been shown that with relatively low processing requirements, which can be available in-field, the repair fully restores the mechanical performance of the MMCRC. Resultant approach offers sustainable solution to improve life of complex composite structures, thus contributing to the priority Hub themes of "Reycling/Reuse". This brings closer the creation of circular economy and more efficient recovery of materials.

Aims and Objectives

Our vision is to reduce the amount of scrapped non-recyclable composite components by developing a new holistic process-for-material and materials-for-process approach that enables accessible, efficient, and reliable repair techniques. The realisation of our vision will enable design for repair manufacturing strategies, which comprises the following:

- Identification of areas susceptible to operational wear, fatigue damage, or environmental degradation, which cannot be efficiently solved without the penalty of weight, cost or excessive complexity;
- Design of replaceable patches right at the stage of manufacturing the new component and involving reformable matrix formulations such as Covalent Adaptive Networks (CANs);
- Implementation of repair process without damaging surrounding structure and continuous composite reinforcement using limited pressure available in-field and local heating solution, such as EM induction.

Outcome and Future Direction

Various manufacturing routes to create epoxy-CAN MMCRC have been explored in manufacturing trials. With the combination of compression moulding and resin infusion, seamless co-hosting of two matrices in one structure has been achieved. The produced samples exhibit acceptable quality of interfaces, proving the feasibility of design and manufacturing integral CAN-epoxy parts.

The L-shape MMCRC have been tested in Curved Beam Strength test till failure. The test configuration was able to induce controlled matrix failure in the CAN targeted region. Delamination in these regions were shown not to be affected by the interface. Thus, the mechanical performance for CAN-MMCRC was assessed in the matrix-dominated failure mode.

The repair process over the tested vacuum-bagged samples have been conducted using conventional oven heating and EM induction. A bespoke coil has been designed in the current project aiming at generating local but uniform heating over the corner areas. The performance of the coil has been assessed and found fit for repair. The samples were then retested and using optical strain measurements. The result showed a great potential of this strategy in full recovery of strength. The restoration of strength has been observed not only for perfect samples but also for the samples with various degrees of ply waviness/wrinkles.

Hence, the feasibility and the strong promise of the suggested concept has been successfully demonstrated. ADDRESS combined several novel concepts, pioneered by the project team, and devise new generic scalable repair methodologies applicable across a wide range of industries such as marine, aerospace, automotive and energy where non-recyclable polymer composites are deployed in high value assets.

The project will pursue several avenues for further development. First, the fundamental manufacturing potential of the CAN-MMCRC will be explored in follow-on Composites Manufacturing Hub project at the University of Birmingham "De-risking manufacturing and enhancing structural efficiency with modular sustainable multi-material", which will examine application of this concept to simplify and control forming processes. Secondly, follow-up activities with the NCC Core Project on Modular Infusion which has a potential for the integration of various aspect of modular technologies in an integral manufacturing paradigm. The application to an NCC Technology Pull Through is also considered.

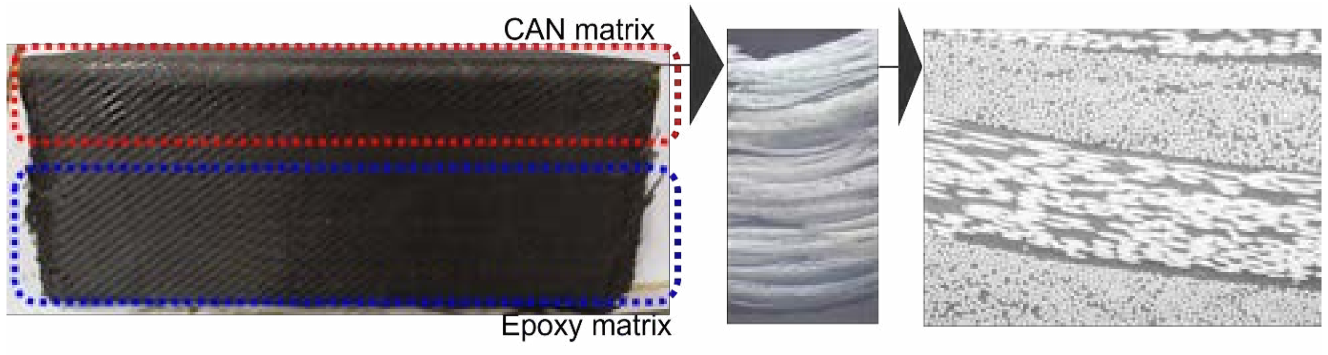


Figure 1. CAN-epoxy MMCRC with microscopy of the CAN-region.

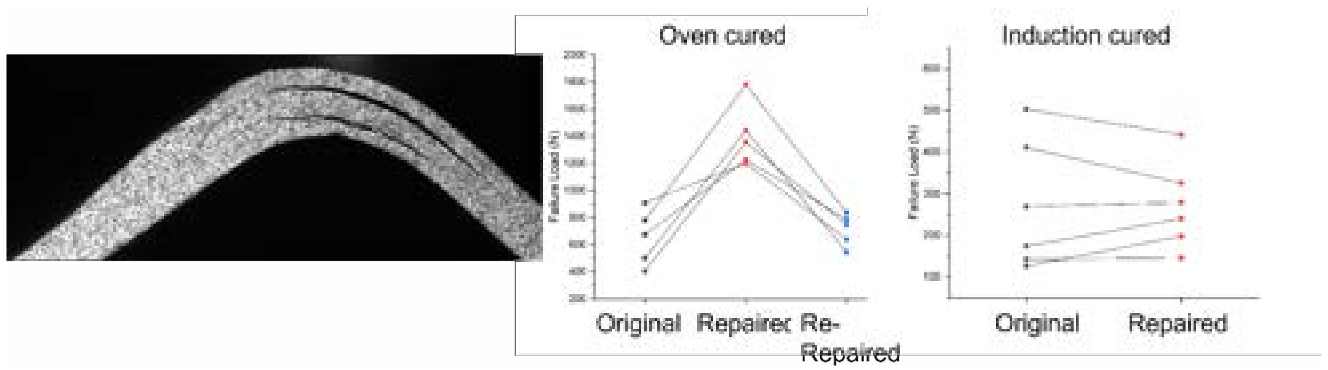
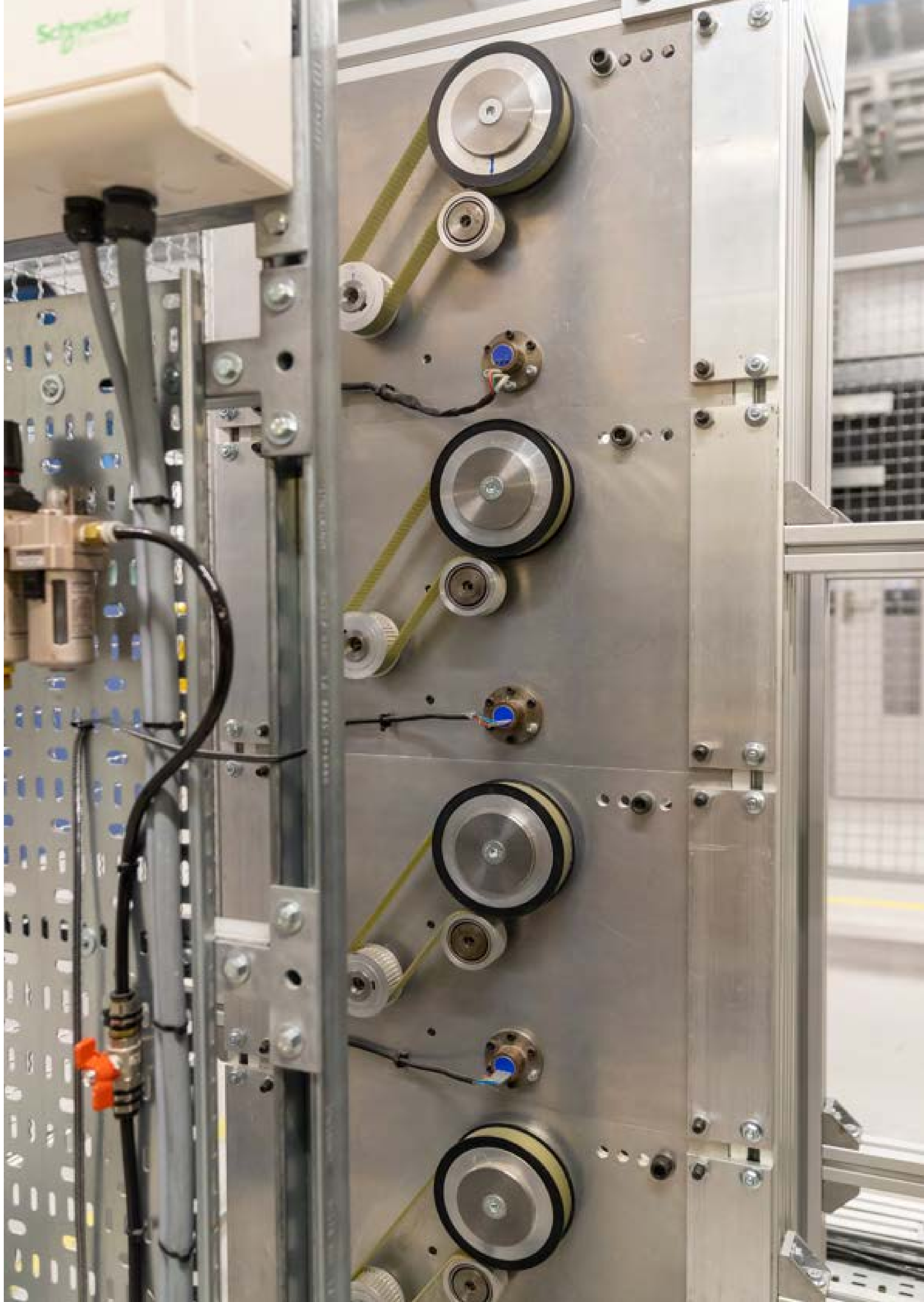


Figure 2. Delaminations induced by bending of the corner samples and failure loads of original and repaired samples.



Recently Completed Feasibility Study
Work Stream 4: Online Consolidation
Research Themes: High-Rate Deposition and Rapid Processing Technologies; Design for Manufacture via Validated Simulation

Additively Manufactured Cure Tooling (ADDCUR)

Project Team

Principal Investigators: Dr James Kratz, University of Bristol; Dr Vimal Dhokia, University of Bath.

Co-Investigators: Dr Maria Valero, University of Bristol; Dr Elise Pegg, University of Bath.

Research Team: Mr Arjun Radhakrishnan, University of Bristol; Mr Vincent Maes, University of Bristol; Mr Max Valentine, University of Bath.

Industry Partners: Airbus, GKN, LAMT, Rolls-Royce, Surface Generation, The National Composites Centre (NCC).

Grant Award: £49,987 **Start:** 01/02/2022 **End:** 31/07/2022

Executive Summary

ADDCUR investigated tooling to reduce embodied energy of composite manufacturing. Specifically, we explored additive manufacturing to design the lightest possible cure tools to increase rate and quality by adjusting the heat distribution in the mould. ADDCUR supports two priority research themes: i) rapid processing technology by curing parts in half the time, and ii) design for manufacture via validated simulation by eliminating costly tool modifications that slow product development time.

This Feasibility Study has demonstrated potential to control composite curing with AM tooling to a level that is unachievable by conventional machining methods. We found that the exothermic overshoot due to curing heat released by the epoxy appears to be proportional to lattice density, while the heating rate due to the low thermal conductivity of polymers was more sensitive to the facesheet thickness. The potential to spatially match the tool properties to the composite part is possible. How this is applied to industrially relevant cases requires further work.

Aims and Objectives

Cure tooling is often an afterthought but is a major non-recurring cost with long lead times and can become a recurring problem. There are no design for manufacture workflows for effective single iteration design of complex manufacturable tooling optimised for energy efficiency. Currently, an AM 'clean sheet design' will require between 7–10 design iterations, often taking months. The approach here has the potential to radically shorten the design to manufacture time of complex tooling, targeting single iteration designs at a considerably lower cost.

The following objectives were addressed:

- Develop a Design for AM workflow for composite cure tooling.
- Evaluate stainless steel AM cure tools for composite moulding requirements, such as surface finish, vacuum bag sealing, and thermal responsiveness.
- Demonstrate energy savings of AM cure tooling during the manufacture of composite parts with in-dustrially relevant features.

Outcome and Future Direction

A design for AM workflow was defined linking together, simulation, design and manufacture specially for the generation of tailored AM composite cure tooling. A typical monolithic cure tool was broken down into a facesheet and lattice. Backing structures were not considered at this TRL. Through the evaluation of the lattice geometries and facesheet thickness, it serves to inform decisions relating to the lattice properties to achieve the desired tooling requirements for complex composite geometries. The work serves to help provide the necessary information to design the lattice volumes by understanding how different lattices behave. Example lattices are shown below in Fig. 1. The tool stiffness was quantified with finite element modelling using ABAQUS software.

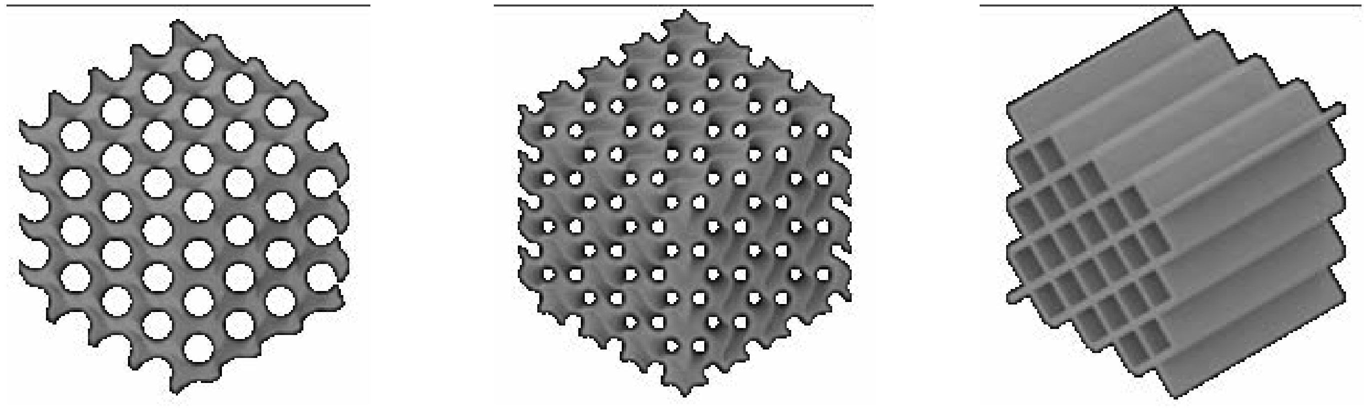


Figure 1. Lattices (l–r) of the repeated gyroid, dual-wall gyroid, and planar diamond.

A total of thirty flat tools were manufactured out of 316L Stainless Steel (SS316L) powder using a Renishaw AM250 L-PBF machine. Some tools were exceptionally light, having a lattice volume density of 7% and a facesheet thickness of 0.75 mm. The as-printed surface had a roughness of Ra 10 microns. Before laying up the composite prepreg laminates, light grit sandpaper removed any partially sintered powder particles from the layup surface and the tools were cleaned. There was no additional post-processing of the tools after removing the support structures from the bottom surface.

The thermal responsiveness of the mould tools was measured by oven curing a prepreg (MTC400-C415T-T700-12K-38%RW-1250) from SHD Composites using vacuum bag only pressure. The composite laminate was prepared using fourteen plies measuring 40 mm x 40 mm to form a theoretical cured thickness of 7 mm. A thermocouple was placed within the prepreg stack right between the seventh and eighth plies to capture the thermal history. A target oven heating rate of 3 °C/min was applied and a cure temperature of 135°C for 1 h. The tools were found to achieve a hard vacuum (50 mbar) and also pass a standard aerospace leak test (no noticeable drop in 5 minutes on an analogue gauge).

The thermal responsiveness of the mould tools is shown in Fig. 2. The tools with thinner facesheets allowed for a faster heating rate as there was less material for the environment to heat up before reaching the composite. The tools with slower heating rates and therefore greater thermal mass were able to mitigate the overshoot effect, leading to smaller overshoot temperatures on the thicker and heavier tools. This indicates that the overshoot appears to be proportional to lattice density, regardless of the plate thickness, while the heating rate was more sensitive to the facesheet thickness.

