CIMComp

EPSRC

Future Composites Manufacturing Research Hub

2021/2022 Annual Report

Underpinning the development of next generation composites manufacturing processes

University of Bath

University of Bristol

Brunel University London

University of Cambridge

Cranfield Manufacturing

The University of Edinburgh

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Warwick The University of Warwick

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Wrexham Glyndŵr University

UKRI Engineering and Physical Sciences Research Council

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Executive Summary

Welcome to the Future Composites Manufacturing Research Hub's fifth Annual Report. After nearly two years of disruption caused by the pandemic, I am pleased to finally see some normality return to our ways of working and also to returning to in person events despite the popularity of our online activities. This last year, the Hub's research and networking activities have built on early successes, and we continue to strengthen our links with industry and focus on training the next generation of composite engineers.

Nick Warrior,
Hub Director

Our projects have made excellent progress and have some interesting results to share. The Hub's Multifunctional Core Project finished at the end of August 2021 and our five remaining Core Projects are on track to finish in the next year. Three of the Hubs' Feasibility Studies ended in 2021 and we funded an additional five Feasibility Studies in late 2021 with a focus on sustainability challenges for fibre reinforced composites.

In August 2021, we launched our third and final Innovation Fellowship call and were pleased to appoint Dr Yang Chen from the University of Bath. I look forward to seeing the results from his research on permeability variability of textile fabrics for liquid moulding.

Following on from the success of our Synergy Workshops held in previous years, in February 2022 we held a third workshop which officially launched the Hub's Synergy Promotion call. We are aiming for the next projects to start in September 2022. The workshop was our first in person event this year and provided Hub members with opportunities to discuss their research and ideas for future Hub projects, and identify and build on current project synergies.

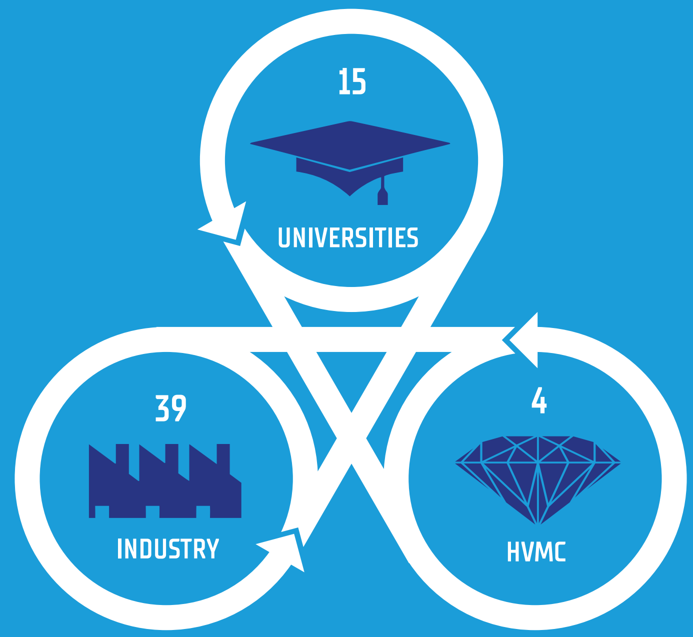
After the cancellation of our Open Day in 2020 due to restrictions imposed by COVID-19, we were pleased to share the excellent work being done by our students and researchers at the Hub Open Day in October, and bring the composites community together, albeit virtually. Our two keynote speakers, Dr Adrian Gill from Vestas Wind Systems and Dr Isabelle Paris, from Bombardier Aviation, both gave some interesting insights into their respective industries and I am very grateful for their presentations. The quick-fire session gave our PhDs and researchers the opportunity to present their research. Many congratulations to George Street on winning 1st prize for his presentation and to the two runners up, Daniel Wilson and Matt Thompson.

Finally, I would like to take this opportunity to thank everyone who contributes to the success of the Hub, and all those who are driving the Hub forward, including our members, industrial collaborators, Advisory Board and the EPSRC.

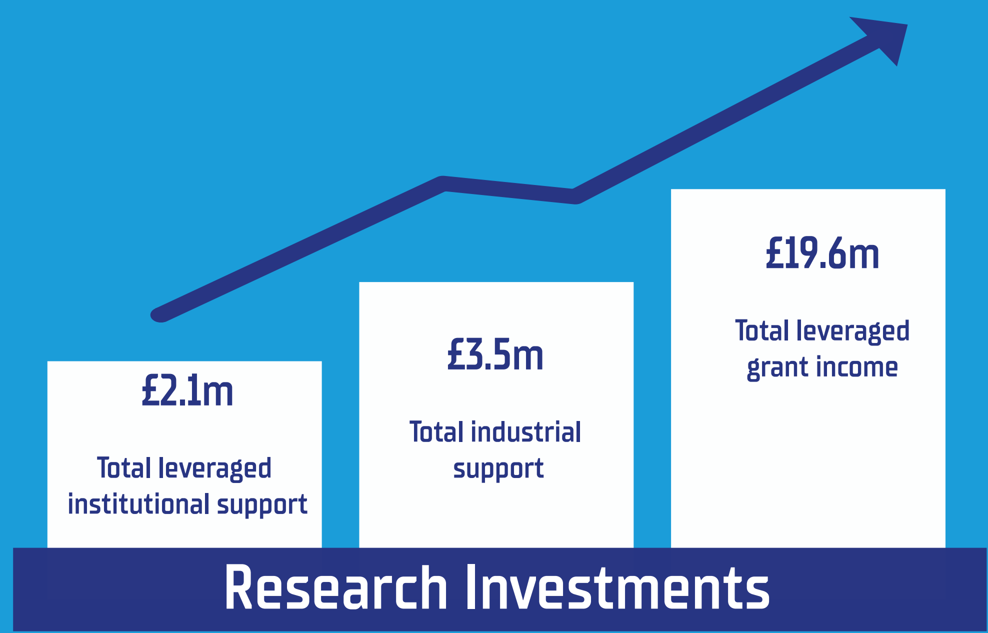
Headline Achievements 2017 - 2022

CIMComp Journal Publications | CIMComp Conference Papers Presented | Patent Applications | Projects Funded

The Hub has grown to a network of 58 organisations



We are currently training



1 Hub Vision and Objectives

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

- Improving existing composites manufacturing processes
- Developing new technologies

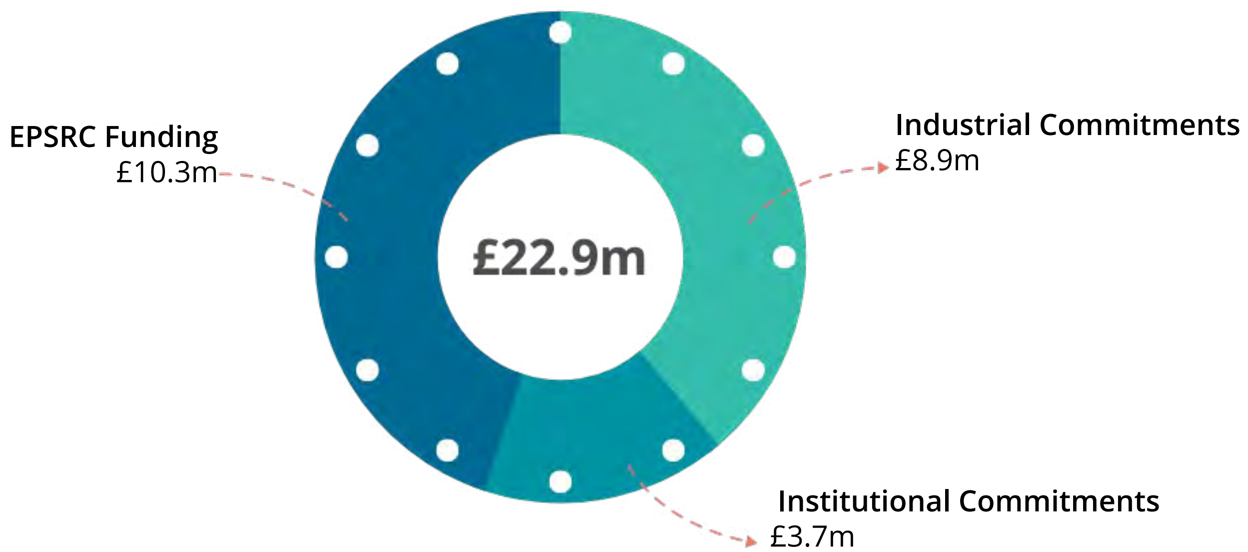
Since 2017, the Hub has built on the success of the EPSRC Centre for Innovative Manufacturing in Composites (CIMComp; EP/I033513/1), with a vision to develop a national centre of excellence in fundamental research for composites manufacturing – delivering research advances in cost reduction and production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

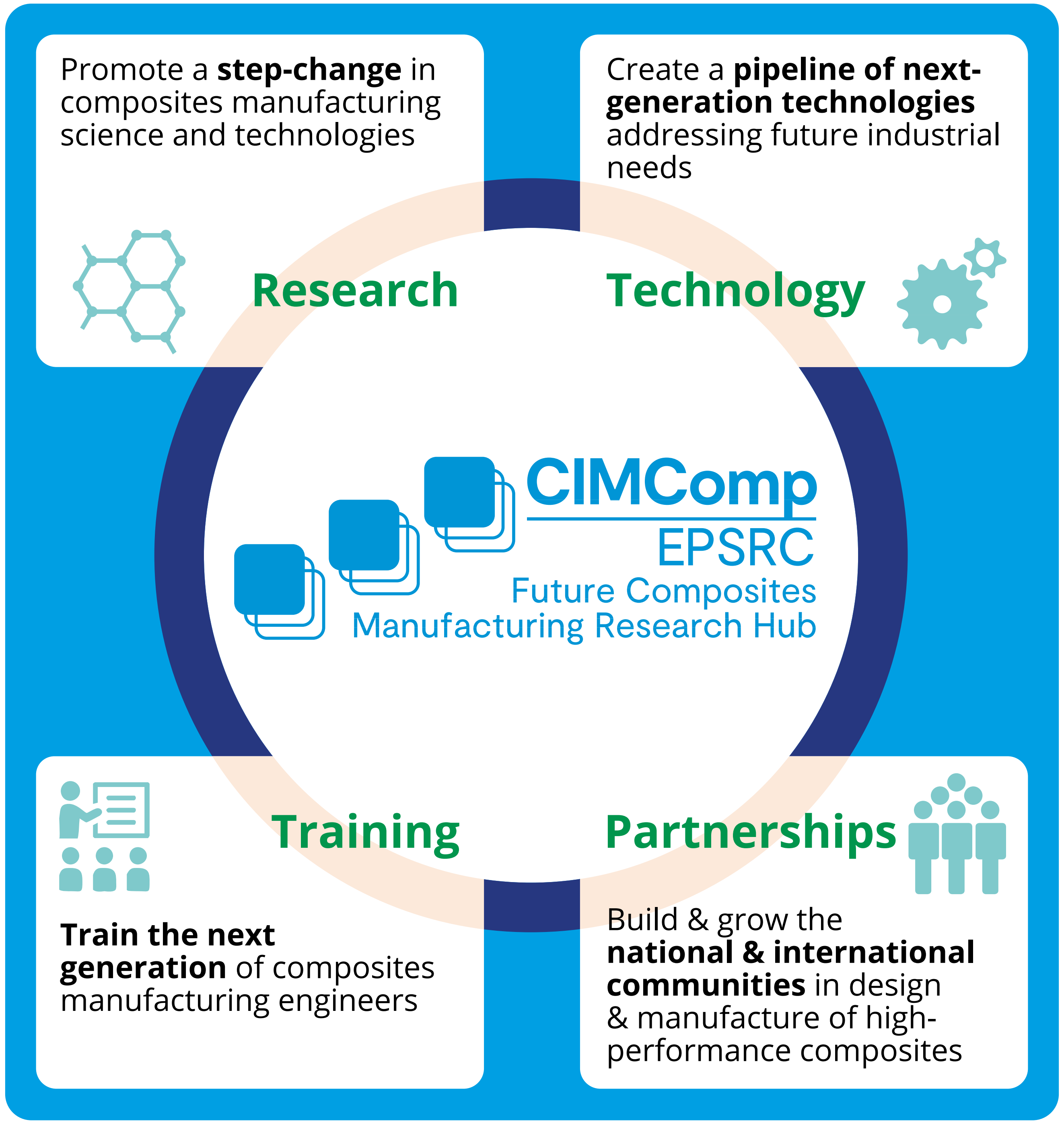
To achieve this vision, the Hub aims to deliver against core objectives in four key areas: research excellence, technology transfer, training and network building.

Hub Funding Model



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

Hub Core Objectives



2 Hub Research

The Hub project portfolio is based on meeting the research challenges facing the UK composites sector and 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.

All 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 Core projects are 36 month collaborations between two universities or disciplines, of values between £375k and £700k. 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. Since 2017 the Hub has funded six Core Projects, 24 Feasibility Studies, three Innovation Fellowships and four Synergy Promotion projects.

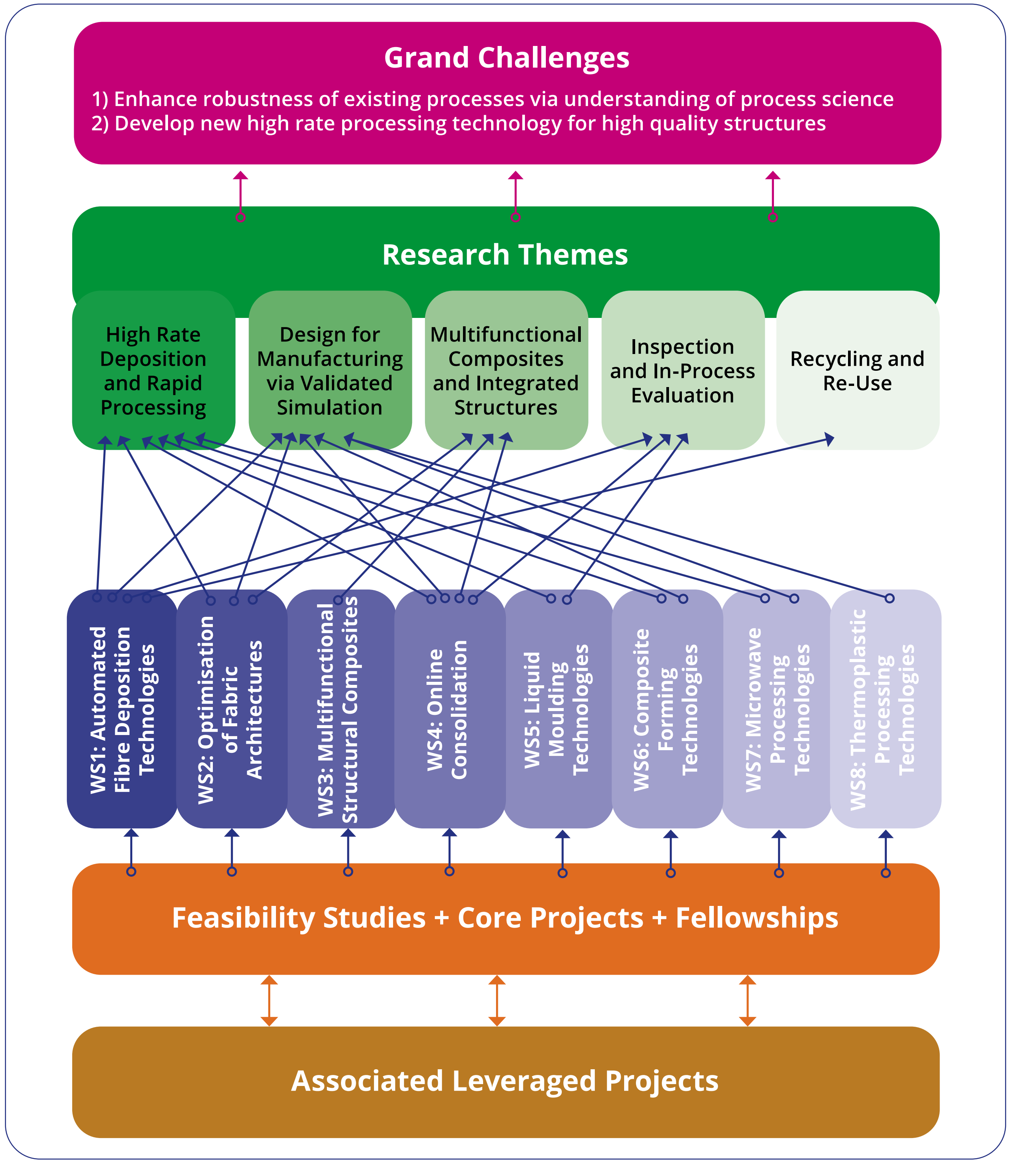
A key aspect to delivering the Hub's Grand Challenges is ensuring that our Core Projects, Feasibility Studies and Fellowships are able to work towards the same goals of meeting the Hub core objectives. In 2019, after consultation with the Hub Knowledge Exchange Committee (KEC), we launched the Synergy Promotion Fund to run alongside our Core Projects and Feasibility Studies.

The Synergy Fund provides funding to enable development of synergies between past and ongoing Hub research activity and new academic contributors. The funding aims to promote collaborative activity for emerging and novel research. Following on from the collaborative opportunities created from our smaller investments awarded in 2019/2020, in February this year we launched a further Synergy Promotion call with a budget to the order of £100k per academic partner. New projects will be announced in May 2022 and we expect them to start by September 2022.

The recent COVID-19 pandemic has led to significant challenges in many of the manufacturing sectors relevant to composites. As budgets are tightened it becomes even more important to conduct research strategically and with a focus on maximising benefits to industry. As the Hub enters the final phase of work, the Strategic Development Committee (SDC) will support the Management Group in promoting the areas of research challenge, particularly in the areas of sustainability as well as seeking to transition existing research out to the HVM Catapults Centres in collaboration with the KEC and wider industry.

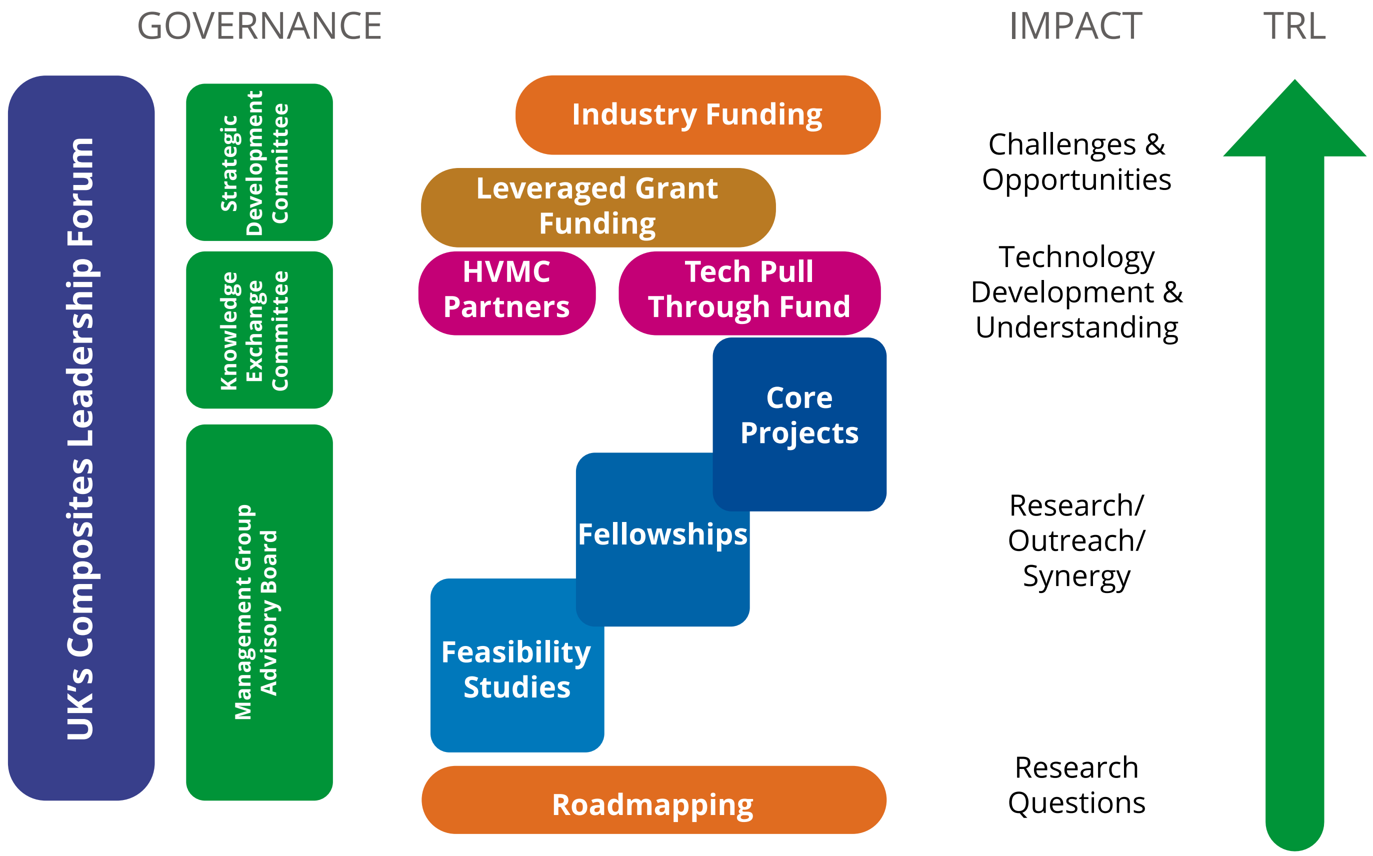
The **Grand Challenges** are addressed by five **Research Themes**, with sustainability underpinning all of the Themes. This includes considering life cycle assessment, energy use and environmental impact measures across the research portfolio. The challenges in each Research Theme are met by relevant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

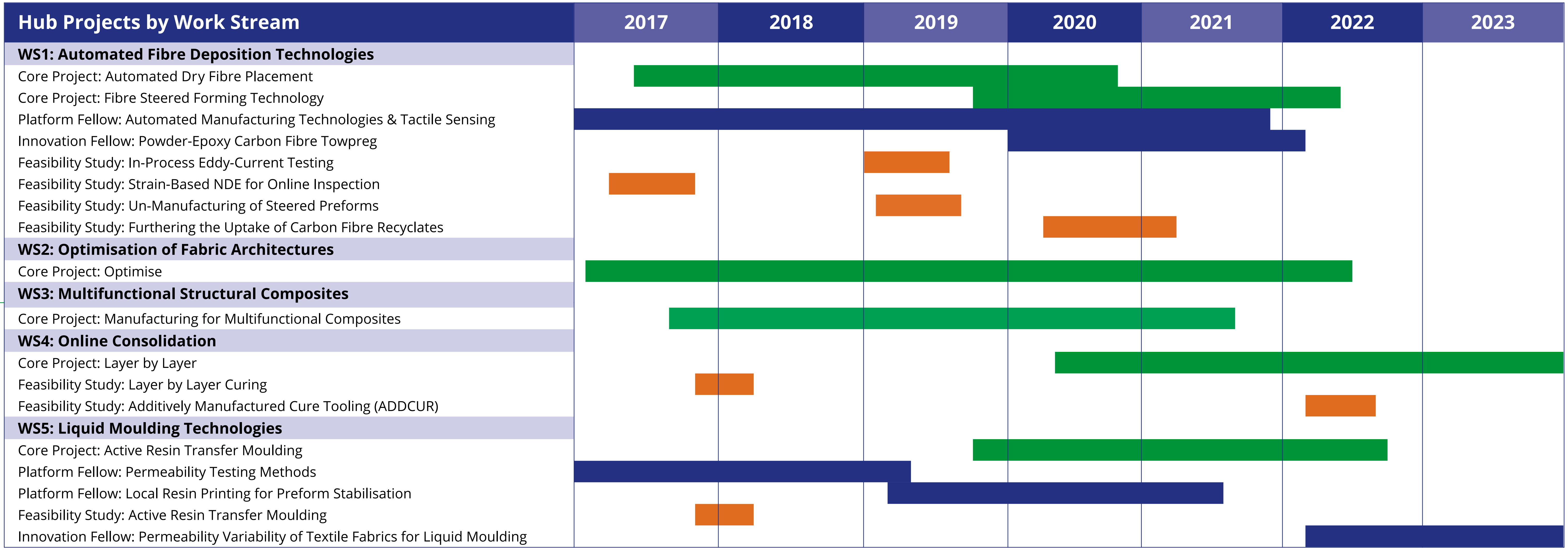


Pathways to Impact

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.



2.1 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							
WS7: Microwave Processing Technologies							
Feasibility Study: Microwave Heating through Embedded Coaxial Cables							
Feasibility Study: Monomer Transfer Moulding							
Feasibility Study: Microwaves for Automated Fibre Placement							
WS8: Thermoplastic Processing Technologies							
Platform Fellow: Rapid Processing Routes for Carbon Fibre / Nylon6							
Feasibility Study: Thermoplastic Framework							
Feasibility Study: In-Situ Polymerisation of Fibre Metal Laminates							
Feasibility Study: Multi-Step Thermoforming							
Feasibility Study: Micro-Integration of Polymeric Yarns							
Feasibility Study: VARIOTHERM							
Feasibility Study: Thermoplastic Double Diaphragm Forming							
Feasibility Study: Rewinding Tape Laying							
Feasibility Study: Advanced Dynamic Repair Solutions for Sustainable Composites							
Feasibility Study: Manufacturing Value-Added Composites for the Construction Sector							

2.2 Core Projects
Work Stream 3: Multifunctional Structural Composites
Manufacturing Multifunctional Composites

Core Project Team

Principal Investigators: Prof Emile S Greenhalgh, Imperial College London; Dr Dmitry Ivanov, University of Bristol.

Research Team: Dr Ian Gent, University of Bristol; Dr Sang Nguyen, Imperial College London; Dr David Anthony, Imperial College London; Ms Caroline O'Keefe, University of Bristol; Ms Maria Valkova, Imperial College London; Dr Arjun Radhakrishnan, University of Bristol; Mr Mark Turk, University of Bristol.

Industry Partners: BAE Systems, Airbus, National Composites Centre, Chomarat.

Grant Award: £707,629 **Start:** 01/09/2017 **End:** 31/08/2021

Executive Summary

Multifunctional composite materials have a key role in meeting the challenges of the climate emergency, driving innovation and sustainability of composites. These materials impact on a wide range of applications including portable electronics, electric transportation and infrastructure. One focus of this three-year project was multifunctional structural power composites which are load-bearing materials that can store electrical energy. The other focus of the project was on manufacturability of electrically conductive composites. Industrial adoption of such multifunctional composites offers a route addressing the societal issues associated with both light-weighting and energy storage. Electrical properties also enable a wide range of applications such as sensing, current collection, and more efficient manufacturing processes. However, the benefits remain constrained by issues associated with manufacture and design with these composites. The focus of this project was to address such challenges and advance transitioning this technology to industry, with the following having been achieved.

For structural power materials, scale-up and optimisation of the manufacture of the electrodes (carbon fibre fabric reinforced by carbon aerogel) was achieved, with active material (MnO2) successfully introduced to enhance the electrochemical performance. We have also refined the device manufacturing process, including separator selection, the influence of manufacturing parameters on electrochemical performance and encapsulation strategies. Close collaboration between University of Bristol and Imperial successfully demonstrated additive manufacturing methods to zone mono-functional and multifunctional domains in components, and a strategy for the manufacture of curved components. This manufacturing concept, enabling creating continuously reinforced multi-matrix composites, reconciles the requirements of formability and functionality in applications such as repair, joining, and reuse. Other explored manufacturing concepts for functioning included hybrid sub-reinforcement and local incorporation of micro-additives. This culminated in the manufacture of an aerospace fuselage beam demonstrator, which powered an aircraft door (www.youtube.com/watch?v=yxa-BOpuDIs). We have also delivered modelling and design tools for structural power materials, including models to predict compaction of the dry laminates during fabrication, prediction of elastic behaviour and optimisation of current collection to minimise resistive losses, the latter being key to scale-up of these devices. The newly developed design tools also examine implications of functional domains on forming. From the design perspective, we have developed and delivered a multifunctional design methodology, and undertaken analysis of adoption strategies for various vehicles, such as an aircraft cabin, fully electric airliner and an electric airtaxi.

Aims and Objectives

The overarching aims of this project were to create a set of tools that would be applicable to facilitate design and manufacture of parts using multifunctional materials, many of which share challenges such as low formability, and provide a holistic methodology which allows all the pros and cons of the new and conventional systems to be compared. These were to be delivered while investigating one specific application - the development of structural supercapacitors through embedding structural carbon fibres in a carbon aerogel (CAG). CAGs are not suitable for structural applications alone, but when combined with structural carbon fibres act as a supporting scaffold. This project built on previous materials R&D, and investigated and addressed the design and manufacturing issues associated with these CAG-based multifunctional composites to facilitate industrial manufacture of multifunctional parts. This had been split into two objectives:

- Explore the manufacturing issues associated with the creation of structural supercapacitors formed into complex geometries, which simultaneously store and deliver electrical energy, whilst carrying mechanical loads.
- Explore manufacturing and design of multi-matrix and multi-fibre graded composites to tailor heat and electrical conduction.

The project objectives include the development of a platform for local functionalisation that can be used both in application to structural supercapacitors and other relevant applications, such as sensing, current collection and efficient processing. The project addresses the processing aspects of domain allocation in continuously reinforced preforms, developing design tools for domain assignment and defect mitigation in functionalised preforms, optimisation of out-of-bag incorporation of functionalised resin suspension, the development of novel hybrid sub-reinforcements, the examination of functional properties of the obtained composites in experiments for sensing and inductive curing.

Progress

Two aspects of structural supercapacitors were considered: manufacture and design.

Regarding Manufacture, the main effort focussed on delivery of a viable method to manufacture with complex geometries. Novel printing processes developed at University of Bristol have allowed creation of domains within the rigid load bearing supercapacitors, integral to formable textiles, allowing production of complex shaped composites parts containing multifunctional structural supercapacitors. We have demonstrated a method to mask/barrier multifunctional/monofunctional domains in the CAGed lamina facilitating complex part production (Deliverable D2).

Validated simulation tools have been created that allow functional and stabilising elements to be placed to control forming deformation and mitigate against defects. The process for manufacturing carbon aerogel-reinforced structural power devices has also been scaled up to about 1 m^2 per batch. Current collection efficiency and CAG production have been identified as limiting factors to scale up, and solutions to these issues have been studied. The use of electrochemical deposition to decorate the carbon aerogel with active elements to enhance the electrochemical performance, along with use of new separator materials, has allowed small-scale multifunctional devices to be made and tested, demonstrating energy and power performance (1.4 Wh/kg and 1.1 kW/ kg) that exceeded the original aspirations. Separator and current collection solutions have been identified and validated, but the issue of encapsulation is still outstanding and a suitable candidate that can provide a light-weight, impervious (and insulating) barrier whilst still transmitting mechanical load across the multifunctional/monofunctional interface, is yet to be identified. This is the subject of a joint ICL/UoB/DU proposal submitted to EPSRC last year.

Finally, a multicell structural beam has been manufactured, containing eight cells, stacking in two stacks of four. The total mass of the beam is 2.6 kg, whilst the total cell mass is 268g (i.e. 10% of component mass). The cells have been demonstrated to power a servomotor in a door, as demonstrated in this video (https://youtu.be/20HMFKRxwR0) (Deliverable D9).

