CIMComp
EPSRC
Future Composites
Manufacturing Research Hub

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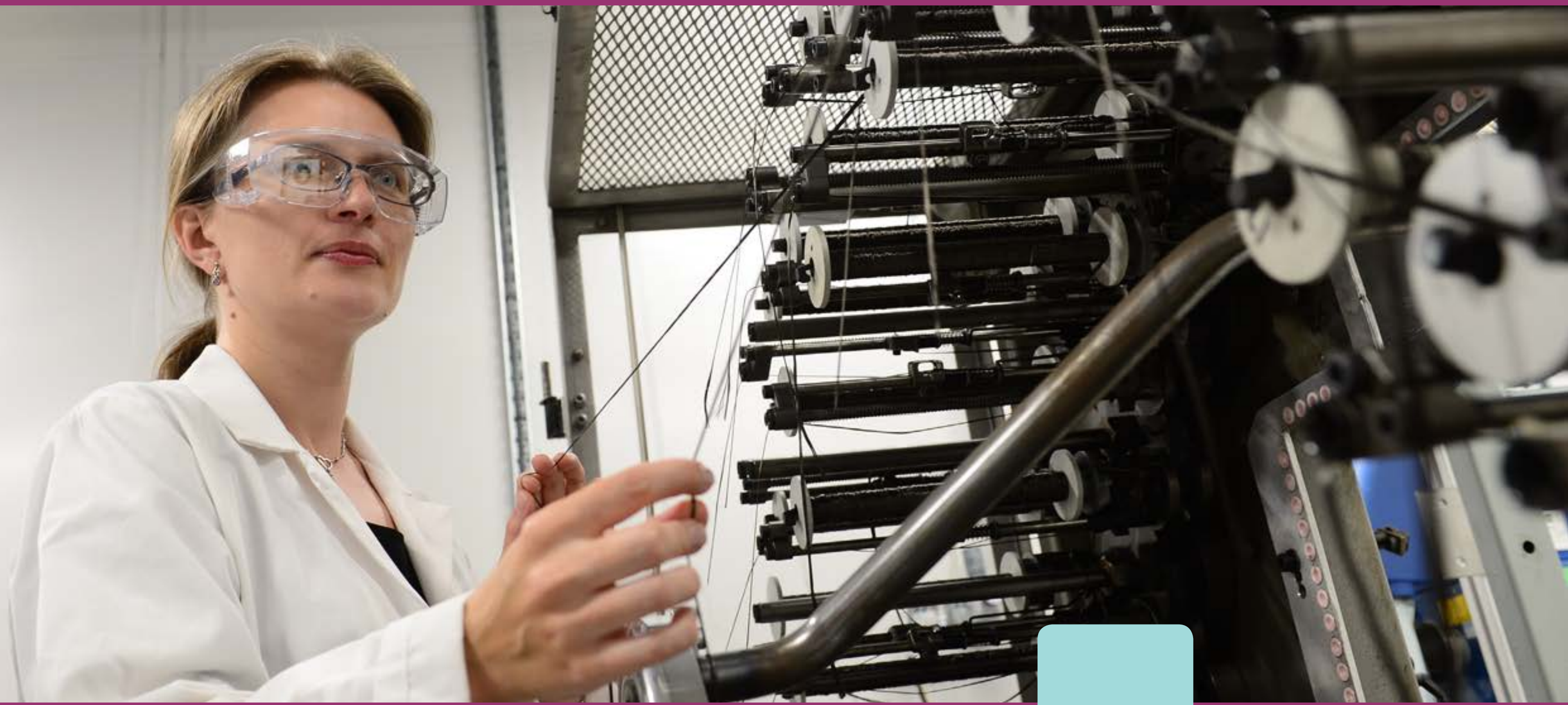
Research Council



EPSRC
Future Composites Manufacturing Research Hub

Underpinning the development of next-generation composites manufacturing processes

ANNUAL REPORT
2018-2019

University of Bristol
Brunel University London
University of Cambridge
Cranfield Manufacturing
The University of Edinburgh
University of Glasgow
Imperial College London
Manchester 1824 The University of Manchester
University of Nottingham UK | CHINA | MALAYSIA
University of Southampton

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Executive Summary

Welcome from the Director

Welcome to the second annual report for the EPSRC Future Composites Manufacturing Research Hub, which contains highlights from another busy and successful year. I had the pleasure of taking over the directorship of the Hub from Prof Andy Long in September 2018, who moved on to become the new Provost and Deputy Vice-Chancellor of the University of Nottingham. I was delighted to have been appointed to such an esteemed position and have enjoyed working with our expanding network of partners to achieve our vision of becoming the national centre of excellence in fundamental research for composites manufacturing.

I am pleased to announce the introduction of three new academic partners following a call in 2018 for Feasibility Studies. Ulster University, the University of Sheffield and Wrexham Glyndwr University have joined the existing Hub Spokes, increasing the number of academic partners to 13, which is a remarkable achievement in just two years. We continued to strengthen our links with the international community in 2018 by hosting an open day in conjunction with the 11th International Conference on Manufacturing of Advanced Composites (ICMAC 11). This 3-day event brought together composite manufacturing scientists, engineers and end users from academia and industry to hear about the latest developments from pioneers within the field. It was attended by over 120 people and had a truly international feel, with delegates travelling from as far as New Zealand, Japan and USA to present papers.

I have particularly enjoyed attending some of our outreach events this year, such as the Advanced Engineering Show at the NEC, which has enabled me to engage further with the wider industrial community and discuss with them the challenges they face. These activities have supported our roadmapping initiative, which aims to collate the low-TRL challenges that currently act as barriers to step-changes in composites manufacturing. We have held a workshop with our key stakeholders to gather this information, which will be presented in conjunction with the wider industry roadmap being developed by the National Composites Centre (NCC). Our links with the High Value Manufacturing Catapult continue to grow. We launched the third Technology Pull-Through (TPT) Programme in collaboration with the NCC in October 2018, to identify technologies at TRL3 with high potential for industrial application. Funding was awarded from NCC and HVM Catapult to exploit technologies to create demonstrators and to integrate them into industrial applications. As part of this initiative, successful projects are advertised to the NCC's members at monthly Research Committee meetings to provide a communication channel across the 'valley of death'.

Members of the Hub have also been successful in securing additional research funding, with the total value for leveraged grants now exceeding £15.0 million. Notably, this includes £6.9 million for an EPSRC Programme Grant led by the University of Southampton, involving the University of Bath, the University of Bristol and the University of Exeter. 'Reshaping the Testing Pyramid' aims to enhance the UK's international position in the aerospace industry by providing a route for lessening regulatory constraints for material certification.

Training the next generation of composite engineers is a vital part of the Hub. Postgraduate student numbers are up 82% since our last report and we have increased the number of postdoctoral researchers by almost 50% across the academic partners. This is partly thanks to our outreach activities and our links with the Industrial Doctorate Centre (IDC) in Composites Manufacturing at the University of Bristol. The IDC has seen the proportion of female researchers increase to 31%, a welcome trend that we continue to encourage. New projects have been initiated at Airbus, Qinetiq, Heraeus and the Offshore Renewable Energy Catapult, whilst the taught component of the programme continues to train our research engineers in the range of skills and knowledge required by the sector.

It's an exciting time and I hope you enjoy reading further about our highlights in composites manufacturing in this report. I would like to take this opportunity to extend my thanks to all those who are driving forward the Hub with dedication, hard work and vision. In particular, I would like to thank Prof Kevin Potter upon his retirement. He is without doubt one of the leading academics in composites manufacturing in the UK and we are grateful for his significant contributions to CIMComp and the Hub over the years. Kevin will be stepping down as the Deputy Director in May 2019 and will be handing over the reins to Prof Ole Thomson, who has been appointed as Kevin's replacement at the University of Bristol. Special thanks are also due to all our researchers, industrial collaborators and, in particular, the members of the Advisory Board. Moreover, we thank EPSRC for their continued support and sponsorship.

Professor Nick Warrior
Hub Director

Since the Hub's launch

28 CIMComp journal papers

120 Annual Open Day delegates

1 patent application filed

110 International Conference on Manufacturing of Advanced Composites (ICMAC) delegates

13 new Feasibility Studies awarded

7 new academic partners joined the Hub

£1m of leveraged institutional support for studentships

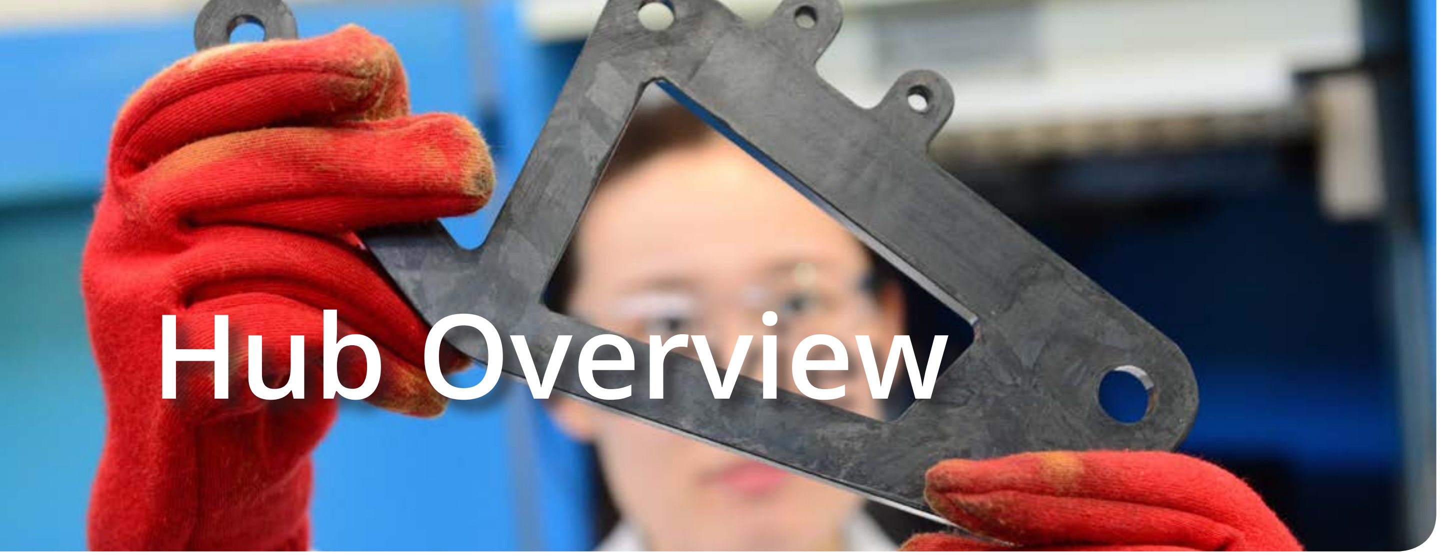
£2.2m of leveraged industrial support

£15m of additional leveraged grant income

+20 PhD students

+14 postdoctoral researchers

+16 project partners



Hub Overview

Hub Vision

The EPSRC Future Composites Manufacturing Research Hub was launched in January 2017 and is a £10.3m investment to expand the national research effort towards delivering a step change in the production of polymer matrix composites, and endeavouring to train the next generation of composite engineers.