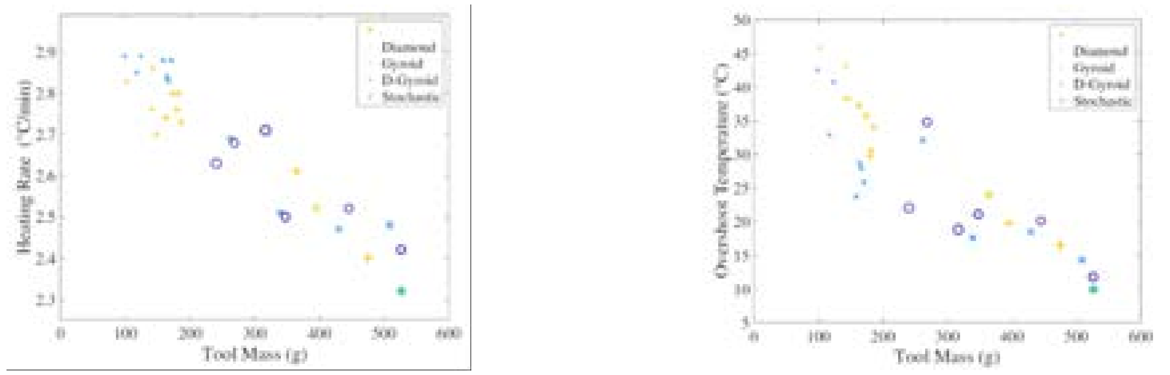


Figure 2. Thermal responsiveness of AM mould tools.

To compare the AM mould tools to conventional tooling, the semi-complex part shown in Fig. 3 was manufactured. The optimal lattice structure was chosen from Fig. 2 and the same materials as above. An equivalent part was manufactured using solid 8 mm thick stainless steel tooling. Even though the curing cycle was not optimised, a 50% energy reduction was measured. A larger exotherm was measured in the part manufactured on the AM tooling, in agreement with the observations shown in Fig. 2. There is room to trade-off exotherm by increasing cure cycle time.

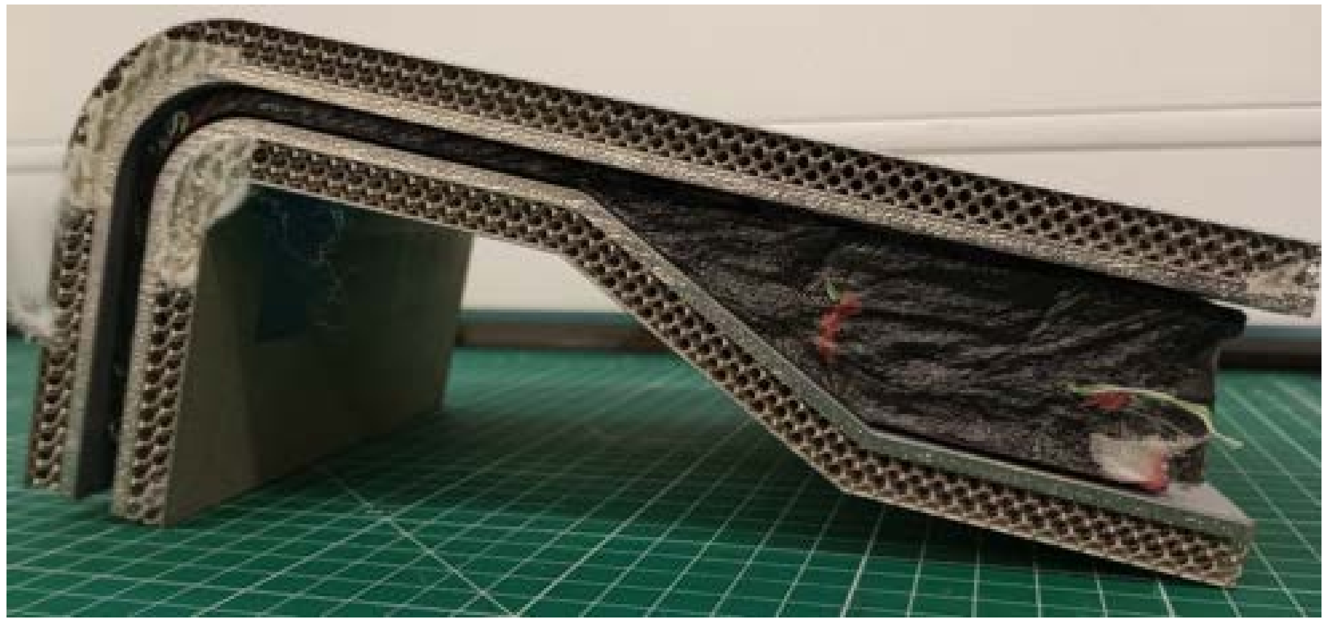


Figure 3. Semi-complex part made using AM tooling.

This Feasibility Study has just scratched the tip of the iceberg of what is possible with AM cure tooling. While tooling has been identified as a priority to help the UK develop capability to digitally design and deliver future composite products, further challenges need to be overcome. Some non-exhaustive topics include: dimensional stability, size of mould tool, tessellation and joining of different tooling segments, lead-times, and in-process monitoring and control of temperature. Developing these approaches could have significant impacts on the UK mould tooling and composites sector. We are working with one of our partners to explore some of these concepts.

Recently Completed Feasibility Study
Work Stream 1: Automated Fibre Deposition Technologies
Research Themes: High-Rate Deposition and Rapid Processing Technologies; Recycling and Re-Use

Furthering the Uptake of Carbon Fibre Recyclates by Converting into Robust Intermediary Materials Suitable for Automated Manufacturing

Project Team

Principal Investigator: Dr Thomas Turner, University of Nottingham.

Co-Investigator: Dr Davide de Focatiis, University of Nottingham.

Research Co-Investigators: Dr Adam Joesbury, University of Nottingham; Dr Colin Robert, University of Edinburgh; Mr Thomas Noble, University of Edinburgh.

Industry Partners: Teijin Carbon Europe GmbH, Swiss Composite Materials & Technologies, SHD Composite Materials Ltd.

Grant Award: £49,840 **Start:** 01/01/2022 **End:** 30/06/2022

Executive Summary

This study addresses the issue of composites sustainability by developing new manufacturing technologies to produce a high performance composite intermediate material from recycled carbon fibre. The format of this product is a powder-coated aligned short fibre tape with high mechanical properties and excellent formability.

This project has excellent alignment with the aims of the Hub, addressing four critical topics:

- Reduce the carbon footprint of composites manufacturing; by furthering the uptake of carbon fibre recyclates, therefore making end of life reuse a more viable option, and so reducing the loss of material to landfill disposal.
- Step towards a new manufacturing technology; that aims to overcome barriers preventing the use of recycled carbon fibre in automated manufacturing processes.
- Analytical study to understand material manufacturing parameters.
- Increasing the manufacturing sustainability of high-performance structures; by enabling the use of aligned recycled carbon fibre in high-accuracy automated fibre placement technologies.

Overall the project has successfully demonstrated an improvement in usability of the existing aligned fibre tapes at low TRL. The programme of work highlighted some issues which were not foreseen at the bid writing stage which have limited progress somewhat compared to the original intentions. In particular, we have not been able to demonstrate use of the material in an automated process or in any end use demonstrator components, but we have uncovered some fundamental phenomena which will drive future development.

The primary impact of this Feasibility Study is to demonstrate that, in contrast to many existing technologies, fibres recovered from end-of-life components can be turned into a format that resembles a virgin material with manufacturing characteristics (such as the ability to be stretch formed) that enhance industrial appeal.

Aims and Objectives

The University of Nottingham has developed a fibre alignment process to process various forms of short fibres (e.g. end of life components, NCF Hoover waste, woven trim scrap, chopped pyrolised fabric) into 300mm wide highly aligned tapes of 100-200gsm areal weight. The viscosity modifier used imparts some strength to the final product when dried but the tapes are very moisture sensitive and have low resistance to elevated temperature, so they are not well suited to use in conventional down-stream processes such as hand laminated or automated preforming.

The aim of this project was to develop a binder doping methodology to provide a robust and handleable RCF-based finished product. The binder is intended to strengthen and stabilise the core of the material. As a second step the dried products are coated with an epoxy powder either as a surface binder for preforming or as a way of incorporating the totality of the matrix resin for compression moulding.

It is intended that the final products could be well suited to automated dry fibre placement or pick and place processes for either resin infusion or prepreg compression moulding.

Outcome and Future Direction

Tape Consolidation Process
The first stage of producing rCF tapes was to process aligned rCF mats into tapes that had sufficient intrinsic properties to accommodate downstream processing. The mat and tape processing requires aqueous processing, various drying and consolidation processes were trialled, the following are ranked from least effective to most effective: ambient conditions > heated press > heated vacuum bag > blotting press. Optimised drying and consolidation resulted in a 30% increase in FVF compared to 'As received' rCF mat.

Doping Process
Accompanying the drying and consolidation study were trials of various doping methods to add an aqueous epoxy resin emulsion in an attempted to improve the properties of dry rCF tapes. The trialled processes are listed in order from least effective to most effective: saturation spray with low concentration mixture > rinsing and 'infusion' with low concentration mixture > minimal spray application of high concentration mixture. SEM images enabled observation of the displacement of residual viscosity modifier from the rCF mat manufacturing process (left image below) and replacement with aqueous solution delivered epoxy (right image below).

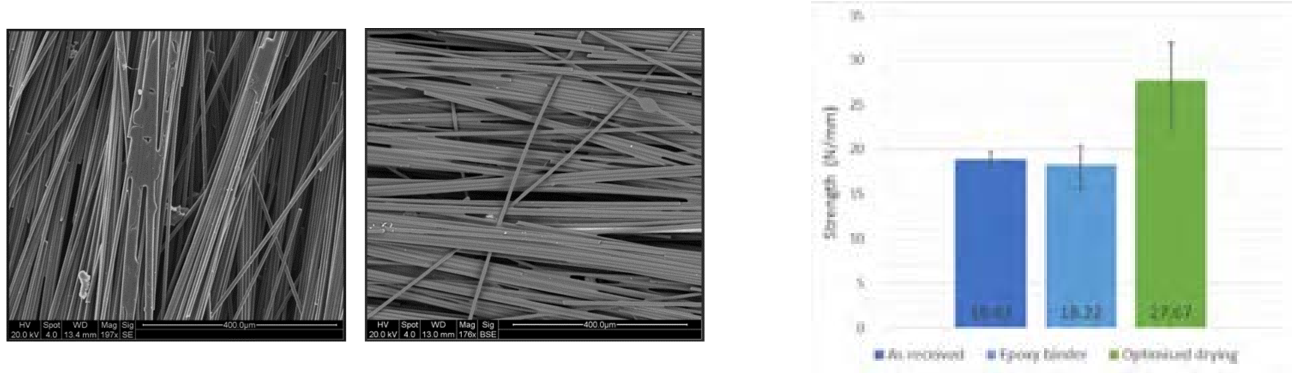


Figure 1. Optimisation of the drying and consolidation process was found to have the greatest impact on improving dry tape strength (at ambient conditions).

Surface Modification

The second stage of the rCF tape manufacturing process was surface application of powder epoxy. The 'As received' aligned rCF tape was found to not have adequate tensile strength to be processable in the UoE powder deposition line. The addition of aqueous binder, though found to have negligible influence on tensile strength, resulted in tapes being more stable during the powder application process.

Manual production of rCF powder-epoxy tapes (Figure 2), with estimated epoxy wt.% of 50 and 55, were measured to have ultimate tensile strengths of 13.9 ± 3.3 MPa. When rCF tapes were processed into laminated composites, by traditional infusion method, the off-axis strength was seen to be improved when aqueous epoxy binder was used to stabilise dry rCF tapes (see Figure 3).

Figure 2. Manual production of rCF powder-epoxy tapes.

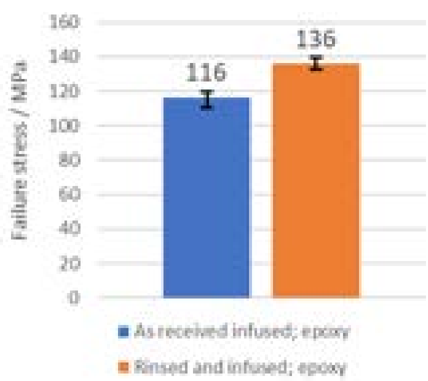


Figure 3. Off-axis strength was seen to be improved when aqueous epoxy binder was used to stabilise dry rCF tapes.

Progression of the Feasibility Study enabled the project scope to accommodate a trial of using carbon fibre recycled from end-of-life composites that were recovered by pyrolysis. This trial was limited to using the recycled carbon fibre in the alignment process. The image below shows the achieved fibre alignment. It can also be seen that fibre dispersion remains a significant challenge when end-of-life recycled fibre is used (see Figure 4).

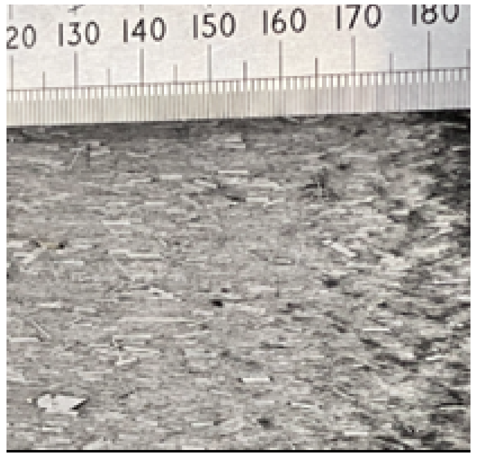


Figure 4. Demonstrating use of end-of-life recycled carbon fibre.

Several demonstration materials will be manufactured to conclude this study:

1. Baseline case with optimised washing in process (no additional treatment).
2. Epoxy binder to stabilise as described above – optimum processing conditions.
3. As (2) with 3% epoxy powder for hand laminating.
4. As (2) with 40% epoxy powder for compression moulding.
5. As (2) with SHD prepreg epoxy for autoclave cure.

The development within this project is related to the underlying alignment technology which is an active area of research for the group. This project has enabled a pathway towards a scaled-up process which will be added to the existing alignment process flow. The binder application and drying process will be added to the current 300mm wide process and proved-out before scaling further.

Obvious avenues for further funding are ATI & IUK funding. We are in discussions with potential partners. We hope to develop a process operating at commercial scale to compete with the other existing and developmental processes delivering intermediates to high performance applications in aerospace interiors and automotive. The technology developed within this project will be employed on the Hub Synergy project ECOTOOL to develop low cost, high performance integrally heated tooling.

Remaining scientific challenges to be explored in future work:

- Application method – how can the location of the binder within the core of the tape be controlled.
- What is the range of forming behaviour that can be achieved with different material combinations?
- What is the performance of the developed materials at different temperatures?
- Stability of material under processing parameters of downstream manufacturing processes, as well as temperature, tensile strength for material to be self-supporting (i.e., tapes will not break as they are fed though deposition machinery).
- Dewatering and removal/management of 'temporary' binder i.e., viscosity modifier.
- Chemical / Physical interactions of viscosity modifier and binder.
- Incorporate intermediate processing stage that conditions the tapes to have a topology that is more suitable for downstream manufacturing processes, i.e., flatter and smoother.
- Analysis methods for effective and efficient measurement of intra-tape binder content and localisation.
- In-process behaviour not fully characterised.
- Laminate performance not fully characterised but dependent on underlying tape structure.

Recently Completed Feasibility Study
Work Stream 8: Thermoplastic Processing Technologies
Research Theme: Recycling and Re-Use

Manufacturing Value-Added Composites for the Construction Sector Using Mixed Waste Plastics and Waste Glass Fibres

Project Team

Principal Investigator: Dr Dipa Roy, University of Edinburgh.

Co-Investigators: Prof Conchur O Bradaigh, University of Edinburgh; Prof Dilum Fernando, University of Edinburgh.

Research Team: Dr Danijela Stankovic, University of Edinburgh; Dr James Davidson, University of Edinburgh.

Industry Partners: John Manville, Paltech, Fibre Extrusion Technology (FET), Capvond, Composite Reinforcement Solutions (CRS).

Grant Award: £49,997 **Start:** 01/12/2021 **End:** 31/05/2022

Executive Summary

Packaging plastic wastes are mostly polyethylene (PE)-based and PE is not commonly used as a matrix in composites due to its lower mechanical properties. PE combined with reinforcement fibres, however, can produce useful composites with an optimum combination of toughness and stiffness. Here the opportunity lies in combining soft packaging waste plastics with waste reinforcement fibres. This was the main objective of this project to develop suitable technology that can combine waste mixed plastics (wMP) with waste glass fibres (wGF) to produce value-added composite products for the construction sector. Such technologies can divert huge volumes of low value wastes (that are not currently re-cycled) from landfill to a circular economy.

Thermoplastic composites were manufactured with wMP/wGF; the tensile, compressive and flexure properties were investigated for the wMP/wGF specimens. Cee-section members were produced as demonstrator components with wGF/wMP (and wGF/wMP/waste carbon fibre hybrid) composites and their axial compressive performance was assessed. The project fits well with the Hub objectives, as recycling and reusing waste materials are the prime focus in this project.

The preliminary results of this project have shown promising properties and two construction companies (end users) are interested in the work. A follow-on project (EPSRC Impact Acceleration Account-Commercialisation Project), which is a continuation of this project, has been funded and has commenced on October 1st 2022. There is a discussion ongoing for a patent application. The Cee-sections produced have shown very encouraging results and there is a possibility that will be taken forward in a separate industry funded project. An Outline Proposal (stage 1) has been submitted in the EPSRC Call and decision is awaited.