Regarding Design, models to predict the consolidation of dry CAGed lamina when assembled into a device were delivered (Deliverable D1). These predicted the fibre volume fraction of the final device and the resulting microstructure. This included phenomena such as nesting of the carbon and glass tows in the laminate. These models were then utilised to predict the mechanical performance (elastic behaviour) of the devices under tensile and in-plane shear loadings. To a limited extent, these models were able to capture the influence of manufacturing defects on the mechanical performance, although further work is required in this area (Deliverable D4). Finally, current collection models were developed to formulate strategies to minimise the resistive losses associated with device scale-up (Deliverable D8). These models quantified the relative contributions from the in-plane, through-thickness and contact resistances, and hence indicated how best to minimise resistive losses for minimal mass: it should be noted that in conventional energy storage devices, the current collectors can account for as much as 25% of the device mass. For multifunctional design we have developed a means to compare between a multifunctional component and a current off-the-shelf assembly of power source and structure. This methodology will permit end-users to quantify the gains in adoption of structural power materials (such as weight or volume saving) over conventional systems. We have undertaken studies for different platforms as to the potential benefits of using structural power materials: in particular, structural power floor panels in the aircraft cabin to power the seat-back entertainment units and power sockets. This work demonstrated that using structural power materials at the performance levels expected to be reached in the next three years, will provide a mass saving of 260kg per aircraft for a 100 seat Airbus 220. This corresponds to an annual reduction of 28 tonnes of CO_2 per aircraft [6] (Deliverable D7). We have also undertaken studies into a fully electric airliner (220 seat aircraft) using a combination of conventional battery and structural power, demonstrating that structural power would be a critical enabler for fully electric aircraft by depressing the performance targets needed for conventional batteries [9]. Finally, we have applied this methodology to other air vehicles, such as drones and air-taxis (four-seat vehicles). Our studies have demonstrated that using structural power in such vehicles has the potential to double the aircraft range. We anticipate publishing this work in the next couple of months.

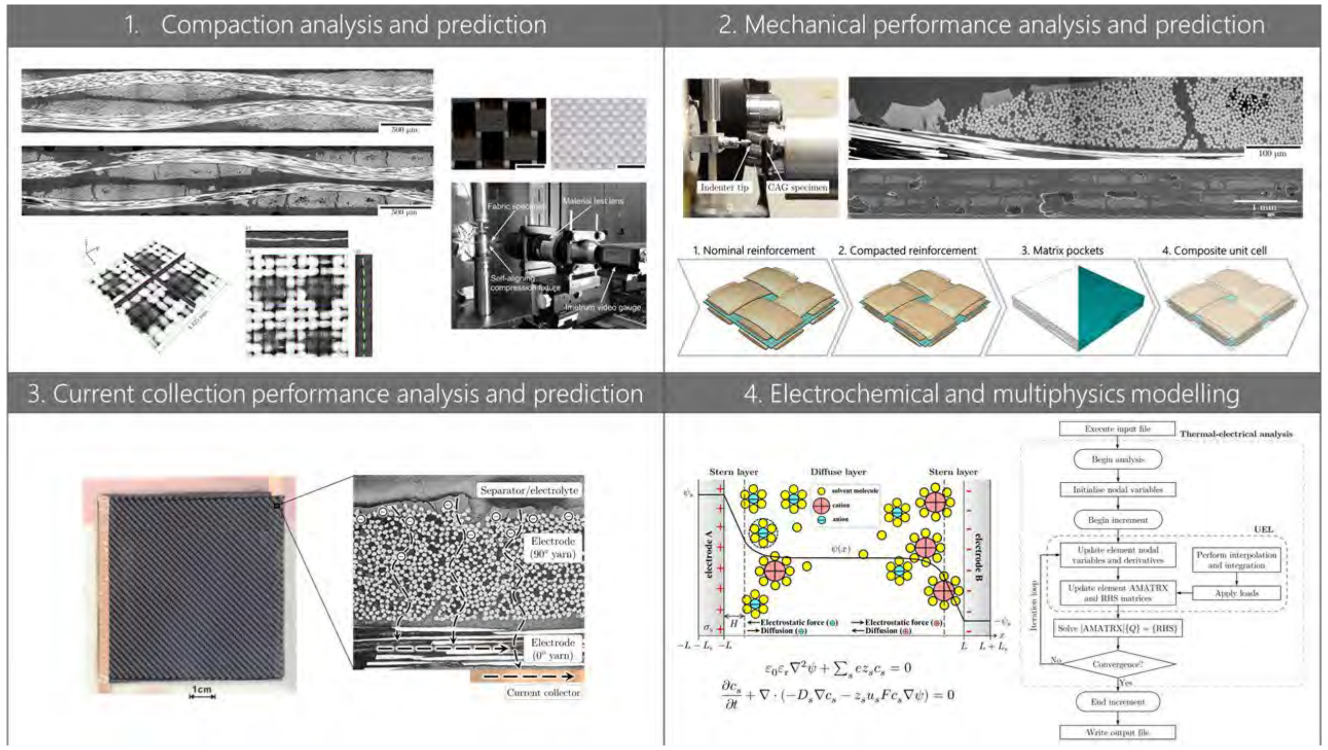


Figure 1. Structural supercapacitor modelling tools delivered

Functional sub-reinforcement has been successfully incorporated using microbraiding and subsequent tufting of yarns containing metal filaments. Tailored matrix and reinforcement placement expands the number of added properties, such as electrical conductivity, providing potential solutions for current collection as well as enabling sensing, new approaches to heating and curing, and repairability. We have demonstrated sensing and accelerated heating using micro-braids and developed an approach to integrating functionalised resins into fabric without vacuum, achieving high local functional properties.

This project pioneered and proved the feasibility of allocating domains for forming deformations and domains for structural power in continuously-reinforced preform (Deliverable D3). This concept paved the way for incorporating non-formable functional areas in complex structures but demanded the tool for designing such systems. This project deployed high-fidelity forming simulations and complemented them with (a) the automatic assessment of defects and their magnitude enabling parametric optimisation, (b) the algorithms for placement of domains or stabilising patches to minimise defect risks and intensity. In contrast to the conventional approach, the algorithms examine the rotation of the material leading to wrinkling rather than shear angle. The numerical tool also examines the possibility to mitigate against forming defects by placing stabilising patches that can be used in conjunction with functional domain or as an independent tool. The potential for such defect optimisation strategy was proven experimentally. The allocation of functional domains in numerical simulations requires knowledge of their properties which can be challenging to measure in isolation from hosting preforms.

A new methodology for testing heterogenous samples with dissimilar regions has been developed in this project (Deliverable D6). It allows assessing viscous and non-linear elastic properties of functional domains hosted in the dry preform. The concept has been validated both in the virtual environment and manufacturing trials with PLA and epoxy patches deposited on the preform surface. Deposition of functional resin is associated with difficulties related to high viscosity additive-rich resin suspension and filtration issues. Local resin deposition, such as liquid resin print, resolved this problem and allows an increase the additives content. However, these manufacturing methods are an out-of vacuum bag process which creates problems with voidage control. The new approach has been developed to create void free patches (Deliverable D5), based on thermal conditioning of the resin, close monitoring of resin state using model-based rheo sensors, and elimination of voidage in the consolidation process.

Tufting using hybrid metal-carbon microbraids was investigated as a prospective route to create materials with high functional properties (Deliverable D11). The presence of metal fasteners not only enhances structural (through-thickness) properties of composite but also enables characterisation of structural integrity by monitoring the evolution of electrical conductivity. Electrical properties of the new materials were assessed in various tests: braided threads in the process of tensioning, tufted samples in the DCB tests, and macro-scale T-section subjected to the separation of tufted web and flanges. It has been confirmed that incorporation of the tufts makes the material much more responsive to monitoring, though positioning of the braid in macrostructures needs to be carefully chosen to respond to the anticipated failure mode. Functional braiding has proven to have large design space – it permits the combination of various materials, patterns, yarn densities. All these factors have implications on manufacturability, electrical and structural properties. Hybrid tufted braid has a complex architecture and there were no readily available tools for detailed assessment of their properties prior to manufacturing: such a tool has been created (Deliverable D12). It deployed an established tool for modelling flat textiles (WiseTex) and then used geometrical operations to roll an initial material form into a braided thread. The results structure is then created in standard FEA software (Abaqus), where its electrical conductivity is assessed. The results of the calculation of effective electrical conductivities were compared with both measurements of electrical conductivity on individual threads and local domains of tufted composite. It has been shown that tufting imbues a substantial boost of electrical conductivity, although the potential is not fully realised by the available manufacturing processes due to wire damage in the process of tufting. The results were presented in the paper O'Keeffe et al.

Enhancing electrical conductivity opens the possibility for more efficient processing. For instance, induction heating allows for faster, less energy demanding heating/curing with more compact heating tooling. This has a great potential for repair, bonding, and joining operations. The manufacturing trials with the functionalised materials proved the feasibility of induction curing, including those based on the glass preforms tufted in an intersecting pattern. More traditional linear patterns showed less energy supply than for a reference preform. The hypothesis, partly corroborated with numerical simulations, is that the metal wires in the current configuration of braided preforms are too fine to be susceptible for EM waves. Modelling tools have been developed to assess various pattern of the tufts as well as the optimisation of many other process parameters (frequency, current, laminate parameters, distance of the coil) (Deliverable D13). The local processing resulted in new manufacturing concept allowing local melting of current collectors for better fibre contacts.

Manufacturing trials on segmentation of formable/functional areas have been successfully conducted using two manufacturing approaches (Deliverable D3. The first one is masking of the formable area with PLA film, infusion with functional precursor into remaining domain, with subsequent pyrolysis, removing the films, and creating the CAG in one go. The second approach is to create separate domains by integrating barriers into the preform that would divide the preform during the infusion of the precursors. Various parameters of barrier integration – shape, sizes, and materials have been trialled. The infusions strategies were successfully managed, and the concept was proven feasible. One of the identified challenges was the deterioration of formable domain caused in the process of pyrolysis. The optimisation of the pyrolysis parameters has helped to address the issue.

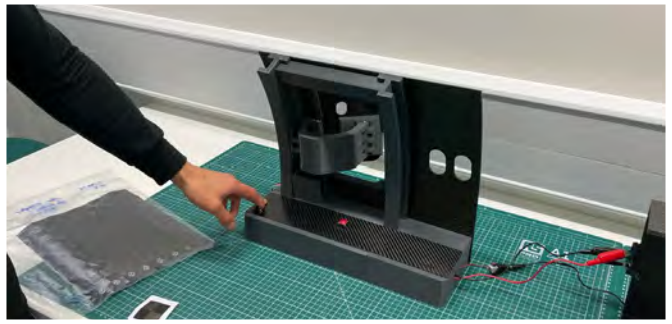


Figure 2. Fuselage door being opened by multifunctional beam

Publications

- Lee C., Greenhalgh E.S., Shaffer M.S.P., Panesar A., Optimized microstructures for multifunctional structural electrolytes, Multifunctional Materials 2(4), (2019).
- Nguyen S., Anthony D.B., Qian H., Yue C., Singh A., Bismarck A., Shaffer M.S.P., Mechanical and physical performance of carbon aerogel reinforced carbon fibre hierarchical composites, Composites Science and Technology 182, (2019).
- Greenhalgh E.S., Asp L.E., Zenkert D., Vilatela J, Linde P., En route to "massless" energy storage with structural power composites, JEC Magazine, pp. 37-39, November, (2019).
- Valkova M., Greenhalgh E.S., Shaffer M.S.P., Kucernak A., Predicting the compaction of hybrid multilayer woven composite reinforcement stacks, Composites Science and Technology 133(105851), (2020).
- Johannisson W., Nguyen S., Lindbergh G., Zenkert D., Greenhalgh E.S., Shaffe M., Kucernak A., A residual performance methodology to evaluate multifunctional systems, Multifunctional Materials, 3, (2020).
- S N Nguyen et al, Conceptual Multifunctional Design, Feasibility and Requirements for Structural Power in Aircraft Cabins, Journal of Aircraft 58(3), 1-112, 2021.
- G Qi et al, The influence of fabrication parameters on the electrochemical performance of multifunctional structural supercapacitors, Multifunctional Materials 4(3), 034001, 2021.
- C Lee et al, Optimization of patch-wise laminated composite panels for enhanced dynamic characteristics, Composite Structures 269, 114017, 2021.
- E Karadotcheva et al, Structural Power Performance Targets for Future Electric Aircraft, Energies 14(19), 6006, 2021.
- M Valkova et al, Predicting the mechanical behaviour of structural supercapacitor composites, Accepted Composites Part A, 2022.
- M Valkova, Predicting the Performance of Structural Power Composites, PhD Thesis, Imperial College London, 2021.
- Chanhui Lee, Design, Characterisation and Application of Structural and Multifunctional Composites to Large Ship Structures, PhD Thesis, Imperial College London, 2021. Greenhalgh E.S., Asp L.E., Zenkert D., Vilatela J., Linde P., En route to "mass-less" energy storage with structural power composites, JEC Magazine, November, 2019, pp. 37-39.
- D. Oberhaus, The Batteries of the Future are Weightless and Invisible, Wired, November 2020.
- Clean Sky 2 announces program updates, G. Nehls (ed), Composites World, November 2020, https://www.compositesworld.com/news/clean-sky-2-announces-program-updates.
- Pernice et al, Mechanical, electrochemical and multifunctional performance of a CFRP/carbon aerogel structural supercapacitor and its corresponding monofunctional equivalents, Accepted to Multifunctional Materials, 2022.
- O'Keeffe C., Manufacture of Hybrid Micro-Braids for Composite Multifunctionality, PhD Thesis, Bristol, 2021.
- Radhakrishnan A., Towards creating multi-matrix continuous fibre polymer composites using an out-of-vacuum bag process, PhD Thesis, Bristol, 2021.
- Turk M.A., Vermes B., Thompson A.J., Belnoue J.P.-H., Hallett S.R., Ivanov D.S., Mitigating forming defects by local modification of dry preforms, Composites A 128 (2020).
- Turk M.A., Cao H., Thompson A., Belnoue J.P-H., Hallett S.R., Ivanov D.S., A New Approach to Measuring Local Properties of Preforms Enhanced for Formability, Frontiers in Materials, Special Issue on Mechanical Testing of Composites Precursors, Submitted.
- O'Keeffe C., Pickard L.R., Cao J., Allegri J., Partridge I.K., Ivanov D.S., Multi-material braids for multifunctional laminates: conductive through-thickness reinforcement, Functional Composite Materials, 2 (2021).
- Radhakrishnan A., Georgillas I., Hamerton I., Shaffer M.S.P., Ivanov D.S., Out-of-vacuum bag processing of printed multi-matrix composites, Composites A, submitted.

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.

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

Grant Award: £698,561 **Start:** 01/05/2020 **End:** 30/04/2023

Executive Summary

This core project addresses the scientific and industrial challenges to efficiently design and manufacture dry fabric preforms. To improve the quality of DDF preforms 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 Manufacture via Validated Simulation.

Aims and Objectives

High-volume production has been identified to be one of the main solutions to reduce the manufacturing costs 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 fibres tows (<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.

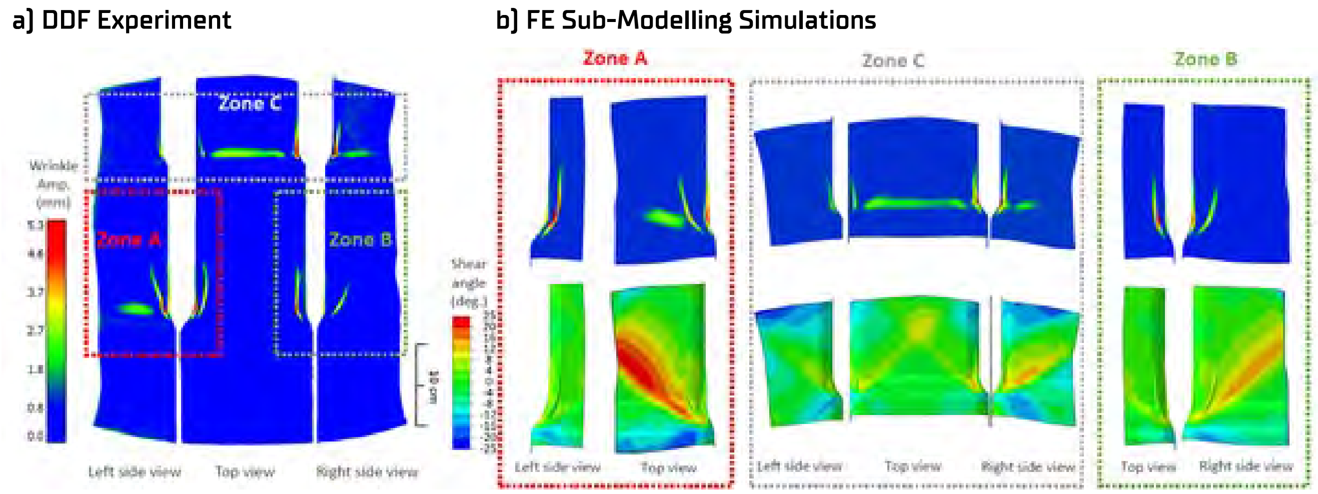


Figure 1. Global-to-local simulation of wing spar to effectively predict small wrinkling defects in double diaphragm forming (DDF) of biaxial non-crimp fabrics: a) overall model, b) critical areas identified by extensive shear angle.

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%. In addition, a reduction of 30% of out-of-plane wrinkle severity showed that pre-tensioning the diaphragms prior to forming is a pivotal step in consistently 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.

Component Design Tools

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

A multi-scale finite element (FE) forming tool was designed to efficiently identify small critical defects (out-of-plane wrinkles magnitude of 1 mm) in large industrial components, i.e. +10m wing spars. The FE results from a global membrane-only model were used to identify the regions where defects could potentially occur using in-plane shear criteria. A refined shell-based model was then run in the critical regions to accurately capture the formation of small wrinkling defects observed during DDF experiments.

For the optimisation of the component geometry, a less computationally demanding tool was created. A machine learning-based model was developed to provide rapid predictions of the location and severity of wrinkling defects during the DDF of large NCF preforms. Geometry-induced wrinkle patterns were extracted from accurate FE simulations, mapped onto 2D surfaces, and transformed into grayscale 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 produce defect-free parts.

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.

Process Improvements

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

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

The formability of biaxial NCF during DDF could also be improved by reducing the friction coefficient between the ply stack and the diaphragms. Forming trials on ramped aircraft spar with complex double curvatures showed that applying liquid resin lubrication on the entire fabric eliminated wrinkles generated during forming. 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.

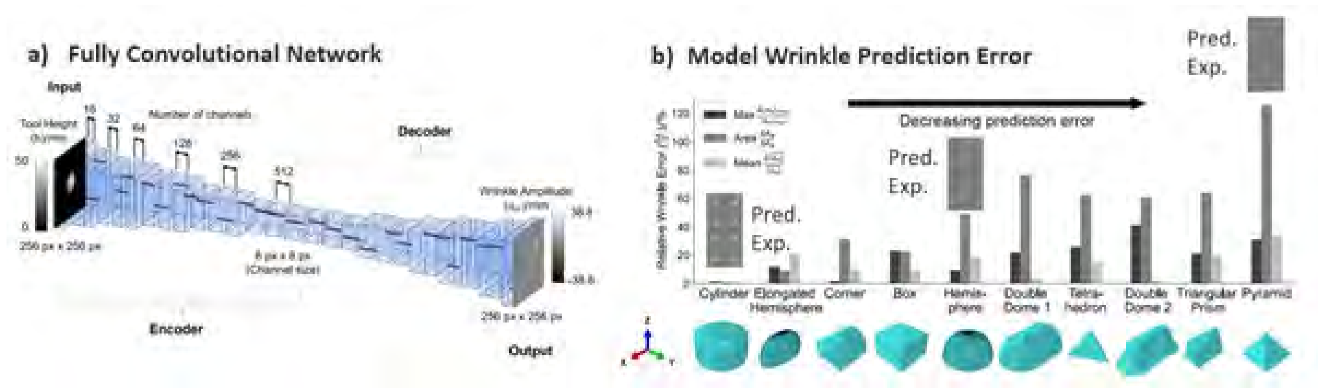


Figure 2. Forming simulation tool developed using machine learning (ML) to rapidly predict from component geometry the amplitude of wrinkling defects across biaxial non-crimp fabric surfaces: a) architecture of ML model, b) evaluation of accuracy with different test shapes.

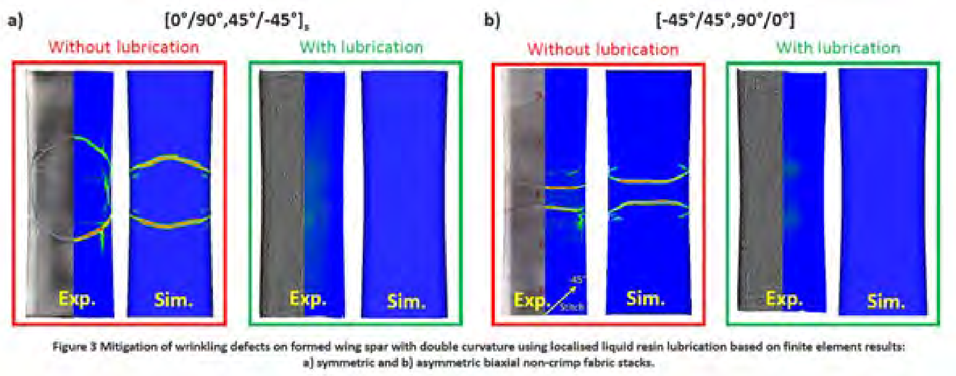


Figure 3. Mitigation of wrinkling defects on formed wing spar with double curvature using localised liquid resin lubrication based on finite element results: a) symmetric and b)asymmetric biaxial non-crimp fabric stacks.

Publications

- 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.
- Yu F., Chen S., Harper L.T., Warrior N.A., Simulating the effect of fabric bending stiffness on the wrinkling behaviour of biaxial fabrics during preforming. Composites Part A: Applied Science and Manufacturing, Vol 143 (2021), 106308.
- Viisainen J.V., Hosseini A., Sutcliffe M.P.F., Experimental investigation, using 3D digital image correlation, into the effect of component geometry on the wrinkling behaviour and the wrinkling mechanisms of a biaxial NCF during preforming. Composites Part A: Applied Science and Manufacturing, Vol 142 (2021), 106248.
- Yu F., Chen S., Harper L.T., Warrior N.A., Double diaphragm forming simulation using a global-to-local modelling strategy for detailed defect detection in large structures. Composites Part A: Applied Science and Manufacturing, Vol 147 (2021), 106457.
- Chen S., Joesbury A.M., Yu F., Harper L.T., Warrior N.A., Optimisation of intra-ply stitch removal for improved formability of biaxial non-crimp fabrics. Composites Part B: Engineering, Vol 229 (2021), 109464.
- Chen S., Joesbury A.M., Yu F., Harper L.T., Warrior N.A., Optimisation of intra-ply stitch removal for improved formability of biaxial non-crimp fabrics. Composites Part B: Engineering, Vol 229 (2021), 109464.
- Yu F., Chen S., Harper L.T., Warrior N.A., Investigation into the effects of inter-ply sliding during double diaphragm forming for multi-layered biaxial non-crimp fabrics. Composites Part A: Applied Science and Manufacturing, Vol 150 (2021), 106611.
- Yu F., Chen S., Harper L.T., Warrior N.A., Simulating the effect of fabric bending stiffness on the wrinkling behaviour of biaxial fabrics during preforming. Composites Part A: Applied Science and Manufacturing, Vol 143 (2021), 106308.
- Viisainen J.V., Yu F., Codolini A., Chen S., Harper L.T., Sutcliffe M.P.F., A Deep Learning Surrogate Model For Rapid Prediction Of Geometry-induced Wrinkles In Fabric Preforming. ICMAC21, Online (2021).
- Codolini A., Viisainen J.V., Yu F., Chen S., Harper L.T., Sutcliffe M.P.F., Numerical Assessment of Variability in Double Diaphragm Forming of Non-Crimp Fabric Preforms. ICMAC21, Online (2021).

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

Core Project Team

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Research Team: Dr Andreas Endruweit, University of Nottingham; Dr Mikhail Matveev, 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:** 31/07/2023

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 result 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 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 parts quality. 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 on-line parameter estimation algorithms to improve resin injection. This control system will minimise occurrence of defects and ensure the process robustness.

Progress

- Current capabilities on sensors for the RTM industry were reviewed. While in-mould pressure transducers remain a standard tool, several new emerging technologies were identified as suitable for industrial and research environments.
- Novel Bayesian inversion algorithm that is able to capture race-tracking and other defects using in-process data has been developed. The algorithm was validated using virtual and lab experiments.

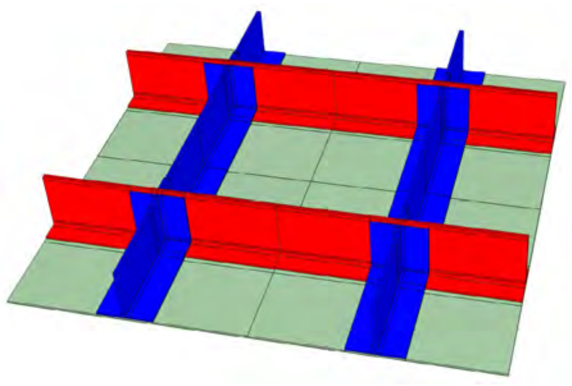

Figure 1. Model of a complex demonstrator: integrated stiffened panel

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. 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 attached to our project. Further testing of the algorithm in virtual and lab settings is also of substantial interest with the ultimate objective to use it in an industrial environment or in active control systems. To this end, we are currently developing a new demonstrator – stiffened panel equipped with sensors. We are expecting to test inversion algorithms on detecting race tracking as well as layup and material defects within this new demonstrator.

Figure 2. The demonstrator prototype: 3D printed closed mould tool

Publications

- Matveev M.Y., Endruweit A., Long A.C., Iglesias M.A., Tretyakov M.V., Bayesian inversion algorithm for estimating local variations in permeability and porosity of reinforcements using experimental data. Composites Part A, 143, 2021.
- Iglesias M.A., Yang Y., Adaptive regularisation for ensemble Kalman inversion with applications to non-destructive testing and imaging, Inverse Problems, 37(2), 2021.

Layer-by-Layer (LbL) Curing

Core Project Team

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MSc Students: Mr Adrien Gilbert, Cranfield University; Mr Asish Kumar Patra, Cranfield University.

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 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 term 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 that 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 geometries and material model development for fast processing resins and made sufficient progress in the objective related to interfacial toughness development during the process. The development of the coupled model of the cure process 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. Overall, the outcomes so far 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.

The outcomes of the core project so far contribute to the 'High Rate Deposition and Rapid Processing Technologies' research priority area of the Hub through the established acceleration of processing. The development of coupled simulation as the basis for design and optimisation of the process contributes to the priority area of 'Design for Manufacture via Validated Simulation'. The ability to process thicker, larger structures through elimination of intense exothermic effects 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.

Aims and Objectives

The aim of the core projects is the development of the Layer by Layer (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 WP1 of the project incorporates a coupled thermo-chemo-mechanical solution and a strategy for addition of elements as the process evolves (D1.1). 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.

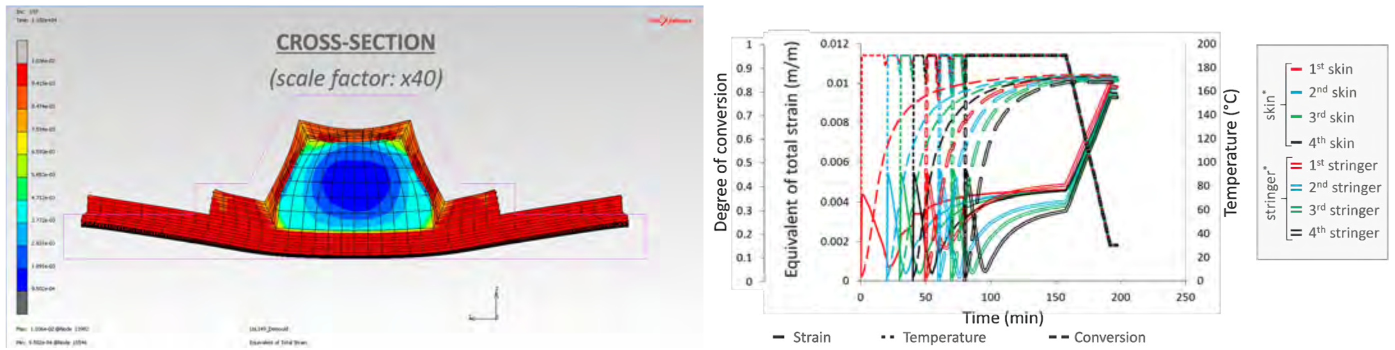

Figure 1. LbL simulation of a stiffened panel: left – total strain distribution and deformed shape (deformation scaled for visualisation) upon placement of the last stringer sublaminate; right – evolution of strain, temperature and degree of cure in the four sublaminates of the skin and of the stringer.

The constitutive models and associated characterisation currently within WP1 available for the 913 and 8552 systems have been extended to the fast cure M78.1 epoxy prepreg (D1.2). Figure 2 illustrates the results of isothermal and dynamic differential scanning calorimetry (DSC) experiments. The results show that the epoxy of the prepreg undergoes an autocatalytic reaction, with the cure becoming very fast (below 3 min) over 140°C. The total heat of reaction is consistent across isothermal and dynamic condition as well as across different rates, which is indicative of lack of thermal history dependence of cure kinetics. The reaction can be modelled using the Karkanas model:

$$\frac{d\alpha}{dt} = k_1\,(1-\alpha)^{n_1} + k_2\,(1-\alpha)^{n_2}\,\alpha^m \qquad (1)$$

where k_1 and k_2 denote rate constants including a diffusion limitations contribution and Arrhenius chemically controlled reaction terms and are n_1, n_2 and m are reaction orders.

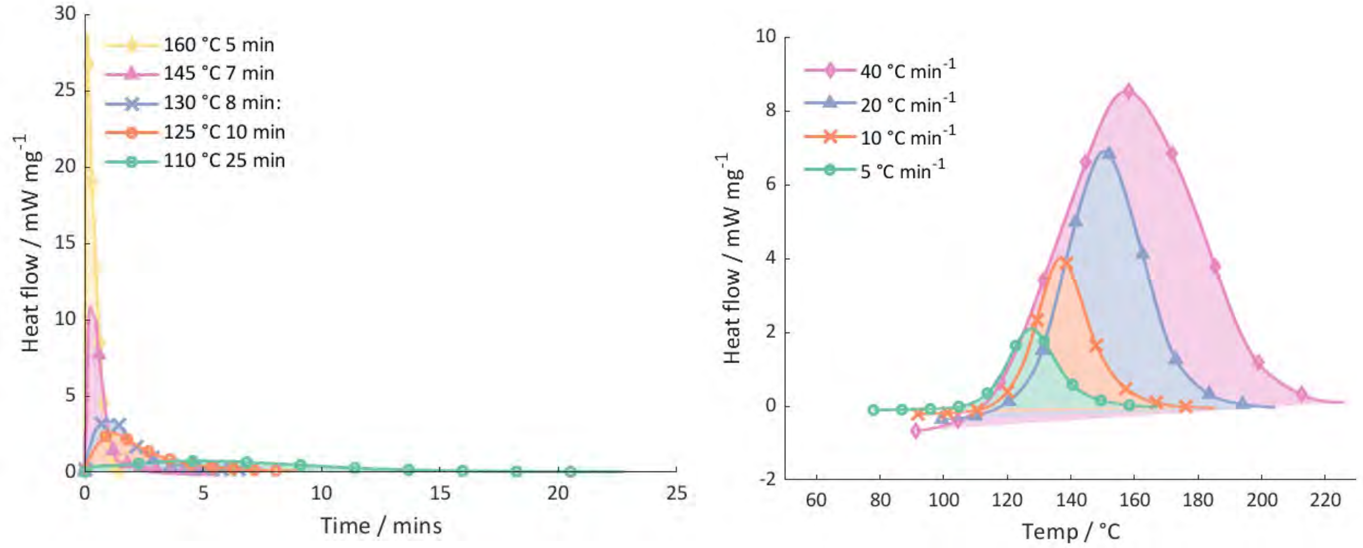

Figure 2. Cure kinetics of M78.1 system: left – isothermal DSC experiments; right – dynamic DSC experiments.

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 within space 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 pre-cure below the gel point resulting in interfacial properties equivalent to those of the virgin material.