The Hub aims to be the

> “national centre of excellence in fundamental research for composites manufacturing”

...building on the foundations of CIMComp, the previously funded EPSRC Centre for Innovative Manufacturing in Composites, which ran from 2011 to 2016.

This forms a key element in the UK’s composites manufacturing R&D strategy.

The Hub will drive the development of automated manufacturing technologies to deliver components and structures for demanding applications, having identified five research priority areas with our industry partners and the broader composites community:

1. High rate deposition and rapid processing technologies
2. Design for manufacture via validated simulation
3. Manufacturing for multifunctional composites and integrated structures
4. Inspection and in-process evaluation
5. Recycling and re-use

Over the seven year period, the Hub will underpin the growth potential of the composites sector, developing the underlying processing science and technology to enhance manufacturing robustness.

The Hub is led by the University of Nottingham and the University of Bristol and includes an additional 8 universities; Brunel University London, University of Cambridge, Cranfield University, the University of Edinburgh, University of Glasgow, Imperial Colleage London, the University of Manchester and the University of Southampton.

Hub Structure

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

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

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

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

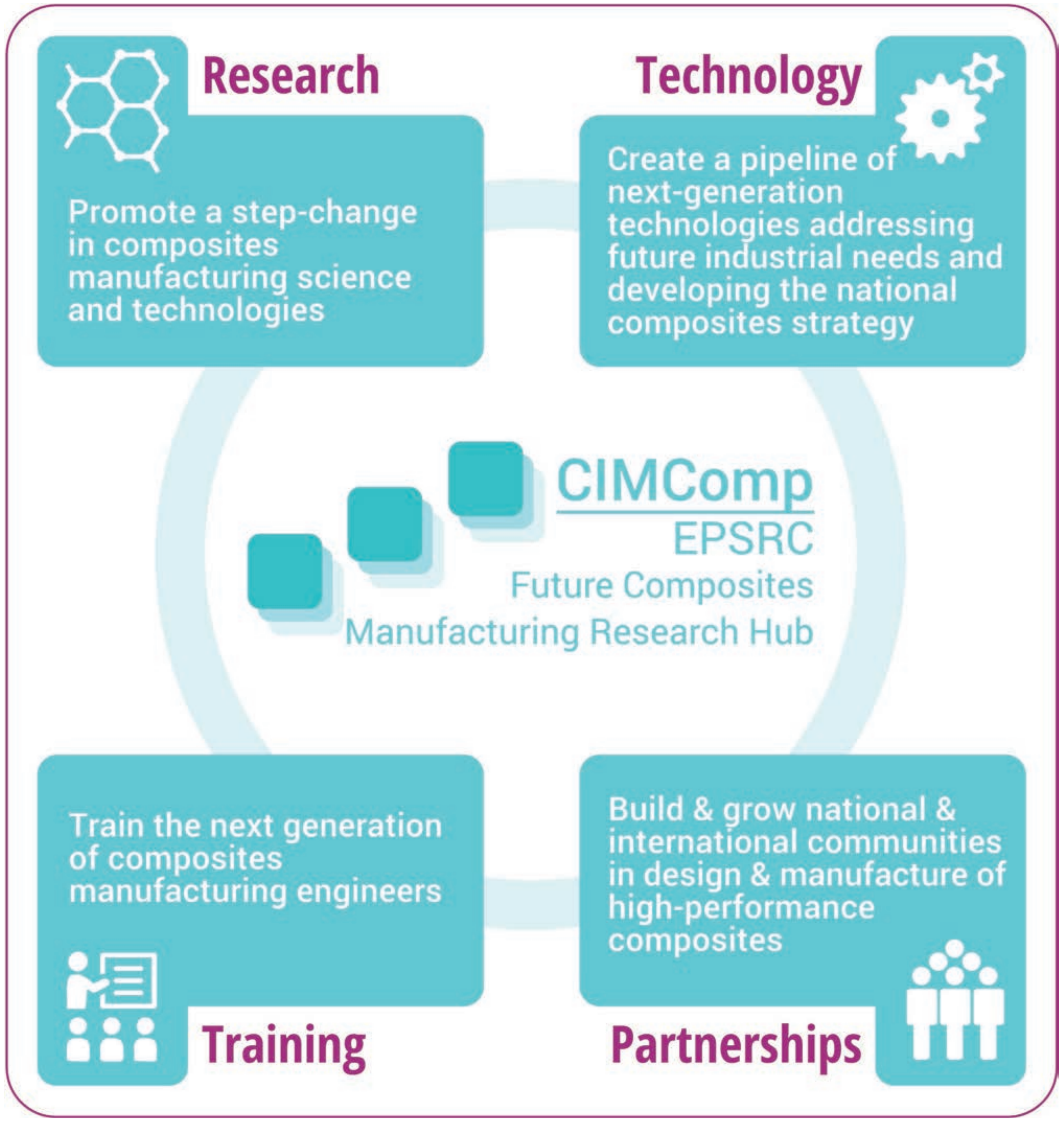
The **Postgraduate Development Committee** (PDC) oversees the training and progression of research students, at doctoral level via the **Industrial Doctorate Centre** (IDC) in Composites Manufacture and at postdoctoral level via the **Researcher Network**. The PDC also manages an international student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

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

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

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

Hub Objectives



Research

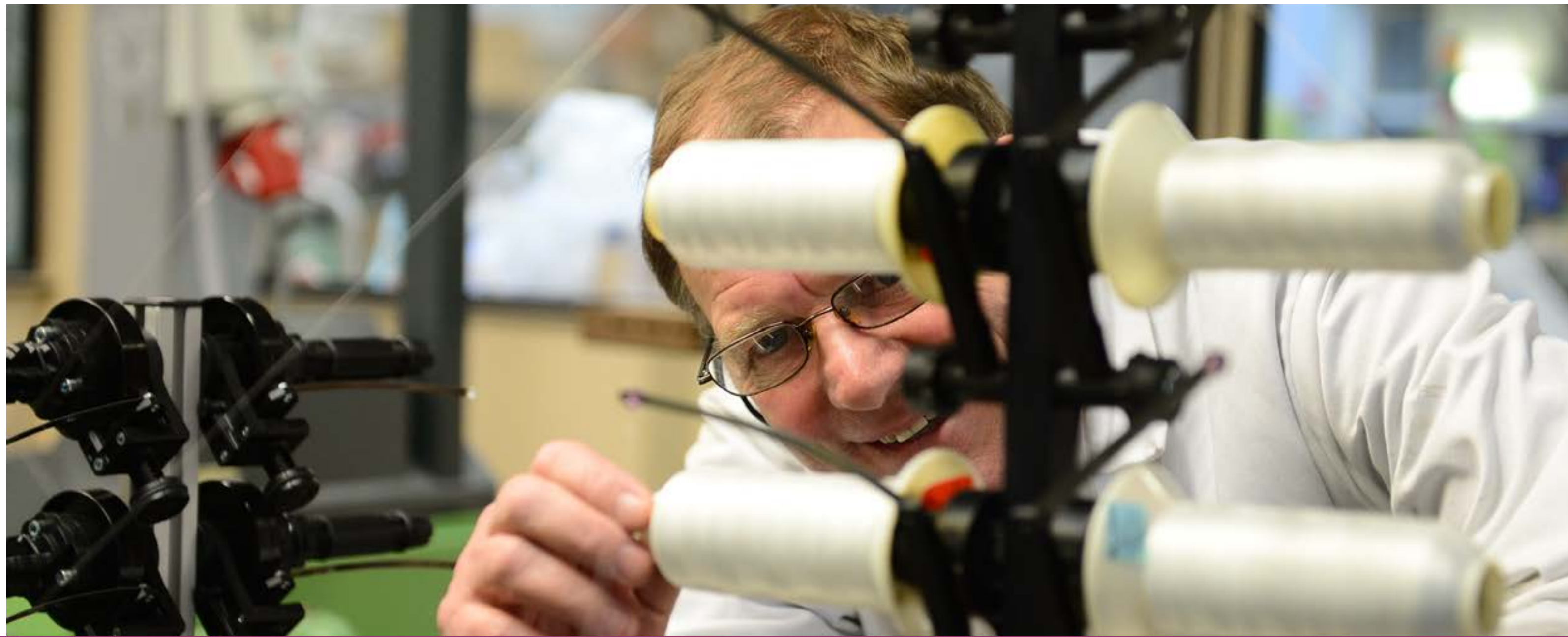
"Underpinned by expertise from across our consortium, including our dedicated Platform Fellows, our research priorities are addressed by a series of collaborative projects involving leaders from academia and industry."