Aims and Objectives

The main objectives of this project:

- To identify a suitable technique that can produce thermoplastic prepreg material combining waste glass fibres (wGF) with mixed waste plastics (mWP) originating from flexible low value plastics packaging wastes.
- To manufacture wGF/wMP laminates and investigate tensile, flexure and compressive properties to assess their suitability for semi-structural applications (in consultation with industrial partners).
- To manufacture and test a demonstrator Cee-section member made of wGF/wMP (or their hybrid) for their compressive loading performance.
- Being a waste product, wGF/mWP composites provide a solution to reuse waste. Thus, re-using the wGF/wMP composites hybridised with rCF for Cee-section members that can be used in the construction industry provides a sustainable solution for waste treatment. In addition, other industrial applications include handrails, non-load bearing wall frames, or other semi-load bearing structures.

Outcome and Future Direction

The most challenging part in this project was the prepreg fabrication using wMP/wGF. Significant manufacturing challenges were encountered at the start of the project to produce wMP/wGF prepregs and the first trial was unsuccessful. Finally prepregs could be produced successfully, but at the very end of the project.

Work carried out before prepreg could be produced: Although prepreg could not be produced at the start of the project, but work was continued to manufacture wMP/wGF composites in lab scale. The manufacturing was not optimised at that point. The fibre content was only ~16 vol% and void content was high (approx. 15%). The mWP primarily consists of different grades of LDPEs. The mechanical properties of wMP/wGF composites (FVF ~16 vol%) were evaluated in comparison to virgin LDPE/wGF composites (FVF ~15 vol%). The properties are presented below in Figure 1.

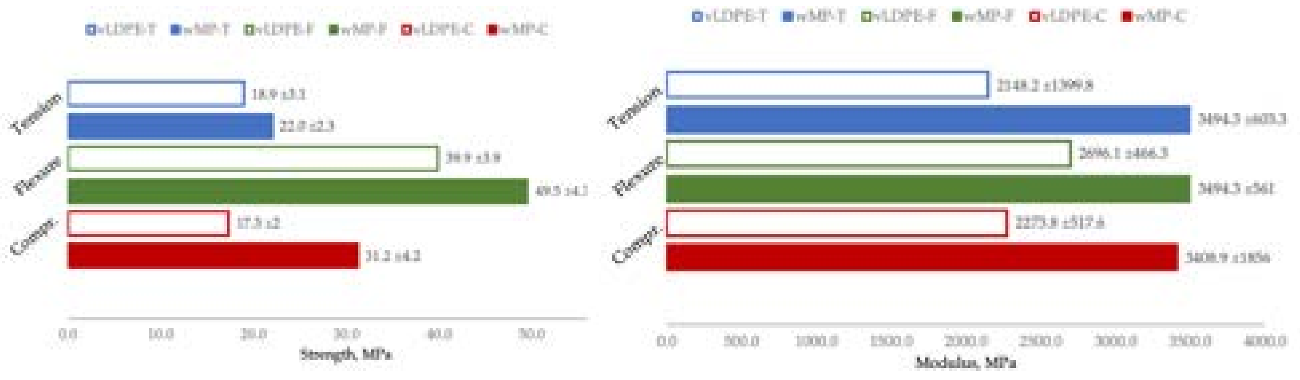


Figure 1. Tensile, flexural and compression strength (MPa) of wMP/wGF composites and virgin LDPE/wGF composites.

A second set of wMP/wGF composites were fabricated taking learning from the first set. The tensile modulus (~500 MPa) and tensile strength (~9 MPa) of unreinforced wMP were increased to ~5.5GPa and ~30 MPa with 23 vol% of wGF content (Figure 2a). The void content was still ~12 vol% and the manufacturing was not fully optimised. If the wGF content can be raised further (target 40-45 vol%) and the composite manufacturing is optimised, the tensile properties can be increased further. The predicted tensile modulus as a function of GF vol% is shown in Figure 2b (using Halpin Tsai eqn.). The interfacial bonding between the wMP and wGF is very promising, as shown in Figure 2c.

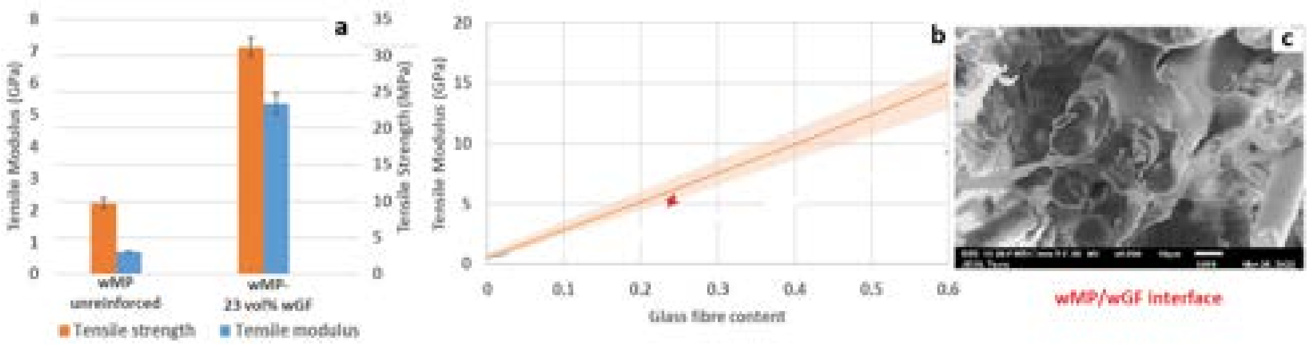


Figure 2. (a) Tensile properties of wMP/wGF composites and unreinforced wMP b) Predicted tensile modulus of wMP/wGF com-posites (red dot indicates experimental value with 23 vol% wGF) c) wMP/wGF interface.

Demonstrator component: Cee-sections as load carrying members were manufactured. Three 175mm web width and 55mm flange width Cee-sections (shown as 175*55PFC in table 1) were fabricated and tested under concentric axial compression (Figure 3). Due to manufacturing error, one of the specimens resulted in 25mm flange width instead of expected 75mm (this specimen is shown as 175*25PFC in Table 1). In addition, one 175*55PFC hybrid specimen was fabricated from mWP reinforced with wGF and recycled carbon fibre (rCF). Once fabricated, specimens were tested under concentric axial compression (Figure 3). The hybrid one performed extremely well and opened up new opportunities of hybridisation. The results of the tested fibre reinforced waste plastic Cee-sections are given in Table 1. Results from HFT Cee-sections and a similar steel Cee-section are also given in Table 1 for comparison.

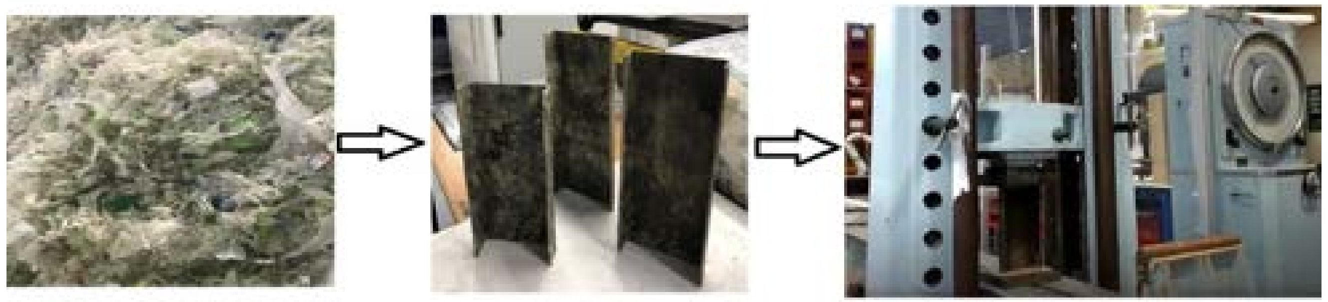


Figure 3. wMP/wGF converted into Cee-sections.

Table Comparison of current study results with existing test results

Section	Materials	Source	Ultimate load, kN	Weight specific load capacity, kN/(kg/m)
175*55PFC	wGF/wP		5.5	5.6
175*55PFC	wGF/wP		7.1	8.4
175*25PFC	wGF/wP		4.7	5.6
175*55PFC	wGF/rCF/wP		14.1	15.1
130*40PFC	GFRP-Timber	[4]	14.7	25.7
C15012	steel	[4]	48.5	20.8
83*34PFC	GFRP-timber	[5]	13.0	26.7
108*54PFC	GFRP-timber	[5]	17.7	22.0
238*79PFC	GFRP-timber	[5]	27.1	19.1
150*75PFC	GFRP-timber	[3]	16.5	16.3
150*75PFC	NFRP-timber	[3]	23.4	14.7
150*75PFC	NMFRP-timber	[3]	24.5	14.3

GFRP glass fibre reinforced polymer
NFRP biotex flax fibre reinforced polymer
NMFRP hemp fibre reinforced polymer
wGF-waste GF,
wP-waste plastics and
wGF/rCF/wP is a hybrid Cee section.

Table 1. Results from HFT Cee-sections and a similar steel Cee-section.

Prepregs Produced

A discussion is ongoing for a patent application. No details are mentioned here on prepreg or composite manufacturing. The composites manufactured from prepregs are shown in Figure 3. The mechanical characterisations, void content and fibre volume fraction analysis will take place in the IAA project.

- An EPSRC Impact Acceleration Award project (£76,840) has been funded to continue this work and the project has started on 1st October 2022. Capvond is industrial partner in this commercialisation project. The prepreg produced in the Feasibility Study project is being used in the IAA project as the starting material.
- The work in the IAA project is being carried out in consultation with Capvond keeping in mind the possibility of translating these composites into real products.
- A discussion is ongoing between University of Edinburgh, our industrial collaborators Johns Manville and Paltech for a possible patent application.
- We are also in discussion with BMI group regarding the possibilities of applying such composites in their product line.
- An outline proposal has been submitted to EPSRC Call and we are awaiting the decision.
- A discussion is ongoing with an industry to take forward the Cee-section work.
- There is a strong potential of real societal impact as industrial partners are involved and highly interested in the work.

Figure 4. Composites manufactured with waste materials.

Recently Completed Feasibility Study
Work Stream 8: Thermoplastic Processing Technologies
Research Themes: Recycling and Re-Use; Rapid Processing Technologies; Inspection and In-Process Evaluation

Rewinding Tape Laying: Can Direct End-of-Life Recovery of Continuous Tapes be a Step-Change in the Sustainability of Thermoplastic Composites

Project Team

Principal Investigator: Dr Davide de Focatiis, University of Nottingham.

Co-Investigators: Dr Samanta Piano, University of Nottingham; Dr Michael Johnson, University of Nottingham.

Research Co-Investigator: Dr Andrew Parsons, University of Nottingham.

Industry Partners: Boeing, Comfil.

Grant Award: £50,000 **Start:** 01/11/2021 **End:** 30/06/2022

Executive Summary

This project explored the feasibility of recovering continuous thermoplastic prepreg from simulated end-of-life parts by a controlled thermal peeling process in such a way as to make the peeled plies re-useable in new parts with minimal post-processing. The fundamental challenges in this project lay in achieving effective separation of laminates with minimal disruption/damage of the fibres.

Despite thermoplastic composites being touted as recyclable materials, the actual means of doing so remains relatively poorly realised. The most recent comprehensive review on continuous fibre thermoplastic composites recycling identified only shredding, pyrolysis, and solvent removal as existing recycling methods. With high value continuous fibre thermoplastics all these methods result in either a downgrading of fibres, a waste of matrix material, or environmental issues and limitations with solvent solubility.

The Feasibility Study was able to successfully demonstrate that peeling of thermoplastic composites can be achieved with minimal force at temperatures close to the melting point of the matrix. It was also discovered that some composite materials also lend themselves to cold peel. The peeled tapes had higher surface roughness than the virgin materials, but the recovered materials were successfully remoulded into new components. The stiffness of the components made with peeled tapes is almost identical to that of components made with virgin tapes, and the strength is still under investigation.

The opportunity for impact is considerable, but there remains research to be done with respect to peeling a more realistic component and doing so in a more automated fashion. Digital twinning and automation will also need to be considered in a future study in this area.

Aims and Objectives

Although >100,000 tonnes of composites are produced in the UK each year, less than 15% is recycled, often through disruptive and energy intensive processes. Thermoplastic composites are by their very nature thermoplastic and offer the same unique opportunities for debonding and direct recovery without downgrading as they do in plastics manufacturing. Considerable understanding exists in the bonding mechanisms of thermoplastic prepregs, particularly since the peel test is widely used in characterising part quality. The aim of this project is to explore the feasibility of demanufacturing a thermoplastic composite through a controlled peel process. The objectives include: (1) the instrumentation of the peel process in order to establish optimal conditions for peel; (2) the identification of suitable metrological techniques for evaluating peel quality; (3) the evaluation of the mechanical performance of components remanufactured from peeled plies.

The fundamental challenges in this project lay in effective separation of laminates with minimal disruption/damage of the fibres. Interlaminar slip happens readily in thermoforming at melt temperatures and so peel with or without the insertion of a separating tool appears eminently achievable. Process degradation of the matrix may be a matrix-specific challenge which will require refinement of the thermal control. When dealing with high performance resins such as PEEK, PAEK and PEI, resin recovery by a peeling route could be enormously valuable, environmentally sustainable, and appears as yet entirely unexplored.

There are undoubtedly areas of industrial interest as the societal drivers for sustainability and the circular economy continue to apply pressure to the composites industries to become greener.

Outcome and Future Direction

- **Instrument a simplified peel tester with controlled heating for tape separation**
  Lack of adhesion to metallic substrate meant that a conventional peel rig was not suited. A simple 2 ply peel set-up was devised, both at a small scale under isothermal conditions for in-strumented study, and at a larger scale with localised heating for material recovery. Static loads were found to be suitable at both scales. The larger scale peel was supported by thermocouple and IR camera temperature measurements.
- **Establish the conditions (eg. temperature, force, speed) required to successfully peel a layer of continuous thermoplastic tape from a simple consolidated structure**
  Requirements for combinations of temperature and force of matrix detachment were explored at small scale using a rheometer with a highly controlled environmental chamber in three modes: transverse extension, lap shear, and small scale peel. Larger consolidated plies were successfully separated to produce two layers. Peel forces were generally low and peel rate was effectively limited by the rate at which heat could be transferred to the tapes. In some thermoplastics (PP/glass and PBT/glass) the separation could be achieved at room temperature with only marginally larger forces.
- **Determine the most appropriate metrological technique to assess the viability of recovered material (in terms of waviness, matrix distribution, defects)**
  An Alicona system utilising variable focus was successful in acquiring gross morphology and provided sufficient resolution to observe fibre alignment, waviness and defects. The system was used to study surface roughness of small scale and large scale peel samples. After peeling with no post-processing the peeled tapes had a higher surface roughness than the virgin tapes by around 1 order of magnitude, but were sufficiently flat to enable hand lay-up for post-processing. Some fibre disruption could be observed in the peeled tapes using a backlight.
- **Attempt basic re-processing of peeled pre-pregs and determine composite properties**
  Peeled tapes were successfully repressed into composites, and no obvious flaws could be seen by eye. The composite parts were cut into test specimens for subsequent stiffness and strength testing. The stiffness measurements of composites made from peeled tapes are comparable to those from virgin materials, and the strength measurements are still in progress.
- **Provide a framework and initial data for a core project addressing the automated circular manufacturing of thermoplastic composites**
  The project has produced considerable experimental data and observations, and these are in the process of being written up in two journal articles. The data is also being presented at two conferences.

The opportunity for impact is considerable, and there remains research to be done with respect to demanufacturing of more realistic components, as well as the automation required to achieve this at scale. There is much promise in being to exploit digital shadows of components in order to plan and execute the demanufacturing. A 2020 patent from Germany has been identified that overlaps some of the concepts concerning peel of thermoplastic plies, but no publications have arisen relating to this. In order to circumvent this, future work may also focus on thermosets and vitrimers which are out of scope of the patent.

The scope of demanufacturing composite components is broad and the current state of research (TRL2, MRL1) lends itself well to a core project in a future hub, or to a larger EPSRC funded project involving multiple partners with expertise ranging from composites manufacturing through to digital twinning, automation, materials technologies and life cycle analysis.