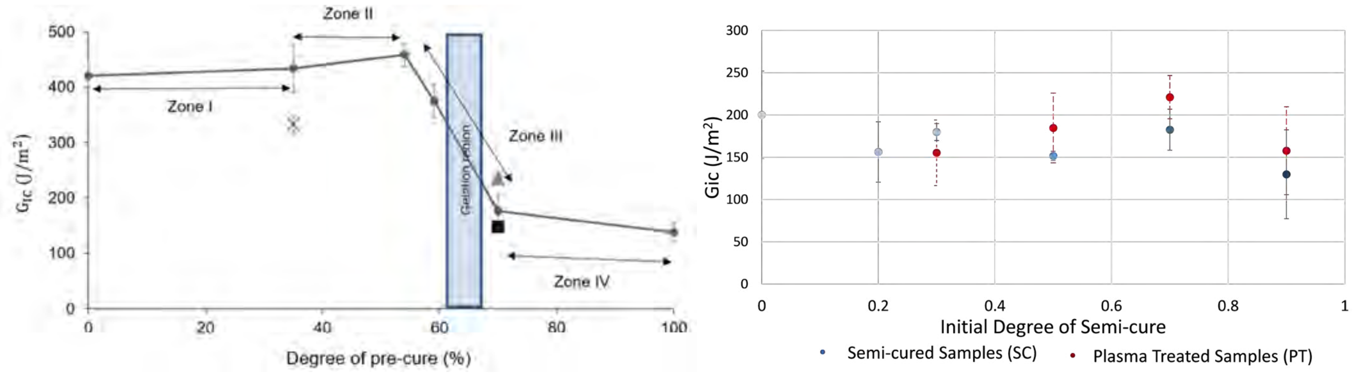

Figure 3. Dependence of toughness on degree of pre-cure: left –epoxy prepreg system; right –epoxy liquid moulding system.

Figure 3 illustrates the dependence of Mode I toughness on the degree of pre-cure of one side of the interface for materials representative of prepregs and liquid moulding epoxy systems. The general behaviour was also applied to a pultrusion system, where Table 1 shows the T-peel toughness for different pre-cure states of both sides of the interface for the XU3508/XB3473 system incorporating PAT-656/B3R release agent. In all cases the behaviour follows the behaviour observed previously 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 4. The imprint of the peel-ply utilised at deposition of the first sublaminate becomes visible once pre-cure 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 system, establishes the main criterion for process design of the LbL process and contributes to D1.3 of the project. The results obtained for a two-sided pre-cure 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.

Top Layer DoC %	Bottom Layer 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

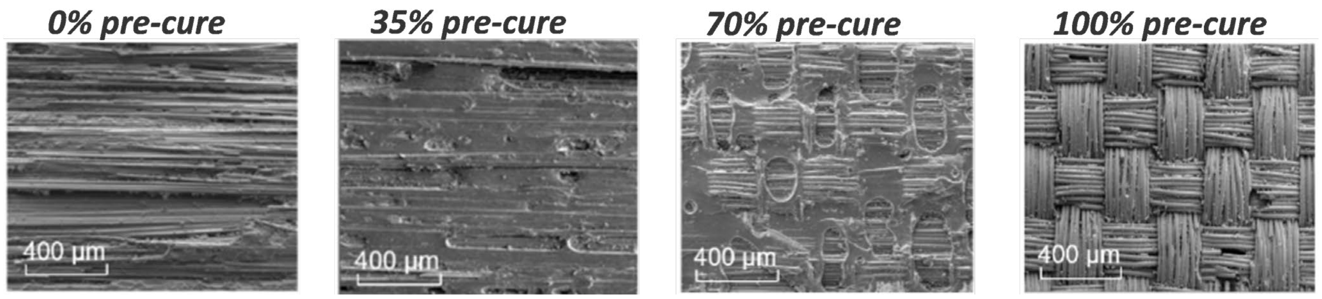

Figure 4. Fracture surface of LbL interfaces of 913 epoxy prepreg for different levels of pre-cure.

The criticality of establishing the degree of pre-cure 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 considerations 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 and the activation energy of the cure kinetics model play the most significant role in propagating variability to the results of the heat transfer calculation.

Parameter	HTC	Tool	Sensitivity: Peak Cure Time	Sensitivity: 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

Activities within WP2 and WP3 concerning the LbL version of AFP have started with simulation of heat transfer effects. The envelope of applicability of LbL based AFP has been established through the application of simulation and optimisation to demonstrate that LbL-AFP yields benefits with respect to both process time and temperature overshoot compared to monolithic curing following completion of AFP. Similarly to the whole layer by layer process investigated in WP1, 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 5 illustrates the dependence of processing time on component size for an epoxy prepreg. LbL-AFP 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 100s of hours the LbL-AFP strategy has the potential of intensification through it scalability potential via use of multiple heads and thick tows. Similar results have been obtained for different epoxies such as the XU3508/XB3473 pultrusion system.

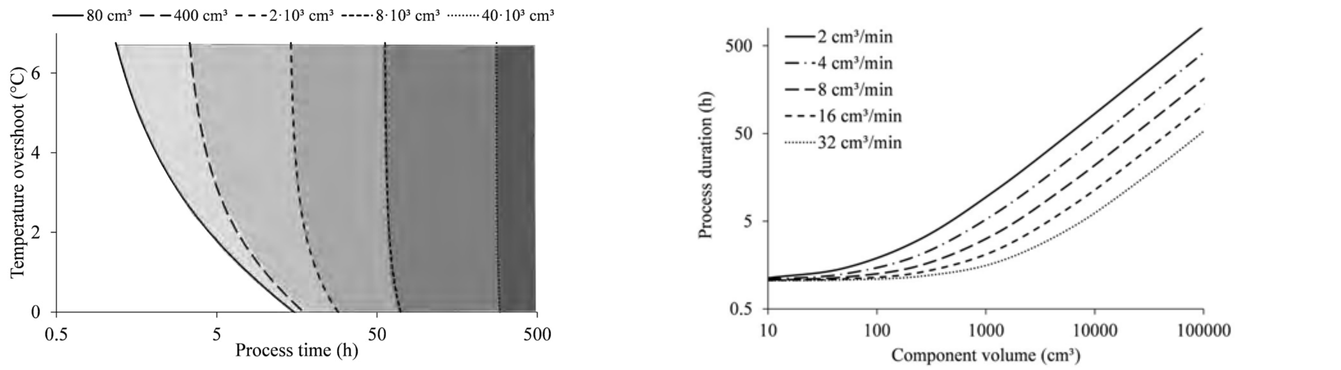

Figure 5. Envelope of applicability of LbL-AFP for the M21 epoxy/carbon prepreg: left – trade-off surfaces for different component volumes governed by thickness; right – process duration as a function of component volume.

In the future implementation of LbL-AFP, accurate knowledge of the temperature of deposited material is necessary for controlling the degree of pre-cure within the acceptable limits for producing an interface with the right levels of toughness. As a prelude to the relevant activity with WP3, 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 6 illustrates the setup and the results of estimation, which is done 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.

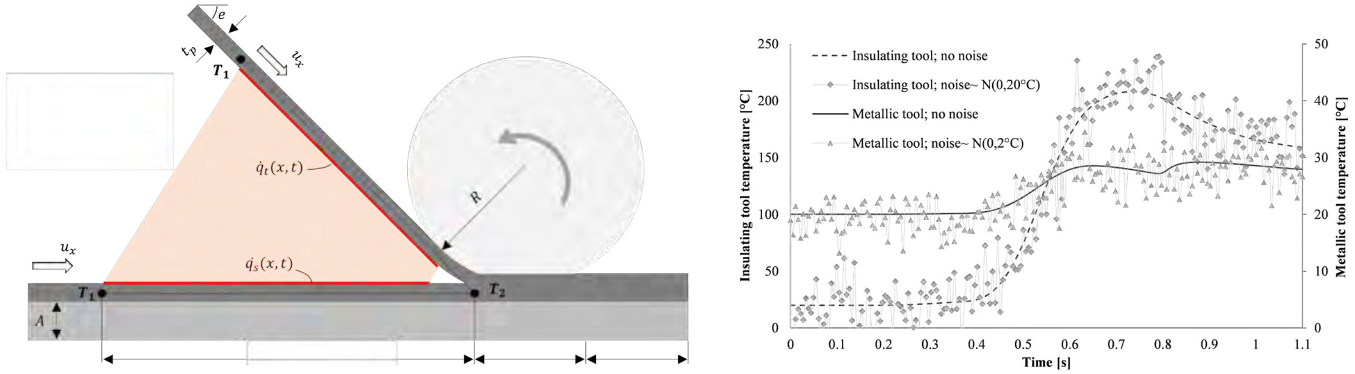

Figure 6. Inverse solution for irradiance estimation in AFP based on tool temperature measurements: left – model setup; right – estimation of irradiance subject to significant level of Gaussian noise.

Publications

- Struzziero G., Barbezat M., Skordos A.A., Consolidation of continuous fibre reinforced composites in additive processes: A review, Additive Manufacturing, Volume 48, Part B, December 2021, 102458.
- 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

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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.

Grant Award: £649,269 **Start:** 01/04/2017 **End:** 30/08/2022

Executive Summary

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.

Bristol has developed a novel automated manufacturing process named 'Fibre-steered forming technology (FSF)' 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. The process starts from designing a flat fibre-steered preform through a Virtual Unforming simulation. In this simulation, from a target 3D preform as an input, a flat preform pattern with fibre steering paths, which can be turned into the target 3D fibre paths after forming, is obtained by reversely forming the target preform. The flat fibre-steered preform is produced by CTS (Continuous Tow Shearing) process and then formed into the target shape using a diaphragm forming process. The FSF process was developed for both continuous fibre prepregs and highly-aligned short fibre prepregs produced by HiPerDiF (high performance discontinuous fibre) process.

This 'lay flat and form' concept has various advantages over the direct 3D AFP deposition process for small complex composite parts. For the AFP to produce such parts, the machine can never reach its maximum lay-up speed, as the lay-up paths become too short to accelerate the head. And the geometry would require fibre-steering with tight steering radii, which results in defects such as tape buckling, gaps, and overlaps. The AFP machine would require more degrees of freedom, increasing the equipment cost. However, the FSF process developed in this project can address the above productivity and steering quality issues by adopting the CTS technology that can steer wide unidirectional tapes with much smaller radii than the AFP's minimum steering radius without causing defects (i.e. 50 mm steering radius for 100 mm wide tapes), as well as by producing the flat fibre steered preform first and forming it into the target 3D shape. Another advantage is that recycled carbon fibre based tapes produced through the HiPerDiF process can also be used, which allows for improving the forming quality and enhancing the sustainability aspect of the FSF process.

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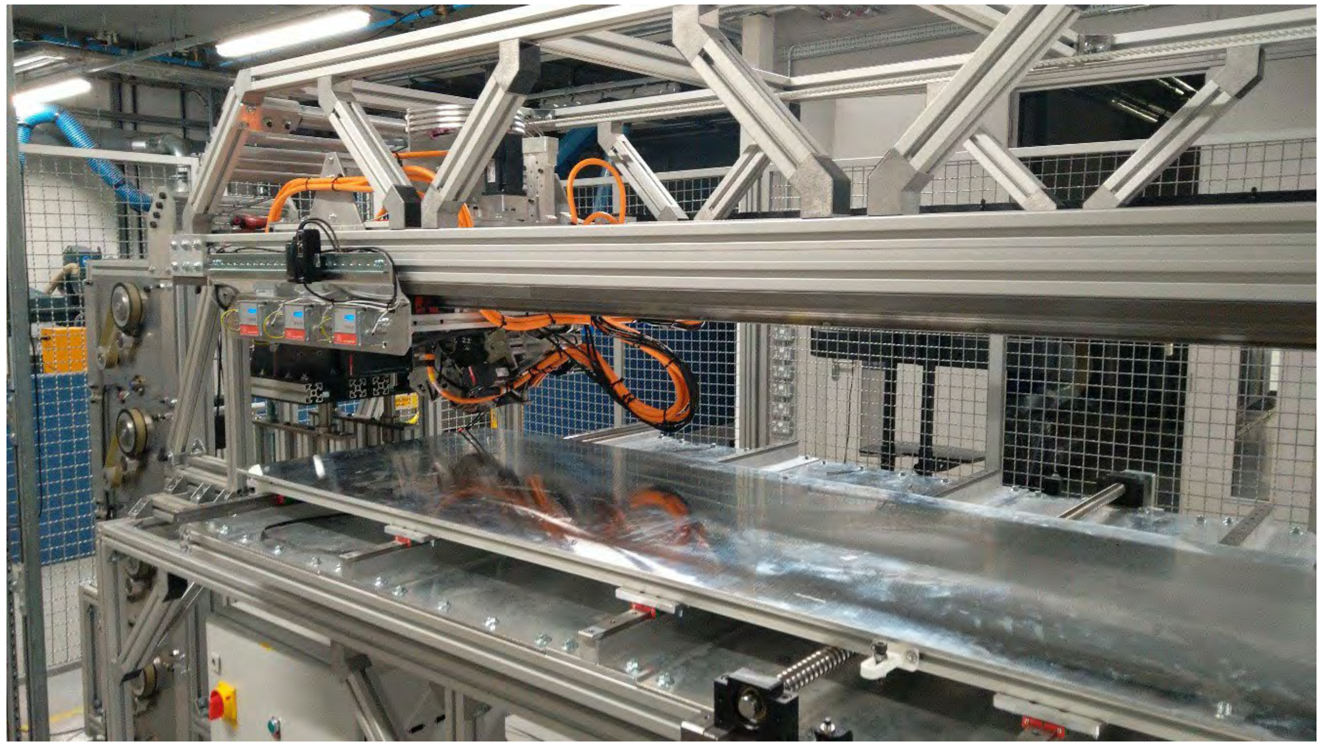


Figure 1. Automated dry fibre placement test rig incorporating digital twin under development.

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 effected 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 will develop and validate 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

The work at Nottingham has focussed on barriers to uptake, identified in collaboration with industrial partners. Challenges this last year have centred on delays in the construction of the deposition test rig mainly due to lab closures and procurement issues associated with the pandemic.

Developments at the University of Nottingham

- Development of a network based flow modelling approach.
- Flow / permeability characterisation of gapped ADFP preforms.
- Development of knowledge of raw material behaviour – thermal, electrical and compaction characteristics.
- Increased understanding of the joule heating mechanism for carbon fibres.
- Development of a digital twinning methodology based on the HDF5 database format.
- A real-time control strategy combining multi-physics co-simulation of thermal and mechanical properties of carbon fibre tapes.

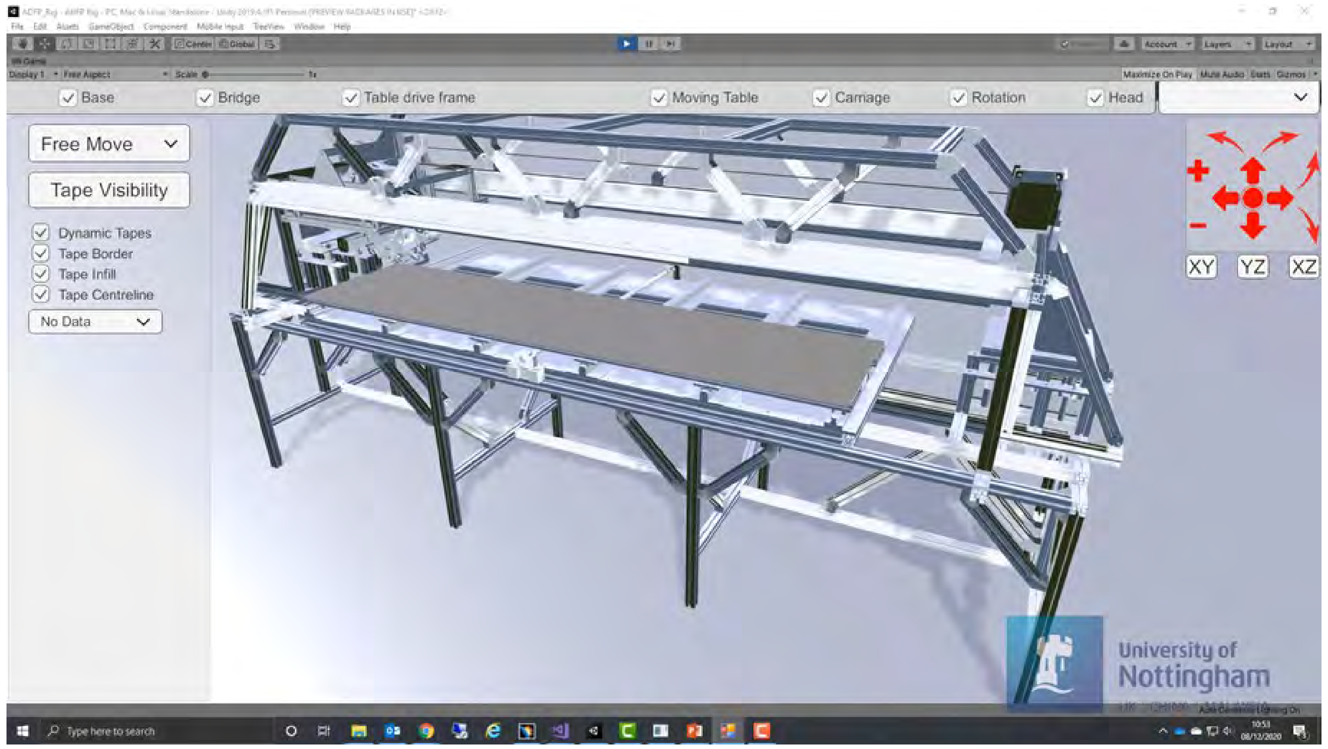


Figure 2. Parallel deposition visualisation during deposition – motion and material deposition behaviour based on machine data streamed in real time

Developments at the University of Bristol

Fibre-steered preform design through Virtual Un-forming simulation

To better demonstrate the differences of steerability and formability between a representative continuous fibre and HiPerDiF prepreg preforms in complex forming scenario, both experimental trials and finite element (FE) models were conducted and developed, respectively, in parallel. The aims of this numerical study are twofold. First, it was to numerically obtain a representative fibre steering path for a 2D preform from a 3D 'as-designed' part, for the purpose of CTS production, based on a previously proposed "unforming" modelling concept, developed through a Hub Feasibility Study project. Numerical tools developed also includes a user-defined material model for HiPerDiF prepreg, which is the second aim of the numerical study.

The material model was developed and validated based on a set of highly-detailed material characterisation testing in different manufacturing environments. High-fidelity and cost-effective forming simulations together with embedded material model were then developed and validated by double diaphragm forming (DDF) tests, a representative comparison between experimental and numerical results of which is shown in Figure 2. In DDF simulation, the forming was modelled by changing the pressure load acting on the diaphragms. The same uniform pressure distribution was given to both upper and lower diaphragms in the opposite directions. After diaphragms and preform were stable, then the pressure acting on the lower diaphragm was gradually reduced so that double diaphragms were formed onto the part, and the preform that is sandwiched between the diaphragms was draped to the shape. The virtual "unforming" is realised by directly reversing process of forming. An initial forming simulation was first performed; nodal displacement histories of the diaphragms were extracted, stored and used for the un-forming simulation. During "unforming", these nodal displacement histories were reversed and assigned to the same nodes of diaphragm models but with the opposite sign so that both diaphragms can deform back from formed geometry to their original states. And the pre-form model sandwiched between the diaphragms was also deformed from its 3D 'as-designed' shape (see Figure 1a) to 2D flat state with steered fibre path (see Figure 1b). Steering angle of spanwise element strips were then generalised to a single spanwise fibre trajectory for CTS production (see Figure 1c).

To accurately capture the behaviour of the continuous and discontinuous preform during the forming/un-forming process, a hybrid approach of material modelling was used: shell (S4R in Abaqus) and membrane element (M3D4R in Abaqus) are superimposed to represent out-of-plane bending and in-plane material properties of preform, respectively. A material model, based on a hypoelastic framework and implemented via a VUMAT subroutine in Abaqus/Explicit, was used to the preform model. Ogden's hyperelastic material model with representative parameters were employed to model diaphragms undergoing large deformation during DDF. Simplified coulomb frictional contact was found effective to simulate interactions of prepregs and prepreg/tooling.

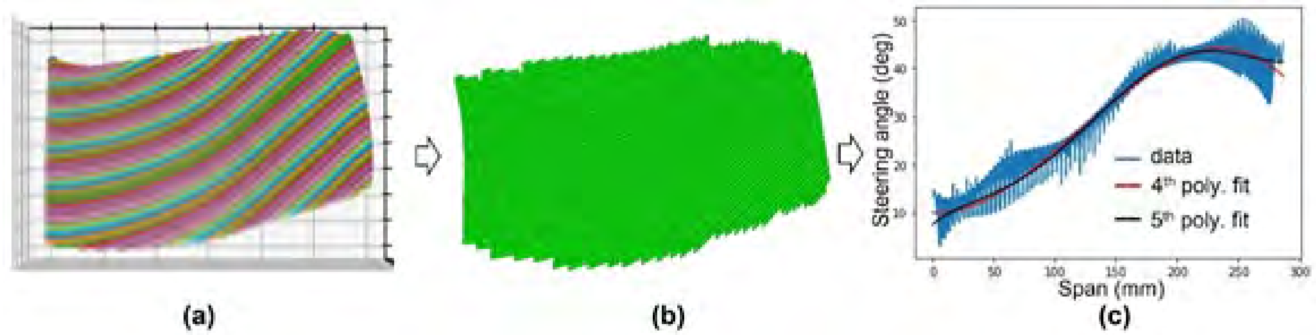


Figure 1. Overall process of deriving steering fibre path from (a) 3D 'as-designed' fibre orientation in code framework to (b) 2D 'un-formed' preform after 'un-forming' simulation in FE framework to (c) 2D generalisation of spanwise fibre steering angle for CTS production.

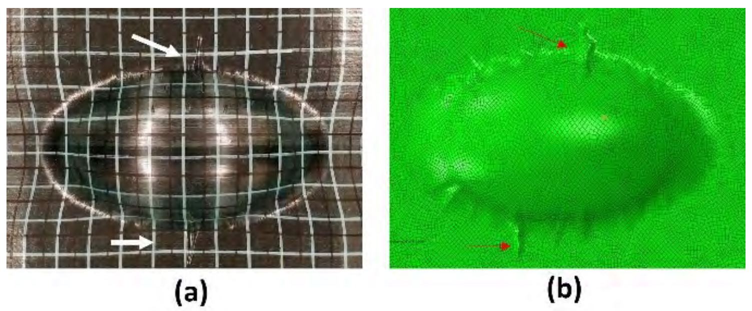


Figure 2. Comparison of wrinkle formation of a single-layered continuous fibre prepreg during double diaphragm forming (a) in experiment and (b) numerical simulation.

It was demonstrated that the developed material model and the forming simulation are capable of capturing intrinsic material behaviours, interply and preform/tooling interactions and wrinkles' formation in both single ply and multiply forming. These set of validated numerical tools were considered to significantly reduce the amount of experimental trials, as well as to elevate productivity and production qualities of high-volume fibre-steered forming technology for both continuous and discontinues prepreg systems.

Material characterisation technique to study the in-plane shear behaviour of unidirectional tapes

To accurately predict the 3D fibre paths after forming and optimally design the 2D fibre paths for the flat preform before forming, the deformation behaviour of the tape materials needs to be fully characterised. It is also important for optimise the CTS process conditions for HiPerDiF tape materials. In this work, a modified picture frame test rig was developed to experimentally study the in-plane shear characteristic of unidirectional tape materials, which has been challenging. As shown in Figure 3(a), the test rig consists of two pairs of picture frames, while the middle frame is shared. The unidirectional tape was mounted horizontally. Each frame has shorter horizontal arms to reduce the fibre length gripped by the vertical frames and minimise the chance of shear buckling of the tape while securing a large enough gap to observe the fibre rearrangement and the uniformity of the shear strain. The middle frame was fixed onto the base of a uniaxial tensile test machine, and the pure shear deformation was introduced by pulling the vertical frames on both sides, which were connected to the crosshead load cell using long wires; the use of long wires minimised the angle change of the loading direction. Figure 3(b) shows the shear stress/strain curves of a carbon fibre unidirectional tape in comparison with the off-axis tension test that is often used to measure the in-plane shear behaviour of a unidirectional prepreg. Although both showed a very similar trend in the small shear angle range, which is the limit of the off-axis tension test, the modified picture frame test successfully managed to introduce high shear strain without causing major tape buckling. This is particularly useful for accessing the processibility of the material for optimal fibre steering using the CTS. The HiPerDiF tape materials are currently being tested using this test rig, and the results will be used for the material models for unforming simulation and CTS process optimisation.

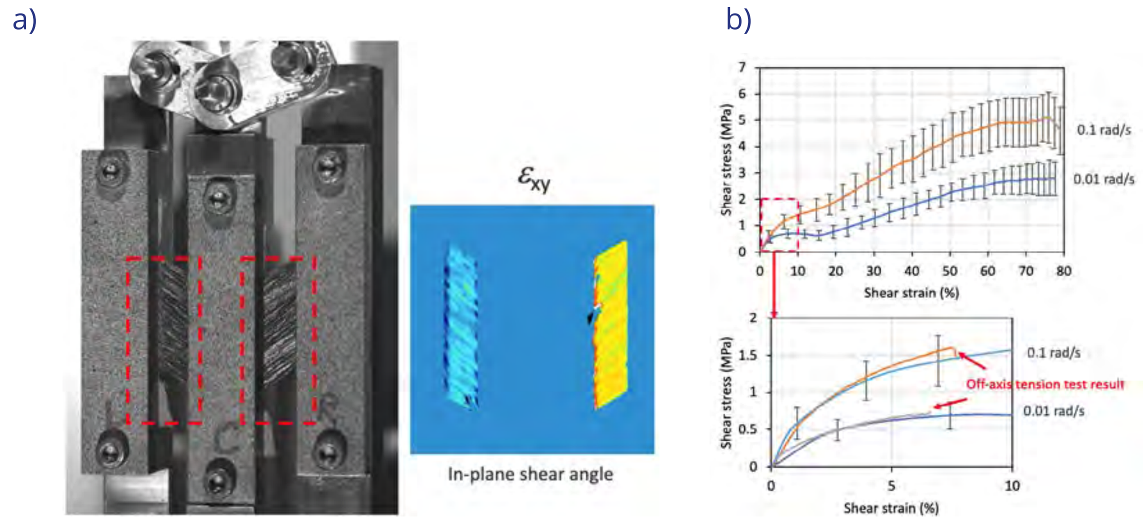


Figure 3. Modified picture frame test rig: (a) photo of the test rig and in-plane strain distribution within the sheared uni-directional tape sample, captured using a digital image correlation technique, (b) obtained shear stress-strain curves (top: test results at two different shear rates, bottom: comparison with off-axis tension test results).

Fibre-steered preform production

Before testing the HiPerDiF tapes, fibre-steered 2D preform samples were produced with unidirectional carbon continuous fibre prepreg tapes using the UoB's CTS prototype machine, and then diaphragm forming tests were carried out on a twisted plate model to validate the Virtual Unforming simulation and the method of extracting a representative fibre path from the unforming simulation results. As shown in Figure 4(a), a dot pattern was formed on a 100 mm wide prepreg tape before the CTS process was used to calculate local shear angle distribution after the diaphragm forming.

To use the HiPerDiF tapes in an automated deposition process, the challenge is its stretchability. For example, AFP machines pull the tapes by pressing the tape onto the substrate while moving their head, which could cause tape breakage if a highly stretchable material. The CTS machine has an advantage that it can actively feed the tape material while minimising the tape tension. A preliminary steering trial with 6 mm wide HiPerDiF tapes on a single tow CTS prototype head showed promising results as shown in Figure 4(b). The same operation mode will be tested for much wider HiPerDiF tapes on a wide CTS head in the next phase.

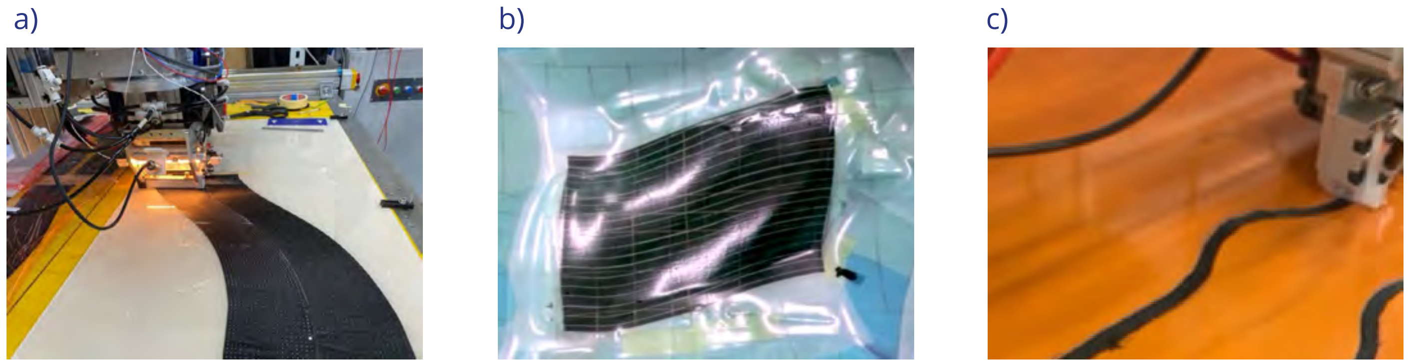


Figure 4. Continuous Tow Shearing process to produce fibre-steered preforms: (a) process of shearing 100 mm wide unidirectional CF/epoxy prepreg tapes, (b) after diaphragm forming on a twisted plate shape, (c) HiPerDiF tape steering trial on a single-tow CTS machine.

Double-diaphragm forming

An in-house double-diaphragm forming rig (as shown in Figure 5(a)) was fabricated for forming trials. In this work, two different doubly-curved shapes were used; a rugby-ball shape (positive Gaussian curvature) and a twisted plate shape (negative Gaussian curvature). To compare the formability, single ply preforms made of continuous carbon fibre prepreg and HiPerDiF prepreg with the same epoxy resin system were prepared and formed on the rugby-ball shape. As shown in Figure 5(b), the HiPerDiF prepreg exhibited a much better forming quality due to its stretchability, although some gaps between the narrow HiPerDiF tapes were present due to the lack of staggering process. Wider HiPerDiF tapes are currently being produced to manufacture fibre-steered and multi-layered preforms for further validating the unforming simulation model. The locations of the dots printed on the top layer as well as the degree of surface wrinkling will be measured using a 3D coordinate measurement machine to calculate the shear strain distribution after forming.

a) b) c)

Figure 5. Double-diaphragm forming rig: a) schematic and photo, b) forming quality comparison between the continuous fibre prepreg and the HiPerDiF prepreg (formed at room temp).

HiPerDiF tape production

The HiPerDiF tape used in this project was produced by the 3rd generation HiPerDiF machine built at the National Composites Centre. The HiPerDiF process is an environmentally friendly process using a water suspension with short carbon fibres. The suspension is injected into the fibre orientation head, and the machine can align the fibres along the production direction, which makes it very suitable for producing long tapes. In this work, 3 mm long carbon fibres were used to produce about 40-50 m long and 30 mm wide tapes for the CTS process. Its fibre steering tests are currently on going to produce multi-layered fibre-steered HiPerDiF preforms for forming trials.

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.

New Manufacturing Techniques for Optimised Fibre Architectures

Core Project Team

Principal Investigators: Prof Andrew Long, University of Nottingham; Prof Prasad Potluri, University of Manchester.

Research Team: Dr Louise Brown (Co-I), University of Nottingham; Dr Mikhail Matveev, University of Nottingham; Dr Shankhachur Roy, University of Manchester; Dr Vivek Koncherry, University of Manchester; Mr Jinseong Park, University of Manchester; Mr Kazi Sowrov, University of Manchester; Mr Sarvesh Dhiman, University of Manchester; Mr Syed Abbas, University of Manchester; Mr Christos Kora, University of Nottingham.

Industry Partners: GKN Aerospace, M Wright & Sons, NCC, AMRC, BAE Systems, ESI, Shape Machining, Hexcel, Sigmatex, Luxfer Gas Cylinders.

Grant Award: £725,425 **Start:** 01/02/2017 **End:** 30/06/2022

Executive Summary

This project aims to discover new 3D textile preform architectures. Computational modelling or "virtual testing" evaluated the utility of different textile designs within an optimisation framework to determine the best solution for a particular application. This framework is not constrained to architectures that can be produced using existing manufacturing technologies such as weaving or braiding. Optimum textile preforms have been realised by modifying existing textile processes as well as by developing entirely new, bespoke manufacturing technologies. This resulted in a step change in performance, leading to significant weight reductions and lower cycle times through routine use of automated manufacturing technologies.

A computation modelling framework was developed for multi-scale and multi-objective optimisation of complex 3D fibre architectures. The framework evaluates multiple possible architectures and determines the best architecture for a particular application. Among the possible properties that the framework can optimise are structural properties of composites and reinforcement permeability. This gives an opportunity to improve both performance and reduce the processing time. It was shown that it is possible to improve performance of composite components by relaxing manufacturing constraints and considering fibre architectures that are not possible to manufacture using available weaving techniques. In particular, at least 10% improvement has been achieved for one demonstrator even when comparing to an already optimised solution that uses commercially available reinforcement.