All projects are expected to address the development of new manufacturing technologies, analytical studies to develop a fundamental understanding of state-of-the-art processes, or the development of process modelling and optimisation techniques. To mitigate against technical risk, each project starts with a short Feasibility Study which, if successful, can lead to a larger Core Project.

Feasibility Studies allow for flexible allocation of resources without over-committing to large projects with uncertain outcomes. These smaller projects therefore generate Hub growth by identifying promising areas of research for which more substantial resources can be committed. Feasibility Studies are the primary mechanism through which new academic partners can gain Spoke status within the Hub.

Core projects are typically a collaboration between two academic partners, and employ two postdoctoral researchers and four PhD students. The Hub provides funding for up to three years and industrial partners are invited to support the project by sponsoring postgraduate students affiliated to the project or offering in-kind contributions. Three Core Projects were launched at the start of the Hub in 2017, based on previous successful research funded through the CIMComp Centre.

The underpinning Platform Research ensures sharing of best practice amongst Hub partners and continuity between research projects. Outputs from our two Fellows, one at the University of Nottingham and one at the University of Bristol, are cross-feeding into the initial Core Projects and have informed the three Feasibility Study calls to date.



Core Projects

New manufacturing techniques for optimised fibre architectures

Start Date:	01/02/2017 End Date: 30/09/2020
PI(s):	Prof Andrew Long (University of Nottingham) and Prof Prasad Potluri (University of Manchester)
Co-I(s):	Dr Louise Brown (UoN)
Researchers:	Dr Mikhail Matveev (UoN), Dr Shankhachur Roy (UoM), Dr Vivek Koncherry (UoM)
PhD students:	Jinseong Park (UoM), Kazi Sowrov (UoM), Sarvesh Dhiman (UoM), Christos Kora (UoN)
Project partners:	Airbus, GKN Aerospace, M Wright & Sons, National Composites Centre, Advanced Manufacturing Research Centre, BAE Systems, ESI, Shape Machining, Hexcel, Sigmatex

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

Executive Summary

This project aims to discover new 3D textile preform architectures, using computational modelling or "virtual testing" to evaluate the utility of different textile designs within an optimisation framework. This framework will not be constrained to architectures that can be produced using existing manufacturing technologies, such as weaving or braiding.

Optimum textile preforms will be realised either by modifying existing textile processes or, where potential benefits justify, by developing entirely new, bespoke manufacturing technologies. This will result in a step change in performance, leading to significant weight reductions and lower cycle times through routine use of automated manufacturing technologies. A CIMComp feasibility study previously demonstrated that, for a specific application, a weight saving of at least 50% can be achieved by relaxing constraints on binder path and in-plane fibre orientations. Here we will further relax constraints on the fibre architecture, aiming to identify and manufacture a number of classes of improved material forms.

Aims and Objectives

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

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

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

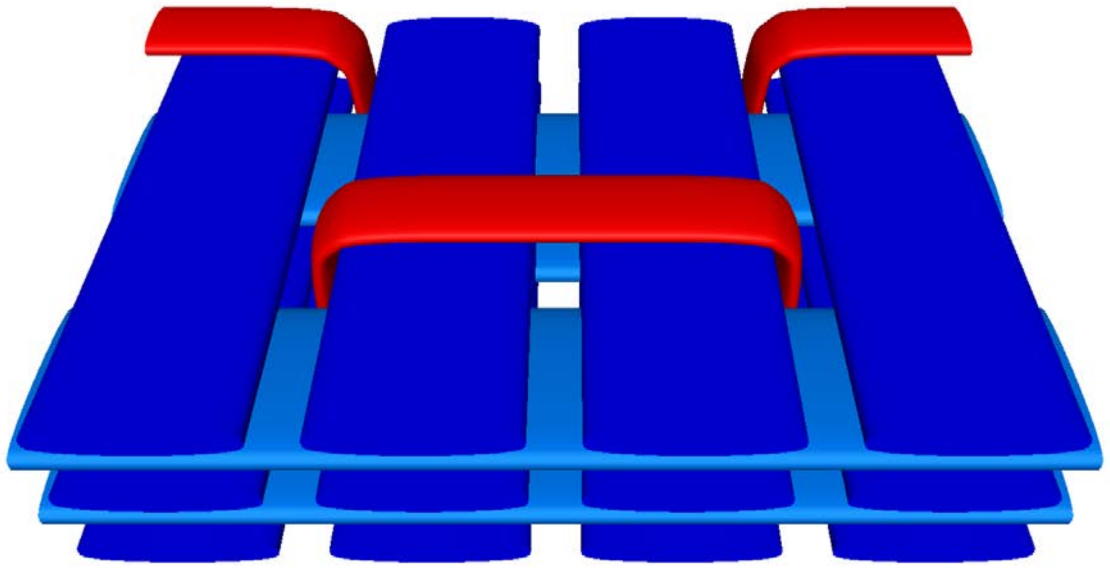


Figure 1a. Meso-scale model of an orthogonal 3D weave.

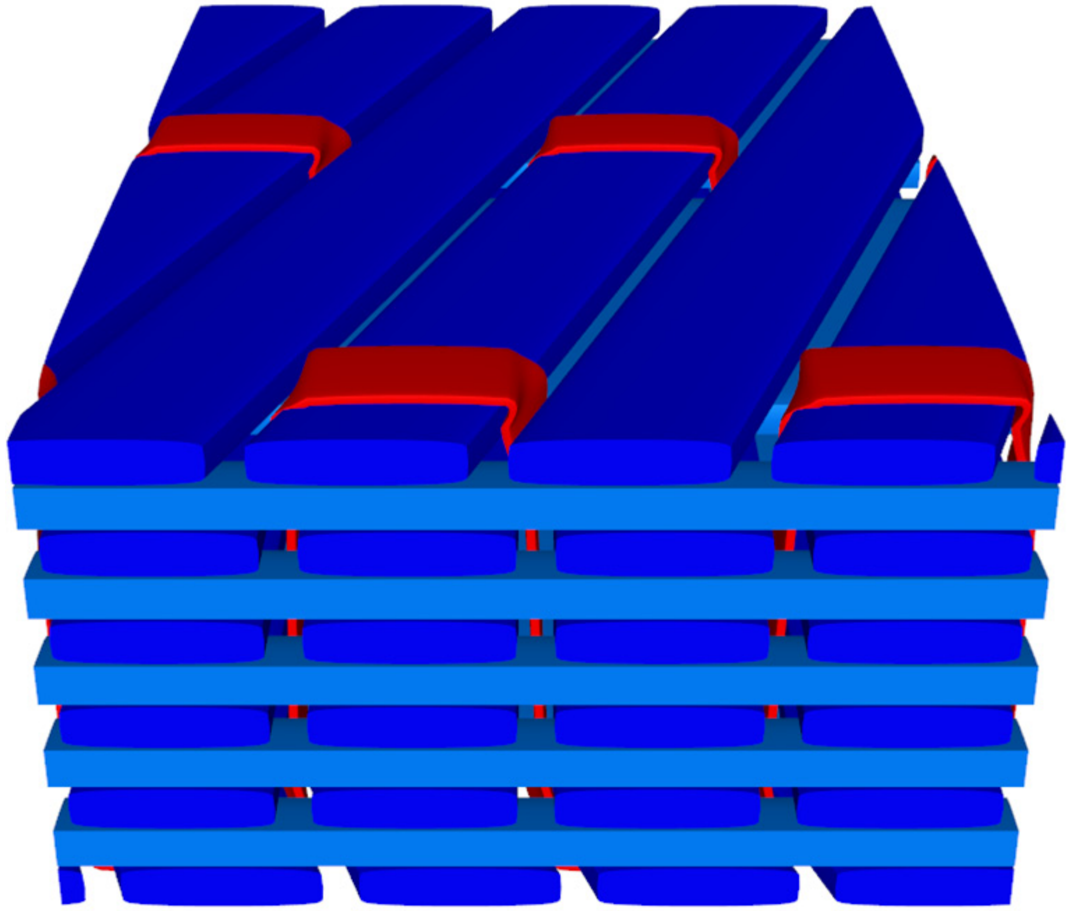


Figure 1b. Meso-scale model of a multiaxial 3D preform.

Progress to Date

The computational framework has been implemented for the development of new preforming technologies and the project is moving towards implementing this for some industrial case studies.

The framework implements a multi-scale approach for modelling composite structures, which ultimately reduces the entire structure down to a meso-scale representative volume element of the material. It creates parameterised meso-scale unit cells of the fibre reinforcements using TexGen, the University of Nottingham's textile pre-processor (Figure 1). Mechanical properties of the unit cells are calculated using Abaqus finite element solver. A new meshing algorithm has been implemented to improve the efficiency of this part of the framework. The meshing algorithm combines octree-based local refinement/coarsening of meshes and surface smoothing. The algorithm is embedded within TexGen and will be published as part of the open-source program.

The framework optimises the meso-scale geometry of fibre reinforcements according to the selected criteria, e.g. minimal weight, within selected constraints, e.g. component target stiffness. The design space (possible configuration of yarns/layers) for the optimisation of the meso-scale geometry is larger than that of conventional 3D textiles. In addition to changing the total number of layers, the spacing between yarns and the binder path, off-axis yarns and changes in fibre orientation are allowed to every layer of the optimise preform. A multi-objective genetic algorithm performs a search over the design space and selects the best solutions according to selected criteria.

One of the selected case studies is the optimisation of fibre reinforcement for a section of a vehicle floor pan, in collaboration with the Advanced Manufacturing Research Centre (AMRC). Two load cases, bending and torsion, are modelled in Abaqus using material properties calculated at the meso-scale. A multi-objective optimisation of the fibre reinforcement predicts multiple optimal solutions, as shown by the Pareto front in Figure 2. This highlights the relationship and trade-offs between the selected optimisation criteria and helps an end-user to select a solution according to the weighting of the requirements.