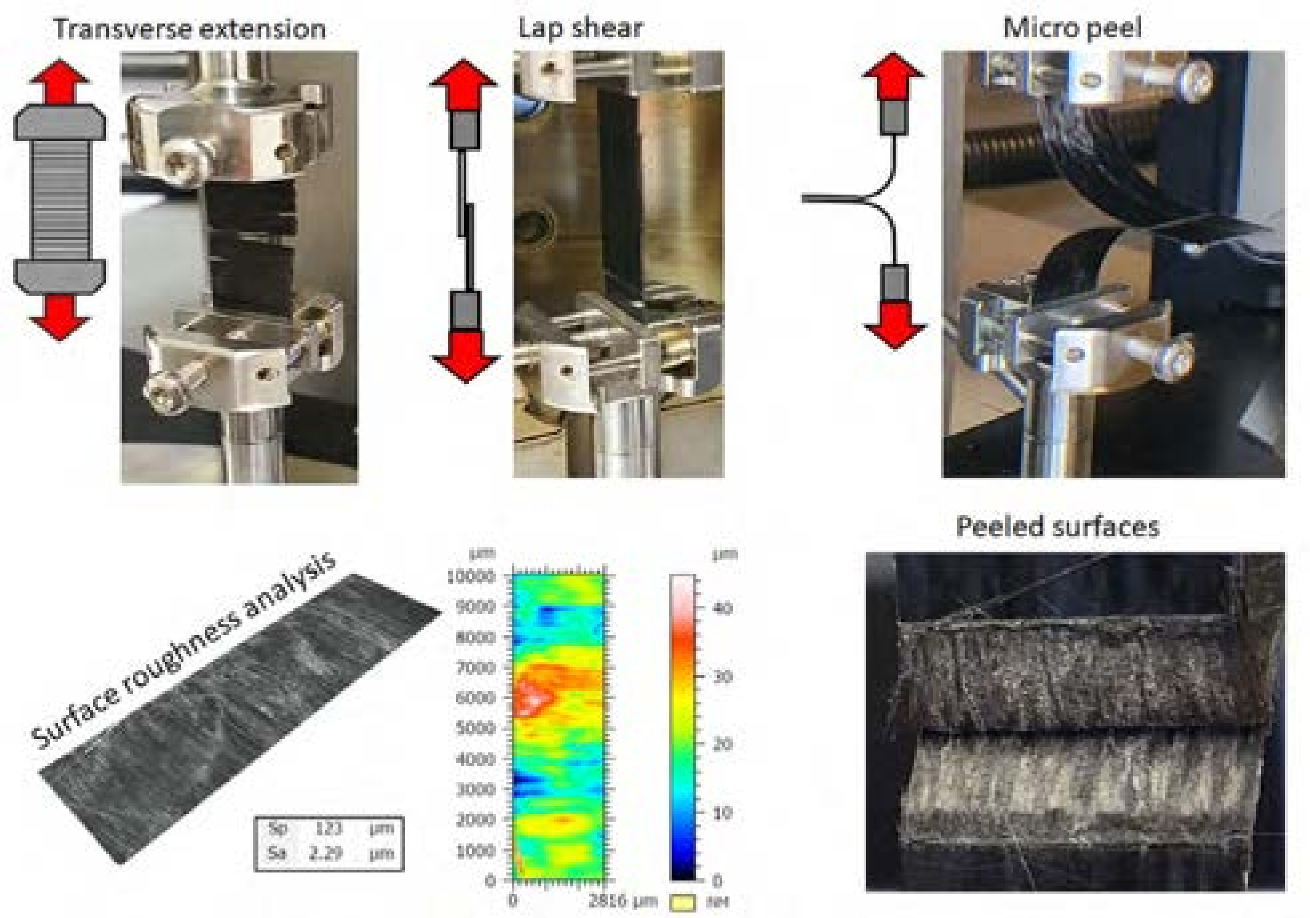


Figure 1. Methods employed to study the detachment of the matrix in order to peel consolidated composite plies. The surface roughness of the peeled surfaces was also recorded.

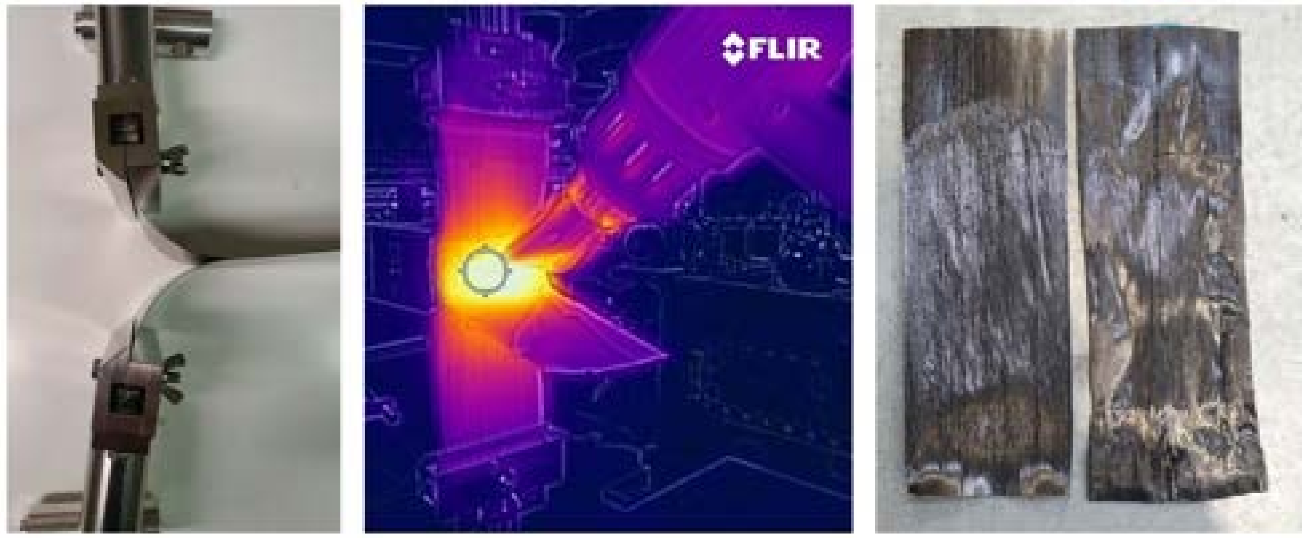


Figure 2. Large scale peeling of consolidated composite plies was achieved using heat and a small load. The peeled plies showed some surface disturbance but could be reprocessed into components with comparable properties to virgin plies.

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:** 31/12/2023

Executive Summary

Accurate permeability data is key to high-fidelity resin flow simulations for Liquid Composites Moulding (LCM) yet remains an unsolved challenge due to variabilities at different length scales. This project will bring powerful numerical methods for statistically accurate permeability calculations and filling fundamental knowledge gaps.

The research fits with the Hub's overall aim/objectives via the following Work Streams (WS):

- This project will, on the one hand, benefit from the outcome of WS2 (e.g. using TexGen to generate unit cells), and on the other hand, provide useful feedback to help optimise fibre architectures from the perspective of permeability uncertainty. There is also a potential to integrate the FFT solver into TexGen to form an integrated design-analysis software, as a complement to the Grid-Average approach.
- The statistical datasets on permeability from this project can be useful for the Bayesian inversion algorithms that is being developed by WS5, in complement to the experimental data collected from sensors. Also, the FFT solver can potentially be plugged into an active control system involving resin flow simulations, and thus help reduce the processing time by accelerating the solution of the physical models.
- This project will be in close connection with WS6. It will acquire input about the preformed textiles' geometries from WS6 and the outcome on permeability statistics will serve as useful guidelines for WS6 to create high-performance preforms suitable for liquid moulding. WS6 presented some techniques for minimising winkles during preforming, namely intra-ply stitch removal and inter-ply friction modification. This project will analyse how the techniques affect local permeability.

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 input 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 Fellowship Project will address the challenges related to permeability variability through an innovative numerical technique based on FFT methods. This project will primarily focus on NCFs, though the developed methodology can be readily applied to other textiles. The three work packages (WP) are as follows:

- **WP1 Development of Multi-Scale Numerical Models**
  To alleviate the issue related to computational cost, this WP will establish a large-scale simulation framework based on the Fast Fourier Transform (FFT) methods. This framework will enable efficient parallel computing with high performance computing (HPC) systems.
- **WP2 Permeability Uncertainty Correlated to Microstructural Variability for NCFs**
  This will involve a large number of experimental tests, mainly using X-ray Computed Tomography (XCT). Advanced and dedicated image processing techniques will be applied and developed for the 3D images of various NCFs. The extracted realistic microstructures will be input into the FFT solvers to calculate the effective permeability using full-field homogenisation techniques.
- **WP3 Development of Stochastic Surrogate Models**
  Although the FFT solvers developed in the previous WP can be efficient, they will still be computationally demanding. To reduce the requirement of HPC capacity, this WP will develop surrogate models based on machine learning techniques, such as convolutional neural networks and physics-informed neural networks. The big datasets produced from the XCT and the FFT simulations will be essential for training these surrogate models.

Progress

So far, the Fellowship has been focusing on WP1, with an additional effort towards to WP2 and WP3.

WP1 Development of Efficient Numerical Solvers for Permeability Calculation
Two FFT solvers have been implemented to predict the permeability of textile fabrics at microscale and mesoscale, respectively.

The microscale FFT solver is based on the algorithm recently proposed by Bignonnet[1], solving the Stokes equation. The implementation has been verified against analytical and previous numerical solutions of simple benchmark problems (with circle, square and sphere inclusions). This model has been implemented with Python and has not yet been parallelised. Even so, it shows an acceptable computation speed. To give an example, the FFT simulation using a 3D image of 121 million voxels (973x1003x124) took 5~7 hours to complete. The simulation used only 1 CPU. It will be largely beneficial if a parallelised version of the method can be implemented. However, this will be a secondary priority in this fellowship, due to two reasons: (i) the microscale permeability has less industrial relevance; (ii) the numerical solver at microscale, even if parallelised, will not be able to predict the permeability at macroscale including tow architectures. Therefore, the focus has been and will be put onto the mesoscale FFT solver. The microscale solver will be used as a supporting tool when required.

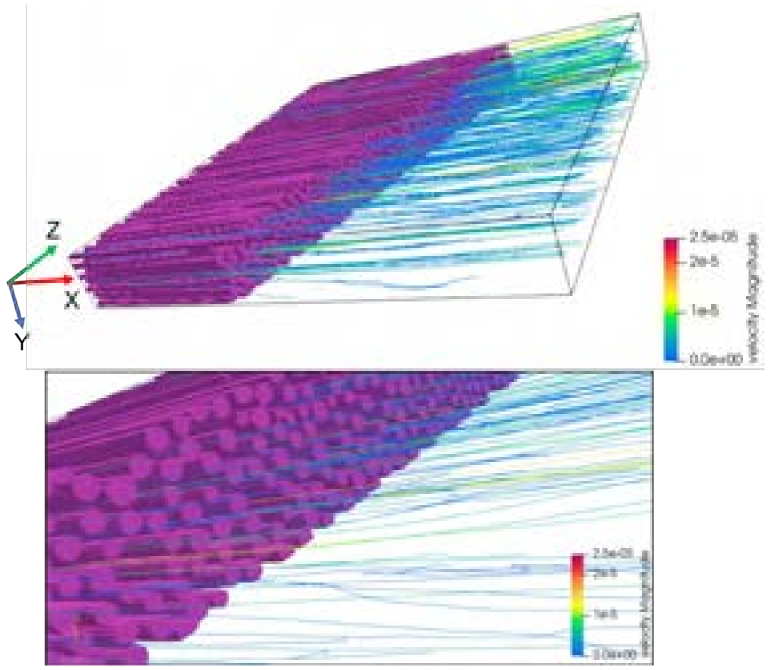


Figure 1. Streamline of the velocity field in the porous medium of carbon fibres, predicted by the FFT-Stokes solver. The fibre structure was extracted from the 3D images provided by the international Virtual Permeability Benchmark exercise[2].

The mesoscale FFT solver is based on a new algorithm proposed in this fellowship, which was inspired by a method recently published by Mezhoud et al[3]. The algorithm solves the Stokes-Brinkman problem using a fixed-point iterative procedure. The Anderson acceleration technique has been adopted, boosting the computation speed by up to 2~3 orders of magnitude, compared to the baseline algorithm of Mezhoud et al. The FFT Stokes-Brinkman model has been verified against analytical and previous numerical results in the literature. It has been implemented with both Python and Fortran.

The Fortran version also incorporates the parallel computing capability via the platform AMITEX[4]. Several large-scale simulations were conducted with this solver. A first example is shown in Figure 2, where the woven structure, generated with TexGen, was input into the FFT solver. For the mesoscale model, the local permeability of yarns also needs to be input. A simplistic parametric study is shown in Figure 2.b-d, using different values of local permeability. Both the local velocity fields and the homogenised macroscopic permeability exhibit a trend of the local permeability effect that is consistent with the intuition.

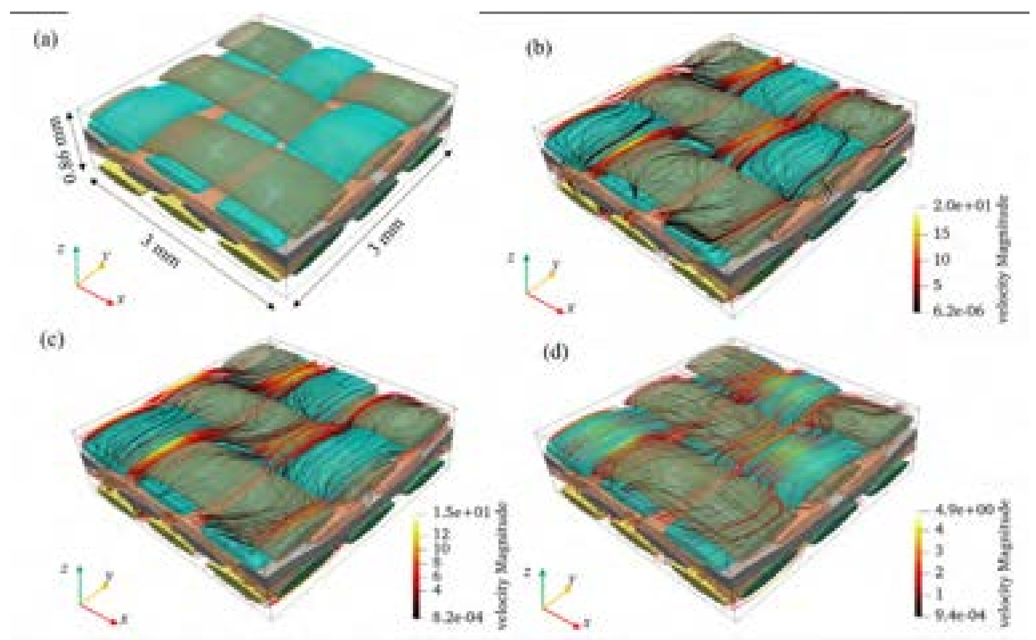


Figure 2. Flow in a dual-scale textile fabric. (a) geometry of the woven architecture (generated with TexGen); (b,c,d) velocity streamlines of the flow for different local permeabilities, k_s="diag" (10^{-6},10^{-7},10^{-7}) mm^2, k_s="diag" (10^{-4},10^{-5},10^{-5}) mm^2, and k_s="diag" (10^{2},10^{-5},10^{-5}) mm^2, respectively. The homogenised permeability tensors are K=$[3.59\ 10^{-4}, 3.59\ 10^{-4}, 3.64\ 10^{-5}]_{(X,Y,Z}$, K=$[4.85\ 10^{-4}, 4.85\ 10^{-4}, 6.76\ 10^{-5}]_{X,Y,Z}$ and K=$[2.36\ 10^{-3}, 2.36\ 10^{-3}, 1.11\ 10^{-4}]_{X,Y,Z}$, respectively for the three configurations.

This example, involving 8 million voxels, was solved using different numbers of CPUs, over the ARCHER2 UK National Supercomputing Service. The fastest computation took only 268 seconds (total time, including data reading and writing). The efficiency of the parallelisation is commonly quantified by a parameter called scalability. This is shown in Figure 3, suggesting a linear scalability until up to 128 cores for this problem of 8 million voxels, demonstrating an outstanding capability of the model in parallel computing.

This mesoscale FFT solver has also been applied to the current Virtual Permeability Benchmark exercise (stage 2). Running with 640 cores, the computations using the image of 164 million (700x680x345) voxels took ~700s, and those using the image of 1 billion (1923x1533x345) voxels took ~6000s. We believe that the parallelised implementation in this work presents the current state-of-the-art of numerical solvers for the Stokes-Brinkman problem, in terms of computation capacity.

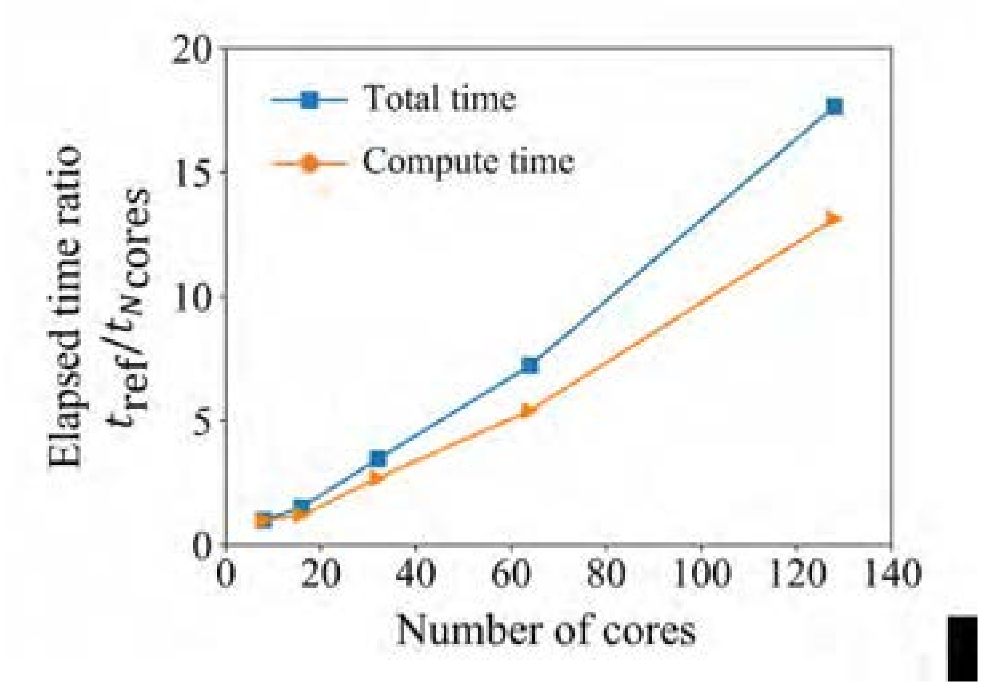


Figure 3. Scalability test of the proposed algorithm. The elapsed time ratio is defined as t_{ref} /t_{Ncores}, where t_{ref} is the time of the simulation with 8 cores, and t_{Ncores} is the time for the simulation with N_{cores} cores. The "total time" is counted from the beginning (data reading) until the final memory deallocation. The "compute time" only includes the time for the fixed-point iterations.