Two industrially relevant product examples were identified- a vehicle floor panel and a composite overwrapped pressure vessel (COPV) in order to demonstrate the benefits of optimised architecture. A 1m x 1m 3D multiaxial fabric (Figure 1) was developed at the University of Manchester and later composite was manufactured at the University of Nottingham. The vehicle floor panel tool received from AMRC was used for the composites and the fabric was easily drapable. Further manufacturing trials are ongoing and expected to be completed by June 2022. Inline radial braiding and hoop winding (Figure 2a) was used to develop composite overwrapped pressure vessel (COPV) demonstrator. The layup and fibre orientation for the COPV was selected based on the optimised parameters for a pressure vessel. Optimised architecture combines the benefits of hoop winding for high pressure retaining while braided architecture will contribute to the impact resistance. Samples will be sent to our industrial partners for burst testing, and comparative analysis of the performance of the demonstrator with respect to the design used currently in the industry, will be carried out.

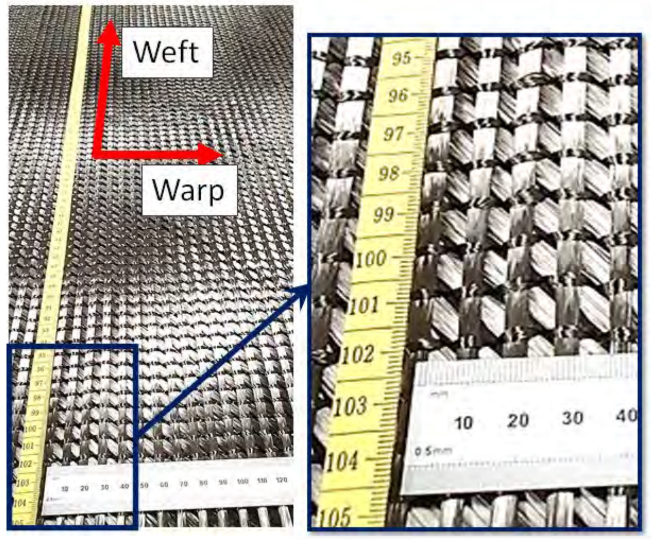
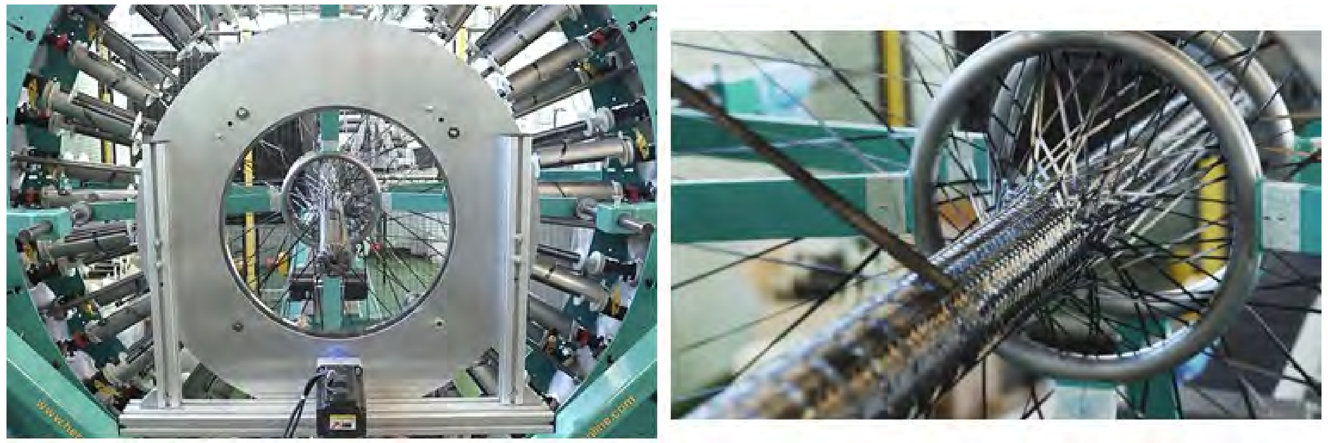


Figure 1. 3D multiaxial preform for vehicle floor panel was developed using a novel manufacturing technique with capability of custom yarn orientation, yarn spacing and thickness.



(a) (b)

Figure 2. (a) Novel tape winding equipment placed in-line with a radial braider at the University of Manchester (b) carbon fibre tape winding on a braided tube.

Aims and Objectives

The project aims to discover new forms of 3D fibre reinforcements for use in manufacturing of composites with mechanical properties better than can be achieved now with conventional 3D reinforcements. These new types of reinforcements will complement and extend the currently available class of 3D textiles such as orthogonal weaves or layer-to-layer weaves. A computational framework, "virtual testing" approach, was developed for evaluating properties of various composites designs and together with an optimisation algorithm selecting the best fibre architecture for a particular application. The computational framework implements a building-block approach where new models can be added at any stage to evaluate more properties of reinforcements and resulting composites. Optimisation algorithms used within the framework enables prediction of the best possible solution or a range of optimal solutions (a Pareto front).

Two case studies, developed through collaboration with industrial partners, will provide a test ground for the project. These case studies will demonstrate the weight-savings or improvement in performance achieved by optimisation of fibre preforms.

New manufacturing techniques were developed to create the optimised fibre preforms. This has been achieved by the modification of existing textile processes, and by developing entirely novel manufacturing processes. The manufactured samples will be used for the validation of the optimisation approach.

Progress

- Computational framework for multi-objective optimisation of fibre reinforcements has been developed. The framework employs multi-scale modelling to predict processing properties (such as permeability) of 3D fibre reinforcements as well as structural properties of composite components.
- A novel meshing technique was developed to aid the optimisation of complex 3D reinforcements of arbitrary complexity, while still maintaining reasonable accuracy and computational costs. The new algorithm was implemented as one of the features within TexGen open-source code and is now released in the public domain.
- The optimisation framework was applied to two demonstrators provided by industrial partners. An automotive component demonstrator, provided by the AMRC, was optimised to maximise its bending and torsional stiffness. It was shown that a novel multi-axial 3D fibre reinforcement can provide up to 10% improvement in properties when compared to the optimised non-crimp fabric component. The second demonstrator, a pressure vessel provided by Luxfer Gas Cylinders, was optimised for a novel fibre architecture. Similar performance was achieved; however, better delamination resistance is expected from the novel fibre architecture.
- Novel multiaxial preforming concepts have been demonstrated; new textile machinery was developed based on these concepts.
- Novel cylindrical multi-axial preforms were developed for application of pressure vessel.
- Two demonstrators, multiaxial floor panel and braid wound pressure vessel, were developed using optimised architecture.

Patents

- Potluri, P., Jetavat, D., Sharma S. (2017) Method and Apparatus for Weaving a Three-dimensional Fabric, US Patent 9,598,798.
- Potluri, P., Koncherry, V., Bisset M. (2021) Inline Graphene Coating, UK Patent Application No. 2117987.4 in the name of Petroliam Nasional Berhad (Petronas) and University of Manchester.

Publications

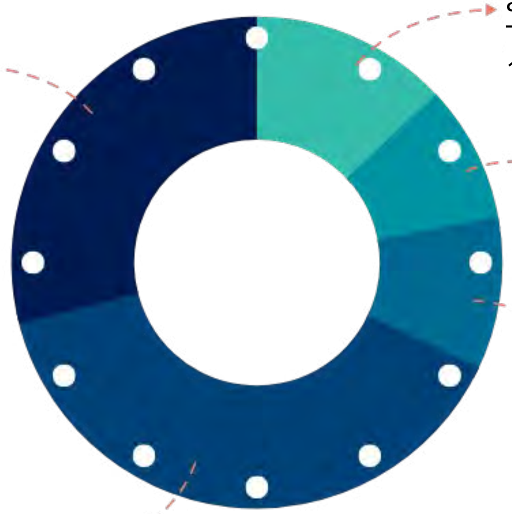
- Selver E., Potluri P., Intra-tow micro-wrapping for damage tolerance, Composites Science and Technology, vol. 213, p. 108935, 2021.
- Yousaf Z., Withers P.J., and Potluri P., Compaction, nesting and image based permeability analysis of multi-layer dry preforms by computed tomography (CT), Composite Structures, vol. 263, p. 113676, 2021/05/01/ 2021.
- Gautam M., Sivakumar S., Barnett A., Barbour S., Ogin S.L., Potluri P., On the behaviour of flattened tubular Bi-axial and Tri-axial braided composites in tension, Composite Structures, vol. 261, p. 113325, 2021/04/01/ 2021.
- Karim N., Sarker F., Afroj S., Zhang M., Potluri P., Novoselov K.S., Sustainable and Multifunctional Composites of Graphene- Based Natural Jute Fibers, Advanced Sustainable Systems, vol. 5, no. 3, p. 2000228, 2021.
- Yuan C., Wang Y., Yousaf Z., Storm M., Vo N.T., Wanelik K., Burnett T.L., Potluri P., Withers P.J. 2020. Following the effect of braid architecture on performance and damage of carbon fibre/epoxy composite tubes during torsional straining, Composites Science and Technology, vol. 200, p.108451.
- Matveev M.Y., Belnoue J.P-H., Nixon-Pearson O.J., Ivanov D.S., Long A.C., Hallett S.R., Jones I.A., (2019) A numerical study of variability in the manufacturing process of thick composite parts, Composite Structures, 208, pp. 23-32.
- Yan S., Zeng X., Long A.C. (2019), Meso-scale modelling of 3D woven composite T-joints with weave variations, Composites Science and Technology, Vol. 171, pp.171-179.
- Yan S., Zeng X., Long A.C., (2018) Experimental assessment of the mechanical behaviour of 3D woven composite T-joints, Composites Part B, Vol. 154, pp.108-113.
- Yan S., Zeng X., Brown L.P., Long A.C., (2018), Geometric modeling of 3D woven preforms in composite T-joints, Textile Research Journal, Vol. 88(16), pp.1862-1875.
- Mesogitis T., Skordos A., Long A.C., (2017), Stochastic simulation of the influence of fibre path variability on the formation of residual stress and shape distortion, Polymer Composites, v38, n12, 2642-2652.
- Endruweit A., Zeng X., Matveev M., Long A.C., (2018), Effect of yarn cross-sectional shape on resin flow through inter-yarn gaps in textile reinforcements, Composites Part A, v104, 139-150.
- Roy S.S., Potluri P., Soutis C., (2017), Tensile Response of Hoop Reinforced Multiaxially Braided Thin Wall Composite Tubes, Applied Composite Materials 24 (2), 397-416.
- Pavlopoulou S., Roy S. S., Gautam M., Bradshaw L., Potluri P., (2017) Numerical and Experimental Investigation of the Hydrostatic Performance of Fibre Reinforced Tubes, Applied Composite Materials 24 (2), 417-448.
- Gautam M., Katnam K.B., Potluri, P., Jha V., Latto J., Dodds N., (2017) Hybrid composite tensile armour wires in flexible risers: A multi-scale model, Composite Structures 162, 13-27.
- Akonda M.H., Stefanova M., Potluri P., Shah D.U., (2017) Mechanical properties of recycled carbon fibre/polyester thermoplastic tape composites, Journal of Composite Materials 51 (18), 2655-2663.
- Göktaş D., Kennon W.R., Potluri P., (2017) Improvement of Mode I interlaminar fracture toughness of stitched glass/epoxy composites, Applied Composite Materials 24 (2), 351-375
- Koncherry V., Potluri P., Fernando A., (2017) Multifunctional Carbon Fibre Tapes for Automotive Composites, Applied Composite Materials 24 (2), 477-493.
- Yousaf Z., Potluri P., Withers P.J., (2017) Influence of Tow Architecture on Compaction and Nesting in Textile Preforms (2017) Applied Composite Materials 24 (2), 337-350.
- Ataş A., Gautam M., Soutis C., Potluri P., (2017) Bolted Joints in Three Axially Braided Carbon Fibre/Epoxy Textile Composites with Moulded-in and Drilled Fastener Holes, Applied Composite Materials 24 (2), 449-460.
- Saleh M. N., Wang Y., Yudhanto, A., Joesbury A., Potluri P., Lubineau G., Soutis C., (2017) Investigating the potential of using off-Axis 3D woven composites in composite joints' applications, Applied Composite Materials 24 (2), 377-396.

2.3 Feasibility Studies

Our latest Feasibility Study call was launched in 2021 in collaboration with three other EPSRC Future Manufacturing Research Hubs: Electrical Machines, Metrology and Photonics, and represented a total of up to £900k funding to support projects at TRL 1 to 3.

The Composites Hub received 27 proposals from 17 universities, each with a focus on Sustainability challenges for fibre reinforced composites. After a review process consisting of international and UK independent reviewers, five projects of six months duration were awarded and started in late 2021 and early 2022. The majority of proposals submitted focused on Hub research themes Inspection and In-process Evaluation and Recycling and Reuse. We look forward to sharing the progress on these new studies as the results become available.

Hub Research Themes



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.

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

Context

The rapid development of fibre reinforced polymer composites has yielded significant benefits in structural efficiency and through life costs. As composites offer many design freedoms, significant cost savings can be made by reducing parts counts and joining operations. However, the drawback is that when a composite component is damaged it is difficult to replace a part that is co-bonded or co-cured into a larger structure, often resulting in disposal of a large asset leading to an increased composites waste mountain. The alternative is to repair, but current techniques are cumbersome and time-consuming, with low confidence in their efficacy for primary structures.

Aims and Objectives

The aim of this project 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 overarching ambition of ADDRESS is to rethink infield composite repair methodologies.

This study will bring together four interconnected work packages to produce a demonstrator showing the entire cycle of manufacture-service-repair-service loop:

- Manufacturing of a component with replaceable MMCRC feature based on vitrimer matrices.
- Impact testing on feature in question to induce matrix damage in the relevant domain and examining the damage in bi-matrix composites.
- Local processing aiming at the demonstration feasibility of removal damaged vitrimer matrix while keeping the host structure intact.
- Reinfusion with repairable matrices and assessment of the obtained component in series of mechani-cal tests against reference configurations.

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.

Industry Partners: Teijin Carbon Europe, Swiss CMT AG (CH).

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

Context

It is accepted that recycling carbon fibre is critical to achieving sustainability within the composites industry. Furthermore, the increased use of composites in industries with comparatively large carbon footprints, such as transport, in turn will boost the sustainability of these industries. The transport sector requires high performance composites to achieve weight reduction, and fuel efficiency goals. Producing high performance composites from rCF remains a significant challenge due to underdeveloped technologies to control short-fibre orientation, handling and accurate placement.

Aims and Objectives

The project will take aligned recycled carbon fibre and stabilise the material, using novel binder technologies, to produce robust intermediary materials. The project aims to reduce the carbon footprint of composites manufacturing and achieve a step towards a new manufacturing technology and a study to understand material manufacturing parameters.

This study will combine expertise in rCF alignment and aqueous binder doping to provide robust handleable aligned rCF for subsequent application of heat reactive epoxy powder to provide interplay tack to 'dry' rCF and fully impregnated prepreg, therefore creating a prototype system for producing rCF intermediary materials.

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.

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

Context

The composites landscape faces significant challenges presented by increasingly compressed design timescales, growing demand in productivity and the soaring complexity within products. Additionally, sustainability is a priority for the UK to achieve its pledge to reduce greenhouse gas emissions before 2030 and achieve net zero by 2050. While lightweight composite structures are expected to help reduce emissions during operation, energy is the single biggest factor in lifecycle analysis of the manufacturing process. However, the way in which composite curing equipment and tooling are designed and manufactured, has not changed since high-performance composites were first used in aerospace applications in the 1970s.

Aims and Objectives

This project will transform how tooling is designed to cure a composite part. It will investigate tooling to reduce embodied energy of composite manufacturing. Specifically, it will explore additive manufacturing to design the lightest possible cure tools to increase rate and quality by adjusting the heat distribution in the mould. The approach taken has the potential to radically shorten the design to manufacture time of complex tooling, targeting single iteration designs at a considerably lower cost. The aim of this study is to reduce the manufacturing embodied energy of composite parts whilst retaining the same quality expected for high-performance structures. The following objectives will be addressed:

- Develop a DfAM workflow for composite cure tooling
- Evaluate stainless steel AM cure tools for composite moulding requirements
- Demonstrate energy savings of AM cure tooling
- AM Tooling will be manufactured by metal powder bed fusion using Bath's Renishaw AM250
- Composite curing industrially relevant parts will be done in Bristol using an autoclave for the highly-tapered part, and in collaboration with Surface Generation for the out-of-autoclave skin-stringer part.

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 Conchúr Ó Brádaigh University of Edinburgh; Prof Dilum Fernando, University of Edinburgh.

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

Grant Award: £49,997 **Start:** 01/10/2021 **End:** 31/05/2022

Context

The level of recycling of plastic packaging waste is a key challenge facing the UK. A recent ban on plastic imports from the UK to Turkey has revealed that the UK still has insufficient technologies and infrastructure for dealing sustainably with the growing plastic waste problem. The quality of the collected plastic packaging waste to date has limited its potential for recycling applications. 30% of the plastic packaging waste is mixed plastic packaging containing food traces which requires pre-treatment before recycling. The current processes for sorting and cleaning plastic waste are labour-intensive and expensive, failing to capture the economic benefit of this resource in a cost-effective manner. There is clearly a need to "upcycle" plastic packaging waste to value-added products. The composites community can play an important role here.

Aims and Objectives

The main aim of this project is to manufacture thermoplastic prepregs using mixed waste plastics and waste glass fibres (GF), to produce laminates and to manufacture a demonstrator component for the construction sector. The composite products developed for the construction sector will allow waste materials used to be utilised for longer time periods (e.g. over 50 years), thus providing an economically attractive solution to deal with the current high volume of wastes. Large volumes of packaging plastic waste could be converted into added-value industrial products without undergoing any further energy-intensive steps such as depolymerisation or incineration. More importantly, this technology will offer a sustainable solution to tackling wastes generated from plastic packaging materials.

- A thermoplastic prepreg role material developed from waste glass fibres and mixed waste plastics (packaging wastes).
- A dataset of mechanical properties/fire resistance properties.
- A demonstrator "Cee" section column.
- Demonstrate potential of thermoplastic prepreg to be used as a sustainable alternative for thin-walled steel and aluminium sections in construction.

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 Partner: Comfil.

Grant Award: £50,000 **Start:** 01/11/2021 **End:** 30/04/2022

Context

The use of thermoplastic composite tapes is accelerating; applied in aerospace, automotive and oil and gas applications through automated fibre placement (AFP), automated tape laying (ATL) and continuous compression moulding (CCM). There is a pressing need to provide a sustainable lifecycle, especially since the majority of thermoplastics are oil derived. Whereas thermoset composites have to rely on more destructive recycling methods such as pyrolysis, solvents or shredding, thermoplastic composites have a unique advantage which has hitherto been unexplored: the ability to be (processed and) reprocessed by heat alone.

With the advent of manufacturing 4.0 and the new paradigm of digital twinning for manufactured components, it is now possible to know the exact construction of a component assembled from consolidated tapes. The location of each of the tapes is known precisely, such that it should be possible, with suitable confirming metrology systems, to locate the ends of a particular tape. If it were possible to free and grip the end of a tape using a suitable tool (e.g. an ultrasonic knife), then with the appropriate application of local heat and load it is conceivable that the tape laying process could be reversed – removing the tape and respooling it. In such a way the material could be recovered without wasteful burning of the matrix, downcycling of the fibre by chopping/grinding for pyrolysis or the use of large quantities of solvents.

Aims and Objectives

The fundamental challenges in this project lie 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 seems 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 entirely unexplored. This project will develop a means of recovering continuous thermoplastic prepreg from end-of-life parts by a controlled thermal peeling process in such a way as to make the peeled plies reuseable in new parts with minimal post-processing. This project focuses on understanding a potentially entirely new process for high quality materials with high-rate potential.

- Instrument a simplified peel tester with controlled heating for tape separation.
- Establish the conditions (e.g. temperature, force and speed) required to successfully peel a layer of continuous thermoplastic tape from a simple consolidated structure.
- Determine the most appropriate metrological technique to assess the viability of recovered material (in terms of waviness, matrix distribution, defects).
- Attempt basis reprocessing of peeled prepregs and determine composite properties.
- Provide a framework and initial data for a core project addressing the automated circular manufacturing of thermoplastic composites.
- Composite curing industrially relevant parts will be done in Bristol using an autoclave for the highly-tapered part, and in collaboration with Surface Generation for the out-of-autoclave skin-stringer part.

Optimised Manufacturing of Structural Composites via Thermoelectric Vario-thermal Tooling (VarioTherm)

Project Team

Principal Investigator: Prof Ton Peijs, University of Warwick.

Research Team: Dr Teodor Chiciudean (Co-I), University of Warwick; Mr Neil Reynolds, University of Warwick; Mr Samson Gnanadass, University of Warwick.

Industry Partners: European Thermodynamics Ltd.

Grant Award: £49,910 **Start:** 01/02/2020 **End:** 30/06/2021

Executive Summary

Traditional tooling systems for medium/high-volume manufacturing of composites include active heating/cooling to regulate the temperature of the tool, incorporating electrical heater cartridges or a cooling/heating circuit with oil or water as the thermal medium. Most such solutions aim at generating a homogeneous, isothermal temperature across the tool and part throughout a given process (cooling or cure). Moreover, for high-volume manufacturing using thermoplastic composites (TPCs), conventional tooling technology is suitable only for non-isothermal stamp-forming where part quality can be compromised due to rapid quenching during forming.

This VarioTherm project proposed to use an array of independently controlled thermoelectric (TE) Peltier modules to enable rapid vario-thermal zone heating/cooling in a metallic mould tool. Here, the hot and the cold side of the Peltier can be switched by simply reversing the polarity of the applied DC current offering bulk heating/cooling and accurate thermoregulation from a simple 'off-the-shelf' thermoelectric module package. Developing this tooling architecture along with the appropriate instrumentation and control system, rapid isothermal processing of thermoplastic laminates was investigated whereby the TPC is optimally-processed at above Tm without the lengthy heating/cooling phases typically experienced during conventional static (melt) pressing. Furthermore, the advanced thermoregulation capability offered by the Peltier module technology was used to investigate the possibility of controlling the development of the polymer morphology during the cooling phase.

In this study, the feasibility of using thermoelectric heating/cooling technology to manufacture a variothermal tooling system for the optimised processing of thermoplastic composite laminates was investigated. Particularly, the project investigated the heating/cooling performance of commodity thermoelectric (Peltier) modules in a tooling system context, delivered several prototype technology demonstrators and applied these prototype systems to process studies using commercially available tape-based aligned fibre reinforced thermoplastic laminate materials. The first prototype tooling system that was developed was built around a single Peltier module

(with control system) and showed that peak heating and cooling rates of >3 °C/s were achievable at the tool surface, demonstrating the capability to execute a heat/cool cycle based on PA6-based TPCs in ~100s. The first full tooling system (2 x 2 Peltier array, single-sided tool) was used to process PP-GF60 laminates at 2mm thick, completing a full heat-dwell-cool cycle in <400 s. Measurements taking during these experiments showed a heating/cooling rate of ~1 °C/s was achievable at the laminate mid-plane, limited by thermal losses from the upper free surface inherent to the use of single-sided tooling. A two-sided system was then developed (each side comprising a 2 x 2 array) and applied to perform a modest parametric moulding study on 4 mm-thick PP and PP-GF60 samples. This study revealed that the cooling rate in the system could be sufficiently controlled and adapted to effect measurable changes in relative crystallinity within the PP as determined via DSC.

Aims, Objectives and Results

The three project deliverables achieved:

- D1: Prototype construction as a technology demonstrator, allowing a feasibility determination of the proposed technology to a selected application.
- D2: Detailed performance data of the system in the context of rapid processing of thermoplastic composites.
- D3: A review of the benefits, limitations of proposed zone heating technology as compared to existing tooling technology.

Deliverable 1

The development of the VARIOTHERM prototype tooling systems was performed in a step-wise manner, delivering multiple tooling systems of increasing capability and complexity

The first stage prototype, the so-called '1-D study', was built to confirm outline feasibility of the application of the Peltier technology and to complete the selection and implementation of the measurement/control system. A single Peltier module was used with an in-house developed PWM control system (Figure 1). Following confirmation of outline feasibility, two further prototypes were developed based on a 2 x 2 array of modules, one single-sided tool **(D1a)**, and a double-sided tooling system **(D1b)**. The single-sided tool was built as a viable demonstration of local control of the process and the double-sided tool to evaluate the rapid processing, the necessity of which was determined due to heat losses observed using **D1a**.

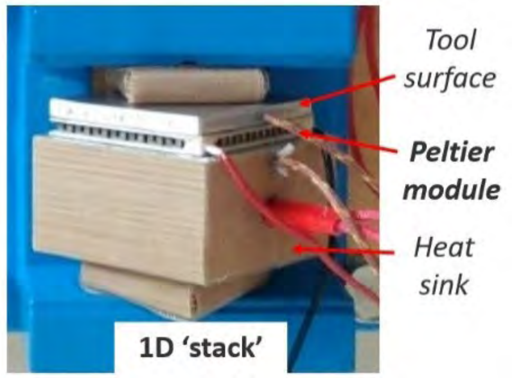


Figure 1. '1-D' VARIOTHERM system

D1a: The prototype was constructed using a 2 x 2 TE module with a flat tool plate of (80 x 80mm), a heat sink (radiator) was attached to the bottom side of the plate with a fan attached below to dissipate heat during cooling (Figure 2). Thermocouples were mounted on the tool surface and on the radiator.
D1b: Based on the results from the single-sided demonstrator tool, a double-sided tool was constructed using the same principles (Figure 3). The prototype consists of a fixed bottom plate tool and a movable top plate tool with radiators and fans at both the plates.

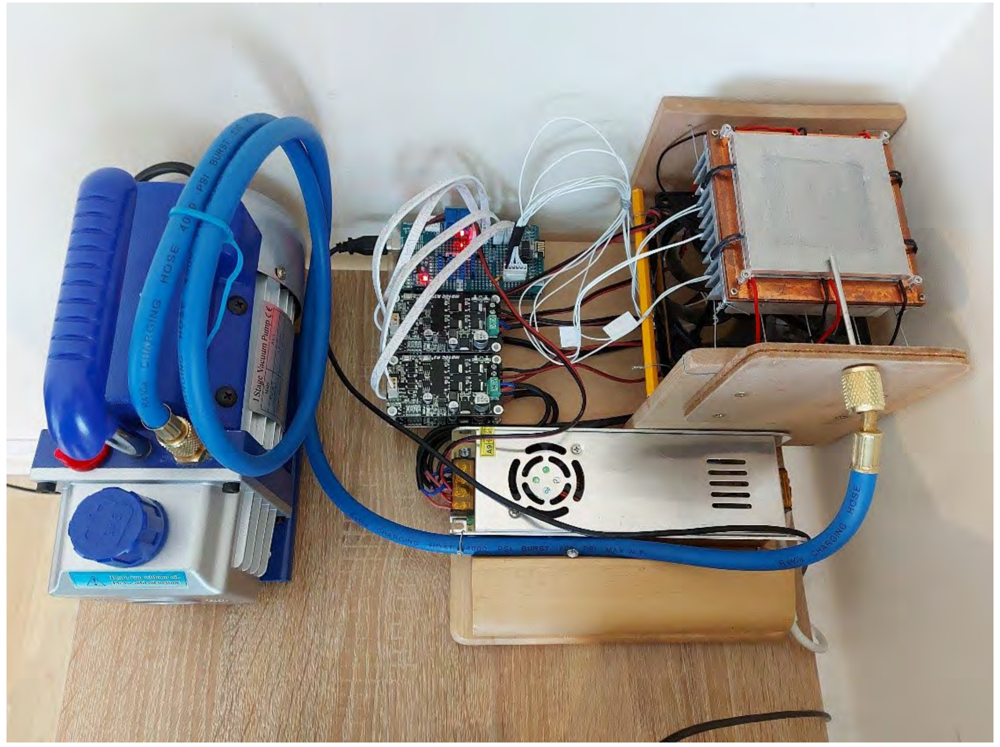


Figure 2. D1a tooling system.

The Peltier systems in both the prototypes were controlled by Arduino hardware, which enables full control over the heating/cooling. The software-controlled system helps in optimising the Peltier system based on the material to be processed.

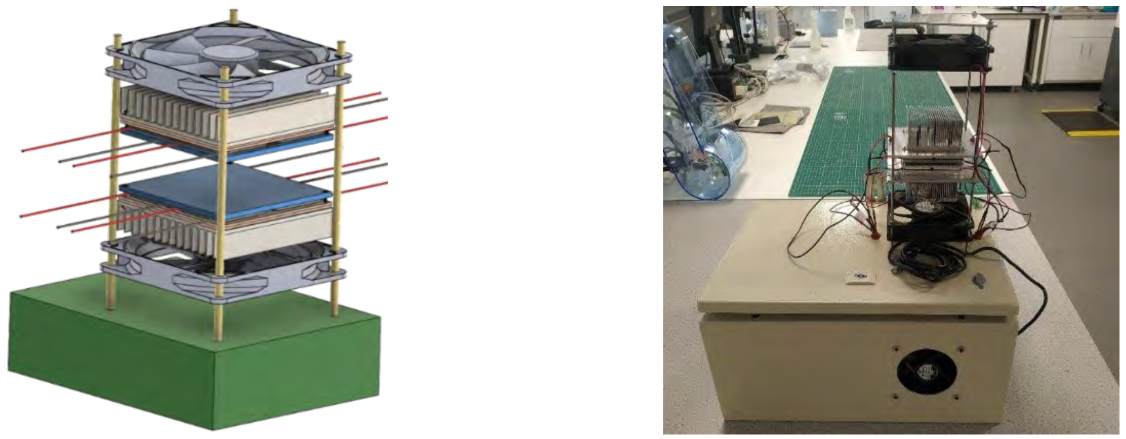


Figure 3. D1b tooling system, a) CAD; b) photograph.

Deliverable 2

The '1-D' system was run without any TPC material and the heating/cooling and control characteristics were evaluated. Using PA6 processing regime as a target, the system was shown to cool from 240°C to 170°C and heat back to 240°C in ~100s, achieving heating/cooling rates of 1-3°C/s, dependent upon the temperature differential (Figure 4).

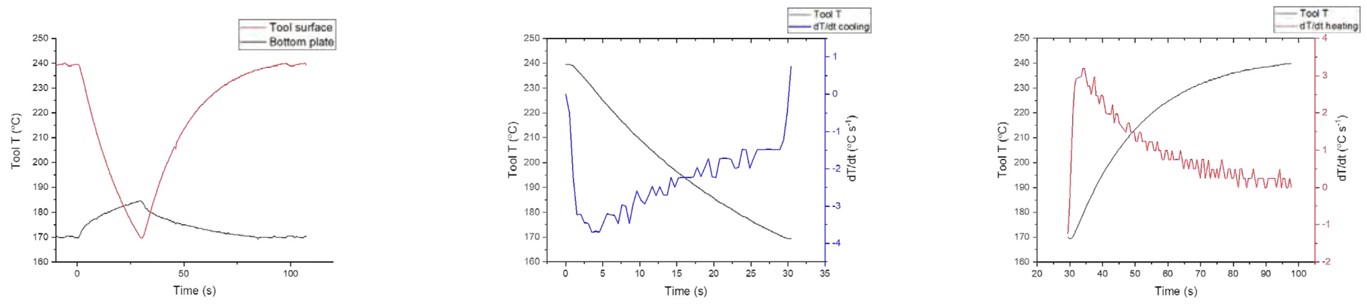


Figure 4. a) Temperature vs. time for tooling system; Temperature and dT/dt vs. time for tool surface, (b) cooling; (c) heating.

Prototype D1a was tested with a PP-GF laminate coupon (50 x 50 x 2mm) vac-bagged to the tool surface to investigate the effects of the heating and cooling rates. The processing time calculated was 400 s (≈6.7 min) with a heating rate of 1-2 °C/s (in material mid-plane), and the time taken to reach 200 °C was 150 s. The cooling rate was -1°C/s and time for the cooling was around 160 s. An exothermic change in sample temperature due to crystallization was detected in the cooling phase. A similar outcome was observed with a similarly-processed PA6 coupon, the exothermic peak identified during cooling at a temperature range between 180 – 190 °C corresponding to the crystallisation peak.