Novel manufacturing techniques are currently under development in order to validate the optimisation algorithms. A technique to place off-axis yarns for 3D preforms has been developed, initially for a flat preform (Figure 3) and subsequently for a tubular preform. The preforms made with this technique are not limited to having most of the layers in a particular direction like orthogonal 3D woven preforms.

Key Findings

- Computational framework for multi-objective optimisation of fibre reinforcements has been developed.
- The computational framework has been applied to an automotive demonstrator component.
- A novel meshing technique has been developed, which will be published as part of the Texgen open-source code.
- A novel multiaxial preforming concept has been demonstrated, which will be realised by developing new textile machinery based on these concepts.
- A novel preforming technique has been developed to manufacture flat and tubular multi-axial 3D fibre preforms.

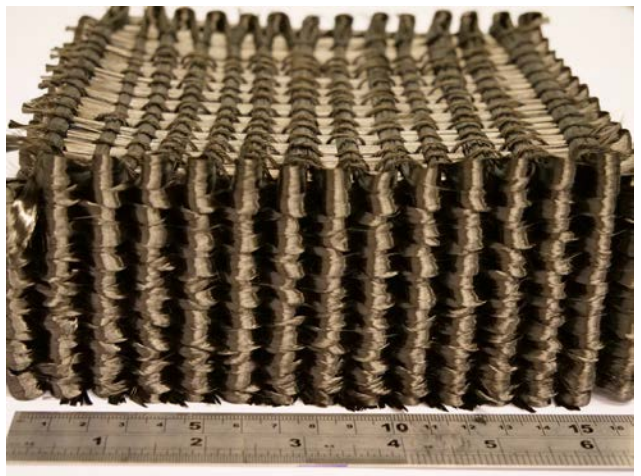


Figure 2. 65 mm thick 3D multiaxial orthogonal preform.

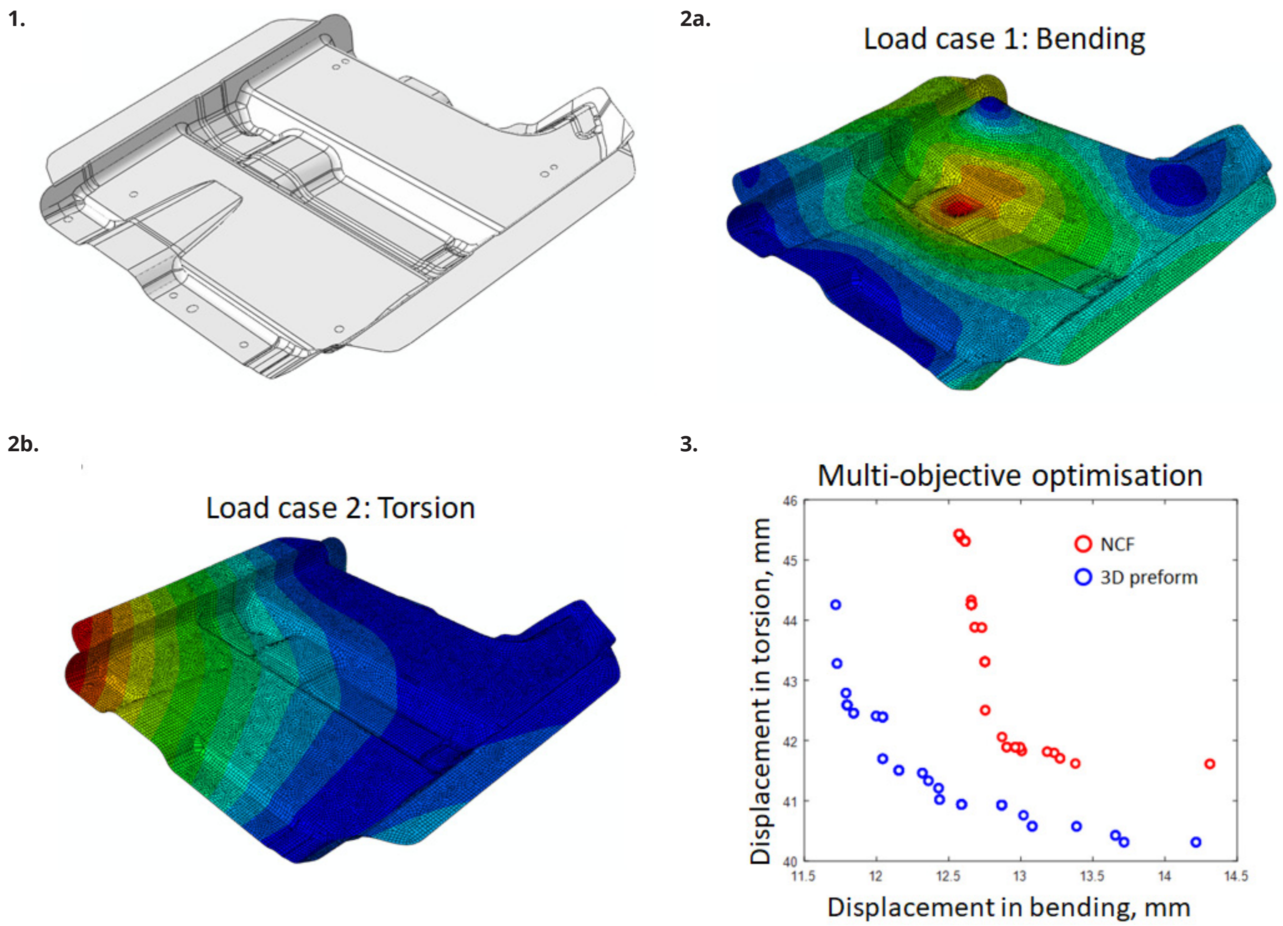


Figure 3. Optimisation of fibre reinforcement for a demonstrator: 1. The geometry of the component; 2. Evaluation of the component's performance in bending and torsion; 3. Pareto front of optimal solutions.

Core Projects

Manufacturing for structural applications of multifunctional composites

Start Date:	01/09/2017 End Date: 30/08/2020
PI(s):	Prof Emile Greenhalgh (Imperial College London) and Dr Dmitry Ivanov (University of Bristol)
Co-I(s):	Prof Ivana Partridge (UoB), Dr Carwyn Ward (UoB), Prof Milo Shaffer (ICL)
Researchers:	Dr Ian Gent (UoB), Dr Sang Nguyen (ICL)
PhD students:	Caroline O'Keeffe (UoB), Arjun Radhakrishnan (UoB), Bethany Russell (UoB), Mark Turk (UoB), Maria Valkova (ICL), Chanhui Lee; (ICL)
Project partners:	BAE Systems, Airbus UK, National Composites Centre, Hexcel, QinetiQ, Chomarat

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

Executive Summary

This core project investigates the design and manufacturing issues associated with multifunctional composites, with particular focus on structural supercapacitors. These multifunctional materials simultaneously store (and deliver) electrical energy whilst carrying mechanical loads. Such multifunctional materials offer a completely different approach to using composites in transport and mobile electronics, and have the potential to provide a step change in weight and volume driven designs.

The research to date has focussed on demonstration of the concept and addressing the scientific challenges associated with this novel class of materials, but within this project, the general design and manufacturing issues associated with structural power materials are being addressed. Such research is vital to facilitate adoption of these materials by industry, and is of general relevance to a wide range of potential multifunctional composite systems, which must harmonise conflicting requirements.

Aims and Objectives

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

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

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

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

Figure 1. PLA mask printed onto woven carbon fabric prior to carbon aerogel precursor infusion.

Figure 2. Prototype of a printed barrier successfully preventing infusion of the carbon aerogel precursor.