WP2 Permeability Uncertainty Correlated to Microstructural Variability for NCFs

The WP so far has focused on data generation from XCT scans and resin flow experiment.

XCT images of textile fabrics have been acquired using the facilities at University of Bath, University of Southampton (via the National X-ray Computed Tomography Hub) and University of Oxford. Multiple resolutions were used to scan the same set of samples. The intention of this is to prepare a database for training neural networks that reconstruct high-resolution information from low-resolution images (often called super-resolution technique). The ultimate goal is to combine this super-resolution capability with the permeability prediction, such that a quick low-resolution XCT scan of textile fabrics will allow the permeability to be accurately determined. In addition, a loading rig has been designed and commissioned for in-situ testing of dry fibre fabrics under lab-based and synchrotron-based XCT. This rig enables flat-surface compaction, as well as V-shape compaction to mimic the forming process at corner. This will be used for the upcoming experiment at DIAMOND light source (title: high speed microtomography of viscous deformation mechanisms in carbon non-crimp fabrics during compaction).

Resin flow experiment was conducted at University of Nottingham with Dr Andreas Endruweit and Dr Mikhail Matveev. Glass NCFs were used in this experiment. Prior to resin infusion, the fabric was subjected to different levels of shearing (manually controlled with a picture frame). The resin flow was recorded with an optical camera. The objective is to use a Bayesian inversion algorithm to map the heterogeneous permeability distribution of the tested NCFs, and then compare it with the FFT simulation results using the same microstructure identified from XCT images. This work is a synergy with the Core Project "Resin injection into reinforcement with uncertain heterogeneous properties: NDE and control".

WP3 Development of Stochastic Surrogate Models

In this WP, several simplistic examples have been used to train Yang Chen on deep learning, in particular neural networks.

Figure 4 shows the preliminary result from a convolutional neural network that reconstructs the high-resolution segmented image from a low-resolution greyscale image. It must be noted that this very promising result may be due to overfitting. More effort will be required to improve this model.

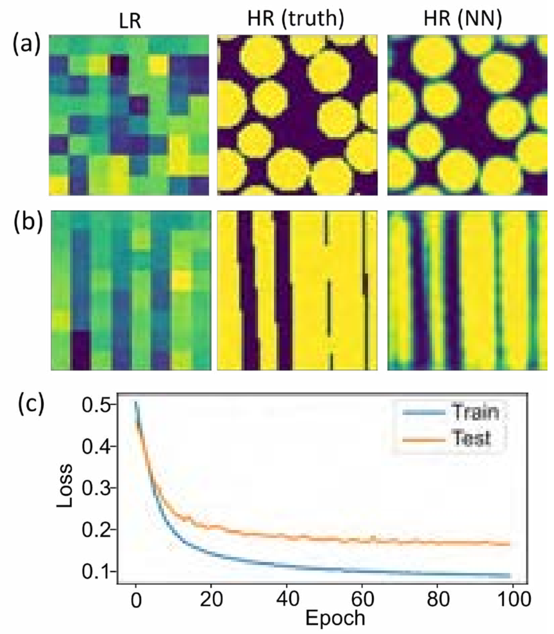


Figure 4. Preliminary result of a super-resolution convolutional neural network. (a-b) shows the two cross-sectional views of a sub-volume of carbon fibres. Thee three columns are low-resolution greyscale image (LR), high-resolution segmented image (HR (truth)), reconstruction of the neural network (NN). (c) shows the learning curve of the neural network.

In terms of surrogate modelling (predicting property from microstructure), the damage modelling data inherited from Yang Chen's previous work for CerTest project were used again for training purpose. A convolutional neural network has been developed, combining an encoder-decoder architecture with attention mechanism. This model showed a good capability in predicting the localised crack patterns in fibre composites[6]. It can potentially be adjusted to predicting the flow in fibre textiles, due to the similarity of the two problems.

The future focus will be switched from the development of FFT solvers to the development of machine learning techniques for (i) processing the 3D image data that are already and will be collected in WP2 and (ii) building the surrogate for permeability prediction using the data generated with the FFT solvers. Furthermore, an exciting approach that should be explored is physics-informed neural networks, which is an elegant framework for merging experimental/simulation data and fundamental physical principles. All these developments will lead to a stochastic understanding of the permeability variability of textile fabrics.

[1] Bignonnet, François. "Efficient FFT-based upscaling of the permeability of porous media discretized on uniform grids with estimation of RVE size." Computer Methods in Applied Mechanics and Engineering 369 (2020): 113237.
[2] Syerko, E., et al. "Benchmark exercise on image-based permeability determination of engineering textiles: microscale predictions." Composites Part A: Applied Science and Manufacturing (2023): 107397.
[3] Mezhoud, Sarra, et al. "Computation of macroscopic permeability of doubly porous media with FFT based numerical homogenization method." European Journal of Mechanics-B/Fluids 83 (2020): 141-155.
[4] https://amitexfftp.github.io/AMITEX/index.html
[5] https://amitexfftp.github.io/AMITEX/index.html
[6] Preprint: "Full-field prediction of stress and fracture patterns in composites using deep learning and self- attention" DOI: 10.13140/RG.2.2.17744.17924

Monitoring of Microwave Cure Process using Novel Planar Optical Sensors

Project Team

Principal Investigators: Prof Janice Barton, University of Bristol; Prof Richard Day, Wrexham Glyndwr University; Dr Christopher Holmes, University of Southampton.

Research Team: Michael Godfrey (student).

Grant Award: £15,000 **Start:** 20/11/2020 **End:** 01/09/2022

Executive Summary

This study looked to understand two poorly understood and connected areas in microwave processing: residual stresses in cured components and temperature. The research question was answered in part with further development of sensor concept required to further progress.

Aims and Objectives

The original aim was to utilise new sensors (based on FHD planar silica) that demonstrated through-thickness strain and temperature measurement for assessment of exotherm and residual strains.

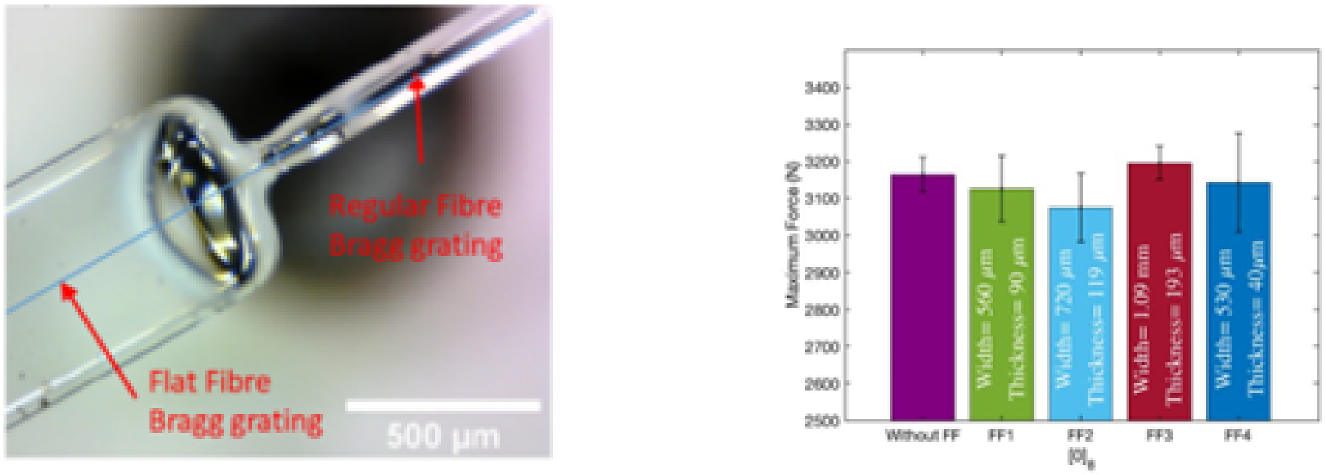
Objectives

- Comparative measurements of temperature, with surface mounted probes.
- Comparative measurements of residual stresses in microwave versus other processes which has not been explored previously.
- Initial experimental results that provide merit needed for a larger EPSRC grant for sensor development.

Outcome and Future Direction

This project was started with one platform (physically machined FHD doped silica [1]) and evolved into using another platform (flat optical fibre) due to challenges found with integrating and monitoring the sensors during harsh environment of composite cure. This was enabled by EPSRC grant EP/V053213/1 (Roll-2-Roll Manufacture of multilayer planar photonics).

Flat Optical Fibre was used due to connectorisation challenges with original technology. During this project a recipe for fusion splicing of regular fibre to flat fibre was successfully demonstrated (Figure 1a), permitting sensor embedment into composite and monitoring thereof during cure.

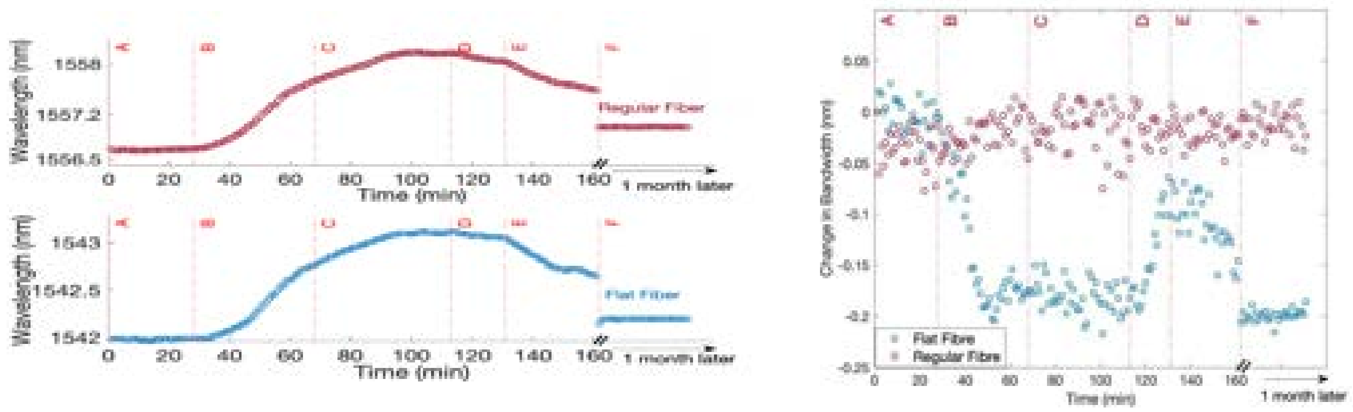


[a] [b]

Figure 1. [a] a micrograph image showing flat optical fibre [100um x 1mm cross-section] fused to regular optical fibre [125um diameter] [b] Bar chart showing short beam shear tests [EN2563] of new flat optical fibre embedded in CFRP coupons. Labelling indicates cross-sectional dimensions of flat fibre and purple is control [no sensor present].

As this was a transition to a new sensor platform it was important to reconfirm (to an extent) the structural integrity of their embedment, shown in Figure 1(b) to have minimal compromise under short beam shear tests (future research proposed to further this investigation, fully comprehensive study deemed out of scope for this project).

The second phase of this work was to ensure and characterise sensor response in an autoclave (based at Southampton), to ensure efficient use of time spent at Wrexham. For this test the sensors were placed inside a prepreg 150 x 150 x 2 mm flat panel with an 8-ply unidirectional layup. The sensors were aligned parallel to the carbon fibre strands. For a comparison flat fibre and regular fibre were tested (Bragg gratings placed in each type).



[a] [b]

Figure 2. The change in [a] Bragg wavelength and [b] bandwidth of the embedded Flat optical fibre [blue] and regular fibre [red].

Figure 2 shows the response of a Bragg grating in regular optical fibre compared to flat optical fibre. Wavelength response (Figure 2(a)) is largely dictated by temperature and strain. Interestingly, the smaller spectral response of the flat optical fibre indicates it is better assessing strain in the composite (lower thermal expansion) than regular fibre, corroborated by an external (reference) flat optical fibre (not shown here). What is more interesting is Figure 2(b), bandwidth. Change in bandwidth is understood to capture difference between through-thickness and in-plane (lateral to cross-section) strains.

The third phase of this work was to conduct tests at Wrexham Glyndwr, within their microwave cavity. For this experiment cross-ply laminate [02,904,02] was investigated, as it was believed that the layup would provide a larger response. A series of sensors were placed in the panel, shown in Figure 3, to test several concepts simultaneously.

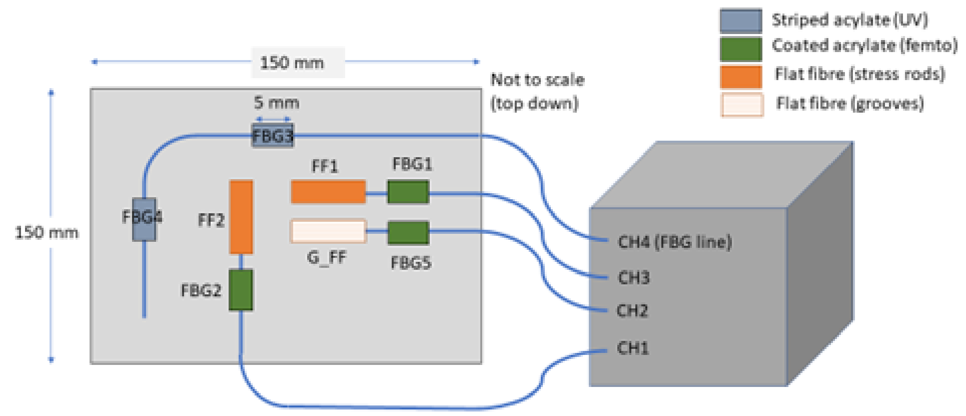
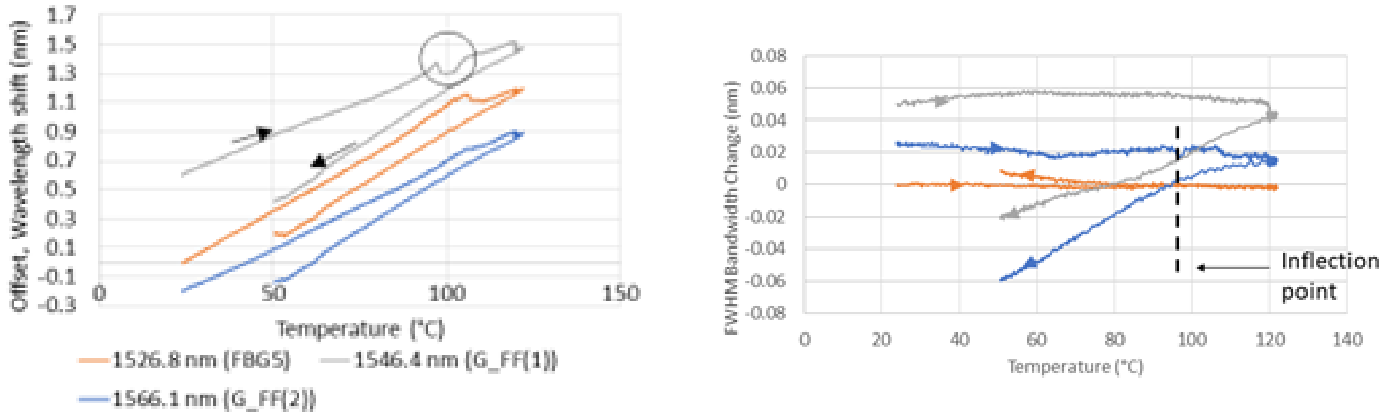


Figure 3 schematic showing placement of sensors into composite panel (cross-ply laminate [02,904,02]), including flat fibre (labelled FF) and regular fibre (labelled FBG).

A lot of data has come from these microwave tests. The most responsive sensor was a prototyped microstructured flat optical fibre (G_FF), response shown in Figure 4. Plotting wavelength response and bandwidth versus temperature shows some interesting changes transitioning through the wetting and gelling temperatures, where inflections are observed. As the two sensors in the microstructured fibre are different in optical response (as designed) it is in theory possible to extract residual stresses. To complete, this requires FEM simulation of strain-optic response (being conducted under a collaboration with University of Bari, Italy).