Prototype D1b was used to process the same PP-GF laminate system at a higher thickness of 4 mm. A crystallisation peak (Figure 5) was noted at the temperature range of 120 – 130 °C while cooling the sample from melt, this was confirmed through DSC.

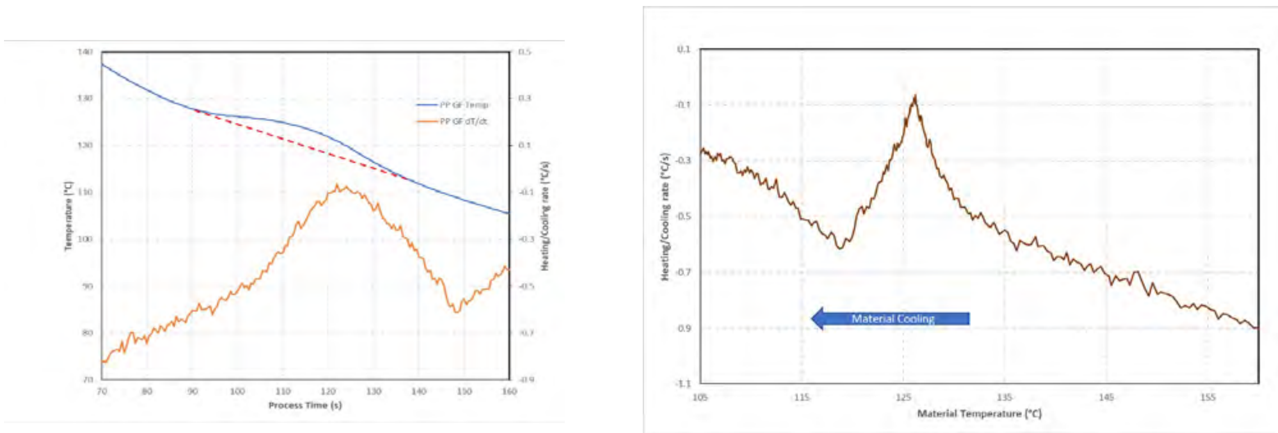


Figure 5. PP-GF cooling using D1b, a) Temperature vs. time; b) rate of heating/cooling rate vs. material temperature

Using **D1b**, PP-GF coupons were cooled at three different rates following melt processing to study the change in morphological structure during cooling. DSC was subsequently performed on these coupons and a change in process induced morphology was seen (shift in melting peaks). As the cooling rates can be easy controlled though Peltier system, it is proposed that degree of crystallinity can readily be optimised in this manner.

Deliverable 3

The Peltier technology as applied to a simple flat aluminium plate tooling system here has delivered typical heating/cooling rates of >1°C/s (peak rates of 3°C/s). A commercially-available proprietary vario-thermal tooling system currently in use at WMG delivers peak vario-therm rates of ~0.6 °C/s. Further, effective temperature regulation using Peltier modules at around the crystallisation temperature could optimise growth of the crystal structures improving the mechanical properties of the sample. This optimisation for a given TPC matrix is now being considered for future projects. The Peltier system at present can operate at up to 250°C which serves as a limitation against processing performance TPCs. The study successfully demonstrated the feasibly of using Peltier systems as active mould temperature control elements thus opening a window for further studies towards developing and optimising the technology for specific industrial applications.

Future Direction

The developed technology has been demonstrated at a TRL +3 level and a joint (WMG and European Thermodynamics Ltd) patent is now being submitted, regarding one aspect of the arising tooling technology, relating to in-situ real-time monitoring of polymer crystallization kinetics during cooling. As a result of this study, WMG HVM-C has sponsored the manufacture of a larger tooling prototype for technology demonstration as part of WMG's National Polymer Processing Centre's TPCs sustainable lightweighting initiative (Peijs et al.). This is currently under manufacture at the industrial project partner's premises. The technology will also be further explored by WMG through the recently awarded £6m ENLIGHTEN (Enabling Integrated Lightweight Structures In High Volumes) programme led by the University of Twente; an industrially funded project with Van Wees B.V. (Netherlands) on recycling of manufacturing waste of thermoplastic UD tapes.

Publications

- Reynolds, N., et al., Direct Processing of Structural Thermoplastic Composites Using Rapid Isothermal Stamp Forming. Applied Composite Materials, 2020.

Completed Feasibility Studies
Work Stream 1: Automated Fibre Deposition Technologies

COMPrinting: Novel 3D Printing of Curved Continuous Carbon Fibre Reinforced Powder-based Epoxy Composites

Project Team

Principal Investigator: Dr Dongmin Yang, University of Edinburgh.

Research Team: Prof Conchúr Ó Brádaigh (Co-I), University of Edinburgh; Dr Colin Robert, University of Edinburgh; Dr Eddie McCarthy, University of Edinburgh; Prof Frank Mill, University of Edinburgh; Dr Lei Wan, University of Edinburgh; Mr Haoqi Zhang, University of Edinburgh.

Industry Partner: FreiLacke GmbH.

Grant Award: £45,759 **Start:** 01/03/2020 **End:** 28/02/2021

Executive Summary

3D printing of continuous carbon fibre-reinforced polymer composites has been gaining rapid momentum across a number of industrial sectors including 3D printer manufacturers, aerospace, automotive, and sporting goods. However, 3D printing of continuous fibre reinforced polymer composites is still facing a few challenges to achieve its full potential, including fibre misalignment, low fibre volume fraction as well as limited print paths. This Feasibility Study aims to prove the concept of 3D printing carbon fibre reinforced powder-based epoxy filaments on a modified 3D printer to enable fast and low-cost printing of continuous fibres with identified paths to achieve comparable mechanical performance with autoclave processed parts. The technology developed will potentially enable the printing of high performance composites with complex geometries (loading bearing fixtures, tools, moulds, etc.) for applications mainly in aerospace and automotive sectors.

A novel 4-axis rotational printing system together with a customised printer nozzle has been developed. Instead of using thermoplastic filament, thermoset filament was fabricated by coating powder-based epoxy on the continuous carbon fibres through an electrostatic deposition process, which shows minimum voids and high fibre volume fractions up to 50%. Printing of the thermoset filament on the rotational printing system demonstrated excellent fibre alignment for both straight and curved printing paths. To evaluate the concept of performance-driven printing of composites by placing the continuous carbon fibres along the principal stress trajectories, the developed filament and printing system were used to print an open-hole composite which was tested against the composite with a drilled hole.

Aims, Objectives and Results

There are four project objectives which are all achieved:

- **OBJECTIVE 1**: Modification of an existing towpregging tapeline for producing low-cost carbon fibre reinforced powder-based epoxy filament (1 to 3k tows, fibre Vf up to 65%) with a low viscosity and high deposition rate for use on FFF 3D printers. This project will increase the versatility of this manufacturing method, to bring forward a faster, more controlled and optimised way to manufacture composites.
- **OBJECTIVE 2**: Design and manufacturing a novel printer nozzle with a rectangular cross-section at the outlet to enable better compression of fibres and modifying a FFF printer head to enable up to 180° rotation to minimise fibre twisting and misalignment when turning.
- **OBJECTIVE 3**: 3D printing powder-based epoxy composites with identified performance-driven curved continuous fibre paths that are demonstrated in our previous numerical study, followed by vacuum bagging and curing in oven.
- **OBJECTIVE 4**: Testing and characterisation of the printed composites using digital image correlation (DIC), SEM as well as X-Ray µCT to evaluate the printing quality and elucidate the failure mechanisms of the printed composites with identified curved continuous carbon fibres.

Objective 1

Modification of an existing towpregging tapeline for producing low-cost carbon fibre reinforced powder-based epoxy filament (1 to 3k tows, fibre Vf up to 65%) with a low viscosity and high deposition rate for use on FFF 3D printers. This project will increase the versatility of this manufacturing method, to bring forward a faster, more controlled and optimised way to manufacture composites.

The tapeline previously developed by Dr Colin Robert for his Innovation Fellowship was modified. Powder epoxy was coated on the continuous carbon fibre tows through an electrostatic deposition process, followed by melting and cooling. The main change was the replacement of the Joule contact heating by lamp infrared heating which turned out to be more effective to keep a good cylindrical shape of the filament (in particular for 1K fibre tows). See Figure 1.

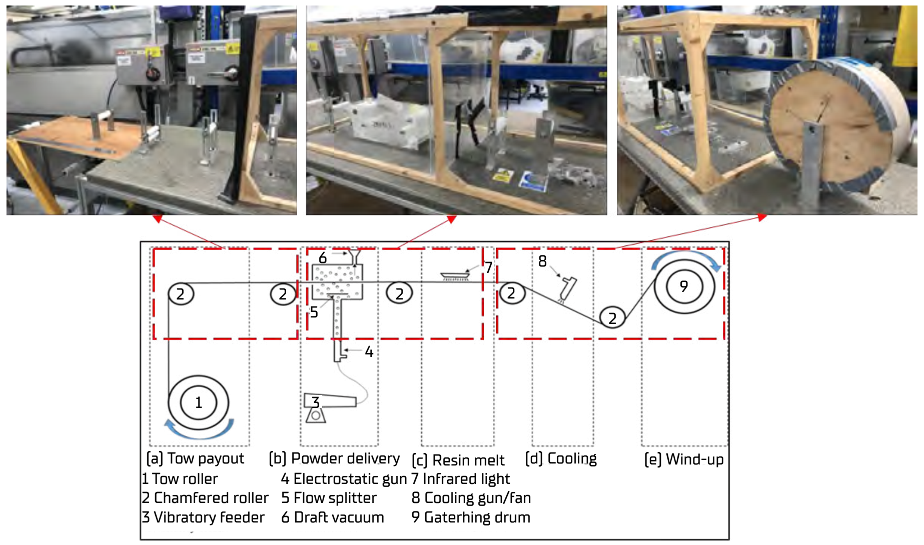
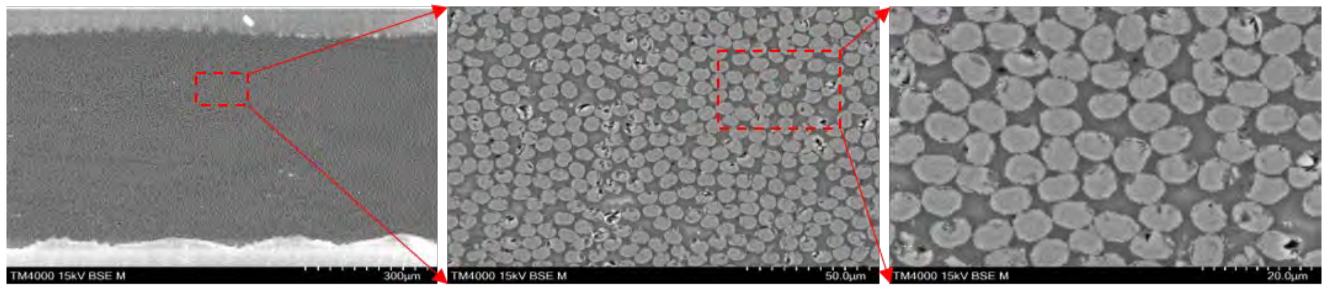


Figure 1. Modified tapeline for fabrication of CF/Epoxy filament

Produced filaments were firstly printed out for UD lamina using modified Prusa i3 printer with a brass nozzle sourced from Markforged. After consolidation in oven with vacuum bagging, cross-section images of the UD sample in Figure 2 shows the epoxy has very good wettability and interfacial bonding with the carbon fibre with minimum voids. Fibre volume fraction was computed to be 50% on average, and this could be increased (or decreased) by adjusting the powder deposition rate. Uniaxial tensile tests of the printed UD CF/epoxy composite in Figure 3 show significant improvement against the samples printed using Mark Two printer using CF/PA6 filament, i.e., stiffness was increased by 147% and strength was increased by 46%.



X300 X1800 X4000

Figure 2. SEM images of printed CF/Epoxy after consolidation

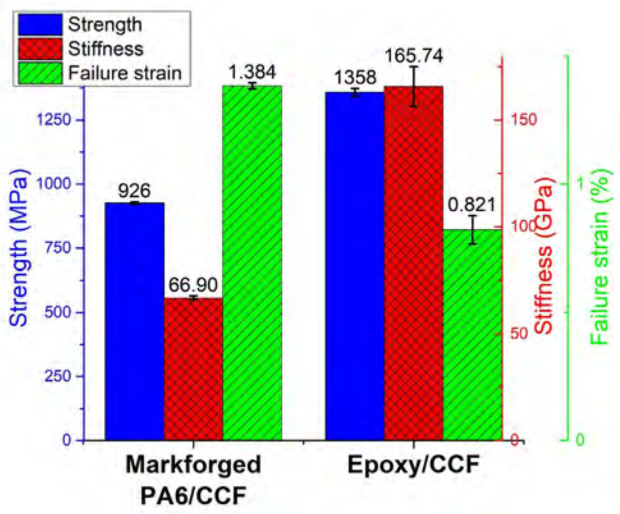


Figure 3. Uniaxial tensile testing results of printed UD CF/epoxy composites

Objective 2

Design and manufacturing of a novel printer nozzle with a rectangular cross-section at the outlet to enable better compression of fibres and modifying a FFF printer head to enable up to 180° rotation to minimise fibre twisting and misalignment when turning.

A specific printer nozzle was designed and manufactured to improve the fibre alignment during printing. The nozzle has a rectangular outlet to have a more even distribution pressure on the printed filament. To accommodate the customised nozzle, an additional rotation was added on the printer head to rotate the nozzle, making sure the nozzle outlet is always perpendicular to the printer direction. Fibre alignment in both straight and curved paths is much improved without noticeable fibre buckling or twisting.

Objective 3

3D printing of powder-based epoxy composites with identified performance-driven curved continuous fibre paths that are demonstrated in our previous numerical study, followed by vacuum bagging and curing in oven.

A composite plate with an open hole under uniaxial tension was chosen as a case study to demonstrate the developed printing system. Finite element analysis was first carried out to identify the maximum principal stress trajectories in the neat polymer under this specific loading condition. The trajectories were processed in Matlab and connected using G-code for the later printing. The rotation of the printer head was synchronised with the printing path direction, ensuring a good fibre alignment at every position in each print path. A substrate was printed separately using short fibre reinforced PA6 to avoid the use of extra metal mould for the subsequent curing.

Objective 4

Testing and characterisation of the printed composites using digital image correlation (DIC), SEM as well as X-Ray µCT to evaluate the printing quality and elucidate the failure mechanisms of the printed composites with identified curved continuous carbon fibres.

Uniaxial tensile tests of the printed open-hole composites were carried out with the assistance of DIC. Results of failure patterns and strain distributions are shown in Figure 4. It was demonstrated that the printed composite with identified fibre paths has much more uniform distribution of strain around the hole. As expected, the drilled composite (printed with straight fibre paths) has strain concentration on both left and right edges of the hole. Markforged Mark Two printed composite has a quasiisotropic lay-up with additional fibres placed around the hole, and the principal strain is concentrated on the +/- 45 degrees leading to a shear failure. One challenge was the unavailable access to high-resolution X-ray micro-CT due to COVID-19, therefore the failure mechanisms and 3D imaging of fibre alignment has not been fully understood yet.

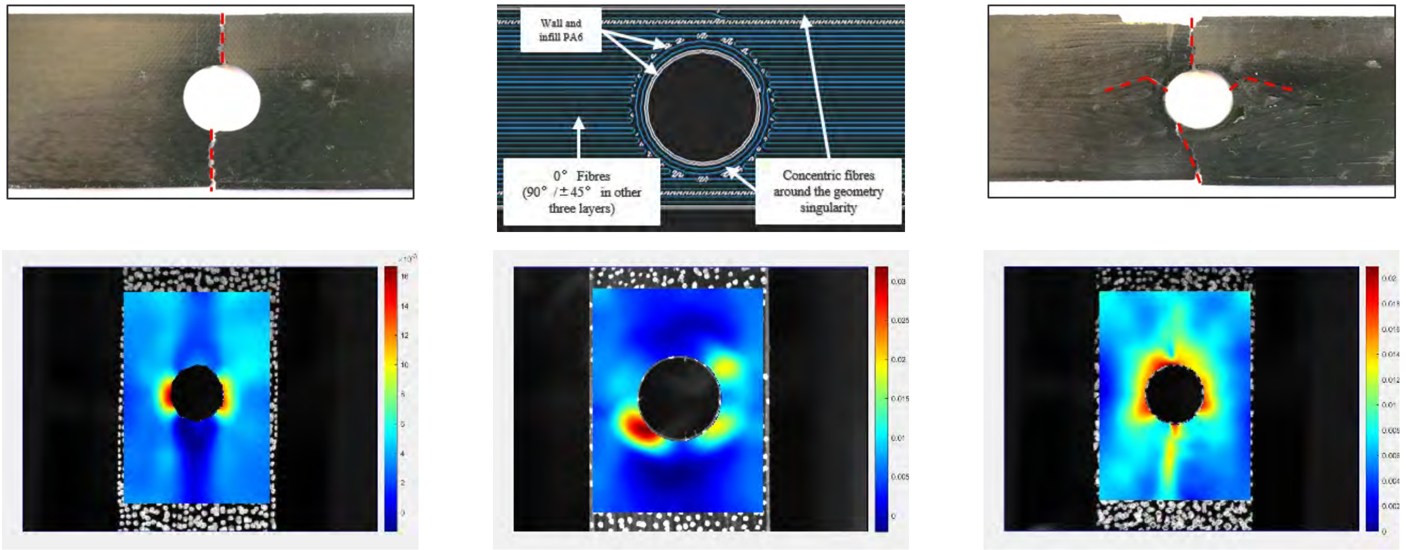


Figure 4. Uniaxial tensile test of printed hole-in-plate composites (failure path & DIC imaging)

Figure 5 shows that the load bearing capacity is improved by 58% (on average) compared to the drilled composites. Very consistent stiffness is achieved as a result of the identified fibre paths. Loading strain Eyy is improved by 26% (on average), and Maxi-principal strain is improved by 120% (on average) around the hole just before the failure. The Markforged Mark Two printed composites have a much lower failure strength and stiffness, although more ductile failure behaviour is found due to the PA6 thermoplastic.

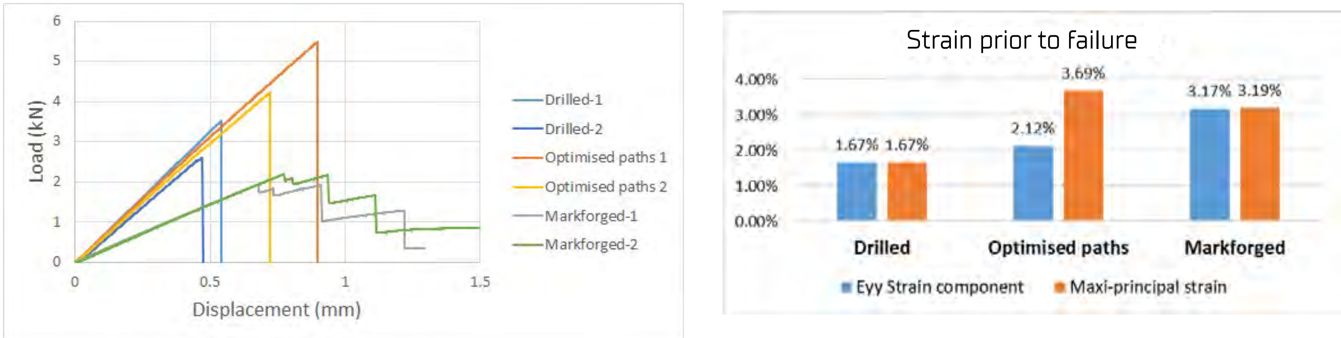


Figure 5. Uniaxial tensile test of printed hole-in-plate composites (Loading curve & maximum strain around the hole just before failure)

Future Direction

The project was linked with an Edinburgh-Ulster Synergy grant to inject short fibre thermoplastic into the 3D printed composite preforms so as to stabilise the curved fibres and keep them in the identified loading paths. There has also been a new collaboration between the PI and the HiPerDif team in Bristol composites group. It has been agreed to trial the rotational printing system to print Bristol's discontinuous long fibres and improve the fibre alignment.

Incorporation of Thermoplastic In Situ Polymerisation in Double Diaphragm Forming

Project Team

Principal Investigators: Dr Lee Harper, University of Nottingham; Prof Conchúr Ó Brádaigh, University of Edinburgh.

Research Team: Dr Andrew Parsons, University of Nottingham; Dr Ankur Bajpai, University of Edinburgh; Mr James Mortimer, University of Nottingham; Dr James Murray, University of Nottingham; Mr Machar Devine, University of Edinburgh.

Grant Award: £49,996 **Start:** 01/07/2020 **End:** 31/03/2021

Executive Summary

Double diaphragm forming (DDF) is a process for producing complex, large preforms for out of autoclave processes. DDF generally requires lower capital investment compared to matched tool forming, but defects such as fibre bridging and fabric wrinkling are more likely to occur. To improve on this, DDF has been combined with a liquid infusion process, where a dry fabric stack held between two flexible membranes (diaphragms) is infused with resin prior to being formed.

There are several benefits for doing this:

- The resin infusion step is performed with flat fabric plies, simplifying the filling stage without geometrical constraints.
- Forming occurs in the presence of a low viscosity liquid, reducing interply friction and diaphragm-fabric friction, improving fabric conformation to the tool.
- The infusion and forming stages are combined into one process, saving time and consumables.

This proposed Feasibility Study is applicable to topics within both the 'Deposition/ Conversion' and 'Moulding' themes of the FCMRH Research Landscape Roadmap.

This project specifically considered the use of thermoplastic resin in the Resin Infusion between Double Flexible Tooling (RIDFT) process. The RIDFT process was applied to Nylon 6 using in-situ polymerisation, but could be adopted for other thermoplastic resins in the future. Greater understanding of RIDFT and optimisation of its capabilities has the potential to generate a step change in the manufacturing of extremely large composite parts (+10m): wing spars, boat hulls, train bodies, turbine blades, architectural panels, etc. with relatively minor capital investment costs.

Aims, Objectives and Results

- Establish the ability to infuse a flat fabric constrained in a flexible vacuum system (between two diaphragms).
- Determine whether the presence of the resin improves forming of the fabric.
- Determine the heating requirements to polymerise the resin after forming.

Deliverables and success criteria:

- Partial success after 6 months: successful infusion and polymerisation of a flat part between diaphragms to achieve at least a rigid solid state.
- Full success after 6 months: successful infusion, moulding and full polymerisation between diaphragms with improved conformation to tool c.f. control panel, with demonstrated improvement in forming behaviour.

Deliverable 1

Manufacture benchtop diaphragm former, suitable for TP liquid infusion

It was made at a small scale to minimise risks to users and to avoid damage to the existing larger system in early trials. The frame was made taking into account several of the risk factors to try and produce an effective solution and to make it suitable for all processing environments, from fume hood to oven. A three part frame with a vacuum channel provided the double diaphragm section and then a vacuum baseplate with removable hemisphere shape comprised the forming section.

Figure 1. Small scale forming frame with vacuum base and hemisphere former.

Deliverable 2

Produce 2D composite panels by vacuum infusion in rigid tooling (baseline)

Some basic laboratory studies were performed to de-risk the process, determining pot life estimation, checking the process would run to completion and most importantly checking the combability of vacuum consumables with the reaction mixture. Most vacuum bagging materials are made of nylon, which is not compatible with the monomer, and so less common materials were considered in consultation with Tygavac and Vac innovation.

Results identified two fluoropolymer films, normally used as release films but with reasonable strain characteristics (Tygavac A4000, Tygavac Wrightlon), and silicone were all suitable. Tubing was limited to PTFE in high temperature environments and silicone at room temperature. A silicone-based tacky tape was identified, however no suitable breather cloth was available. For the initial trials a slow catalyst was used, to ensure plenty of time to fill and form before polymerisation (30-60 minutes). A much faster catalyst is available that would enable faster production (e.g. 2-3 minutes).

After considerable efforts in developing a suitable infusion protocol using simple resin mixing, flat panels were produced using both glass and carbon reinforcements. The glass and carbon both had specially adapted sizing treatments to suit the APA6 monomer. Infusion was performed between two flexible diaphragms, but was supported by a rigid tool.

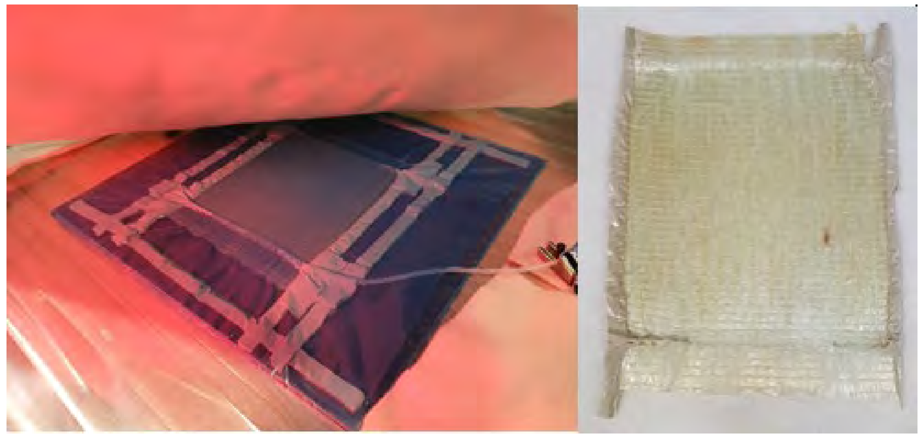


Figure 2. Flat infusion with resulting panel.

The heated and purged mixing system at Edinburgh was then incorporated into the process. The system was initially used in it's RTM state, both as a burn in test after recommissioning and to test panel production using the fast and slow catalyst systems. This also ensured that the sizing on the glass, which was originally intended for use with the fast catalyst, was compatible with the slow catalyst. Discussing potential benefits of a mixed catalyst system with Johns Manville will be part of the project review.

After successful RTM production, the mixing system was modified to interface with a vacuum infusion setup, to provide a much improved resin supply to the process. A buffer vessel was used to decouple the pressure of the mixing system from the resin bag infusion. Production of panels was successful through this route.

To expand potential manufacturing options by decoupling filling from forming, a fill, quench, reheat process was investigated. Infusion was conducted at temperature, before being allowed to cool. The cooled panel was then either reheated immediately to react, or left for a day before reheating. In both cases the reaction appears to have been completed successfully, although degree of conversion is still under investigation. This would potentially allow short term storage of filled frames prior to forming.

Deliverable 3

Produce 2D composite panels by vacuum infusion in rigid tooling (baseline)

D3 was to produce flat panels in flexible tooling, using the forming frame, with only the vacuum providing rigidity to the system (unsupported diaphragms). Severe racetracking occurred and the original mitigation methods were either impractical or ineffective. Blocking off the vacuum gallery with tape or other material did not prevent the very low viscosity resin bleeding through. Modifications to the frame were considered, but were beyond budget in this early study. Instead, perimeter tacky tape was used as a temporary measure to isolate the reinforcement. Through-bag connections were avoided during the infusion stage, to prevent the likelihood of the diaphragm failing during forming due to any stress concentrations.

While this proved to be entirely suitable for initial trials with an epoxy resin, there were limitations with the in situ polymerisation approach. The infusion was observed to progress rapidly and completely, where excellent wet out was achieved and the resin successfully polymerised to produce approximately 60% fibre volume fraction composites. However, interlaminar consolidation was poor, essentially resulting in a stack of well wet out thermoplastic tapes. This was ascribed to potential loss of vacuum consolidation as a result of a blockage in the vacuum line and/or the action of gravity on the unsupported diaphragms. A number of solutions were investigated, including heated vacuum lines and angled fill, but with mixed success. Ultimately this proved to be a less significant issue when forming (see D4).

Deliverable 4

Produce 3D composite components between diaphragms to at least rigid solid

D4 was to produce formed components using the in situ polymerisation process and ideally to demonstrate the benefits of filling prior to forming. The benefits to forming were first demonstrated with epoxy, where hemispheres produced by first filling a flat reinforcement and then forming (fill-form) achieved better forming results (fewer wrinkles/less bridging) than hemispheres made by forming a reinforcement before infusion (form-fill).

A successful form-fill experiment has been conducted with carbon fibre and the in-situ polymerisation process. Effectiveness is limited by the consumables and there is an apparent imbalance in pressure acting on the hemisphere. However, the result was well consolidated in the sections that did not experiencing fabric bridging. The Ph.D. student at Nottingham is continuing with this work and additional examples are expected soon. Further refinement of the infusion equipment would improve the result.

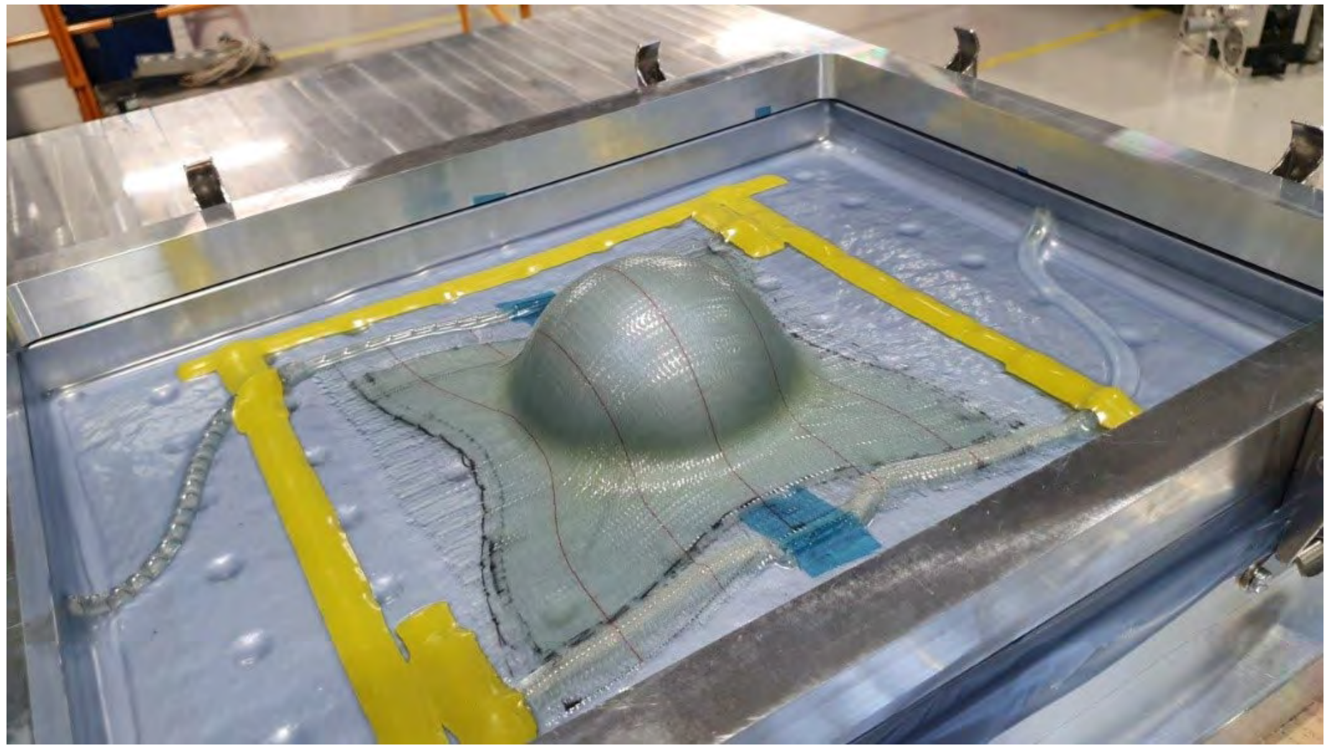


Figure 3. Filled then formed epoxy hemisphere with fewer wrinkles.

Future Direction

The final result is somewhere between 'partial' and 'full' success. Most aspects were demonstrated and the process was shown to be feasible at a small scale, but full success cannot be claimed since the infusion mixing system has not been fully combined with the forming frame. The results of the project are in review with industry partners with a view to scoping out follow on studies. There are continuing activities at both sites at present, but funding is limited. Now that travel restrictions have been removed, it would be possible to combine the equipment from both sites to demonstrate the process, as was originally intended. As well as process improvements, fundamental questions have been identified in relation to very low viscosity infusion and these would form the basis of an EPSRC supported study (either through a Hub Core Project or a Responsive Mode application). Other opportunities will be explored, potentially in conjunction with the NCC, AMRC or industry. Talks are also taking place with Arkema to discuss the potential of using Elium in this system as well.