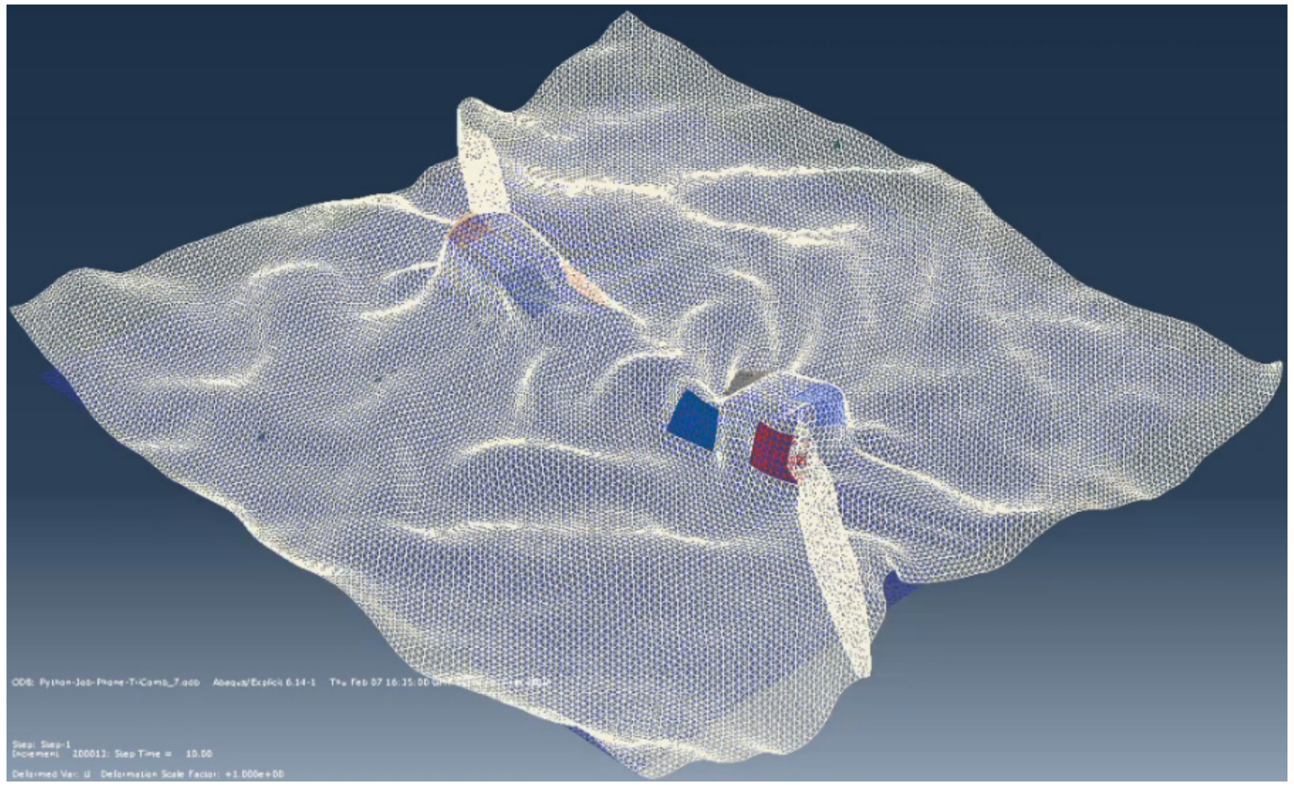


Figure 3. Simulation of forming over a complex component with integrated patches.

Progress to Date

- One specific focus over the past year was to develop a viable method to enable structural power composites to be manufactured with complex geometries.
- Currently, the rigid CAG reinforcement used to enhance both mechanical and electrochemical performance hinders formabililty over a tool.
- Overcoming this challenge paves the way for structural power composites to be used in a much greater range of applications than would otherwise be possible.

a) The project has been exploring new manufacturing approaches for creating a multi-material system combining various matrices, additives and sub-reinforcements in one integrated system. Efficient functionalisation of a structural composite can be achieved by a) incorporating matrices with added properties in continuously reinforced material, b) incorporating functional sub-reinforcements. Methods of combining composite matrices are not trivial and currently there exist no conventional industrial methods enabling manufacturing of multi-matrix composites with controlled boundaries between the domains. It has been shown that such composites can be created using innovative sequential infusion and imprinting domain boundaries. Efficient integration of functional reinforcement was realised using micro-braiding of yarns containing metal filaments and subsequently introducing them through tufting. Tailored matrix and reinforcement placement substantially expands the library of methods allowing to achieve high level of added properties, such as electrical and thermal conductivity, magnetic and induction susceptibility, etc. These properties enable sensing, new approaches to heating and curing, and repairability.

b) One of the fundamental challenges associated with structural supercapacitors is their formability. Carbon aerogel enabling energy storage is stiff and brittle and cannot be easily adapted to complex shape composites. Separating the domain of structural and functional materials paves the way to storing higher energy in complex shaped components. The newly tested approach showed the feasibility of creating islands of load bearing supercapacitors embedded into formable textiles. Subsequent infusion process allows to realise formable material containing multifunctional structural supercapacitors.

The project explored feasibility of new approaches to forming where precise introduction of imprinted elements, informed by numerical simulations, helps not only to place functional elements but also to mitigate against critical defects. It has been shown through simulations and manufacturing trials that placing stabilising elements in the critical location may help to redistribute fibre orientation and control deformation of the composite precursor. Patch placement allows simpler arrangements of the forming process and more sophisticated control of composite morphology. This approach is particularly relevant in the context of multi-domain composites where material costs are higher and hence, more attention needs to be paid to defect mitigation.

Key Findings

- The process for manufacturing carbon aerogel-reinforced structural power devices has been scaled up, enabling batch production of laminates to be made with a higher carbon aerogel content than had previously been achieved.
- Trials involving direct printing of polylactic acid to mask selected regions of dry carbon fabric prior to the carbon aerogel manufacturing process have demonstrated that we can create internal domains (see Figure 1 and 2).
- Electrochemical deposition has been used to coat active elements onto the carbon aerogel to further enhance the electrochemical performance. Preliminary studies have been performed to optimise the deposition conditions to achieve the maximum electrochemical performance.
- Two suitable separator materials: spread glass fabric and a non-woven ceramic reinforced polyester, have been selected and acquired. Small scale multifunctional devices using these separators have been made and tested electrochemically, demonstrating energy and power performance (1.4 Wh/kg and 1.1 kW/kg), exceeding the original aspirations.
- Conceptual designs have been developed for two structural supercapacitor aircraft door frames to demonstrate the capabilities to manufacture (a) curved components and (b) components having continuity of the load transfer between monofunctional and multifunctional zones.
- A finite element model of the multifunctional fabric-reinforced composites has been developed. The model realistically represents the internal architecture of the composite through consolidation process modelling (see Figure 3).
- Combined experimental and computational studies (see Figure 4) have demonstrated complex intra-yarn nesting of electrode and glass fabric plies to be a key microstructural feature of these composites, which arises during their consolidation. The increased nesting may enhance their delamination resistance as well as power density of these hybrid composites.

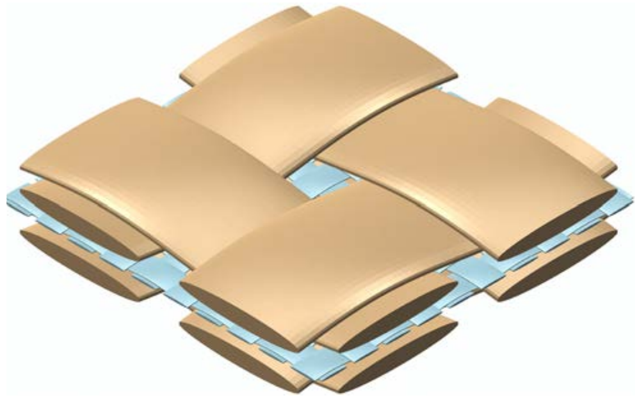
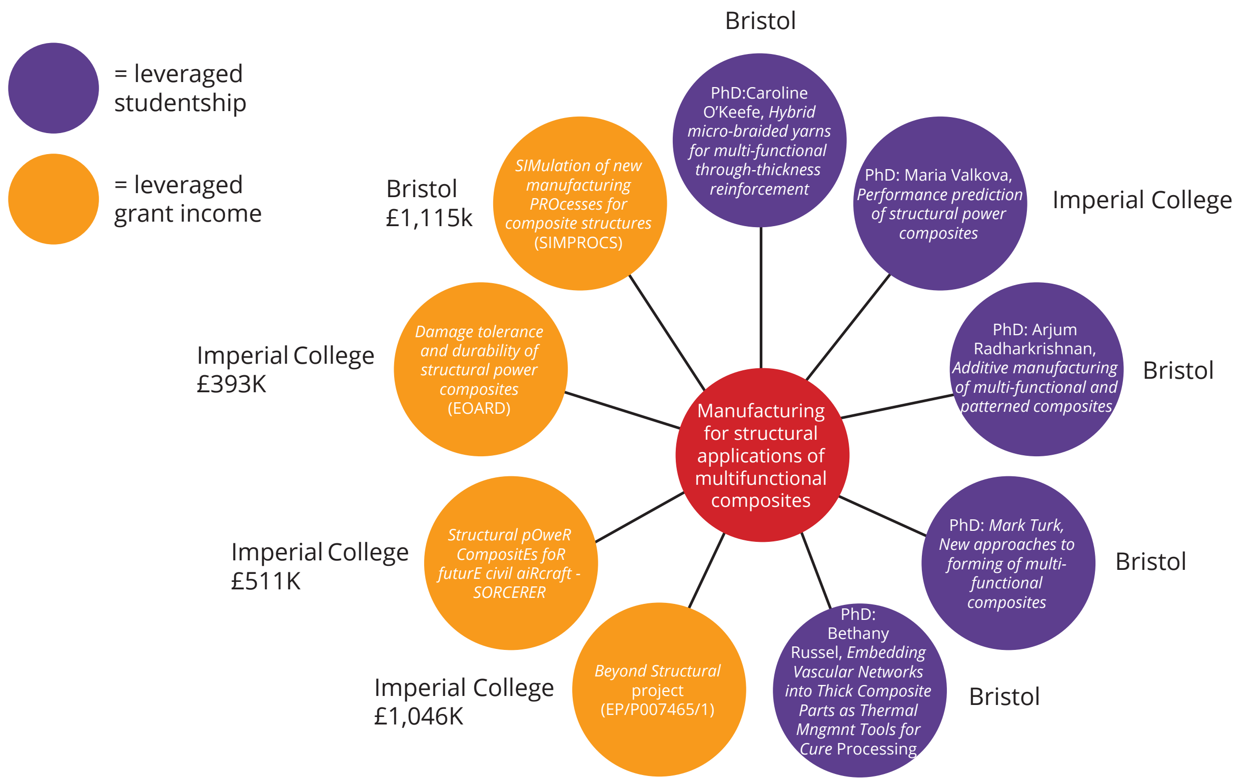


Figure 4. Idealised geometry of multifunctional composite reinforcement layup.



Core Projects

Technologies framework for automated dry fibre placement (ADFP)

Start Date:	01/04/2017 End Date: 31/03/2020
PI:	Dr Tom Turner, Associate Professor (University of Nottingham)
Co-I(s):	Dr Andreas Endruweit, Associate Professor (UoN)
Researchers:	Dr Anthony Evans (UoN), Dr Adam Joesbury (UoN)
PhD students:	Usman Shafique (UoN), Shimin Lu (UoN)
Project partners:	ESI, Coriolis, GKN Aerospace, AMRC, National Composites Centre, MTC, WMG, Airbus, Rolls-Royce, Hexcel, Composites Integration

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

Executive Summary

This core project investigates the rate and quality limiting factors concerned with the manufacturing of components via Automated Dry Fibre Placement (ADFP). It has been established that the fibre deposition rate is typically less than 1m/s for commercial systems, governed by dynamic limitations such as heavy deposition heads and physical limitations, such as low material adhesion.