(a) (b)

Figure 4 Temperature versus (a) central wavelength and (b) bandwidth for the grooved microstructured sensor (G_FF). Showing two different sensor elements within the flat fibre sensor (grey and blue) and an in-line regular fibre comparison (FBG_5 in orange). Arrows indicated ramp-up and ramp-down parts of cure.

Despite initial challenges, most objectives have been met and papers successfully published from this work. There is a final piece of work that links simulation (FEM strain-optic response) to experimental results, to extract residual stresses. Proposed EPSRC funding for flat optical fibre development will help achieve full monitoring capability and drive towards eventual commercialisation. We have garnered industrial support (Airbus, GKN Aerospace, McLaren Automotive) and other Hub members (University of Nottingham, University of Warwick, University of Hertfordshire) in addition to University of Southampton, University of Bristol and Wrexham Glyndwr, to further progress this work, subject to funding.

Publications

- Holmes C., Godfrey M., Mennea P.L., Zahertar S., and J. M. Dulieu-Barton. Flexible Photonics in Low Stiffness Doped Silica for use in Fibre Reinforced Polymer Composite Materials, Optical Materials (Amst), vol. 134, p. 113133, (2022).

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.

Research Team: Mr Lichang Lu, Loughborough University; Mr Sandy Guo, Loughborough University.

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

Grant Award: £205,711 **Start:** 01/09/2022 **End:** 30/10/2023

Context

With the ever increasing demand for zero-impact, clean and sustainable manufacturing, the environmental impact of the composite production and end-of-life (EoL) stages, apart from their advantages during the use phase, need to be considered. Efforts have been dedicated towards end-of-life solutions for carbon fibre recycling (Gen2), as well as new manufacturing methods (out-of-autoclave) away from traditional energy and capital-intensive autoclave based methods. Nevertheless, an innovative yet industrially feasible manufacturing instrument to provide a highly energy-efficient and safe manufacturing route to deliver a step-change in the manufacturing stage of composites is still missing. The composite industry is consequently falling short of meeting the growing demands for the sustainability and a circular economy.

This project aims to close the loop for the composite industry, developing an energy efficient and highly safe manufacturing tooling based on recycled composite waste for advanced composite manufacturing. The key novelty of this research is its capability to achieve an energy efficient and intrinsically safe 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 composite waste will be upcycled as novel value added heating sources towards a circular composite economy. Compared to traditional metal tooling, this novel composite tooling can achieve a high resource and energy efficiency, alongside a closely matched coefficient of thermal expansion (CTE) between tooling and fibre reinforced composites. Therefore, the developed composite tooling can deliver reduced tooling costs and lead time, enabling a faster and cheaper manufacturing to benefit not only research laboratories but also industries like automotive and renewable energy (e.g. wind turbine blades). The new understanding developed in the field of manufacturing and resistive heating based on recycled carbon fibres (rCF) will greatly benefit academic communities. Although at a low TRL, the ultimate goal of this project is to develop a novel piece of manufacturing instrument based on upcycled wastes to achieve a faster, cheaper, safer, and energy efficient manufacturing, with the capability to satisfy various curing cycle requirements, contributing to the sustainable and clean growth of composite industry and unique capability of UK manufacturing sector.

Aims and Objectives

There is a considerable potential for composite tooling with integral heating for energy efficient manufacturing with closely matched CTE and reduced lead time. However, many challenges exist such as the safety hazards of current overshoot during exothermic thermoset curing, the intrinsic changes in electrical conductivity of carbon fibre over thermal cycles which require complex control system, and the durability of additive manufactured tooling. ECOTOOL will take a new approach: utilising positive temperature coefficient (PTC) effect where resistive heating with autonomous cut-off and full reversibility can be achieved based on the thermal expansion of polymer matrix at desired temperature, in combination with commercially available tooling prepregs, to develop a safe and self-regulating integral heating composite tool. By embedding this smart heating unit in series connection with rCF resistance heating sections (Figure 1.), alternating efficient heating and smart self-regulating units will be developed as integral heating layer in composite tooling. This proposal will therefore develop a new manufacturing instrumentation by upcycling rCF as conductive functional fillers to achieve both self-regulating heating and efficient resistive heating, together with designs capable of achieving various practical manufacturing requirements including different curing profiles and uniform heating over large areas.

ECOTOOL will use industrial scale compounding and assembly, replacing traditional heating trace wires for integral heated composite tooling. The project aims to develop an energy efficient composite tooling with integral heating and safety based on recycled composite waste, allowing flexible manufacturing with reduced cycle time, tailored tool shapes and heating profiles, capable to cure components out-of-oven for a wide range of composite applications.

The following objectives will be addressed in ECOTOOL:

- Fabricate sustainable composite tooling based on recycled carbon fibres with high energy efficiency (90% energy use reduction) and tailored heating profiles, closing the loop of advanced fibre reinforced composites;
- Examine the durability and reliability of developed tools, examine the quality of both instrument and composites manufactured by new composite tooling;
- Examine and demonstrate the environmental impact and embedded carbon footprint of developed composite tooling, including the high energy efficiency during the manufacturing stage of the components. The end-of-life options of developed composite tooling will also be explored in collaboration with Gen2.

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:** 01/09/2022 **End:** 30/08/2022

Context

Discontinuous fibre composites are currently the only realistic solution for making complex composite components in under 5 minutes. Associated manufacturing processes are easily automated, as fibre placement/alignment does not need to be precise, whilst offering the opportunity to incorporate recovered materials from waste streams or end-of-life components. Hybrid fibre architectures containing both continuous and discontinuous fibres are under development to expand the performance envelope of these materials, offering solutions to produce structural components within similar cycle times. 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. 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. The resulting process is rapid, with Takt times similar to conventional injection moulding (90-120 seconds), but the overall part cost is minimised by only using high-performance materials in areas where they are truly required.

Combining these dissimilar materials from different processing routes is challenging, with greater opportunities for higher levels of variability and critical defects. The degree of bonding at the overmoulding interface is typically the weakest point of the structure and can lead to significant weight penalties if not designed correctly. Pre-consolidated inserts must be ideally held below the melt temperature of the polymer, in order to withstand the high injection pressures, which can lead to poor adhesion between the insert and the overmoulding material. 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.

Furthermore, the melt flow distance also influences the bond strength, as the melt temperature decreases along the length of a rib during injection. It is therefore challenging to measure the interfacial strength for overmoulded parts because of the variability experienced due to the mixed failure modes and non-planar fracture sites, resulting from the interaction of the continuous fibres with the short-fibre injection moulded materials. It is also difficult to use coupon tests to capture the size and scale effects that occur in more complex geometries.

These challenges could potentially be addressed through greater use of robust simulations, to virtually explore the effects of processing parameters (temperature, injection pressure), material parameters (Vf, fibre length) and design (geometry, tooling) on final part quality, prior to committing to physical trials. This would increase the number of applications where overmoulding can be applied (e.g., UAVs) and help considerably reduce product development times and costs.

Aims and Objectives

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.

Novelty

Current thermoforming simulation tools are computationally inefficient and cannot be integrated with existing injection moulding simulation tools to model the combined process effects. The influence of the short-fibre injection phase on the integrity of the organosheet insert is commonly overlooked. This project sets to develop new numerical tools that can efficiently support the design and manufacture of overmoulded thermoplastic composites, building upon existing expertise and constitutive models available at the University of Bristol (UoB) and the University of Nottingham (UoN).

Timeliness

Wider adoption of the injection overmoulding process will help to reduce the sector's dependency on thermoset-based materials for producing structural components, offering a more sustainable thermoplastic-based alternative that can be more readily recycled. In addition, injection moulding compounds readily use short fibres (<5 mm), providing a circular economy for thermoplastic composites waste.

Transformative Aspects

Thermoplastic injection overmoulding has the potential to offer aerospace quality components at automotive production rates, but the effective combination of these two manufacturing processes makes component variability a concern. Thermoforming and injection moulding both share complex time, temperature and pressure dependencies, which make overall process optimisation difficult by trial and error. A dedicated process model will avoid costly mistakes and allow a reduction in process variability through identification of robust process parameters. It will thus unlock more rapid industrial uptake of this high-rate deposition process, offering production volumes exceeding 100,000 parts per annum.

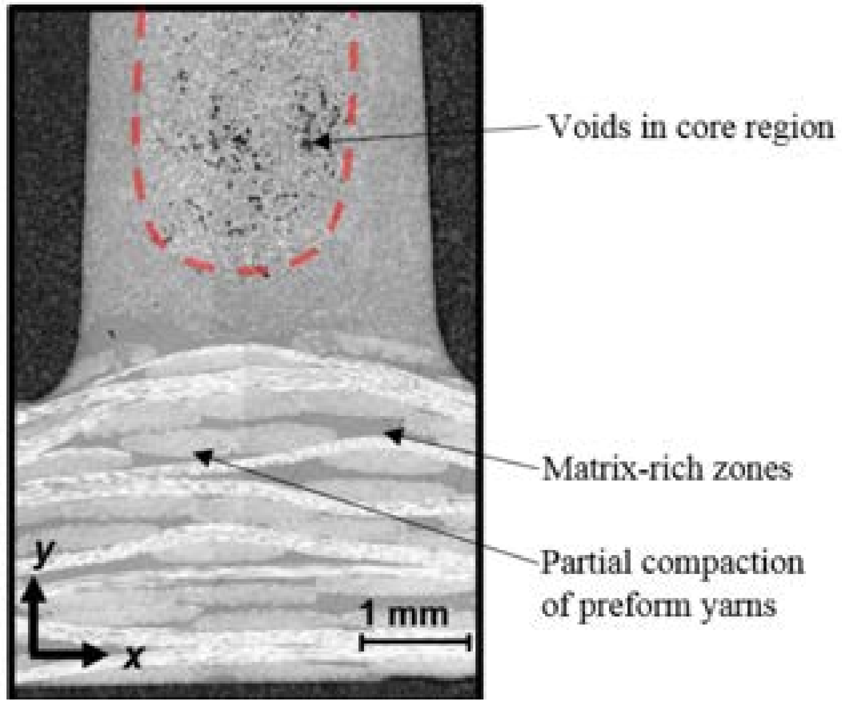


Figure 1: Bondline defect in an overmoulded part created by a differential of pressure in the organosheet [1].

[1]Valverde M.A., Kupfer R., Wollmann T., Kawashita L.F., Gude M. and Hallett S.R. Influence of Component Design on Features and Properties in Thermoplastic Overmoulded Composites, Composites Part A: Applied Science and Manufacturing 132, 105823 (2020).

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 Conchur O Bradaigh, 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.

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

Grant Award: £199,865 **Start:** 01/09/2022 **End:** 30/09/2023

Context

This project brings together expertise in in-situ moulding at the University of Edinburgh with expertise in forming at the University of Nottingham and builds on a previous Feasibility Study on integration of thermoplastic in situ polymerisation (TPIP) with double diaphragm forming (DDF).

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 recently finished Feasibility Study established the basic process, determining processing parameters and de-risking manufacturing. This successor project will develop the technology to make parts with realistic geometries, using the new 'tea tray' DDF tooling at the University of Nottingham. It will demonstrate the ability to achieve effective forming using low viscosity resins and tie that to software developments in conjunction with ESI.

The DDF tool at the University of Nottingham is based on the tool at the AMRC and so the development pathway is streamlined. Using this link, the project can establish key components of the process (frame design, injection system requirements, drying, manufacturing window) to take this to TRL 3, before translating to the Catapult. The DDF matched tool provides an easily controlled temperature cycle at a medium scale to establish and de-risk the process before progressing to a larger, single sided double diaphragm tool using non-contact heating. The University of Nottingham have a small scale double diaphragm former and the AMRC have a much larger version (3 x 1.8 m), so there is an available pathway to progress to larger parts without the need for matched tooling. The process also enables the introduction of remouldable 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.

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-Investigators: Prof Ken Kendall, University of Warwick; Dr Lee Harper, University of Nottingham.

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

Industry Partners: Ford, DowAksa, Gestamp.

Grant Award: £193,278 **Start:** 01/11/2022 **End:** 30/10/2023

Context

This project will be based on the automated forming and compression moulding developments at the University of Nottingham and University of Warwick. These will be combined with novel prepreg re-processed technology to deliver zero-waste manufacturing solutions for structural composite components, using hybrid fibre architectures.

Composites manufactured using prepreg typically generate 30%-50% of manufacturing waste, which usually ends up in landfill, having negative impact on the environment and resulting in substantial costs. Research has shown that the CO_2 emissions associated with manufacturing virgin material is significantly higher (up to 80%) than for retrieving fibres from manufacturing scrap. Developing commercially viable solutions to reclaim and reuse carbon fibre prepreg is therefore of great industrial interest, increasing material efficiency, reducing manufacturing cost, and most importantly avoiding landfill. The key to prepreg reuse is to handle the manufacturing waste "here-and-now" to eliminate further cost and emissions during transportation, developing intermediate products that fit readily within existing manufacturing processes and infrastructures. Unlike existing hybrid moulding processes utilising commercial sheet moulding compounds (SMC) and continuous fibre prepreg, all of the fibre reinforcement for this project will be obtained from a single source of continuous fibre prepreg.

By using different cutting strategies, the same prepreg material can be transformed into different material phases with different purposes:

- Continuous prepreg acts as the primary structure responsible for carrying and transferring loads.
- Prepreg chip based SMC can be moulded to provide stiffening features such as ribs, or as a damage tolerant outer layer to protect the continuous plies.
- Prepreg patches can act as a sacrificial ply between the chip based SMC and the continuous prepreg to minimise disturbance to the continuous fibre architecture caused by the flow of SMC; or as a core material sandwiched between continuous prepreg plies to increase the flexural rigidity of the part.

Manufacturing of composites with hybrid fibre architectures has attracted great interest, which calls for research into new hybridisation strategy to maximise the use of different materials' functionalities and improve design flexibility. On the other hand, the current environmental crisis calls for more sustainable processing solutions to reduce costs, reduce carbon emissions and avoid landfill. The new process combining novel fibre architecture hybridisation and fibre recycling and reuse is essential to address these challenges.

The proposed new process not only addresses a significant sustainability challenge, but also offers several advantages over conventional SMC/prepreg hybrid moulding, such as greater design flexibility and potentially improved part quality and performance. It also eliminates resin compatibility concerns, as all material phases will contain the same formulation. The technology can also be applied to design of thermoplastic composites.

Aims and Objectives

This project aims to create a practical solution by co-moulding continuous fibre prepreg with both formats of waste prepreg (chips and patches) together to form a hybrid material. This creates an opportunity for producing highly optimised architectures by aligning the continuous fibres in the virgin prepreg with the principal stresses to satisfy the primary load case, whilst exploiting the waste materials for alternative functionalities, such as stiffening geometry (ribs), core material for sandwich panels, or for damage tolerance requirements. The patches can be cut as simple, nestable shapes to maximise material utilisation and minimise charge preparation times, and the remaining material from the prepreg scrap can be processed into chip-based SMC. The prepreg chips will be engineered to produce high levels of in-plane and out-of-plane material flow, whilst the slits in the prepreg patches will be used to improve the in-plane shear behaviour of the fabric. Both re-processed prepreg formats will require extensive trials to understand the optimum cutting patterns to achieve the desired in-mould effects.

This research aims to deliver a new hybrid compression moulding process combining discrete continuous fibre prepreg patches and prepreg chip based SMC from recycled prepreg manufacturing waste, along with the virgin continuous prepreg to achieve 100% material utilisation.

Key objectives include:

- Develop a robust re-processing method for manufacturing prepreg-based SMC based on UoW's existing compounding line.
- Determine the optimum chip size for the prepreg-based SMC through experimental flow characterisation to maximise the material's ability to flow both in-plane and out-of-plane.
- Explore a range of nesting strategies for prepreg patches through experimental compression moulding trials.
- Manufacture of demonstrator components using the proposed new hybrid moulding process to achieve zero-waste target.

4 Hub Training

We are currently training 44 PhD students, 50 EngDs and 44 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

This year 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 five day practical programme covering mould design, CNC tool programming, kit templating and nesting, laminating and inspection. The course has received positive feedback from all attendees and further sessions are planned in 2023.

Hub students and researchers at the August 2022 training course at Pentaxia

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, five exchanges have taken place and we continue to encourage our students to participate.

This year EngD student Lachlan Williams from the University of Bristol visited Airbus in Hamburg, Germany, and Hub researcher Andrea Codolini from the University of Cambridge visited the University of British Columbia with the view to strengthening links with the Hub and initiating a collaboration.

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.

This year Dr Oriol Gavalda Diaz from the University of Nottingham was appointed as the new chair following Dr Mikhail Matveev's promotion to an academic position within the Faculty of Engineering at Nottingham.