Powder-Epoxy Carbon Fibre Towpreg for High Speed, Low-Cost Automated Fibre Placement

Project Team

Principal Investigator: Dr Colin Robert, University of Edinburgh.

Research Team: Mr Thomas Noble, University of Edinburgh.

Industry Partners: Swiss CMT, FreiLacke, Toray, Coriolis Composites.

Grant Award: £219,110 **Start:** 01/10/2019 **End:** 31/01/2022

Executive Summary

The main project objective was to develop automation of a towpregging tapeline (TPTL, Figure 1), producing low-cost powder-based epoxy carbon fibre composite with a high deposition rate for use on automated fibre placement (AFP) machines. This project increased the versatility of this manufacturing method, to bring forward a faster, more controlled and optimised way to manufacture composites.

A novel powder-based epoxy from FreiLacke was used in this study. The powder epoxy has significant advantages compared to its liquid equivalents: low minimal viscosity, low exotherm, ability to pre-shape different parts and co-cure them in a one-shot process and stability at ambient temperature (no refrigeration requirement). These advantages result in lower manufacturing costs and quicker production of mechanically superior composite parts compared to standard liquid epoxy-based composites.

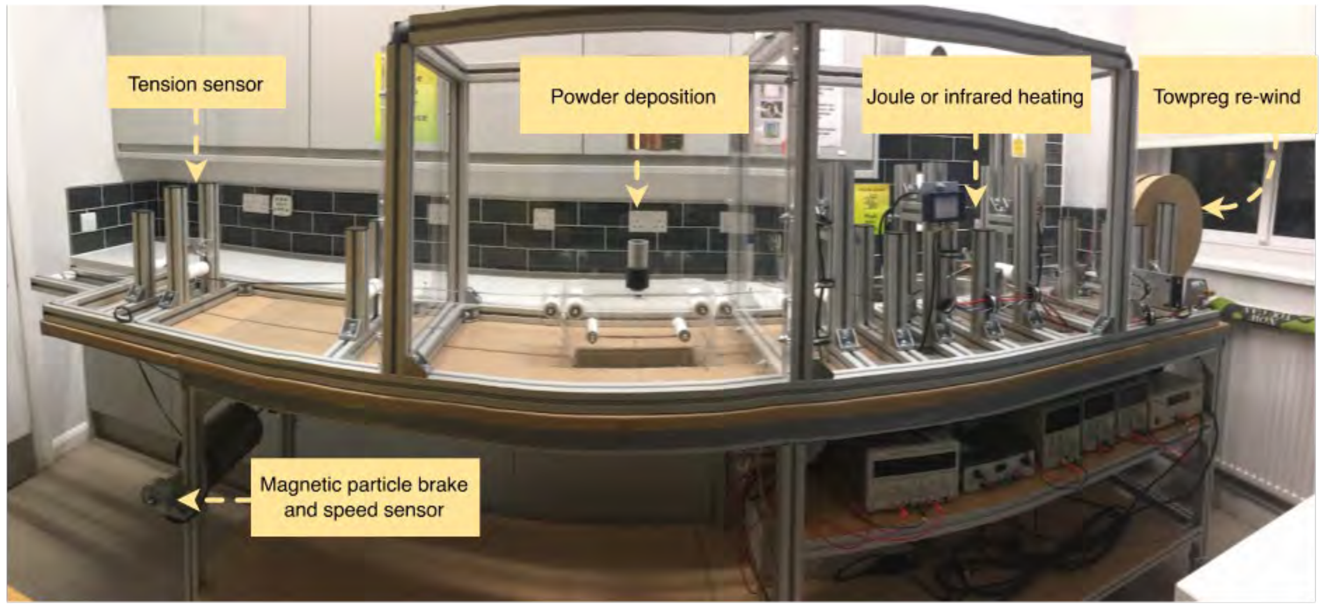


Figure 1. Automated Powder Epoxy Tapeline

Aims and Objectives

The project aimed to produce a fully automated low-cost, high-speed tapeline to produce powder-based carbon fibre towpreg. The tapeline process aimed to be controlled via a Human Machine Interface enabling auto correction depending on the parameters inputs.

Industrial advantages of this method:

- High volume manufacturing capabilities.
- Low cost of the towpregging process: powder is inexpensive (c. £8/kg). As the tape is completely stable at ambient temperatures, there is no need for sub-zero environment storage.
- Full automation of the whole process: labour cost reduced and more reliability.
- A new panel of powder-based epoxy systems that can be tailored depending on the application: "slow" to "flash" cure, incorporation of toughening and hardening agents.
- Tow to composite process: crimp due to weaving or stitching is avoided and fibres are always kept under tension, leading to better alignment and mechanical properties.

Milestone 1

Production of carbon fibre tape "as is" for Coriolis Composites
The first major milestone of the project was to deliver a substantial length (over 200 meters) of tape of the right width (12.7mm) with a consistent FVF, for initial trials on Csolo©.

Milestone 2

Automation and control of the tapeline to produce a high quality, homogeneous and optimised tape with low-cost, high-volume characteristics

- **D2.1**: Increase TPTL temperature control: an array of non-contact infrared sensors were added to carefully monitor the temperature at the melting and cooling stations.
- **D2.2**: Increase TPTL tension control: controlling the tension is paramount in this project. First, tension meters monitored the tension applied on the carbon fibres. The towpreg tension was also monitored using force gauges. Finally, a tachometer was placed on the reel to ensure a constant speed.
- **D2.3**: Automation of the tapeline: centralised the TPTL parameters using a HMI system such as LabVIEW.

Milestone 3

Manufacture AFP grade tape and CFRP parts; compare cost and mechanical properties of TPTL based-CFRP to standard process-based CFRP and technology transfer

- **D3.1**: Manufacture plates with commercial out-of-autoclave prepreg with the same carbon fibres (T700s© from Toray) and investigate mechanical properties.
- **D3.2**: Compare mechanical properties to plates originally manufactured with AFP processing with the original non-optimised towpreg.
- **D3.3**: Optimization of process: manufacture plates and perform mechanical testing of CFRP samples depending on TPTL processing settings to reach the optimal TPTL manufacturing conditions.

Progress

- The use of Powder-Epoxy Carbon Fibre Towpreg in hydrogen pressure vessels has been successful.
- The ability to co-cure and stitch through uncured powder epoxy parts as per the Synergy Promotion study (see below). There is potential for out-of-autoclave one shot cure applications.
- The technology developed will create a step change in processing of epoxy based towpregs and will permeate in new markets allowing for new applications thanks to a low CAPEX and OPEX.
- Strong emphasis on potential applications in renewable energies (especially tidal & wind turbine blades, hydrogen) for powder epoxy technology.

Future Direction

- The development of an automated manufacturing tapeline for the epoxy technology brings us closer to renewable applications. In this respect, Edinburgh Innovation has granted an IAA commercialisation project in collaboration with Addcomposites, a low-cost Automated Fibre Placement company, in order to build a low CAPEX & OPEX hydrogen tank demonstrator.
- Once industrial collaborators start using the technology for their own applications, the technology will be licensed and the tapeline system patented.

Publications

- Zhang H., Wu J., Robert C., Ó Brádaigh C.M., Yang D., 3D printing and epoxy-infusion treatment of curved continuous carbon fibre reinforced dual-polymer composites, Composites Part B: Engineering, Volume 234, 2022, 109687, ISSN 1359-8368.
- Davidson J.R., Quinn J.A., Rothmann C., Bajpai A., Robert C., Ó Brádaigh C.M., McCarthy E.D., Mechanical characterisation of pneumatically-spliced carbon fibre yarns as reinforcements for polymer composites, Materials & Design, Volume 213, 2022, 110305, ISSN 0264-1275.
- Noble T., Davidson, J.R., Floreani C., Bajpai A., Moses W., Dooher T. McIlhagger A., Archer E., Ó Brádaigh C.M., Robert C., Powder Epoxy for One-Shot Cure, Out-of-Autoclave Applications: Lap Shear Strength and Z-Pinning Study. J. Compos. Sci. 2021, 5, 225.
- Floreani C.; Robert C.; Alam P.; Davies P.; Ó Brádaigh C.M., Mixed-Mode Interlaminar Fracture Toughness of Glass and Carbon Fibre Powder Epoxy Composites—For Design of Wind and Tidal Turbine Blades. Materials 2021, 14, 2103.
- Hassan E.; Zekos I.; Jansson P.; Pecur T.; Floreani C.; Robert C.; Ó Brádaigh C.M.; Stack M.M., Erosion Mapping of Through-Thickness Toughened Powder Epoxy Gradient Glass-Fiber-Reinforced Polymer (GFRP) Plates for Tidal Turbine Blades. Lubricants 2021, 9, 22.
- Robert C., Pecur T., Maguire J.M., Lafferty A.D., McCarthy E.D., Ó Brádaigh C.M., A novel powder-epoxy towpregging line for wind and tidal turbine blades, Composites Part B: Engineering, Volume 203, 2020, 108443, ISSN 1359-8368.

Synergy Promotion Project

Powder Epoxy for OneShot Cure, Out of Autoclave Applications: Lap Shear Strength and Z-Pinning Study

Project Team

Principal Investigator: Dr Colin Robert, University of Edinburgh.

Research Team: Dr Thomas Noble, University of Edinburgh; Mr James R. Davidson, University of Edinburgh; Mr Christophe Floreani, University of Edinburgh; Dr Ankur Bajpai, University of Edinburgh; Mr William Moses, Ulster University; Mr Thomas Dooher, Ulster University; Prof Alistair McIlhagger, Ulster University; Dr Edward Archer, Ulster University, Prof Conchúr M. Ó Brádaigh, University of Edinburgh.

Grant Award: £11,255 **Start:** 01/01/2020 **End:** 31/05/2020

Project Summary and Results

Large composite structures manufactured out-of-autoclave require the assembly and bonding of multiple parts. A one-shot cure manufacturing method is demonstrated using powder epoxy. Lap shear plates were manufactured from powder epoxy and glass fiber-reinforced plastic with four different bonding cases were assessed: secondary bonding using standard adhesive film, secondary bonding using powder epoxy, co-curing, and co-curing plus a novel Z-pinning method.

This work investigates the lap shear strength of the four cases in accordance with ISO 4587:2003. Damage mechanisms and fracture behaviour were explored using digital image correlation (DIC) and scanning electron microscopy (SEM), respectively. VTFA400 adhesive had a load at break 24.8% lower than secondary bonding using powder epoxy. Co-curing increased the load at break by 7.8% compared to powder epoxy secondary bonding, with the co-cured and pinned joint resulting in a 45.4% increase. In the co-cured and co-cured plus pinned cases, DIC indicated premature failure due to resin spew. SEM indicated shear failure of resin areas and a large amount of fiber pullout in both these cases, with pinning delaying fracture phenomena resulting in increased lap joint strength. This highlights the potential of powder epoxy for the co-curing of large composite structures out-of-autoclave.

This initial study was a promising proof of concept to demonstrate the advantages of the powder epoxy resin when combined with co-curing and pinned joining methods. The very specific processing properties of the powder epoxy system allowed to show the best of both thermoset (low viscosity, better co-curing mechanical properties) and thermoplastic (non-brittle pinning on complex structures, higher toughness), allowing co-curing and pinning all at once, leading to vastly superior mechanical properties when combined.

Overall, the powder epoxy resin has a range of advantages, making it a suitable candidate for the co-curing of large composite structures. Future work will involve employing the co-curing and pinning bonding methods on more complex structures, for example on thick section composites such as tidal turbine blades. Automated applications, such as additive manufacturing, will also be considered. There will be the ability to locally change the polymeric properties to meet specific requirements, e.g., erosion protection.

Numerical Simulation of Compression Moulding of SMC/Prepreg

Project Team

Principal Investigator: Dr Connie Qian, University of Warwick.

Industry Partners: Toray AMCEU, Toray Engineering D Solutions.

Grant Award: £206,664 **Start:** 22/01/2020 **End:** 21/04/2022

Executive Summary

Compression moulding of SMC/prepreg hybrid is an attractive solution for high-rate manufacturing of high-performance composite structures, and is the one composites manufacturing process that has the potential to meet future automotive weight saving demands for cost, volume and structural integrity. However the poor understanding in material behaviour and consequently the lack of robust numerical design tool has prohibited such process to be widely adopted in industry. This Innovation Fellowship aims to address the current gaps identified through the development of reliable material models, enabling process simulation for compression moulding of SMC/ prepreg hybrid.

To date extensive validation studies have been carried out to understand the limitations of existing process simulation models and new constitutive material models are being developed, where significant improvements over existing models have been demonstrated. A bespoke squeeze flow/compaction testing rig has been produced, enabling material characterisation to be carried out under typical compression moulding conditions. Additional simulation studies have also been conduced to assess the accuracy of fibre prediction models for compression SMC and a numerical simulation framework has been developed for downstream mechanical properties prediction.

Aims and Objectives

This project aims to develop a dedicated numerical simulation tool for compression moulding of SMC/prepreg hybrid through the delivery of novel experimental methods for characterising the material behaviour of SMC and prepreg under typical compression moulding conditions.

The project contains the following work packages (WP) and objectives:

- WP1: Prepreg material characterisation and model development
  - 1.1: Assess the capabilities and limitations of existing prepreg forming/compaction models.
  - 1.2: Develop experimental methodology for characterising the material behaviour under typical compression/hybrid moulding conditions.
  - 1.3: Develop validated constitutive model based on the data collected from the experimental characterisation study (input from Bristol's DefGen project).

- WP2: SMC material characterisation and model development
  - 2.1: Assess the capabilities and limitations of existing SMC compression moulding models. (Input from APC 10 TUCANA project and in-kind contribution from Toray AMCEU).
  - 2.2: Develop experimental methodology for characterising the material behaviour for SMC under typical compression/hybrid moulding conditions.
  - 2.3: Develop validated constitutive model based on the data collected from the experimental characterisation study.

- WP3: SMC mechanical properties model development
  - 3.1: Assess the capabilities and limitations of existing fibre prediction models for long-discontinuous fibre composites (input from the EPSRC Future metrology hub Feasibility Study).
  - 3.2: Develop meso-scale mechanical properties prediction models using the fibre orientation results obtained from the selected fibre prediction models. (material donation from Toray AMCEU and software support from Toray Engineering D solutions).
  - 3.3: Validate the mechanical properties prediction results using experimental data collected from experimental moulding trials and tensile testing.

- WP4: Process simulation model development for SMC/prepreg hybrid
  - 4.1: Combine the newly developed material models for hybrid moulding process simulation.
  - 4.2: Experimental validation for the hybrid process simulation model and identify the limitations of the new model and proposed future work.

Progress

A prepreg compaction model (Figure 1) is currently under development with the support from Bristol's former DefGen project. Correct force-displacement response has been achieved using the original hyperelastic model and experimental data generated through the DefGen project. However, Bristol's original model was developed in ABAQUS/standard using a UMAT subroutine, which is being converted to a VUMAT for ABAQUS/explicit in this project, enabling ALE adaptive mesh (for SMCs undergo large deformation) to be applied in hybrid moulding simulations. Furthermore, the original model has only been validated for low pressure range (up to 20 bar). The presence of SMC in a hybrid moulding process can lead to very high pressure (up to ~500bar). Therefore, further experimental testing will be performed to characterise the material behaviour at much higher pressures, and the new model will be validated using the corresponding experimental data.

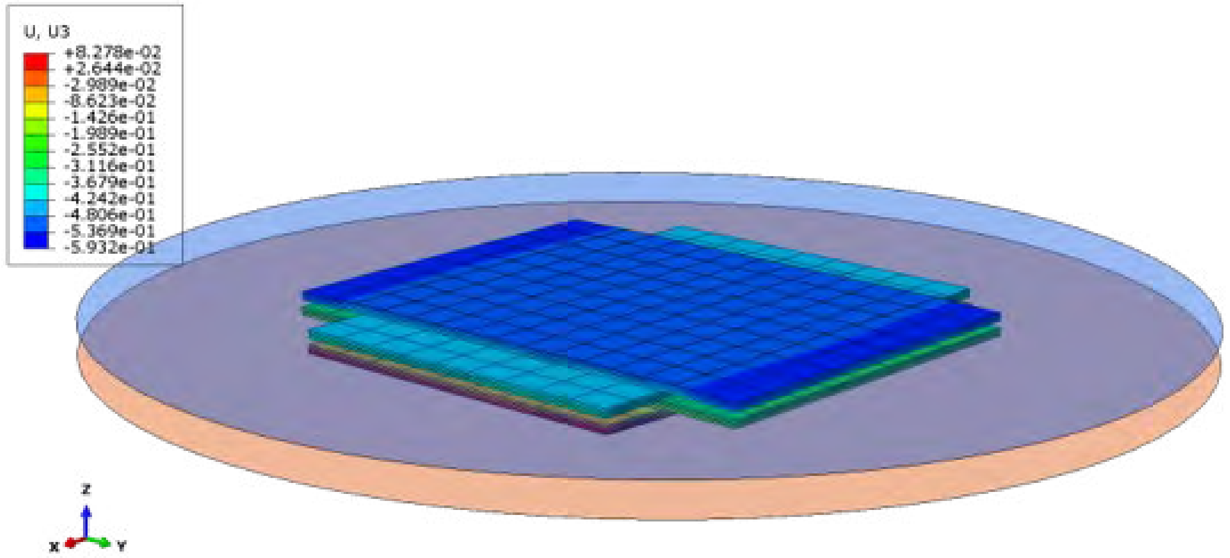


Figure 1. The prepreg compaction model in ABAQUS

A comprehensive assessment of existing SMC compression moulding simulation models has been conducted at the beginning of WP2.Commercial software including Moldex3D, 3D TIMON and Moldflow have been compared where the accuracy of each software is benchmarked against experimental moulding trials in terms of the compression forces and filling pattern predictions. All commercial models assessed in this study have adopted shear viscosity based constitutive material models which have failed to correctly predict the compression forces or the filling patterns in both in-plane and out-of-plane scenarios. It is difficult to fully understand the limitations of each the software due to the confidential nature of commercial products. Nevertheless the observations from this study suggest that developing dedicated constitutive models for SMC compression moulding is necessary.

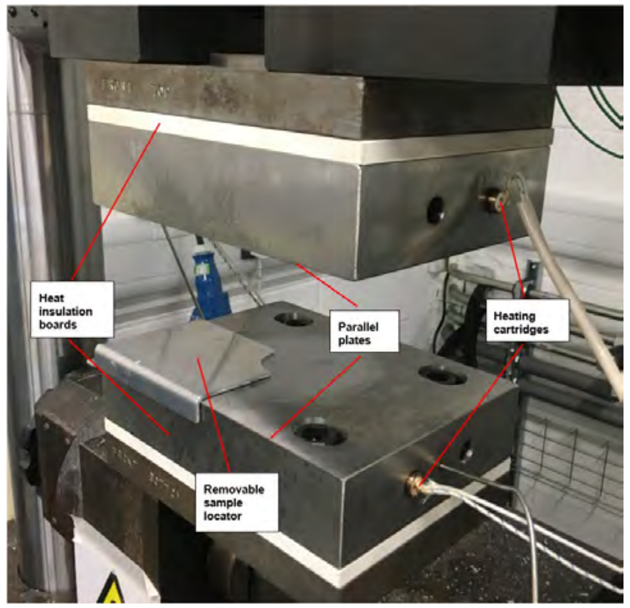


Figure 2. The existing squeeze flow rig

A dedicated material model has therefore been developed for SMC flow simulation. The model describes the flow behaviour of SMC using a compressive stress-strain relationship and the squeeze flow test (Figure 2) has been employed to determine the material input data. The squeeze flow testing results have suggested that the material behaviour is both rate dependent and temperature dependent. The new material model has been implemented in ABAQUS using an in-built plasticity model and validated through simulation of the squeeze flow test. Due to the approximation used in the ABAQUS in-built plasticity model, the predicted compressive forces diverted from the experimental values towards the end of the test. Nevertheless, the proposed model has demonstrated significant improvement compared to commercial software.

The proposed new constitutive model has also been assessed using full component process simulation of a flat plaque geometry. Despite the process simulation aborted prior to the end of fill due to numerical challenges, the proposed new model has demonstrated significant improvements over commercial software in terms of predicted compression forces and filling patterns (Figure 3).The numerical challenges, such as excessive element distortions due to fibre buckling at the mould edge and the complicated contact problems along with the large deformation of SMC will be investigated within this project.

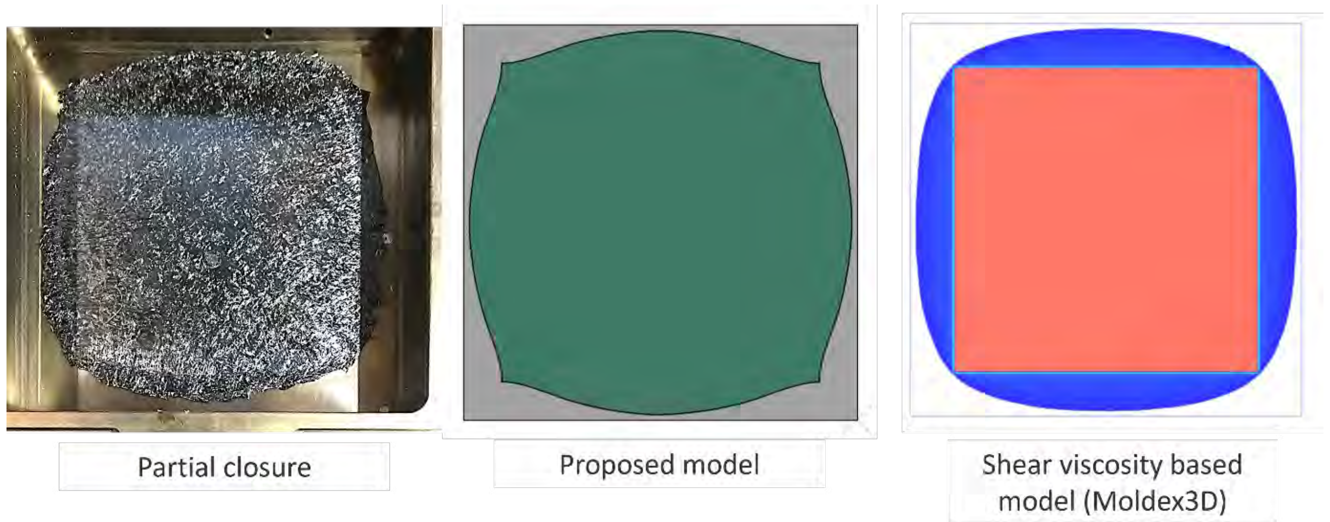


Figure 3. Comparison of filling patterns predicted by different models against the experimental partial closure

A new squeeze flow rig (Figure 4) has been manufactured of which the design is based on an existing rig at WMG. The new squeeze flow rig will be used for both SMC flow characterisation and prepreg compaction testing. The new rig features greater testing area, enabling representative sample sizes to be tested for long fibre based SMC, and various instrumentation such as LVDTs and pressure transducers can also be accommodated. The new squeeze flow rig also features guide columns to ensure parallelism between the plates during the tests.

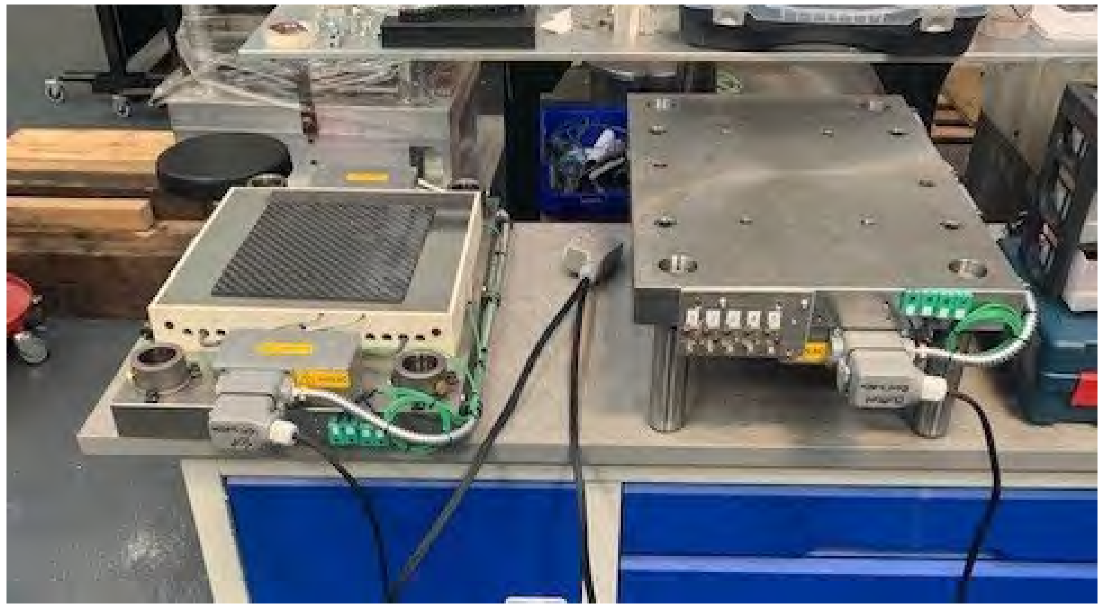


Figure 4. The new squeeze flow rig

The first part of WP3 aims to assess the predictive validity of existing fibre orientation models. The selected fibre prediction models include the Folgar-Tucker (FT) model and the Direct Fibre Simulation (DFS) model, where the former is implemented in commercial software Moldex3D and the latter is implemented in commercial software 3D TIMON. The experimental data are obtained using CT scanning technique, developed through the Feasibility Study "Experimental Investigation of Fibre Content and Orientation Distributions in Compression Moulded Sheet Moulding Compound" Funded by the EPSRC Future Metrology Hub. In general, both models have demonstrated adequate accuracy when predicting the fibre orientation. The DFS model offers added benefit of taking into account the random nature of the material, although it cannot accurately capture the physical behaviour of individual fibres in the areas where high level of fibre/mould and fibre/fibre interactions present (Figure 5).

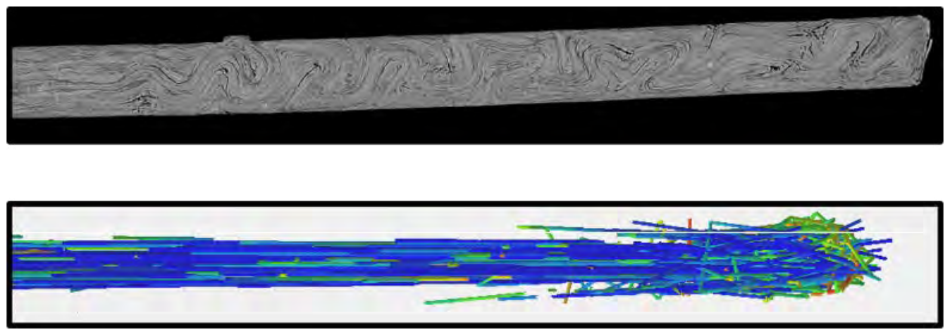


Figure 5. Comparison of fibre architecture near the mould edge between the CT scanning results and the results predicted by the DFS model

A meso-scale RVE modelling approach has then been developed based on the DFS model, where the fibre orientation resultant from the manufacturing process can be accounted for in mechanical properties prediction (Figure 6). The new modelling approach has been demonstrated through a case study where the tensile properties of samples in the longitudinal and transverse to the flow direction are investigated. The results predicted using the new model show good agreement with the experimental data (Figure 7).

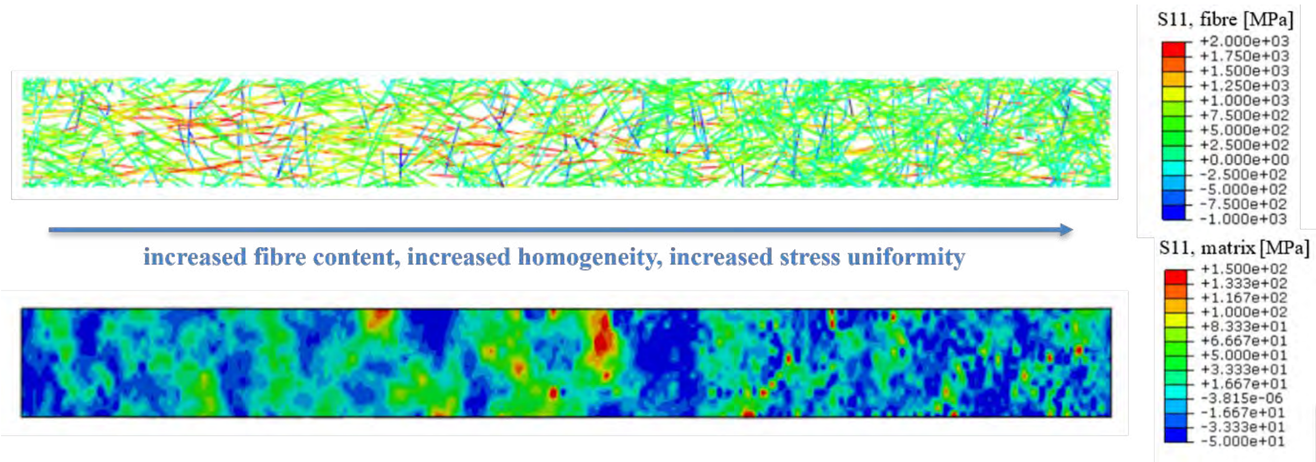


Figure 6. Stress distributions within an example SMC tensile sample: the effects of heterogeneity

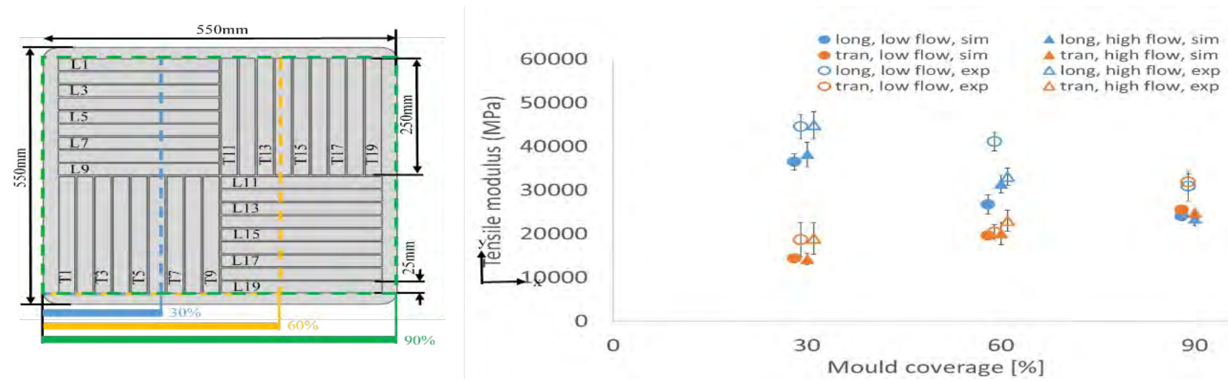


Figure 7. Comparison of the predicted tensile modulii between the numerical simulation and the experimental data (right) for the case study (left).

Future Direction

The current process simulation model developed requires further low TRL development before it can be fully implemented in industrial orientated applications, for instance the out-of-plane flow behaviour for SMC needs to be studied to fully understand the flows into complicated features such as ribs. Additional development will also involve incorporating suitable fibre prediction models identified through this project into the process simulation model, completing the framework linking process simulation with mechanical properties predictions.

The SMC element of this project has already attracted some industrial interests. WMG has recently teamed up with Creative Composites and Engenuity developing a proposal aiming to enable the use of discontinuous fibre composites for structural applications in the aerospace industry, where the experimental flow characterisation method and the numerical simulation tools developed in this project will be adopted in the new project.

Although the current work has been established based on SMC, the skills and knowledge acquired in this project can be applied for many other different types of long, discontinuous fibre reinforced composites. Therefore, further research opportunities will also focus on sustainable manufacturing using reclaimed and recycled materials, where the use of discontinuous fibres are very common.