However, robustness of the technology is also a primary issue, as machine downtime contributes to limiting production rates. There is the potential to build on other work in related fields as some of these factors are not exclusively limited to the ADFP process and are being addressed by automation and machine design within the manufacturing industry, including the drive towards Industry 4.0.

The project work packages have been developed to align with each stage of the manufacturing process.

These include 4 key areas:
1. Using simulation tools to establish the suitability of ADFP for specific components and to optimise processing parameters;
2. Studying the application of the binder to enable low cost tow-based fibres to be utilised;
3. Using high rate data acquisition to accompany closed-loop control to overcome machine and material variabilities;
4. Tailoring the permeability of ADFP materials, by taking advantage of different layup strategies using gaps and data collected during the deposition process.

Aims and Objectives

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

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

Progress to Date

- Manufactured laboratory scale 2D ADFP rig for high rate deposition process (up to 3m/s), with additional sensors to determine fibre position and force/torque.
- Identified a suitable heating method for fast response rates and high heating rates >1000°C/s. Resistance heating trials have been performed to create an initial temperature control, in addition to the creation of a Human-Machine Interface to transfer data between the IPC and server, and synchronisation between the motion and the temperature data.
- Online binder application trials have been conducted using inkjet printing to tailor binder 'patterns' for deposition of tow based material to reduce costs.
- The compaction response of stabilised slit tapes has been compared to that of carbon fibre tows.
- Compaction and thermal FEA simulations have been developed to capture the behaviour during the ADFP fibre deposition stage.
- The influence of inter-tow gaps on preform permeability has been studied using numerical models and experimentally measured values using preforms provided by the National Composites Centre. Large scale (>70mm) unit cells have been determined for macroscale infusion simulations implemented within PAM-RTM (ESI Group).

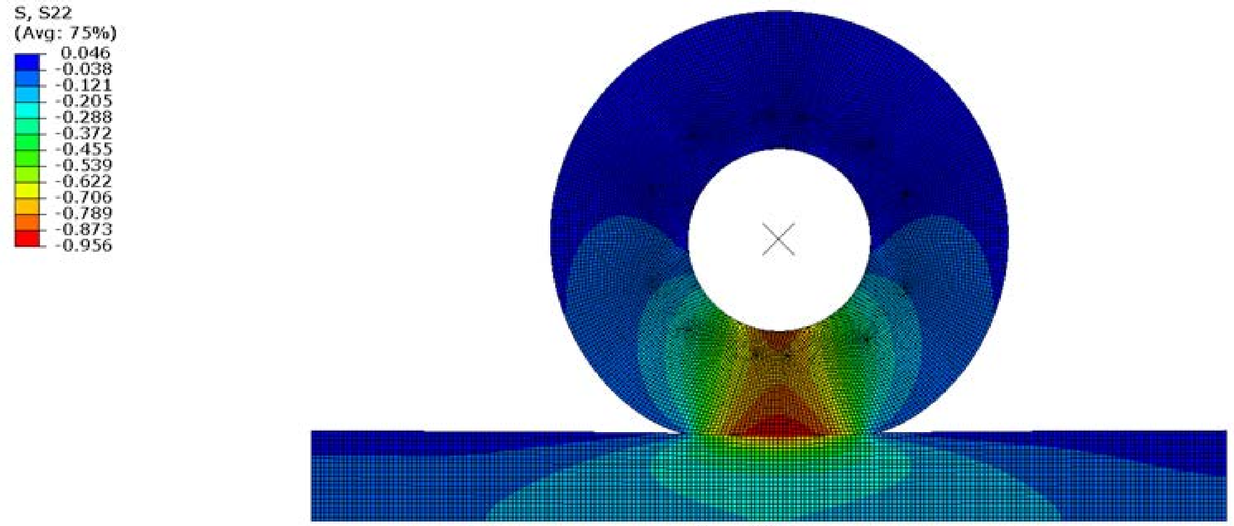


Figure 1. Finite Element simulation of compliant roller and compliant dry fibre bed. The output from this model is used to provide pressure distribution information for a multi-physics compaction / binder curing preform simulation which ultimately will be used to provide real-time control of the deposition head.

Key Findings

Previous development of the ADFP process has focussed on optimisation of materials to suit the existing deposition heads, this has resulted in a costly material which behaves much like a pre-impregnated slit fabric. This project attempts to rethink the process philosophy from first principles by developing deposition technologies which use materials in their lowest cost raw form. This has required the development of multi-physics models to describe the complex behaviour of the easily deformed materials.

Using a novel real-time control methodology the developed models are able to impact real-time operation of the developed sensor-rich ADFP test rig in order to create preforms with higher quality than existing methods and to build a digital twin of the preform to collect manufacturing data and inform downstream processes.

The developed test rig uses a post-processor-free approach where parts are manufactured direct from the CAD model of the part, this is facilitated by a new data format for storing ply / course data.

A novel method for determining the infusion characteristics of the manufactured preforms is also under development. The permeability of gapless preforms is very low and so the infusion process can be lengthy for complex parts. A detailed study is underway into the optimisation of gaps within the preform which serve to improve the permeability without compromising mechanical properties. In the longer term, computationally efficient models of actual as-deposited preforms will inform the infusion process on the shop floor.

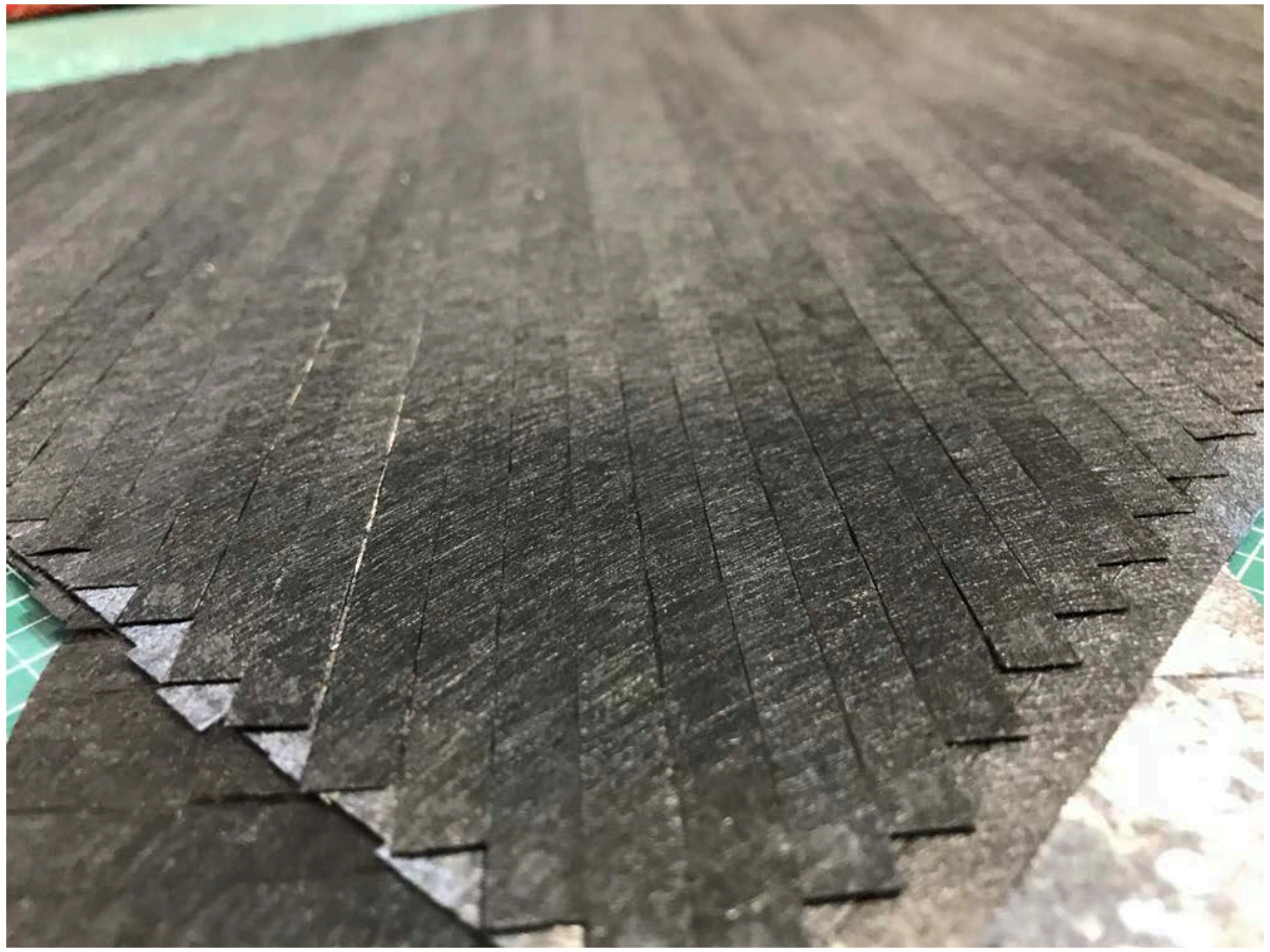


Figure 2. Dry fibre preform showing deposited tows, edge crenulations and evidence of gaps and overlaps. Permeability of the preforms is highly dependent on the gap size making an accurate representation of the as-manufactured fibre architecture important.