Researcher Network Committee

Dr Oriol Gavalda Diaz (Chair)	University of Nottingham
Ms Ángela Lendínez Torres	University of Nottingham
Mr Raul Andres Gomez Quinones	University of Bristol
Dr Monali Dahale	Ulster University
Patrick Sullican	University of Bristol
Dr Yang Chen	University of Bath

Early- Career Feasibility Studies

The projects funded following the Researcher Network Award call launched in July 2021 have both finished, and a new call was launched in December 2022. Applications that met the first stage criteria were invited to present a 10-minute overview to a panel made up of representatives from the Hub's industry partners. Funding of up to £10k per project was awarded for two projects focusing on the sustainable manufacturing of composites and addressing at least one of the Hub's five priority areas.

- Dr Monali Dahale, Ulster University, Mr Antony Samy, Ulster University, and Mr Joseph Humphries, University of Nottingham, *"Manufacturing and modelling of variable thickness near-net-shaped 3D woven composites for complex aerospace structures".*

- Dr Akram Zitoun, Brunel University and Dr Mehdi Asareh, Cranfield University, *"AITROCOMPS: AI-driven through-thickness reinforcement design optimisation for multifunctional composite structures".*

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 last year enabling an additional senior postdoctoral researcher to progress over a 3-year period to a permanent academic position in the Faculty of Engineering at the University of Nottingham.

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. As the end date for finalising the taught component of the EPSRC funded CDT was set to be 30 September, the last of the units were taught in week long blocks in August 2022. All EPSRC funded students finalised the formal taught component, with only the study tour left to do. It meant a very busy year for some of the newer recruits. To build on the experience gained, and to continue to offer an EngD in composites manufacturing, the IDC team set about designing a new programme that utilises existing taught units at the University of Bristol. The new programme was approved in July 2022, and recruitment to the programme has started.

The taught component is delivered over three years designed to engage students and provide 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 Net Zero. The units do not have pre or co-requisites and hence 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 with a business area related to the student's research and offers an opportunity to reflect on their research experience and it's wider ranging impact on society. Students are encouraged to use a variety of media in the final report to effectively communicate their findings.

The National Composites Centre (NCC) are providing full sponsorship of the students on the new IDC; the programme is currently seeking other industrial partners. 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. Two new EngD students were hired this year (see below) and it is envisaged that at least 5 more will be hired next year. Our new projects include: Through-Life Damage and Environmental Assessment, Recycled Fibre/Matrix Interfacial Properties, Composite Shielding against Directed Energy, High-Rate Automated Deposition of CFRP for Rapid Production, Advanced Tooling, In-Process Material Inspection and Verification, Re-Using Manufacturing Waste.

In May the long-standing Director of the IDC, Professor Ivana Partridge, retired. Her successor is Professor Janice Barton who led the development of the new programme. A new IDC manager Helen Howard and a new IDC administrator Caroline Perkins have recently started.

IDC New Starters for 2022-2023:	
	
Jack Davies, NCC Registered at University of Bristol, supervisor Dimitry Ivanov Project Title: Reducing waste and cost in large scale infusions through adaptive process control.	**Jordan Forbes Thomas, NCC** Registered at University of Bristol, supervisor Neha Chandarana Project Title: Smart composite pressure systems.

Successful EngD Vivas, Destinations and Forthcoming Thesis Submissions:	
Matt Etchells *"High-Pressure Resin Transfer Moulding (HP-RTM) Process Optimisation"*	Advanced Research Engineer at National Composites Centre, Bristol
Robbie Herring *"NDT vs manufacturing (composite wind turbine blades)"*	Research Engineer at Offshore Renewable Energy Catapult
Daniel Griffin *"Enabling data-driven research and development in composite product engineering: An over-braiding case study"*	Advanced Research Engineer at National Composites Centre, Bristol
Pete Calvert *"Pursuit of a repeatedly defect free, in tolerance as-moulded component through development of data-driven, adaptive, capable preforming and moulding processes irrespective of process variation"*	Industrial Composite Manufacturing Engineer for Airbus Operations
Harry Clegg *"Exploring the possibilities and pushing the boundaries of TTR"*	Director Nesbitt Clegg
Caterina Palange *"Sustainable cellulose nanofiber composites - The effects of surface modification of micro fibrillated cellulose on its dispersion and reinforcement potential in polyolefin composites"*	Project Manager at Sartorius Stadium Chromatography in Havant
Harry Barnard *"Composites to metal joining methodologies for high tensile load applications"*	Senior Design Engineer - National Oilwell Varco
Laxman Sivanathan *"Developing process control in contact moulding and infusion processing for low cost high volume manufacture of critical safety products"*	R&D Manager, Jo Bird & Company Ltd
Jakub Kucera *"Automating design For Manufacture" of Aerospace Composite Components"*	Research Engineer at the National Composites Centre, Bristol
Preetum Mistry *"Lightweighting of railway vehicles"*	Director of Growth at STUDIO AZAM
Petar Zivkovic *"Improvements and innovations in automated fibre placement"*	Industrial Composite Manufacturing Engineer - OMICI

To Graduate:	
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

Awaiting Viva:	
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

Professor Janice Barton and EngD students represented the IDC at 'Futures 2022' an outreach event that took place at SS Great Britain in Bristol in September.

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.

Last year we appointed a Hub EDI champion, Dr Connie Qian from the University of Warwick, to help 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. This year, an EDI Committee was created to help further achieve those objectives.

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	University of Nottingham
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

International Mission with the University of British Columbia

The Hub hosted a virtual international mission with the Composites Research Network (CRN) based at the University of British Columbia (UBC) in February 2022. CRN is a collaboration of academic and industry partners with a mission to translate research into practice for effective and low-risk knowledge-based composites manufacturing and design. The virtual mission was attended by more than 100 delegates from academia and industry (including automotive, composite manufacture, and software development). Initial presentations by Hub Director Professor Nick Warrior, and Professor Anoush Poursatip of the CRN, provided an engaging insight into the two organisations and their activities. Members of the CRN described the exciting work of the Knowledge in Practice Centre (KPC), whilst Hub members presented the innovative research currently being undertaken relating to curing, digitisation of deposition, and forming technology, with collaboration invitations being suggested in each. Convergent Manufacturing Technologies, a spin-off from the University of British Columbia Composites Group, discussed their role in solving the needs of industrial businesses through unique sophisticated simulation hardware and software. Early-career researchers from both the Hub and UBC, gave short presentations outlining current research in key areas including digitisation, thermoplastics, simulation, and the globally important field of sustainability. The session proved a success in creating a dialogue between Hub researchers and our colleagues in Canada, and with scope for several international links already being discussed, the Hub look forward to exploring new relationships and potential collaborative projects.

Sustainability Seminars

In conjunction with the National Composites Centre (NCC), the Hub participated in a Sustainability workshop at the NCC, Bristol & Bath Science Park, in March 2022. A combination of presentations and interactive sessions gave delegates the opportunity to discuss Sustainability challenges and developments within the Composites Manufacturing sector. The workshop aimed to highlight the sustainability activities within the NCC, strengthen links with the Hub and identify ongoing and future research challenges.

The Hub held a second Sustainability session in October 2022, at the AMRC, Sheffield, with an aim to build upon the successes of the first workshop. Similarly to the previous seminar, the topics of discussion were Life Cycle Assessment, design and manufacturing processes, sustainable materials and recycling methodologies. Over eighty individual research challenges were identified from the workshop sessions. The day was attended by representatives from several universities, research organisations, Catapult Centres and industry.

The output from the sessions can be found here: https://cimcomp.ac.uk/wp-content/uploads/2023/03/Roadmapping-Outputs-Sustainability-Challenges.pdf

MACH 2022

The Hub joined the Future Metrology Hub and the Future Electrical Machines Manufacturing Hub on a collective Hub stand sponsored by the EPSRC at The Manufacturing Technologies Association Exhibition in April 2022 at the National Exhibition Centre (NEC) Birmingham, UK. It was a great opportunity to engage with the other Hubs and connect on a national manufacturing level with the wider engineering community.

JEC World 2022

JEC is the leading international composites show and the Hub Business Development Managers, Simon Quinn and James Whyman attended the show held in Paris in May 2022.

There was representation from more than one hundred countries and over a thousand exhibitors presented their ground breaking innovations to 20,000 trade visitors. Key themes emanated from amongst the stands and speakers, notably sustainability, the circular economy and turning waste and recycling into opportunities. Attending JEC gave the Hub's new Business Development Managers exposure to the industrial international composites community, and an insight into their current challenges. Several contacts were made, for potential future collaboration and some early discussions and information sharing has already taken place.

UK Manufacturing Day

The Hub participated in the National Manufacturing Day, held on 7 July 2022 at the University of Nottingham. The Composites Lab and other labs within the Advanced Manufacturing Building opened their doors to the public and local schools, who were treated to short presentations and demonstrations delivered by the University's Engineering researchers and PhD students. The day was an enormous success with over 150 visitors attending.

A discussion about sheet moulding compounds led by PhD student Daniel Wilson.

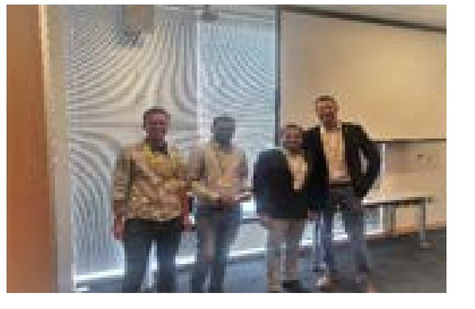
A live demonstration of prepreg compression moulding from Dr Andrew Parsons.

Hub Open Day

The Hub held its annual Open Day in September 2022 at the AMRC, Knowledge Transfer Centre, Sheffield, and was delighted with the attendance of over 130 international academic and industrial delegates.

Dr Stu Morris, Engineering Director at Pentaxia, led the first keynote presentation with a fascinating presentation on his background and connection with the composites sector. The second keynote speaker Josh Sherwood, Composites Research Engineer from GKN Aerospace, presented an informative, high-level overview of the ASCEND project, a cross-sector composite Technology and Supply-Chain development programme, joining the Aerospace and Automotive supply chains. There were interesting presentations on current Hub projects, and developments on the Technology Pull-Through Programme presented by Matt Scott from the National Composites Centre (NCC). Delegates were invited on an impressive tour of the AMRC facilities at the 'Factory of the Future Laboratory'.

This year's Young Engineers and Student (YES) competition, hosted by The Society for the Advancement of Material and Process Engineering (SAMPE UK & Ireland) invited students to participate in a 'Design and Make' competition to manufacture a composite crash structure that could protect an egg during a crash landing. There were three participating teams and the winning team were the University of Edinburgh Composites Group. It was a fantastic opportunity for students to put their composites design and manufacturing experience into action and represent their institution.



Tim Wybrow SAMPE committee board member presented the SAMPE competition prizes to the winning team 'The University of Edinburgh Composites Group', the team members were: Muhammad Waqas, Arun Kumar Alapati, Murat Celik and Thomas Noble.

Students and Researchers from all Hub spokes were invited to present a poster on their current research. The best placed posters were:

- 1st Place Dr Shuai Chen, University of Nottingham, "Prediction of Double Diaphragm Forming Defects for Large-Scale Composite Components".
- 2nd Place Dr Oriol Gavalda Diaz, University of Nottingham, "Reprocessability and Repairability of Vitrimer Epoxy Carbon Fibre Reinforced Polymers (vCFRPs)".
- Joint 3rd Place Joe Soltan, Industrial Doctoral Centre, University of Bristol, "Modular Infusion: Novel Approaches to Segregation and Control of Flow Fronts Within Liquid Resin Moulding".
- Joint 3rd Place Will Darby, Industrial Doctoral Centre, University of Bristol,"Overmoulding of Butt Jointed Aerostructures (OBStruct)".
- Joint 3rd Place – George Street, University of Nottingham, "Modelling Non-Isothermal Thermoforming Behaviour of CF/PA6 Composite Laminates".

The Hub supported The International Conference on Manufacturing of Advanced Composites (ICMAC 2022) on 14 September 2022 which was also held at the AMRC, University of Sheffield.

International Composites Summit (ICS)

Following the success of exhibiting at the first International Composites Summit (ICS) in 2021, the Hub returned in 2022. ICS is the only UK exhibition focused solely on the global composites market, bringing together leading industry professionals to address the worldwide opportunities within the sector. Hub members enjoyed talking to the composites community about the innovative work on manufacturing being conducted within our research projects.

The Hub team exhibiting at ICS, from left to right, Business Development Manager James Whyman, University of Nottingham, Administrator Joanne Eaves, University of Nottingham and Business Engagement Manager, Simon Quinn, University of Bristol.

Professor Nick Warrior and James Whyman at the Advanced Engineering Show.

Advanced Engineering Show

The Hub exhibited at the Advanced Engineering Show in November 2022. This show is the UK's largest annual engineering and manufacturing event, connecting OEMs, Tier 1 manufacturers, and supply chain partners with a host of interactive stands and demonstrations. The Hub's stand attracted an array of visitors from the Engineering community. The two-day event was a positive and engaging experience as new contacts were established and existing relationships were refreshed.

Composites Laboratory Tour - Advanced Manufacturing Building, University of Nottingham

It was our pleasure to host 40 Indonesian final-year undergraduate students at the University of Nottingham's Advanced Manufacturing Building, and introduce them to some of the world-class manufacturing equipment in the Composites Laboratory. The students are studying with the University of Nottingham for a semester on a programme directly funded by the Indonesian Ministry of Education. The programme is part of a broader strategic engagement between the University and Indonesia. Our PhD students and researchers were on hand to discuss their research, and answer questions.

Indonesian undergraduate students taking a tour of the Composites Laboratory at the University of Nottingham.

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.

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
Chair of the Researcher Network
University of Nottingham

Professor Janice Dulieu-Barton
Deputy 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

Dr Amir Rezai
Industrial Representative
BAE Systems

Mr Andy Smith
Industrial Representative
Gordon Murray Design

Ms Naomi South
EPSRC Representative
EPSRC

Mr Tim Wybrow
Industrial Representative
NEOS Composites

Dr Adrian Gill
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Vestas Wind Systems

Investigators

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Professor Janice Dulieu-Barton
University of Bristol

Dr Jonathan Belnoue
University of Bristol

Professor Richard Butler
University of Bath

Professor Richard Day
Wrexham Glyndwr University

Dr Davide De Focatiis
University of Nottingham

Professor Chris Dodds
University of Nottingham

Dr Andreas Endruweit
University of Nottingham

Professor Emile Greenhalgh
Imperial College, London

Professor Stephen Hallett
University of Bristol

Dr Lee Harper
University of Nottingham

Dr Philip Harrison
University of Glasgow

Dr Robert Hughes
University of Bristol

Dr Darren Hughes
University of Warwick

Dr Marco Iglesias
University of Nottingham

Professor Derek Irvine
University of Nottingham

Dr Dmitry Ivanov
University of Bristol

Dr Mike Johnson
University of Nottingham

Dr Mihalis Kazilas
Brunel University

Dr Eric Kim
University of Bristol

Professor Vasileios Koutsos
University of Edinburgh

Dr James Kratz
University of Bristol

Professor Andrew Long
University of Nottingham

Dr Mikhail Matveev
University of Nottingham

Dr Edward McCarthy
University of Edinburgh

Dr Euan McGookin
University of Glasgow

Professor Alistair McIlhagger
Ulster University

Dr Andrew Mills
Cranfield University

Dr Daniel Mulvihill
University of Glasgow

Professor Conchur O'Bradaigh
University of Edinburgh

Professor Ivana Partridge
University of Bristol

Dr Andrew Parsons
University of Nottingham

Professor Ton Peijs
University of Warwick

Professor Steve Pickering
University of Nottingham

Professor Prasad Potluri
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Dr Connie Qian
University of Warwick

Dr Andrew Rhead
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Dr Daniel Richards
University of Glasgow

Professor Paul Robinson
Imperial College, London

Dr Dipa Roy
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Professor Milo Shaffer
Imperial College, London

Professor Ian Sinclair
University of Southampton

Dr Alex Skordos
Cranfield University

Professor Adam Sobey
University of Southampton

Dr Michael Sutcliffe
University of Cambridge

Professor Ole Thomsen
University of Bristol

Professor Michael Tretyakov
University of Nottingham

Dr Thomas Turner
University of Nottingham

Dr Carwyn Ward
University of Bristol

Professor Nick Warrior
University of Nottingham

Dr Dongmin Yang
University of Edinburgh

Dr Han Zhang
Queen Mary University of London

Researchers

Dr Debabrata Adhikari
University of Nottingham

Dr Mehdi Asareh
Cranfield University

Dr Chrysoula Aza
University of Bath

Dr Ankur Bajpai
University of Edinburgh

Dr Hasina Begum
University of Warwick

Dr Kaan Bilge
Imperial College, London

Dr Aurele Bras
Cranfield University

Dr David Brigido
University of Bristol

Dr Dan Bull
University of Southampton

Dr Shuai Chen
University of Nottingham

Dr Yang Chen
University of Bath

Dr Andrea Codolini
University of Cambridge

Dr Lawrence Cook
Cranfield University

Dr James Davidson
University of Edinburgh

Dr Dorian Dixon
Ulster University

Dr Thomas Dooher
Ulster University

Dr Wenbo Duan
Brunel University

Dr Michael Elkington
University of Bristol

Dr Anthony Evans
Hexcel Composites

Mr Josh Evans
University of Warwick

Dr Ian Gent
University of Bristol

Mr Tharan Gordon
University of Bristol

Dr Robin Hartley
University of Bristol

Dr Alex Ilchev
University of Nottingham

Dr Adam Joesbury
University of Nottingham

Dr Vivek Koncherry
University of Manchester

Mr Anatoly Koptelov
University of Bristol

Dr Nataliia Luhyna
Wrexham Glyndwr University

Dr Dimitrios Mamalis
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University of Bristol