Publications

- Zhang H., Wu J., Robert C., Ó Brádaigh C.M., Yang D., 3D printing and epoxy-infusion treatment of curved continuous carbon fibre reinforced dual-polymer composites, Composites Part B: Engineering, Volume 234, 2022, 109687, ISSN 1359-8368.
- Davidson J.R., Quinn J.A., Rothmann C., Bajpai A., Robert C., Ó Brádaigh C.M., McCarthy E.D., Mechanical characterisation of pneumatically-spliced carbon fibre yarns as reinforcements for polymer composites, Materials & Design, Volume 213, 2022, 110305, ISSN 0264-1275.
- Noble T., Davidson, J.R., Floreani C., Bajpai A., Moses W., Dooher T. McIlhagger A., Archer E., Ó Brádaigh C.M., Robert C., Powder Epoxy for One-Shot Cure, Out-of-Autoclave Applications: Lap Shear Strength and Z-Pinning Study. J. Compos. Sci. 2021, 5, 225.
- Floreani C.; Robert C.; Alam P.; Davies P.; Ó Brádaigh C.M., Mixed-Mode Interlaminar Fracture Toughness of Glass and Carbon Fibre Powder Epoxy Composites—For Design of Wind and Tidal Turbine Blades. Materials 2021, 14, 2103.
- Hassan E.; Zekos I.; Jansson P.; Pecur T.; Floreani C.; Robert C.; Ó Brádaigh C.M.; Stack M.M., Erosion Mapping of Through-Thickness Toughened Powder Epoxy Gradient Glass-Fiber-Reinforced Polymer (GFRP) Plates for Tidal Turbine Blades. Lubricants 2021, 9, 22.
- Robert C., Pecur T., Maguire J.M., Lafferty A.D., McCarthy E.D., Ó Brádaigh C.M., A novel powder-epoxy towpregging line for wind and tidal turbine blades, Composites Part B: Engineering, Volume 203, 2020, 108443, ISSN 1359-8368.

Innovation Fellowships
Work Stream 5: Liquid Moulding Technologies

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

Vision

Emerging high-performance computers along with robust parallelisation algorithms bring a great opportunity to tackle complex problems with large-scale simulations. Also, the democratisation of X-ray computed tomography (X-CT) at both laboratory and industrial scales offers much easier access to this 3D imaging technique, with improved spatial and time resolutions. This project will embrace the recent development of these technologies and establish innovative methodology for permeability assessment.

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 create a step-change for LCM processes, by bringing powerful numerical methods for statistically accurate permeability calculations and filling fundamental knowledge gaps. The Fellowship will offer the PI a precious opportunity to apply his modelling skills to real-world problems and to build his leadership in developing numerical tools for composites and manufacturing.

Background

Liquid Composite Moulding (LCM) is an important method for composites manufacturing, yet suffers a limitation in reproducibility due to material and process uncertainties. 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 3D 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 longstanding challenge to determine the permeability of fibre reinforcements. Experimental measurement is time and labour-intensive and difficult to be reproduced due to the uncontrolled variations in material and experimental condition. Analytical models have been successful in predicting permeability in simplified situations (e.g. uniformly dispersed fibres), yet they fail to provide faithful values for complex textile reinforcements in which fibres and fibre tows exhibit more random features.

Numerical models can explicitly take into account the geometrical variations, whose accuracy relies on the accuracy of the microstructural description. The latter requires fine meshes and hence limits most of the current existing numerical approaches. Recent advances in large-scale simulations and data-driven techniques offer new opportunities to push this limit for the application of permeability prediction. This project will address the challenges related to permeability variability through an innovative numerical technique based on Fast Fourier Transform (FFT). This project will primarily focus on non-crimp fabrics (NCFs), though the developed methodology can be readily applied to other textiles.

Aims and Objectives

Development of multi-scale numerical models

To alleviate the issue related to computational cost for multiscale permeability calculations, this project will establish a large-scale simulation framework based on FFT methods. This framework will enable efficient parallel computing with high-power supercomputers.

Permeability uncertainty correlated to microstructural variability for NCFs

NCFs have great potential for use in high-performance composite materials, yet comprehensive understanding on how their specific geometric features affect local permeability is still lacking. This project will conduct a comprehensive analysis correlating the geometrical variability to permeability uncertainty. Virgin and preformed NCFs with typical geometrical features will be selected based on the input from CIMComp.

Development of stochastic surrogate models

As an efficient alternative to computationally demanding simulators, various surrogate models have been successfully applied to permeability prediction for geomaterials, such as Gaussian process regression (GPR), support vector machine (SVM) and convolutional neural network (CNN). Based on these recent works, the project will build a surrogate model dedicated to textile permeability. It will rely on the big datasets produced from the X-CT images and large-scale simulations.

Progress

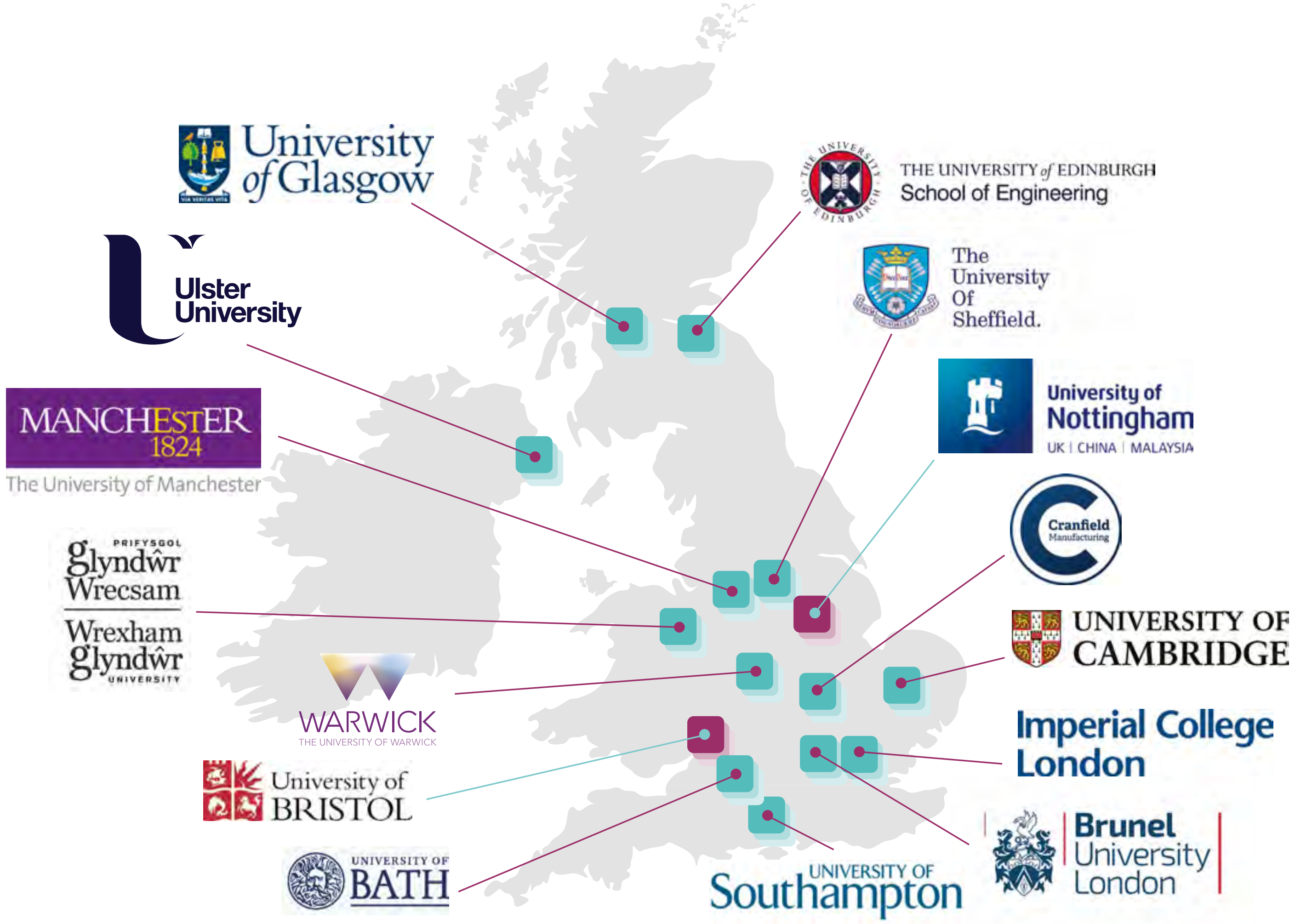
This project has been recently awarded and we look forward to sharing the results in the next year.

3 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. One of the KPIs defined for the Hub was to leverage a further £20m of funding for new research projects, some of which were intended to extend beyond the life of the current programme. The current total leveraged grant income stands at £19.5m.

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 College, Southampton and Cranfield), has primarily been through Feasibility Study calls. Successful applicants are invited to become Spokes and we currently have 15 academic members participating in the Hub.



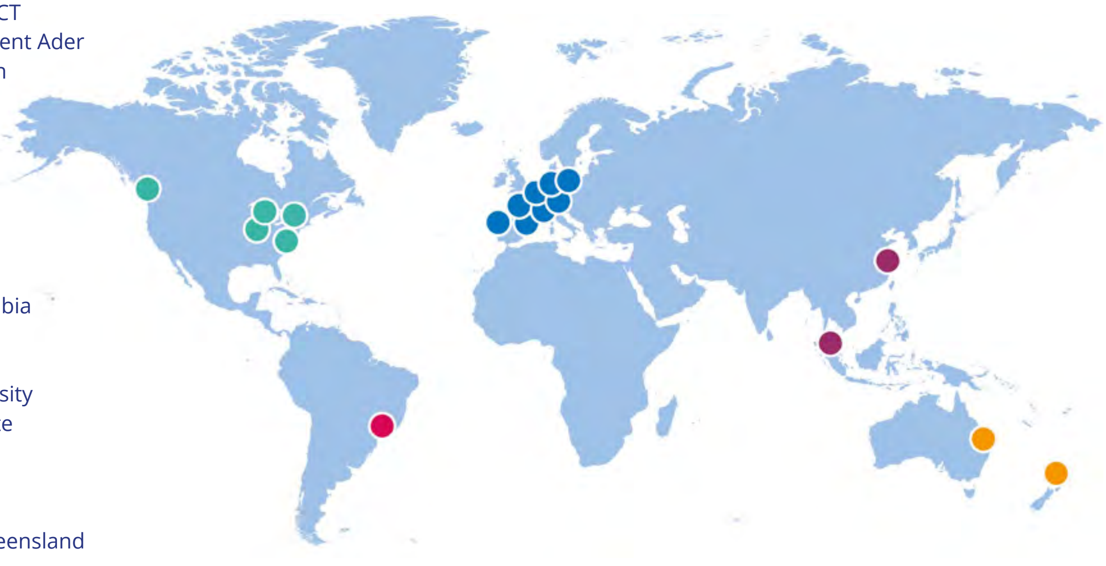
International Network

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 three Study Placements within our international partner network, helping students to foster independence.

- Aachen
- Dresden
- École Centrale de Nantes
- EPFL
- Federal University 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



International Missions

Part of our strategy to develop our international network is participation in international missions to expand our network to understand the composite research capabilities of international stakeholders. Given the recent restrictions on travel imposed by the pandemic, the Hub organised two virtual missions, each attended by over 100 delegates from academia and industry. These allowed delegates to present information on their background and expertise, as well as discuss their research.

- In May 2021, the Hub organised a webinar with the German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt – DLR). DLR is the national centre for aerospace, energy and transportation research of Germany. It operates at 20 locations throughout Germany and is engaged in a wide range of research and development projects in national and international partnerships. In addition to conducting its own research projects, DLR also acts as the German space agency. As such, it is responsible for planning and implementing the German space programme on behalf of the German federal government.

- In February 2022, a mission was organised with the University of British Columbia (UBC). The Composites Research Network (CRN) based at UBC, 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. Founded in 2012 with a $9.8m investment from Western Economic Diversification Canada, the CRN supports small and medium sized enterprises across Canada to understand, define and solve technical challenges allowing development of new processes and to grow product lines for future expansion.

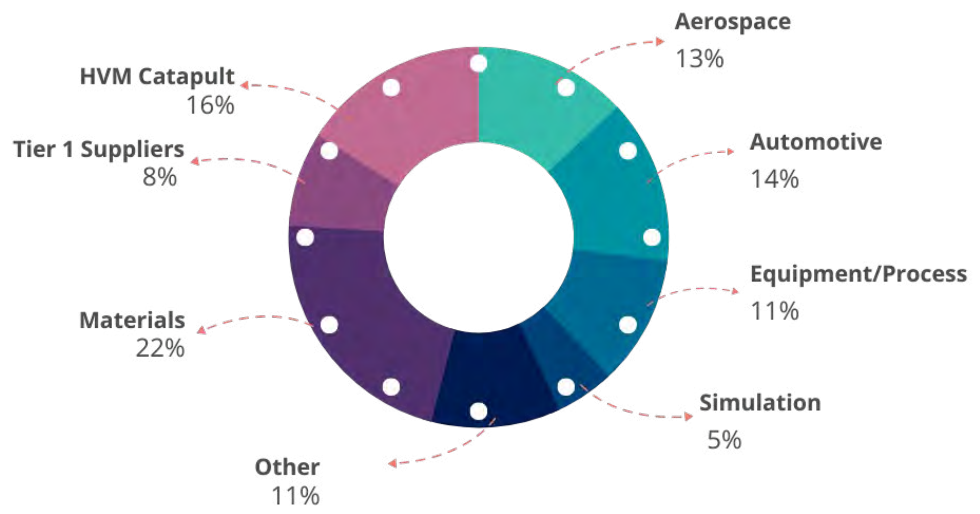
The International Missions were successful in creating what was in many instances a dialogue for the first time between Hub researchers and our colleagues in Germany and Canada, and with scope for several international collaborations already being discussed, it is likely that exciting new projects and areas of research will be created.

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.

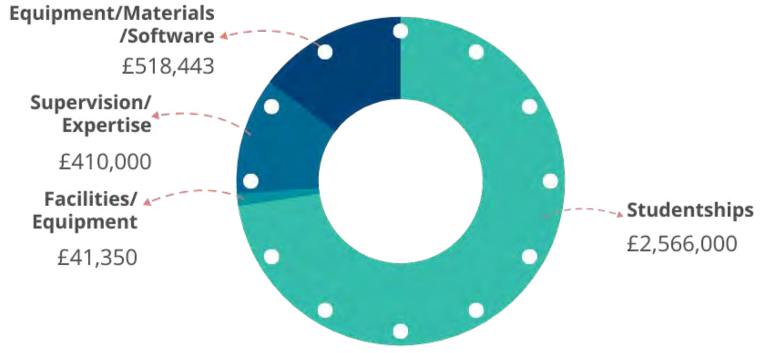
Hub Partners by Sector



Industry and Catapult 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 £3.5m of leveraged support in the form of studentships, supervision, materials and access to equipment.

Categories of Contributions Leveraged

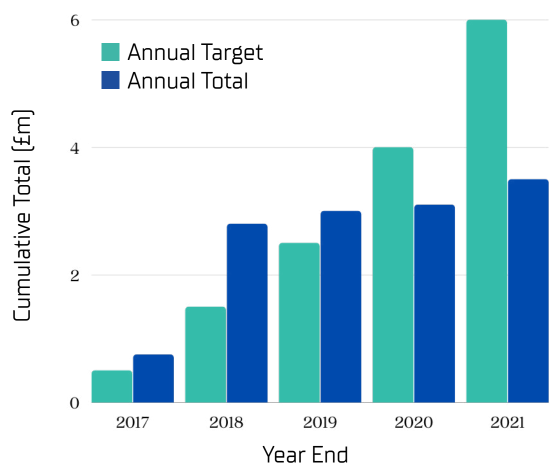


Industry contributions totalling £3.5m to date
Largest contribution is for studentships
National Composites Centre is the largest supporter to date - £1.4m

The cumulative value of support from our Industrial Partners to date is presented below, in addition to other leveraged contributions including student support, supply of materials, use of facilities and software. The graph summarises the contributions made by the 18 industry partners, plus the contributions from the 4 HVM Catapult Centres who originally wrote letters of support for the Hub. By December 2021, we have leveraged 58% of our £6m 2021 target. 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 Core Projects and Feasibility Studies.

Industry Leveraged Contributions



Associated Leveraged Projects

Links with associated leveraged projects have enabled us to build a wider network and develop key skills. £19.6m has been leveraged for new grants, including an EPSRC Strategic Equipment Grant (EP/T006420/1), a Programme Grant (EP/S017038/1), and more recently the Industrial Strategy Challenge Fund (ISCF) Manufacturing Made Smarter Challenge (EP/V061798/1). The overall aim of the Manufacturing Made Smarter Challenge is to help the UK's manufacturing industry become more productive and competitive through innovation and adoption of digital technologies.

Industry Partners

The University Of Sheffield. Advanced Manufacturing Research Centre Boeing
AIRBUS
ASTON MARTIN
BAE SYSTEMS
BENTLEY
Bitrez
COMPOSITE INTEGRATION ltd
CORIOLIS composites
DASSAULT SYSTEMES
esi get it right®
European Thermodynamics Limited Intelligent Thermal Management
GE Aviation
FreiLacke
GKN AEROSPACE
GORDON MURRAY DESIGN
HEXCEL
LUXFER GAS CYLINDERS
mtc Manufacturing Technology Centre
M.Wright & Sons Ltd. Engineered Textile Structures (Established 1860)
NATIONAL COMPOSITES CENTRE
NetworkRail
PAC GROUP
PENTAXIA
Rolls-Royce®
SCOTT BADER
SHD composites advanced composite materials
sigmatex material innovation
TORAY Innovation by Chemistry
WMG THE UNIVERSITY OF WARWICK

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

4 Hub Training

We are currently training 38 PhD students, 47 EngDs and 33 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 Programme 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.

Vitae Researcher Development Framework (RDF)
This year the Hub became a member of the Vitae Researcher Development Framework (RDF), which 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.

ESI Training
A bespoke training course was developed by Hub industry partner ESI. ESI specialises in providing state-of-the-art technology in physical system simulation and have been an active and valued collaborator of the Hub since its inception in 2017.

ESI offered Hub students and researchers the opportunity to learn more about their software packages. The training course consisted of 10 sessions spread over two weeks, covering PAM-FORM and PAM-RTM. The training in the first week offered attendees the chance to develop tools to simulate preforming processes for dry textiles and thermoforming of prepregs materials. The second week focused on PAM-RTM, targeting a range of liquid composite moulding techniques including Resin Transfer Moulding, Vacuum Infusion and compression-RTM.

Following positive feedback from the attendees, this course will be run again later this year and we are working with other industry partners to organise similar bespoke training.

International Exchange Programme (IEP)

In October 2021, the Hub refreshed and relaunched its IEP, which offers students the opportunity to participate in an exchange to a partnering international institution. 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, three exchanges have taken place and we continue to encourage our students to participate.

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), 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.

Mikhail Matveev (Chair)	University of Nottingham
Anthony Evans	University of Nottingham
Ángela Lendínez Torres	University of Nottingham
Connie Qian	University of Warwick
Patrick Sullican	University of Bristol
Shankhachur Roy	University of Manchester

Researcher Network Committee
Given the restrictions imposed by COVID-19 in 2020-2021, a combination of virtual and face to face events were organised for PhDs and researchers. The events were well attended and virtual events proved an effective and flexible approach for the sharing of research and virtual lab tours. In early December, the Researcher Network held its first in-person networking event since February 2020. Hub researchers were invited to visit Hub partner Warwick Manufacturing Group (WMG). The event, including a lab tour, was attended by 30 researchers from six universities across the UK (Bristol, Cambridge, Edinburgh, Manchester, Nottingham and Sheffield).

Early-Career Feasibility Studies
A Researcher Network Award call was launched in July 2021. Proposals had to focus on the manufacturing of fibre reinforced polymer composites, and the call was open to researchers who are currently employed or study at one of the 15 Hub spokes. After submitting their application, applicants were required to give a short presentation of their research ideas to a panel chaired by Dr Ian Gent from GKN Aerospace (Hub alumnus). While all presentations were of very high quality, two £5k proposals were selected for funding:

- **George Street, University of Nottingham:**
  The effect of non-isothermal conditions on the shear behaviour of fibre reinforced thermoplastic composites.
- **Dr Geir Olafsson and Dr Iryna Tretiak, Bristol:**
  Inspection and in-process evaluation of prepreg fibre volume fraction for improved part quality.

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 this 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.

The Centre offers a 4-year Engineering Doctorate (EngD) programme in Composite Manufacturing that is positioned at the intersection of materials, manufacturing and design. Students spend 75% of their time conducting industrially driven research within their sponsoring company. The EngD programme comprises a specialist academic taught component and a major industrially based research project delivered at TRL 3-5.

IDC New Starters for 2021-2022:	
Jack Holyoak	Project Title: Manufacturing Advanced Structural Composites Sustainable Prepreg Material Industrial Sponsor: SHD Composite Materials Ltd Academic Supervisor: Dr Lee Harper, University of Nottingham
Ralph Andrez Gomez Quinones	Project title: Fast Simulation Tools for Predicting Consolidation-induced Defects in Large Scale Aerospace Components Industrial Sponsor: Stelia Academic Supervisor: Dr Jonathan Belnoue, University of Bristol

In October 2021 the IDC held an in-person IDC Showcase event to welcome current EngD students, industrial and academic supervisors, our external examiner, invited VIP guests and several alumni to Engineers' House in Bristol. There were around 50 people in attendance for a day that included 12 oral presentations and a quick-fire poster session. There was a lively discussion that was expertly chaired by the IDC alumni. The successful event was celebrated by a reception and dinner providing all present a long-awaited opportunity to network and discuss activities in person in an informal setting. There is another Showcase planned for February 2023.

The IDC 2021 brochure was launched at the event and can be accessed by clicking here. It contains technical posters from all current EngD candidates as well as selected personal 'EngD journeys' and descriptions of several specialist Study Tours.

IDC Notable Achievements

In addition to a number of conference presentations, journal papers and the descriptions of achievements by our EngDs already published in the IDC 2021 brochure, the following needs to be noted for this year:

- Nikita Gandhi achieved an examination qualification for the Level 2 Ultrasonic Inspection of aerospace composite components. This exam included practical assessments with manual, semi-automated, and automated methods and written component of ultrasonic theory and application to industry. With the 800 hours practical experience obtained over the last 3 years, she will be certified to sign off inspections in industrial applications.
- Alumnus Dr Petar Zivkovic and EngD student Ms Claudia Jimenez-Martin became part of the Airbus 'Wing of Tomorrow' project team, involved in the assembly of the first future 'eco-wing' prototype. Claudia has recently taken on hosting the Bristol Doctoral College's podcast, and recorded an episode with alumnus Dr Alex Cochrane on the topic of careers post PhD / EngD.
- Preetum Mistry achieved several top places in UK based student lecture competitions, as well as a number of journal papers enabling him to develop new ideas to support him in securing a competitive EPSRC Doctoral Prize Fellowship, to be mentored by Professor Andrew Long, University of Nottingham. In addition, his group from the University of Nottingham have won 1st place in the academic entry for the SAMPE Video Competition 2021: 'Resilience During Covid'.
- Patrick Sullivan and Dr Mo Abolkheir have had a patent granted for a new goal line technology that could replace TMO, VAR and Hawk-Eye. Using the Half-Causation Method (a framework for developing inventions and getting them patented) and Patrick's idea, the pair developed patent 2588495, a 'Positional detection system'. While not strictly related to Patrick's EngD project, the patenting experience will always be valuable.

Graduated since last report:	
Sarvesh Dhiman	Composite Development Engineer at M Wright & Sons Ltd
Gabriele Voto	Research Assistant at Cranfield University
Jack-Linley-Start	Trainee patent attorney
Simon Wilkinson	Employment at the National Composites Centre, Bristol; now Simulation Research Engineer at AniForm Engineering

To graduate:	
Daniel Griffin *"Enabling data-driven research and development in composite product engineering: An over-braiding case study"*	Full-time employment at the National Composites Centre, Bristol
Preetum Mistry *"Lightweighting of railway vehicles"*	EPSRC Doctoral Prize Fellow, University of Nottingham

Successful EngD Vivas, Destinations and Forthcoming Thesis Submissions

Awaiting viva:	
Robbie Herring *"Leading Edge Erosion of Wind Turbine Blades: An Assessment and Improvement of the Translation Between Test Results and In-situ Performance".*	Research Engineer at Offshore Renewable Energy Catapult
Jakub Kucera *"Automating 'design For Manufacture' of Aerospace Composite Components".*	Employment at the National Composites Centre, Bristol
Matt Etchells *"High-Pressure Resin Transfer Moulding (HP-RTM) Process Optimisation".*	Employment at the National Composites Centre, Bristol

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. This year we appointed a Hub EDI champion, Connie Qian from the University of Warwick, to help deliver our strategic aim of creating a fully inclusive culture that is proactive in initiating change and driving forwards best practice in EDI matters.

5 Hub Outreach Activities

Hub Open Day

The Hub Open day was a huge success in October 2021, with a virtual attendance of 95 delegates from a range of PhDs, postdocs, UK and international academics, and industrial partners. It was hosted online by the University of Edinburgh, a Hub Spoke, ahead of the International Conference on Manufacturing of Advanced Composites (ICMAC).

The Hub welcomed keynote speakers Dr Adrian Gill, from Vestas Wind Systems, who gave an informative presentation on 'Composites Manufacturing in the Wind Industry, and Dr Isabelle Paris from Bombardier Aviation, who gave an equally interesting presentation on 'Industry Perspectives on Composite Airframe Structures Development and Certification'.

The day was split into parallel sessions, each comprising of a selection of presentations by Core Project leads and Innovation Fellows. This structure provided delegates with the opportunity to transition between sessions to listen to their preferred talks. The quick fire student session consisted of 18 PhD student and Researcher presentations, which was a great opportunity for them to showcase highlights of their current research. The best presentation was judged online by delegates, and the winning prize was awarded to George Street, University of Nottingham, for this presentation 'Thermal Management for Low-Cost Thermoplastic Composite Components'.

A 'Composite Design and Make' competition was held during the Open Day, in conjunction with the Society for the Advancement of Material and Process Engineering (SAMPE) UK and Ireland Chapter. Participants applied their engineering knowledge to build a composite bridge with allocated materials, to support a 1kg load at the mid-span, but with an overall structural mass of less than 250g. The challenge was well received with three teams from the University of Bristol and the National Composites Centre, the University of Edinburgh and the University of Nottingham competing for the cash prize. The winning team was 'Uni Edi' with a bridge span of 4.57m and a mass of 249g.

Advanced Engineering Show

The Hub were pleased to return to face to face events in November 2021 and attended the Advanced Engineering Show at the NEC, Birmingham, UK. It is the UK's largest annual engineering and manufacturing event that connects OEMS, Tier 1 manufacturers and supply chain partners. The Hub's newly designed stand attracted a lot of interest from delegates and provided an opportunity for Hub members to network and engage with the industrial community.

Hub Webinars

Our webinars have continued to be hugely successful with registrations for each webinar reaching over 100 delegates. The Hub held two webinars in 2021, delivered by projects leads and researchers.
In May 2021, the research teams from the Universities of Manchester and Nottingham presented their work from Core Project 'New Manufacturing Techniques for Optimised Fibre Architectures'. The project aims to discover new forms of 3D fibre reinforcements for use in manufacturing of composites with mechanical properties better than can be achieved now with conventional 3D reinforcements.
In September 2021, Professor Emile Greenhalgh from Imperial College London, presented research investigating the design and manufacturing issues associated with Hub Core Project on multifunctional composites. The presentation entitled 'Design and Manufacturing Issues for Mutifunctional Structural Composites' gave an overview of emerging technologies, with particular focus on structural power composites: structural composites imbued with the capacity to store and deliver electrical energy.
Recordings of the webinars are available on our website - www.CIMCOMP.ac.uk

International Composites Summit (ICS)

The Hub attended the two-day International Composites Summit on 8th - 9th September at the ILEC conference centre, Earls Court, London. The conference was the first face to face event the Hub has participated in since the start of the pandemic and we were pleased to see some familiar and new faces at the event. We look forward to attending more events in the next year and meeting up in person with our industrial and academic partners as the pandemic restrictions ease.

Synergy Promotion Workshop

In February 2022, the Hub organised a Synergy Promotion workshop to officially launch the next Synergy call. A combination of presentations and interactive group sessions provided Hub members with opportunities to discuss their research and ideas for future Hub projects, and identify and build on current project synergies. Research outcomes from the last round of Synergy Promotion projects were also presented:

- Connecting the work on microwave processing of composites with expertise in sensor development for temperature and stress management (Janice Barton, Richard Day, Adam Sobey, Christopher Holmes).
- Investigate the use of powder epoxy to co cure preforms (Colin Robert, Edward Archer).
- Compile a database of raw micro CT scans from current and past projects (Stephen Hallett, Mikhail Matveev).

6 Hub Governance

The Management Group is supported by the Advisory Board and three committees: Knowledge Exchange Committee, 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. This year we were pleased to increase membership and welcome Dr Adrian Gill from Vestas Wind Systems. We also welcome Dr Amir Rezai from BAE Systems, who replaces Brett Hemingway following his retirement.

From top left to right: Prof Janice Dulieu-Barton, Deputy Director of the IDC; Prof Mike Hinton, Chair of the AB; Dr Mike Johnson, Chair of the PDC; Dr Mikhail Matveev, 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 Mikhail Matveev). 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 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 Thybo Thomsen
Deputy Hub Director
University of Bristol

Dr Thomas Turner
Deputy Hub Director
University of Nottingham

Dr Lee Harper
Hub Manager
University of Nottingham

Alex Hammond
Hub Deputy Manager
University of Nottingham

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

Andrew Mills
Deputy Chair of the Postgraduate Development Committee
Cranfield University

Dr Mikhail Matveev
Chair of the Researcher Network
University of Nottingham

Professor Ivana Partridge
Director of Industrial Doctorate training Centre
University of Bristol

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 Group

Professor Remko Akkerman
Scientific Expert
University of Twente

Dr Rob Backhouse
Industrial Representative
Rolls-Royce

Craig Carr
Industrial Representative
GKN Aerospace

Dr Enrique Garcia
Industrial Representative
National Composites Centre

Dr Warren Hepples
Industrial Representative
Luxfer

Professor Mike Hinton
Advisory Board Chair
CTO, HMV Catapult

Tom James
Industrial Representative
Hexcel Reinforcements

Dame Professor Jane Jiang
Scientific Expert
University of Huddersfield

Professor Ian Kinloch
Scientific Expert
University of Manchester

Professor Veronique Michaud
Scientific Expert
EPFL

Dr Amir Rezai
Industrial Representative
BAE Systemes

Andy Smith
Industrial Representative
Gordon Murray Design

Naomi South
EPSRC Representative
EPSRC

Tim Wybrow
Industrial Representative
NEOS Composites

Dr Adrian Gill
Industrial Representative
Vestas Wind Systems

Investigators

Dr Edward Archer
Ulster University

Professor Janice Barton
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
University of Nottingham

Professor Stephen Hallett
University of Nottingham

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

Edward McCarthy
University of Edinburgh

Dr Euan McGookin
University of Glasgow

Professor Alistair McIlhagger
Ulster University

Andrew Mills
Cranfield University

Dr Daniel Mulvihill
University of Glasgow

Professor Conchur O'Bradaigh
University of Edinburgh

Professor Ton Peijs
University of Warwick

Professor Steve Pickering
University of Nottingham

Professor Prasad Potluri
University of Manchester

Dr Andrew Rhead
University of Bath

Dr Daniel Richards
University of Glasgow

Professor Paul Robinson
Imperial College, London

Dr Dipa Roy
University of Edinburgh

Professor Milo Shaffer
Imperial College, London

Professor Ian Sinclair
University of Southampton

Dr Alex Skordos
Cranfield University

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

Researchers

Dr Debabrata Adhikari
University of Nottingham

Dr Chrysoula Aza
University of Bath

Dr Ankur Bajpai
University of Edinburgh

Dr Jonathan Belnoue
University of Bristol

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
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Dr Yang Chen
University of Bath

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Dr Dorian Dixon
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Dr Thomas Dooher
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Dr Wenbo Duan
Brunel University

Dr Michael Elkington
University of Bristol

Dr Anthony Evans
University of Nottingham

Dr Ian Gent
University of Bristol

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

Dr Nataliia Luhyna
Wrexham Glyndwr University

Dr Dimitrios Mamalis
University of Edinburgh

Dr Asimina Manta
Wrexham Glyndwr University

Dr Mikhail Matheev
University of Nottingham

Dr Sang Nguyen
Imperial College, London

Dr Thomas Noble
University of Edinburgh

Dr Laura Pickard
University of Bristol

Dr Connie Qian
University of Warwick

Dr Arjun Radhakrishnan
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Dr Calvin Ralph
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Dr Neil Reynolds
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Dr Colin Robert
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Dr Shankhachur Roy
University of Manchester

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Dr Danijela Stankovic
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Dr Ric (Xiaochuan) Sun
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Dr Mario Valverde
University of Bristol

Dr Verner Viisainen
University of Cambridge

Dr Gabriele Voto
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Dr Lei Wan
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Dr Logan Wang
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Dr Bohao Zhang
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** Highlighted names are new starters in 2021/2022*

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University of Nottingham

Rob Iredale
University of Bristol

Rajan Jagpa
University of Bath

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

Angela Lendinez Torres
University of Nottingham

Shimin Lu
University of Nottingham

James Mortimer
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Ulster University

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University of Bristol

Michael O'Leary
University of Bristol

Jinseong Park
University of Manchester

Gwladys Popo
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Bethany Russell
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George Spackman
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University of Nottingham

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Mark Turk
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** Highlighted names are new starters in 2021/2022*

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Joe Soltan
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Hexcel

Simon Wilkinson
University of Bristol
National Composites Centre

Lachlan Williams
University of Bristol
Airbus

Maria Zilidou
University of Bristol
Qinetiq

Petar Zivkovic
University of Bristol
Rolls-Royce

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 80 since January 2017.