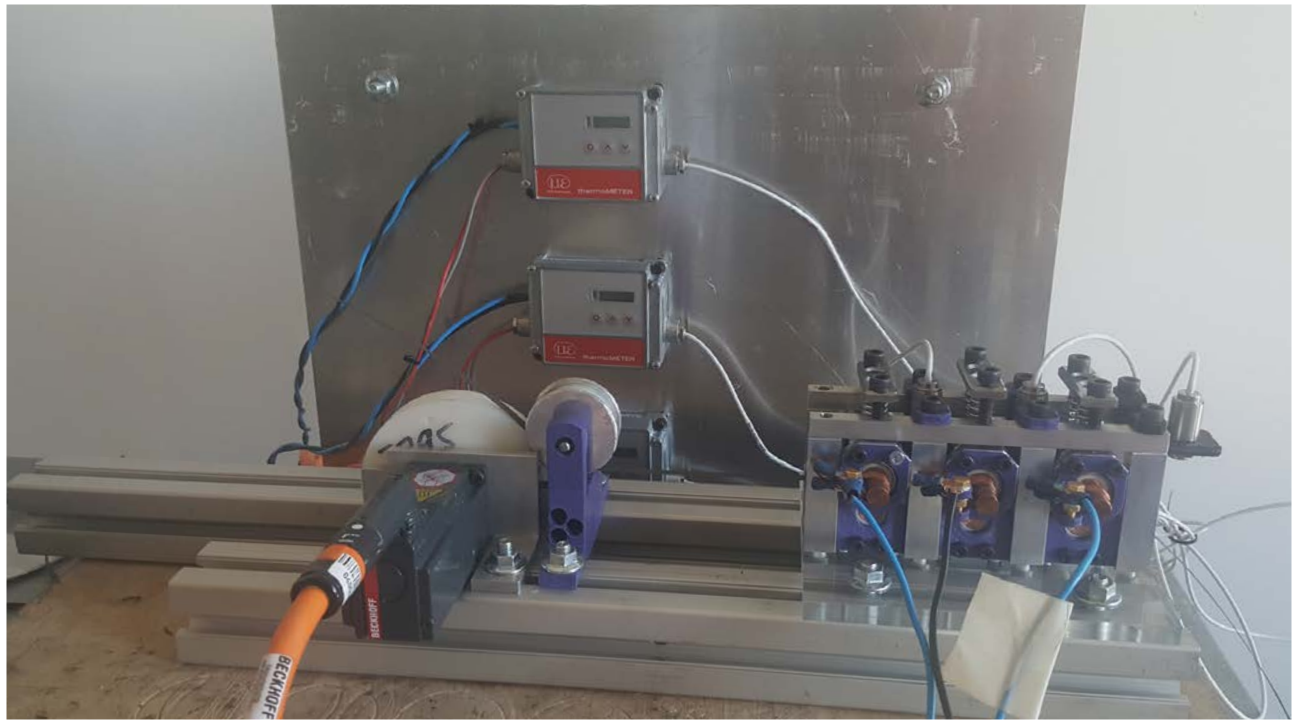
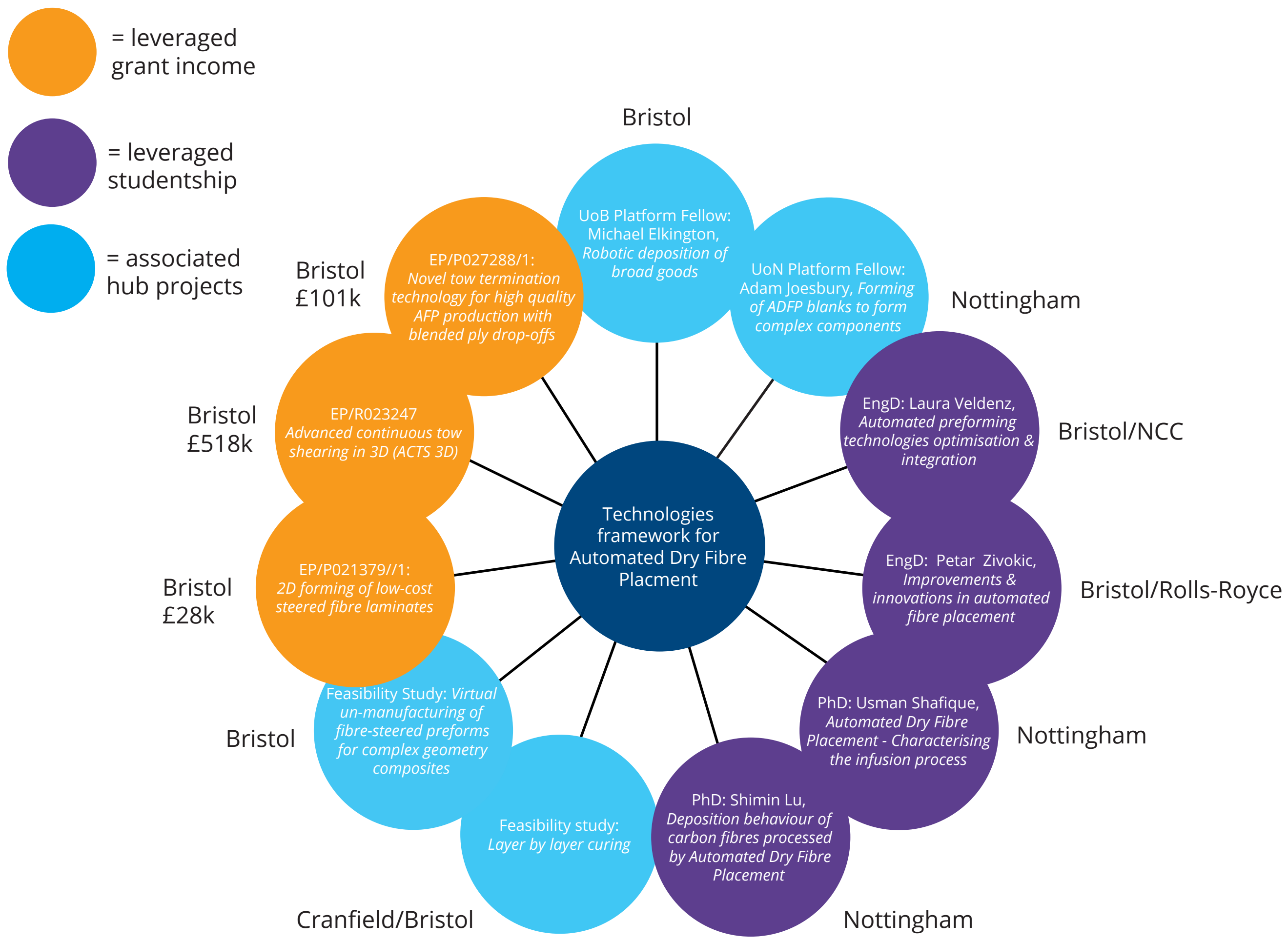


Figure 3. Test bench developed for resistance heating trials. Temperature data is gathered via IR thermocouples at 150ms intervals and used to control the power input to the tow in realtime accounting for environmental temperature and tow resistivity changes as well as dynamic nip-point temperature requirements.



Can a composite forming limit diagram be constructed?

Start Date:	22/01/2018 End Date: 21/07/2018
PI:	Prof Michael Sutcliffe (University of Cambridge)
Researchers:	Dr Jin Zhou (UoC)
PhD students:	Verner Viisainen (UoC)
Project partners:	Hexcel Leicester, Dassault Systèmes

"2D fabric reinforcements are typically formed at low pressures to create complex 3D preforms prior to the introduction of liquid resin during the moulding stage. The formation of defects during fabric draping affects the performance and quality of the final component."

Executive Summary

In 3D preforming, defects such as fabric wrinkling are typically measured qualitatively, but only at the end of the forming process, giving no understanding of the level of wrinkles formed or how they developed. The aim of this project was to demonstrate the feasibility of developing a forming limit diagram (FLD) for textile composites, similar to those used for sheet metal forming, to capture the limits imposed by defects such as macro-wrinkling, tow-level buckling and yarn sliding.

The feasibility study has demonstrated that an experimental set-up using digital image correlation is able to provide data to correlate wrinkling with fabric deformation. The strain measurements can be manipulated to find strains in critical directions, for example along the tows or in the direction of maximum compressive strain. For the NCF fabric considered, there does not appear to be a simple correlation between the observed strains and the onset of wrinkling.

While the experimental work provides the tools to explore wrinkle development (see Figure 1), meso-scale architecture-based FE modelling will be needed to guide a wrinkling criterion which can be used in conjunction with these measurements. A process-specific forming limit diagram, showing the range of shear strains and blank holder forces leading to wrinkling, has been drawn up from the measurements (see Figure 2). In conjunction with simplified FE modelling, this could be applied in principle to different forming situations, using FE modelling to predict the corresponding variations in shear strain in these processes. In summary the proposed hybrid approach, of using experimental characterisation in conjunction with a simple FE model, shows considerable promise as a way of defining the forming limits for composite fabrics. Further work is needed, particularly on extending the range of deformation processes and understanding the link between changes in tow architecture and wrinkling.

Key Findings/Notable Achievements

Objective 1. Use existing measurements of wrinkle formation in woven and NCF fabrics to develop a preliminary forming limit diagram;

The project has successfully developed measurement techniques in order to allow development of a preliminary forming limit diagram. Difficulties in identifying appropriate failure criteria highlight the need for a better micromechanical model of wrinkling to inform the forming limit diagram development. A process-specific forming limit diagram has been produced, which can form the basis for a proposed hybrid experimental/simulation approach to FLD development.

Objective 2. Extend the range of test configurations to explore the generality of the derived forming limit diagrams;

Only preliminary work has been done in this area, due to the challenges of developing the forming limit diagram. However the FE model has successfully been applied to other test configurations, albeit without validation.

Objective 3. Examine the feasibility of using a range of finite element calculations to interpolate and extrapolate the forming limit diagram from a limited set of tests;

This objective has not been met, with the focus of research remaining on the first objective.