Dr Laura Pickard
University of Bristol

Dr Connie Qian
University of Warwick

Dr Arjun Radhakrishnan
University of Bristol

Dr Calvin Ralph
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Dr Neil Reynolds
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Dr Colin Robert
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University of Manchester

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AMRC Sheffield

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Dr Ric (Xiaochuan) Sun
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Dr Max Valentine
University of Bath

Dr Mario Valverde
University of Bristol

Dr Verner Viisainen
University of Cambridge

Dr Gabriele Voto
Cranfield University

Dr Lei Wan
University of Edinburgh

Dr Logan Wang
University of Bristol

Ms Rachel Weare
University of Warwick

Dr Xun Wu
University of Bristol

Dr Bohao Zhang
University of Bristol

Dr Jin Zhou
University of Cambridge

** Highlighted names are new starters in 2022/2023*

PhD Students

Syed Abbas
University of Manchester

Matthew Bower
University of Sheffield

Iain Campbell
University of Glasgow

Michael Causon
University of Nottingham

Murat Celik
University of Edinburgh

Matthew Collinson
University of Sheffield

Ubong Equere
Cranfield University

Salem Eroul
University of Nottingham

Dimitris Fakis
Brunel Composites Centre

Adam Fisher
University of Bristol

Albert Gibbs
University of Nottingham

Sandy Guo
Queen Mary, University of London

Joseph Humphries
University of Nottingham

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Irene Jimenez-Fortunato
University of Southampton

Anton Koenraadt
University of Warwick

Christos Kora
University of Nottingham

Guy Lawrence
University of Nottingham

Chanhui Lee
Imperial College, London

Yilong Li
University of Cambridge

Angela Lendinez Torres
University of Nottingham

Lichang Lu
Queen Mary, University of London

Shimin Lu
University of Nottingham

Vincent Maes
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James Mortimer
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William Mosses
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Antony Nixon
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Caroline O'Keefe
University of Bristol

Michael O'Leary
University of Bristol

Jinseong Park
University of Manchester

Gwladys Popo
University of Nottingham

Arjun Radhakrishnan
University of Bristol

Bethany Russell
University of Bristol

Usman Shafique
University of Nottingham

Sangeethsivan Sivakumar
University of Manchester

Alice Snape
University of Sheffield

Kazi Sowrov
University of Manchester

George Spackman
University of Nottingham

George Street
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Matthew Thompson
University of Nottingham

Kostas Tifkitsis
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Mark Turk
University of Bristol

Maria Valkova
Imperial College, London

Daniel Wilson
University of Nottingham

Jibran Yousafzai
University of Bristol

Fei Yu
University of Nottingham

Haoqi Zhang
University of Edinburgh

** Highlighted names are new starters in 2022/2023*

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University of Bristol
Elmar

Ashley Barnes
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Nikita Budwal
University of Bristol
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Ben Chappell
University of Bristol
iCOMAT

Harry Clegg
University of Bristol
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Alex Cochrane
University of Bristol
Rolls-Royce

Anastasios Danezis
Cranfield University
Heraeus

Will Darby
University of Bristol
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Jack Davies
University of Bristol
National Composites Centre

Sarvesh Dhiman
University of Manchester
M Wright & Sons

Mattia Di Francesco
University of Bristol
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Phil Druiff
University of Bristol
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Huw Edwards
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Matt Etchells
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Zoe Fielden-Stewart
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Vincent Gill
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Daniel Griffin
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Robbie Herring
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SHD Composite Materials

Claudia Jimenez-Martin
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Airbus

Dimitris Karanatsis
University of Nottingham
Hexcel

Jakub Kucera
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David Langston
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ORE Catapult

Jack Lindley-Start
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Josh Loughton
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Humza Mahmood
University of Bristol
Airborne Composites Ltd

Ffion Martin
University of Nottingham
Jaguar Land Rover

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Fiberlean

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Stelia Aerospace

Anagnostis Samanis
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Owen Taylor
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Laura Veldenz
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Simon Wilkinson
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University of Bristol
Airbus

Maria Zilidou
University of Bristol
Qinetiq

Petar Zivkovic
University of Bristol
Rolls-Royce

** Highlighted names are new starters in 2022/2023*

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 100 since January 2017.

2023

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169. Brown L. 'Automatic Generation of Predictive Models for Optimisation of Complex 3D Woven Structures'.

168. Codolini A. 'Experimental Investigation of Process-Induced Defects in DDF of Non-Crimp Fabric Preforms'.

167. Collinson M. 'Low Power Curing of Composites using Direct Electric Cure for Aerospace Applications'.

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

165. Holmes C. 'Integrated In-Process Sensing and Evaluation for High Value Composite Assets using Noval Flat Optical Fibres'.

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'.

160. Neunkirchen, S. 'Spectroscopic monitoring of prepreg properties'.

159. Nguyen, D. 'In-process detection and automatic response to AFP deposition defects'.

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'.

153. Samanis, A. 'Real-time identification of material properties and process parameters for induction manufacturing of composites'.

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151. Traiforos, N. 'An experimental investigation and modelling of the factors contributing to spring-in of composite L-shape structures'.

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147. Aslani, A., Pickering, S., Turner, T. 'Assessing the impact behavior of highly aligned fiber hybrid composites'.

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'.

145. Dahale, M., Samy, A.A., Ralph, C., Archer, E., Brelsdford, R., Stewart, G., Hodge, S., McIlhagger, A. 'Influence of textile design plan on the performance of 3D woven carbon/epoxy composites'.

144. De Focatiis D.S.A., Endruweit, A., Joesbury, A., Choong G.Y.H., Call, D., Ghose, S., Johnson, B. A., Park, C.Y. 'Development of the ASTM D8336 21: Standard Test Method for Characterizing Tack of Prepregs Using a Continuous Application and Peel Procedure'.

143. Dulieu-Barton, J., Harrell, T., Thomsen, O. 'A new test for validating models of lightning strike damage on CFRP laminates'.

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141. Evans, J., Butler, R., Rhead, A. 'Data-Driven Damage and Analytical CAI Models for Rapid Strength Prediction.'

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138. Hartley, R., Partridge, I., Tilbrook, D., Kratz, J. 'The Effects of Interleaf Architecture on Composite Toughness'.

137. Hii, A.K.W., El Said, B., Hallett, S.R. 'Development of a Concurrent Multi-scale Analysis Framework using Shell Elements for the Progressive Failure Analysis of Composites'.

136. Hisham, N. S., Shaffer, M., Li, Q. 'The application of coated carbon nanotubes in lightweight metal matrix composites'.

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'.

133. Liu, Yi., Bilotti, E., Peijs, T., Zhang, H. 'Sustainable multifunctional composites: from energy efficient manufacturing to integrated sensing and de-icing capabilities'.

132. Li, Q., Hisham N.S., Xu, Z., Nasiri, S., Shaffer, M., Zaiser, M. 'Nanoparticle reinforced light weight metal composites'.

131. Maes, V.K., Radhakrishnan ,A.,, Kratz, J. 'Zonally heated tooling for moulding complex and highly tapered composites parts'.

130. Maierhofer, T., Hernandez, T., Loukaides, E.G., Bisagni, C., Carr, C., Butler, R. 'Fracture toughness and performance of resistance welded and co-bonded thermoset-thermoplastic composite hybrid joints'.

129. Matveev, M., Endruweit, A., Iglesias, M., Tretyakov, M. 'Minimisation of number of sensors for defect detection in Resin Transfer Moulding'.

128. Medeau, V., Kazemi, E.F., Greenhalgh, E., Pimenta, S., Finlayson, J., Pinho, S. 'Helicoidal layups and interleaved hybrids: a novel design methodology for impact resistant composite structures'.

127. Oddy, C., Topalidis, I., El Said, B., Ekh, M., Hallett, S., Fagerström, M. 'Calibrating Macroscale Models of 3D-Woven Composites: Complimenting Experimental Testing with High Fidelity Mesoscale Models'.

126. Olafsson, G., Jack, T., Dulieu-Barton, J. 'Assessment of complex structural scale composite structures by adapting thermoelastic stress analysis for 3D perspective imaging'.

125. O'Leary, M., Hartley, R., Kratz, J., McMahon, T. 'The Effect of Semi-Curing on Infused Laminate Inter facial Properties'.

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'.

121. Qian C. C., Yuan H.,Khan M.A., Kendall K.N. 'Numerical

simulation for compression moulding of sheet moulding compound'.

120. Qian, C., Yuan, H., Khan, M., Kendall, K. 'Squeeze Flow of Carbon Fibre Sheet Moulding Compound in Compression Moulding'.

119. Radhakrishnan, A., Valentine, M., Maes, V., Valero, M., Pegg, E., Dhokia, V., Kratz, J. 'Linking dimensional stability of semi-cured components to tooling design during assembly'.

118. Ramakrishnan, K.R., Dulieu-Barton, J. 'Combined DIC-Infrared thermography for high strain rate testing of composites'.

117. Scarth C., Rhead A.T., Butler, R. 'Bayesian calibration of a finite element stiffened panel model using experimental compression test data'.

116. Sivakumar, S., Potluri, P., Ro, S.S., Fernando, A. 'Measurement of Carbon Fibre Tow Damage during Preforming through Electrochemical Impedance Spectroscopy'.

115. Sun, X., Xu Xiaodong, Takayuki, S., Wisnom, M. 'An Experimental Study of Crack Propagation in Stiffened Over-height Compact Tension Specimens'.

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'.

110. Tretiak, I., Jones, J., Sun, X., Valverde, M., Kratz, J., Nguyen, D. 'Real-time Material Measurement for Automated Fibre Placement'.

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'.

107. Wowogno A., Tretiak, I., Hallett, S.R., Kratz, J. 'Influence of Automated Fibre Placement processing parameters on the consolidation of out-of-autoclave prepreg'.

106. Wu, X., Finlayson, J., Wisnom, M., Hallett, S. 'Improved Energy Absorption of Novel Hybrid Configurations Under Static Indentation'.

105. Xu, Z., Tonry, C., Beckwith, C., Kao, A., Shaffer, M., Pericleous, K., Li, Q. 'High speed imaging of the ultrasonic deagglomeration of nanoparticles in water'.

104. Yao, X., Wang, Y., Liu, Y., Bilotti, E., Zhang, H. 'Tailored Out-of-Oven Curing of high performance FRPs Utilising a Double Positive Temperature Coefficient Effect'.

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'.

102. Yuan, H., Khan, M., Qian, C., Reynolds, N., Kendall, K. 'Experimental investigation and simulation of the intra-ply shear property for the unidirectional prepreg forming'.

<u>Poster Submission</u>

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'.

The fifth International Symposium on Automated Composite Manufacturing (ACM5) Bristol UK, 6-7 April 2022

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)'.

85. Wang, Y., Belnoue, J.P.H., Ivanov, D., Hallett, S.R., 'A Modelling Framework For The Evolution Of Prepreg Tack Under Processing Conditions'.

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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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81. Celik M., 'Contact Resistance Heating of Unidirectional Carbon Fibre Tows'.

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'.

65. Yang D., 'Hybrid manufacturing of curved continuous carbon fibre reinforced dual-polymer composites'.

64. Yu F., Chen S., Harper L.T., Warrior N.A., 'Double diaphragm forming simulation using a multi-resolution modelling strategy for defect detection in complex structures'.

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63. Nguyen S.N., 'Structural Power in Future Transportation: Research Opportunities and Challenges', the Institution of Engineering Decarbonisation in Transport Webinar Series, 30 September 2021. https://events.theiet.org/events/how-do-you-decarbonise-the-transport-sector-part-1/.

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61. Greenhalgh E.S., 'Tri-Agency Symposium on Multifunctionality, System Endurance & Intelligent Structures', 36th Annual Technical Conference of the American Society for Composites, Texas A&M, 20 September 2021.

60. Greenhalgh E.S., 'Instrumentation Analysis and Testing Exhibition', Silverstone, 14 September 2021.

59. Roy S.S., Liu Y., Lloyd B., Potluri P., Whitham A., 'Structural Performance of Composite Tubes Developed Using 3D Complex Winding in Comparison to Braided and Filament Wound Architectures, International Conference on Composite Structures (ICCS 24) 14 - 18 June 2021a Porto, Portugal.

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56. Sun X., Belnoue J., Chul Kim B., Wang W., Hallett S., 'Virtual Un-manufacturing of Fibre-steered Preforms for Complex Geometry Composites', Procedia Manufacturing, Volume 47, 2020, Pages 197-201.

55. Qian C., Kendall K., 'A digital twin for compression moulded sheet moulding compound', SAMPE Europe 2020.

54. Greenhalgh E.S., Gordon Research Conference on Multifunctional Materials and Structure, Ventura, CA, January 2020.

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53. Vissainen V., Zhou J., Sutcliffe M. 'Characterisation of the wrinkling behaviour of a biaxial non-crimp-fabric during forming'.

52. Chen S., McGregor O., Endruweit A., Harper L., Warrior N. 'Finite element forming simulation of complex composite sandwich panels'.

51. Yu F., Chen S., Harper L., Warrior N. 'Finite Element Modelling of Bi-axial Fabric with Considering Bending Stiffness for Composites Preforming'.

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

49. Mikhail Matveev, Shankhachur Roy, Vivek Koncherry, Louise Brown, Prasad Potluri, Andrew Long. 'Meso-scale optimisation and manufacturing of continuous fibre 3D reinforcements'.

48. Koncherry, Park, Sowrov, Potluri, Matveev, Brown, Long. 'Novel Manufacturing Techniques for Optimized 3D Multiaxial Orthogonal Preform'.

47. Anthony, Nguyen, Senokos, Bismarck, Greenhalgh, Shaffer. 'Hierarchical carbon aerogel modified carbon fiber composites for structural power applications'.

46. Valkova, Greenhalgh, Shaffer. 'Predicting the Consolidation of Fabric-Reinforced Structural Power Composites'.

45. Nguyen, Pouyat, Greenhalgh, Shaffer, Linde. 'Structural Power Performance Requirements for Future Aircraft Integration'.

44. Greenhalgh, Shaffer, Kucernak, Senokos, Nguyen, Pernice, Zhang, Qi, Anthony, Balaskandan, Valkova. 'Future Challenges and Industrial Adoption Strategies for Structural Supercapacitors'.

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'.
39. Thomsen O,T. 'Buckling behaviour of UD carbon / Epoxy panels subjected to direct lightning strike'.

38. O'Bradaigh C, M, Mamalis D, Flanagan T, Doyle A., 'Tidal turbine blade composite using basalt fibre reinforced powder epoxy'.

37. Clegg H, Dell'Anno G, Scott M, Partridge I., 'Suppressing delamination in composite intersections with tufting and Z-pinning'.

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36. Elkington, M., E. Almas, B Ward-Cherrier, N. Pestell, C. Ward, N. Lepora. Layup end effectors with tactile sensing capabilities, 4th International Symposium on Automated Composites Manufacturing, Montreal 25th April 2019.

35. Druiff P., Di Francesco M., Dell'Anno G., Ward C., 'Wet Fibre Placement Process Optimisation', 4th International Symposium on Automated Composites Manufacturing, Montreal 25th-26th April 2019.

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34. Belnoue J., Sun R., Cook L., Tifkitsis K., Kratz J., Skordos A.,' A layer by layer manufacturing process for composite

structures'.

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'.

29. Sutcliffe M., Zhou J., Viisainen V., 'Wrinkle formation characterisation during the forming of non-crimp fabrics'.

28. Veldenz L., Di Francesco M., Giddings P., Kim B.C., Potter K., 'Overcoming challenges in manufacturing complex structures with automated dry fibre placement'.

27. Warrior N., Chen S., McGregor O., Harper L., 'Forming Simulations for 3D Curved Sandwich Panels'.

Other Conferences

26. Mills A., 'Affordable Thermoplastic Matrix CFC / Metallic Framework Structures Manufacture', 8th International Symposium on Composites Manufacturing for High Performance Applications, November 2018, Netherlands.

25. Roy D.,' Manufacturing Thermoplastic Fibre Metal Laminates (FML) by the In-Situ Polymerisation Route', Thermoplastic Composites 2018: High volume manufacturing for transport applications, October 4, 2018.

24. Jiménez-Fortunato I., Bull D.J., Dulieu-Barton J.M., Thomsen O.T.,' Towards combining imaging techniques to characterise defects and damage in composite structures', SAMPE Conference on Large Structures in Composite Engineering, Southampton, 2018.

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.

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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'.

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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.

1. Veldenz L., Di Francesco M., Atwood S., Giddings P. Kim B.C., Potter K., 'Assessment of Steering Capability of Automated Dry Fibre Placement through a Quantitative Methodology', International Symposium on Automated

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