2022

80. Zhang, H., Li, A., Wu, J., Sun, B., Wang, C., Yang, D. (2022) Effectiveness of fibre placement in 3D printed open-hole composites under uniaxial tension, Composites Science and Technology, vol 220, 109269. Grant Number: Grant Number: EP/P006701/1. doi.org/10.1016/j.compscitech.2022.109269

79. Parsons, A.J.,Gonciaruk, A., Zeng, X., Thomann, F.S., Schubel, P.J., Lorrillard, J., Johnson,M.S. (2022) Controlling mass loss from RTM6 epoxy resin under simulated vacuum infusion conditions, Polymer Testing, vol. 107, 107473. Grant Number: EP/P006701/1. doi.org/10.1016/j.polymertesting.2022.107473

2021

78. Belnoue, J.P.H., Valverde, M.A., Onoufriou, M., Sun (Ric), X., Ivanov, D.S., Hallett, S.R. (2021) On the physical relevance of power law-based equations to describe the compaction behaviour of resin infused fibrous materials, International Journal of Mechanical Sciences, vol 199, 106425. Grant Number: EP/P006701/1. doi.org/10.1016/j.ijmecsci.2021.106425

77. Chen, S., Joesbury, A., Yu, F., Harper, L.T., Warrior, N.A. (2021) Optimisation of intraply stitch removal for improved formability of biaxial non-crimp fabrics, Composites Part B: Engineering vol 229, 109464. Grant Number: EP/P006701/1. doi.org/10.1016/j.compositesb.2021.109464

76. Elkington, M., Almas, E., Ward-Cherrier, B., Pestell, N., Lloyd, J., Ward, C., Lepora, N. (2021). Real Time Defect Detection During Composite Layup via Tactile Shape Sensing. Journal of Science and Engineering of Composite Materials. Grant Number: EP/P006701/1. doi.org/10.1515/secm-2021-0001

75. Gautam, M., Sivakumar, S., Barnett, A., Barbour, S., Ogin, S.L., Potluri, P. (2021) On the behaviour of flattened tubular Bi-axial and Tri-axial braided composites in tension, Composite Structures, vol 261, 113325. Grant Number: EP/P006701/1. doi.org/10.1016/j.compstruct.2020.113325.

74. Harrison, P., Gonzalez Camacho, L.F. (2021) Deep draw induced wrinkling of engineering fabrics, International Journal of Solids and Structures, vol 212, 220 - 236. Grant Number: EP/P006701/1. doi.org/10.1016/j.ijsolstr.2020.12.003.

73. Hubert, P., Kratz, J. (2021) Tool interface pressure during the forming of model composite corners, Composites Part A: Applied Science and Manufacturing, vol 151, 106639. Grant Number: EP/P006701/1. doi.org/10.1016/j.compositesa.2021.106639

72. Iglesias, M., Yang.Y. (2021) Adaptive regularisation for ensemble Kalman inversion, Inverse Problems, vol 37, Number 2, 025008. Grant Number: EP/P006701/1. doi.org/10.1088/1361-6420/abd29b

71. Jiménez-Fortunato, I., Bull, D.J., Thomsen, O.T., Dulieu-Barton, J.M. (2021) On the source of the thermoelastic response from orthotropic fibre reinforced composite laminates, Composites Part A: Applied Science and Manufacturing, vol 149, 2021, 106515. Grant Number: EP/P006701/1. doi.org/10.1016/j.compositesa.2021.106515

70. Karadotcheva, E., Nguyen, S., Greenhalgh, E., Shaffer, M., Kucernak, A., Linde, P. (2021) Structural power performance targets for future electric aircraft, Energies, vol 14, Issue 19, 6006. Grant Number: EP/P006701/1. doi.org/10.3390/en14196006

69. Karim, N., Sarker, F., Afroj, S., Zhang, M., Potluri, P., Novoselov, K.S. (2021) Sustainable and Multifunctional Composites of Graphene-Based Natural Jute Fibers, Advanced Sustainable Systems, vol 5, issue 3, 2000228. Grant Number: EP/P006701/1. doi.org/10.1002/adsu.202000228

68. Matveev, M., J., Endruweit, A., Long, A.C., Iglesias, M.A., Tretyakov, M.V. (2021) Bayesian inversion algorithm for estimating local variations in permeability and porosity of reinforcements using experimental data, Composites Part A: Applied Science and Manufacturing, vol 143, 106323. Grant Number: EP/P006701/1. doi.org/10.1016/j.compositesa.2021.106323

67. Mistry, P.J., McRobie, C.A., Johnson, M.S., Jones, I.V. (2021) Design of A Lightweight Multifunctional Composite Railway Axle Utilising Coaxial Skins, Journal of Composites Science, vol 5, 77. Grant Number: EP/P006701/1. doi.org/10.3390/jcs5030077

66. Mistry, P.J., Johnson, M.S., Li, S., Bruni, S., Bernasconi, A. (2021) Parametric sizing study for the design of a lightweight composite railway axle, Composites Structures, vol 267, 113851. Grant Number: EP/P006701/1. doi.org/10.1016/j.compstruct.2021.113851

65. Nguyen, S., Millereux, A., Pouyat, A., Greenhalgh, E.S., Shaffer, M.S.P., Kucernak, A.R.J., Linde, P. (2021) Conceptual Multifunctional Design, Feasibility and Requirements for Structural Power in Aircraft Cabins, Aerospace Research Central. Grant Number: EP/P006701/1. doi.org/10.2514/1.C036205

64. Noble, T., Davidson, J.R., Floreani, C.,Bajpai, A., Moses, W., Dooher, T., McIlhagger, A., Archer, E., Ó Brádaigh, C.M., Robert, C. (2021) Powder Epoxy for One-Shot Cure, Out-of-Autoclave Applications: Lap Shear Strength and Z-Pinning Study, Journal of Composites Science, vol 5, Issue 9. Grant Number: EP/P006701/1. doi.org/10.3390/jcs5090225

63. O'Keeffe C., Pickard L.R., Cao J., Allegri J., Partridge I.K., Ivanov D.S, (2021) Multimaterial braids for multifunctional laminates: conductive through-thickness reinforcement, Functional Composite Materials, vol 2, article 5. Grant Number: EP/P006701/1. doi.org/10.1186/s42252-021-00018-0

62. Qi, G, Nguyen, S., Anthony, D. B., Kucernak, A. R. J., Shaffer, M. S. P., Greenhalgh, E. S. (2021) The influence of fabrication parameters on the electrochemical performance of multifunctional structural supercapacitors, Multifunctional Materials, vol 4, Issue 3, 034001. Grant Number: EP/P006701/1. doi.org/10.1088/2399-7532/ac1ea6

61. Robert, C., Mamalis, D., Obande,W., Koutsos, V., Ó Brádaigh, C.M., Ray, D. (2021) Interlayer bonding between thermoplastic composites and metals by in-situ polymerization technique, Journal of Applied Polymer Science, vol 138, Issue 40, 51188. Grant Number: EP/P006701/1. doi.org/10.1002/app.51188

60. Selver, E., Potluri, P. (2021) Intra-tow micro-wrapping for damage tolerance, Composites Science and Technology, vol 213, 108935. Grant Number: EP/P006701/1. doi.org/10.1016/j.compscitech.2021.108935

59. Street, G.E., Mistry, P.J., Johnson, M.S. (2021) Impact Resistance of Fibre Reinforced Composite Railway Freight Tank Wagons, Journal of Composites Science, vol 5, Issue 6. Grant Number: EP/P006701/1. doi.org/10.3390/jcs5060152

58. Struzzieroa, G., Barbezata, M., Skordos, A. (2021) Consolidation of continuous fibre reinforced composites in additive processes: A review, Additive Manufacturing, vol 48, Part B, 102458. Grant Number: EP/P006701/1. doi.org/10.1016/j.addma.2021.102458

57. Sun, X., Belnoue, J.P.H., Wang, W., Kim, B.C., Hallett, S.R. (2021) "Unforming" fibre-steered preforms: Towards fast and reliable production of complex composites parts, Composites Science and Technology, vol 216, 109060. Grant Number: EP/P006701/1. doi.org/10.1016/j.compscitech.2021.109060

56. Valverde, M.A., Belnoue, J.P.H., Kupfer, R., Kawashita, L.F., Gude, M., Hallet, S.H. (2021) Compaction behaviour of continuous fibre-reinforced thermoplastic composites under rapid processing conditions. Composites Part A: Applied Science and Manufacturing, vol 149, 106549. Grant Number: EP/P006701/1. doi.org/10.1016/j.compositesa.2021.106549

55. Viisainen, J. V., Sutcliffe, M.P.F. (2021) Characterising the variability in wrinkling during the preforming of non-crimp fabrics, Composites Part A: Applied Science and Manufacturing vol 149, 106536. Grant Number: EP/P006701/1. doi.org/10.1016/j.compositesa.2021.106536

54. Viisainen, J.V., Hosseini, A., Sutcliffe, M.P.F. (2021) Experimental investigation, using 3D digital image correlation, into the effect of component geometry on the wrinkling behaviour and the wrinkling mechanisms of a biaxial NCF during preforming. Composites Part A: Applied Science and Manufacturing, vol 142, 106248. Grant Number: EP/P006701/1. doi.org/10.1016/j.compositesa.2020.106248

53. Yousaf, Z., Withers, P.J., Potluri. P. (2021) Compaction, nesting and image based permeability analysis of multi-layer dry preforms by computed tomography (CT), Composite Structures, vol 263, 113676. Grant Number: EP/P006701/1. doi.org/10.1016/j.compstruct.2021.113676

52. Yousefi, N; Evans; A, D., Harper, L.T., Maples, H.A., James, T.,Bismarck, A. (2021) Solid Epoxy Resin Systems for Automated Composite Manufacturing. Composites Part A: Applied Science and Manufacturing, Volume 142, 2021, 106205. Grant Number: EP/P006701/1. doi.org/10.1016/j.compositesa.2020.106205.

51. Xiao, Z., Harrison, P. (2021) Design of buckling and damage resistant steered fibre composite laminates using trellis shear kinematics, Composite Structures, Vol 260, 113526. Grant Number: EP/P006701/1. doi.org/10.1016/j.compstruct.2020.113526.

50. Yu, F., Chen, S., Harper, L.T., Warrior, N.A. (2021) Double diaphragm forming simulation using a global-to-local modelling strategy for detailed defect detection in large structures, Composites Part A: Applied Science and Manufacturing, vol 147, 106457. Grant Number: EP/P006701/1. doi.org/10.1016/j.compositesa.2021.106457

49. Yu, F., Chen, S., Harper, L.T., Warrior, N.A. (2021) Investigation into the effects of interply sliding during double diaphragm forming for multilayered biaxial non-crimp fabrics, Composites Part A: Applied Science and Manufacturing, vol 150, 106611. Grant Number: EP/P006701/1. doi.org/10.1016/j.compositesa.2021.106611

48. Yu, F., Chen, S., Harper, L. H., Warrior N.A. (2021) Simulating the effect of fabric bending stiffness on the wrinkling behaviour of biaxial fabrics during preforming, Composites Part A: Applied Science and Manufacturing, vol 143, 106308. Grant Number: EP/P006701/1. doi.org/10.1016/j.compositesa.2021.106308

2020

47. Budwal, N., Kasper, K., Goering, J., Ward, C. (2020) Flexible, low-cost tooling solutions for a one-shot resin infusion of a 3D woven and multi-textile preform, Procedia Manufacturing, Vol 51, 856863. Grant Number: EP/P006701/1. doi.org/10.1016/j.promfg.2020.10.120

46. Chai, Y., Wang, Y., Yousaf,, Z., Storm, M., T. Vo, N., Wanelik, K., Burnett,T.L., Potluri, P., Withers, P, J. (2020) Following the effect of braid architecture on performance and damage of carbon fibre/epoxy composite tubes during torsional straining, Composites Science and Technology, Volume 200, 108451. Grant Number: EP/P006701/1. doi.org/10.1016/j.compscitech.2020.108451

45. Gandhi, N., Rose, R., Croxford, A., Ward, C. (2020) Developing a high-fidelity knowledge base for improvements in the non-destructive testing of advanced composite material products, Procedia Manufacturing, vol 51, 2020, 345352. Grant Number: EP/P006701/1. doi.org/10.1016/j.promfg.2020.10.049

44. Harrison, P., Campbell, I., Guliyev, E., McLelland, B., Gomes, R., Curado-Correia, N., McGookin, E., Mulvihill, D.M. (2000) Induction melt thermoforming of advanced multiaxial thermoplastic

composite laminates. Journal of Manufacturing Processes, Volume 60, Pages 673-683. Grant Number: EP/P006701/1. doi.org/10.1016/j.jmapro.2020.10.026

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

42. Mistry P.J., Johnson M.S., Galappaththi, U.I.K. (2020). Selection and Ranking of Rail Vehicle Components for Optimal Lightweighting using Composite Materials. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit. 133. Grant Number: EP/P006701/1. doi.g/10.1177/0954409719877774

41. Matveev, M.Y., Brown, L.P., Long, A. C. (2020) Efficient meshing technique for textile composites unit cells of arbitrary complexity. Composite Structures, Volume 254, 2020, 112757. Grant Number: EP/P006701/1. doi.org/10.1016/j.compstruct.2020.112757

40. Sun, X., Belnoue, J., Kim, B.C., Wang, W.T., Hallett, S. (2020) Virtual Unmanufacturing of Fibre streered performs for complex geometry composites, Procedia Manufacturing, vol 47, 197-201. Grant Number: EP/P006701/1. doi.org/10.1016/j.promfg.2020.04.175

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

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

37. Willicombe, K., Elkington, M., Hamerton, I., Ward, C. (2020) Development of Novel Transportation Shells for the Rapid, Automated Manufacture of Automotive Composite Parts, Procedia Manufacturing, Vol 51, 2020, 818-825. Grant Number: EP/P006701/1. doi.org/10.1016/j.promfg.2020.10.115

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

2019

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

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

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

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

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

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

29. Mistry, P, J., Johnson, M. S. (2019). Lightweighting of Railway Axles for the Reduction of Unsprung Mass and Track Access Charges. Part F: Journal of Rail and Rapid Transit. Grant Number: EP/ P006701/1. doi.org/10.1177/0954409719877774

28. Russell, B.K., Takeda, S., Ward. C., Hamerton, I. (2019). Examining the influence of carboxylic anhydride structures on the reaction kinetics and processing characteristics of an epoxy resin for wind turbine applications. Reactive and Functional Polymers, vol 144, 104353. Grant Number: EP/P006701/1. doi.org/10.1016/j.reactfunctpolym.2019.104353G

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

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

2018

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

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

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

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

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

2017

20. Akonda, M., Stefanova, M., Potluri, P., & Shah, D. (2017). M e c h a n i c a l Properties of recycled carbon fibre/polyester thermoplastic tape composites. Journal of Composite Materials. 51 (18), 2655-2663. Grant Number: Not acknowledged. doi.org/10.1177/0021998316672091

19. Atas, A., Gautam, M., Soutis, C., Potluri, P. (2017) Bolted Joints in Three Axially Braided Carbon Fibre /Epoxy Composites with Moulded-in and Drilled Fastener Holes. Applied Composites Materials. 24 (2), 449-460. Grant Number: Not acknowledged. doi:10.1007/s10443-016-9542-z

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

3. Saleh, M., Wang, Y., Yudhanto, A., Joesbury, A., Potluri, P., Lubineau, G., Soutis, C. (2017). Investigating the Potential of Using Off-axis 3D Woven Composites in Composite Joints Applications. Applied Composite Materials. 24 (2), 377-396. Grant Number: Not acknowledged. doi. org/10.1007 /s10443-016-9529-9

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

1. Yousaf, Z., Potluri, P., Withers, P. (2017). Influence of Tow Architecture on Compaction and Nesting in Textile Preforms. Applied Composite Materials. 24 (2), 337-350. Grant Number: Not acknowledged. doi.org/10.1007/s104 43-016-9554-8

Conferences

2022

83. Sowrov K., Fernando A., Koncherry V., Withers P., Potluri P., 'Damage Evaluation in 3D Woven Composites with Warpway and Weft-way Binders,' in AIAA SCITECH 2022 Forum, January 2022, p. 1421.

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', in AIAA SCITECH 2022 Forum, January 2022, p. 1422.

2021.

81. Greenhalgh E.S., 'Clean Sky 2 Research Programme: Developments and Progress', AIAA SciTech 2021, January 2021.

80. 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', Oral presentation at International Conference on Manufacturing of Advanced Composites (ICMAC 2021), Edinburgh, UK.

79. 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/.

78. Çelik M., Noble T., Maguire J., Robert C., Ó Brádaigh C.M., 'Optimised Joule Heating of Carbon Fibres in a Low-cost, High-speed Powder-Epoxy Towpregging Pilot Production Line', Poster presentation at SAMPE Europe Conference, 29 - 30 September, 2021 Baden/Zürich – Switzerland.

77. 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.

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

75. 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.

74. Roy S. S., Wu, Z., Atas A. & Potluri P., Experimental and Numerical Analysis of Braided Box Section With Optimised Axial Reinforcement In: International Conference on Composite Structures (ICCS 24) 14 - 18 June, 2021 Porto, Portugal.

73. Viisainen J., Codolini A., Sutcliffe M.P.F.,'A deep learning surrogate model for rapid prediction of geometry-induced wrinkles in fabric preforming', ICMAC 12, Edinburgh (2021)

72. Yu F., Chen S., Harper L.T., Warrior N.A., 'Double diaphragm forming simulation using a multiresolution modelling strategy for defect detection in complex structures', ICMAC 12, Edinburgh (2021)

71. Chen S, Yu F., Joesbury A., Harper L.T., Warrior N.A., 'Local intraply stitch removal for improved formability of biaxial non-crimp fabrics', ICMAC 12, Edinburgh (2021)

70. Codolini A., Viisainen J.V., Sutcliffe M.P.M., 'Numerical Assessment of Variability in Double Diaphragm Forming of Non-Crimp Fabric Preforms', ICMAC 12, Edinburgh (2021)

69. 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', ICMAC 12, Edinburgh (2021)

68. Matveev M., 'Defect detection and process control in resin transfer moulding', ICMAC 12, Edinburgh (2021)

67. Fisher A., 'The significance of spatial temperature variations in large volume oven curing', ICMAC 12, Edinburgh (2021)

66. Yang D., 'Hybrid manufacturing of curved continuous carbon fibre reinforced dual-polymer composites', ICMAC 12, Edinburgh (2021)

65. Celik M., 'Contact Resistance Heating of Unidirectional Carbon Fibre Tows', ICMAC 12, Edinburgh (2021)

64. Sowrov K., 'Analysing the Influence of Binder Architectures on Compressibility and Permeability of 3D Woven Preforms with Warp Way and Weft Way Binders', ICMAC 12, Edinburgh (2021)

63. Collinson M., 'Development of integrated electrical self-sensing in aerospace CFRP components' ICMAC 12, Edinburgh (2021)

62. Moses W., 'Novel through Thickness Reinforcement Method for Carbon Composite Structures with No Reduction in In-Plane Properties', ICMAC 12, Edinburgh (2021)

61. Qian C., 'Experimental and Numerical Characterisation of Fibre Orientation Distributions in Compression Moulded Carbon Fibre SMC', ICMAC 12, Edinburgh (2021)

60. Endruweit A., 'Time-temperature dependant adhesive tack and contact area development between prepreg carbon fibre tape and rigid substrate', ICMAC 12, Edinburgh (2021)

59. Robert C., 'Powder Epoxy Towpregging Tapeline for Automated Fibre Placement', ICMAC 12, Edinburgh (2021)

58. Soltan J., 'Modular Infusion: Novel Approaches to Segregation and Control of Flow Fronts within Liquid Resin Moulding', ICMAC 12, Edinburgh (2021)

57. Grimes B., 'A computational and experimental analysis of the influence of guide ring size on fibre architecture in the braiding process', ICMAC 12, Edinburgh (2021)

2020

56. Sun X., Belnoue J., Chul Kim B., Wang W., Hallett S., 'Virtual Unmanufacturing 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.

2019

53. Vissainen V., Zhou J., Sutcliffe M., 'Characterisation of the wrinkling behaviour of a biaxial non-crimp-fabric during forming', ICCM22, Melbourne, Australia, August 2019

52. Chen S., McGregor O., Endruweit A., Harper L., Warrior N., 'Finite element forming simulation of complex composite sandwich panels', ICCM22, Melbourne, Australia, August 2019.

51. Yu F., Chen S., Harper L., Warrior N., 'Finite Element Modelling of Biaxial Fabric with Considering Bending Stiffness for Composites Preforming', ICCM22, Melbourne, Australia, August 2019.

50. Evans A., Turner T., Endruweit A., 'Development of Automated Dry Fibre Placement for High Rate Deposition', ICCM22, Melbourne, Australia, August 2019.

49. Mikhail Matveev, Shankhachur Roy, Vivek Koncherry, Louise Brown, Prasad Potluri, Andrew Long, 'Mesoscale optimisation and manufacturing of continuous fibre 3D reinforcements', ICCM22, Melbourne, Australia, August 2019.

48. Koncherry, Park, Sowrov, Potluri, Matveev, Brown, Long, 'Novel Manufacturing Techniques for Optimized 3D Multiaxial Orthogonal Preform', ICCM22, Melbourne, Australia, August 2019.

47. Anthony, Nguyen, Senokos, Bismarck, Greenhalgh, Shaffer, 'Hierarchical carbon aerogel modified carbon fiber composites for structural power applications', ICCM22, Melbourne, Australia, August 2019.

46. Valkova, Greenhalgh, Shaffer, 'Predicting the Consolidation of Fabric-Reinforced Structural Power Composites', ICCM22, Melbourne, Australia, August 2019.

45. Nguyen, Pouyat, Greenhalgh, Shaffer, Linde, 'Structural Power Performance Requirements for Future Aircraft Integration', ICCM22, Melbourne, Australia, August 2019.

44. Greenhalgh, Shaffer, Kucernak, Senokos, Nguyen, Pernice, Zhang, Qi, Anthony, Balaskandan, Valkova, 'Future Challenges and Industrial Adoption Strategies for Structural Supercapacitors', ICCM22, Melbourne, Australia, August 2019.

43. Jimenez Fortunato I., Bull D., Dulieu-Barton J., Thomsen O., 'Damage characterisation of composite components using fullfield imaging techniques', ICCM22, Melbourne, Australia, August 2019.

42. Gent I., Mann N.L., Ward C.,' Localised inkjet printing of resin additives for selective property enhancement', ICCM22, Melbourne, Australia, August 2019.

41. Murray J, Gleich K, McCarthy E.D, O'Bradaigh O., 'Properties if Polyamide-6 Composites using Thermoplastic Resin Transfer Moulding', ICCM22, Melbourne, Australia, August 2019.

40. Pappa E., 'Optimization of Carbon Fibre reinforced polymer (CFRP) composites with a thin embedded polyurethane film', ICCM22, Melbourne, Australia, August 2019.

39. Thomsen O,T., 'Buckling behaviour of UD carbon / Epoxy panels subjected to direct lightning strike', ICCM22, Melbourne, Australia, August 2019.

38. O'Bradaigh C, M, Mamalis D, Flanagan T, Doyle A., 'Tidal turbine blade composite using basalt fibre reinforced powder epoxy', ICCM22, Melbourne, Australia, August 2019.

37. Clegg H, Dell'Anno G, Scott M, Partridge I., 'Suppressing delamination in composite intersections with tufting and Z- pinning', ICCM22, Melbourne, Australia, August 2019.

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.

2018

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

33. 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.

32. 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.

31. 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.

30. Matveev M., Endruweit A., Long A.C., Iglesias M.A., Tretyakov M.V., 'Fast algorithms for active control of mould filling in RTM process with uncertainties', Proceedings of FPCM-14, Sweden, May 2018.

29. Matveev M., Koncherry V., Roy S.S., Potluri P., Long A. (2018) 'Novel textile preforming for optimised fibre architectures', IOP Conference Series: Materials Science and Engineering, 406 (1).

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

27. Belnoue J., Sun R., Cook L., Tifkitsis K., Kratz J., Skordos A.,' A layer by layer manufacturing process for composite structures', 11th International Conference on Manufacturing of Advanced Composites Nottingham, ICMAC July 2018, Nottingham, UK.

26. Elkington M., Gandhi N., Libby M., Kirby A., Ward C.,' Collaborative Human-Robotic Layup', 11th International Conference on Manufacturing of Advanced Composites Nottingham, ICMAC July 2018, Nottingham, UK.

25. Harrison P.,' Multistep thermoforming of multicavity multiaxial advanced thermoplastic composite parts', 11th International Conference on Manufacturing of Advanced Composites Nottingham, ICMAC July 2018, Nottingham, UK.

24. Mamalis D., Obande W., Koutsos V., Ó Brádaigh C., Roy D., 'Novel infusible thermoplastic matrix in fibre metal laminates', 11th International Conference on Manufacturing of Advanced Composites Nottingham, ICMAC July 2018, Nottingham, UK.

23. 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', 11th International Conference on Manufacturing of Advanced Composites Nottingham, ICMAC July 2018, Nottingham, UK.

22. Sutcliffe M., Zhou J., Viisainen V., 'Wrinkle formation characterisation during the forming of non-crimp fabrics', 11th International Conference on Manufacturing of Advanced Composites Nottingham, ICMAC July 2018, Nottingham, UK.

21. Veldenz L., Di Francesco M., Giddings P., Kim B.C., Potter K., 'Overcoming challenges in manufacturing complex structures with automated dry fibre placement', 11th International Conference on Manufacturing of Advanced Composites Nottingham, ICMAC July 2018, Nottingham, UK.

20. Warrior N., Chen S., McGregor O., Harper L., 'Forming Simulations for 3D Curved Sandwich Panels', 11th International Conference on Manufacturing of Advanced Composites Nottingham, ICMAC July 2018, Nottingham, UK.

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.

16. Mamalis D., Obande W., Koutsos V., Ó Brádaigh C.M., Roy D., 'Fabrication and Mechanical Characterisation of Thermoplastic Fibre-Metal Laminates Produced by In-situ Polymerisation Route', 18th European Conference on Composite Materials, Athens, Greece, 2018.

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 substructures', International Conference on Modern Practice in Stress and Vibration Analysis (MPSVA 2018), Cambridge, 2018.

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

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

2017

10. Bull D.J., Dulieu-Barton J.M., Thomsen O.T., Butler R., Rhead A.T., Fletche, T.A., Potter K.D.,' Reshaping the testing pyramid: utilisation of data-rich NDT techniques as a means to develop a 'high fidelity' component and substructure testing methodology for composites', 21st International Conference on Composite Materials Xi'an, 20-25th August 2017.

9. Koncherry V., Pate, D., Yusuf Z., Potluri P.,' Influence of 3d weaving parameters on preform compression and laminate mechanical properties', 21st International Conference on Composite Materials Xi'an, 20-25th August 2017.

8. Roy S.S., Yang D., Potluri P.,' Influence of Bending on Wrinkle Formation and Potential Method of Mitigation', 21st International Conference on Composite Materials Xi'an, 20-25th August 2017.

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', 21st International Conference on Composite Materials Xi'an, 20-25th August 2017.

6. Yan S., Long A.C., Zeng X., 'Design optimization of 3D woven T-joint reinforcements', Proceedings 21st International Conference on Composite Materials (ICCM-21), Xi'an, China, August 2017.

5. Zympeloudis E., Potter K., Weaver P.M., Kim B.C.,' Advanced Automated Tape Laying with Fibre Steering Capability Using Continuous Tow Shearing Mechanism', 21st International Conference on Composite Materials Xi'an, 20-25th August 2017.

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 Composites Manufacturing. Montreal 2017.

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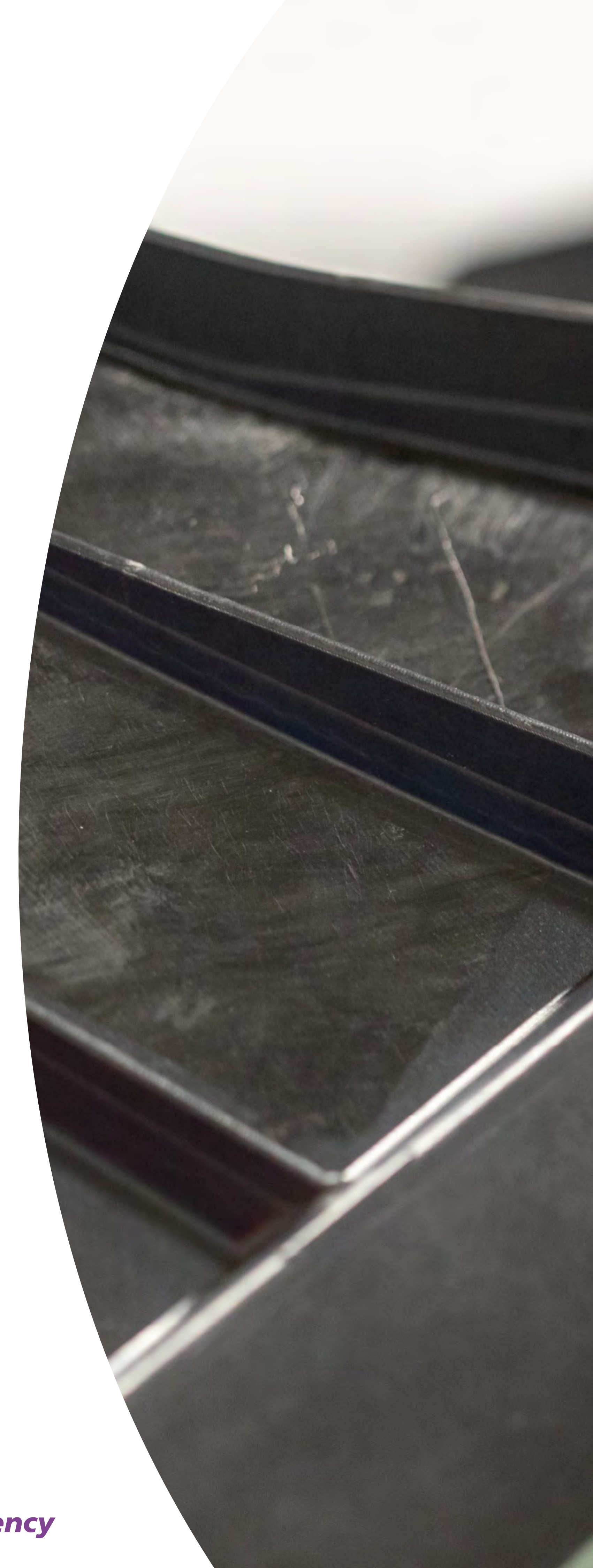

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