Objective 4. Use the results to inform a full-scale proposal which will develop the concept of forming limit diagrams to include a wider range of materials and forming situations.

The feasibility study has successfully identified an experimental route to forming limit diagram measurements, highlighting deficiencies in our understanding of wrinkling which need to be tackled to develop the concept further. Hence this key objective, of informing a full-scale proposal, has been met.

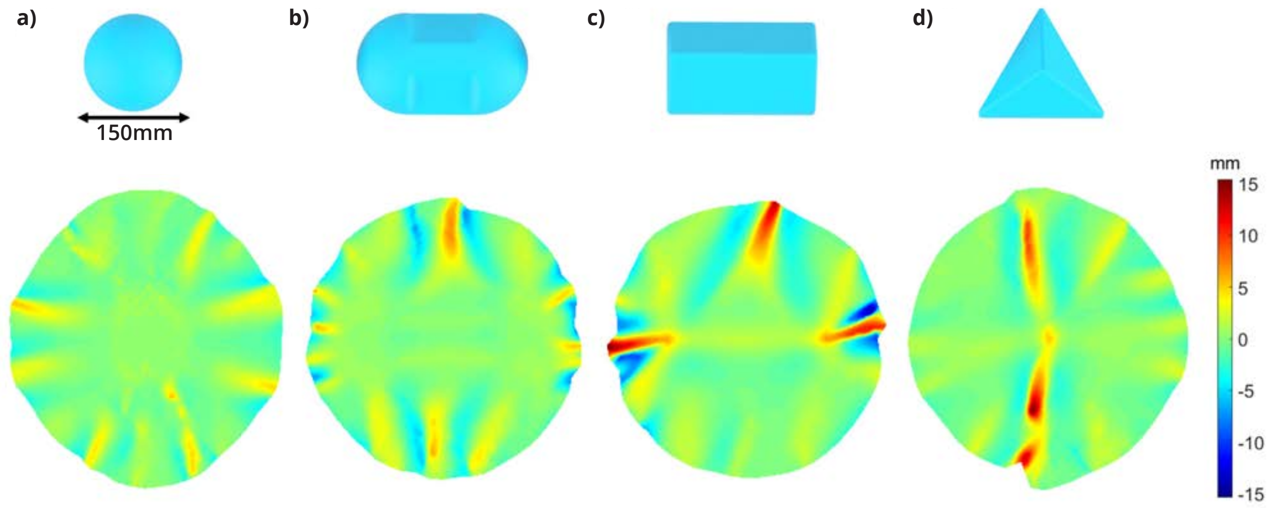


Figure 1. The punch forming geometry and associated wrinkling amplitude maps at the end of forming for four different test cases: a) hemisphere, b) double dome, c) triangular prism, d) tetrahedron.

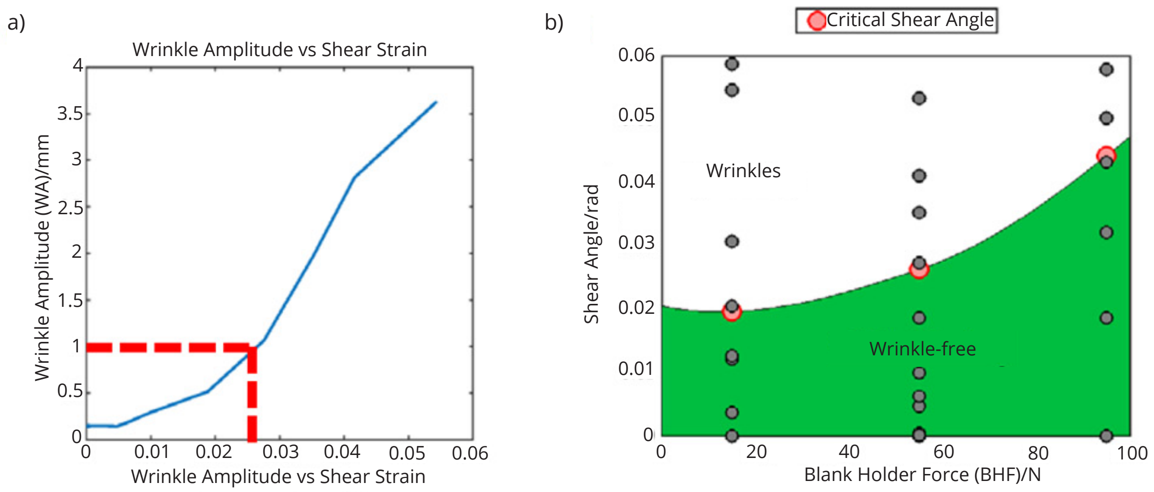


Figure 2. A process-specific forming limit diagram for a hemisphere: (a) Identification of critical shear angle at onset of wrinkling, (b) Combination of shear angle and blank holder force giving wrinkling.

Multi-step thermoforming of multi-cavity multi-axial advanced thermoplastic composite parts

Start Date: 02/04/2018 End Date: 01/10/2018

PI: Dr Phillip Harrison (University of Glasgow)

Co-I(s): Dr Euan McGookin (UoG), Dr Daniel Mulvihill (UoG)

Researchers: Brian McLellend (UoG), Aleksandar Angelov (UoG)

PhD student: Iain Campbell (UoG)

Project Partners: Institute of Science & Innovation in Mechanical & Industrial Engineering (INEGI), Porto, Induction Coil Solutions, Forrest Precision Engineering

"Rapid thermo-forming of advanced thermoplastic composite laminates is of particular interest to the automotive industry, but the problem of wrinkling in pre-consolidated multi-axial laminates remains a severe constraint, especially when considering moulds of high geometric complexity."

Executive Summary

Structural components designed to support multi-axial loads typically require fibres to be orientated in multiple directions. Rapid manufacture of these components using multi-axial thermoplastic sheets induces large relative displacements between adjacent plies during forming, creating large inter-ply shear stresses at the interfaces. The solution to mitigating wrinkling of multi-axial sheets proposed here is to reduce the mechanical coupling by using molten metal as a lubricant.

An experimental investigation has been conducted to explore the viability of using induction heating to facilitate the defect-free forming of multi-axial pre-consolidated advanced thermoplastic composites into complex multi-cavity geometries. The research focuses on the use of tin as a medium with which to both heat and lubricate the forming laminate. Initial tests demonstrate the viability of the fundamental ideas of the process. Induction heating is used to melt the tin sheet (See Figure 1), which in turn is shown to melt the matrix phase of carbon-nylon composite laminates when stacked in a hybrid composite/tin layup. Tests demonstrate that at least three sheets of tin can be simultaneously melted using an appropriate induction heating system. The design and manufacture of a novel low-cost reconfigurable multi-step forming tool demonstrates how the tin can also be squeezed out of the layup leaving very little residual metal in the consolidated composite. The multi-step tool is used both on its own to create flat consolidated laminates, and together with segmented tooling to rapidly manufacture a composite part with a multi-cavity geometry. In this investigation an axisymmetric geometry based on a sinusoidal generator spline (referred to as a "ripple") containing 3 cavities was used to demonstrate the technique.

The multi-step forming tool can be fitted into any press or universal test machine and be used with almost any component geometry. Due to time constraints and the large number of experimental parameters that influence the outcome of each experiment, a more rigorous parametric study is required to optimise the processing conditions. Nevertheless, given the challenges of the project, results so far have been very encouraging and no doubt could be significantly improved with further research and development. The efficiency of induction heating in relation to radiant heating and the ability to rapidly manufacture multi-axial, multi-cavity parts suggests that induction melt forming could become a viable method of manufacturing highly complex defect free advanced composite geometries in the future.

Key Findings/Notable Achievements

A multi-cavity, multi-axial carbon-nylon geometry was formed, which was free of forming induced defects such as wrinkling or de-cohesion of plies (See Figure 2). The forming operation starts in the centre of the component and works outwards towards the perimeter, minimising drag between the forming sheet and the mould tools. This method has been proven to generate the required pressure-driven squeeze flow to expel the molten tin from the laminate during forming and overcome the problem of defects associated with surface drag between the tool and the composite when forming complex geometries containing multiple cavities. Results also suggest that the tin interlayer successfully achieved the twin goals of both heating and lubricating the forming thermoplastic laminate.

Typically, in a combined radiant heater / shuttle system, the composite is heated in air to well-above the required composite forming temperature to account for transfer-related cooling. In contrast, the setup devised in this investigation eliminates the need for a shuttle system and reduces the associated polymer degradation due to a lower maximum processing temperature and the air-free environment experienced by the composite. The energy efficiency and speed of induction heating in comparison to radiant heating suggests that this new process could also be relatively cost-effective, but detailed cost modelling is required to fully understand this point. To summarise, induction melt-forming could offer a step-change in performance compared to existing advanced composite press-forming technology. Potential advantages include; improved surface quality and reduced wrinkling of the formed part, reduced polymer degradation, lower energy costs and faster production rates. The main obstacle in attaining these advantages lies in improving control and fundamental understanding of the process.

Figure 1. Initial tests using an induction heating coil to melt tin sheet.

Figure 2. A defect free formed multi-cavity, multi-axial carbon-nylon 'ripple' geometry. The part consists of a [0/90/90/0/45/-45]S layup. Tin expelled from the layup is evident around the perimeter of the formed part.

Layer by layer curing

Start Date:	20/11/2017 End Date: 01/06/2018
PI(s):	Dr Alex Skordos (Cranfield University), Dr James Kratz (University of Bristol)
Researchers:	Dr Lawrence Cook (CU), Dr Jonathan Belnoue (UoB), Dr Ric Sun (UoB), Dr Jinhu Chen (CU), Mehdi Asareh (CU)
PhD students:	Kostas Tifkitsis (CU)
Project partners:	Coriolis, Heraeus, Airbus, National Composites Centre

"Material placement, consolidation and curing have historically remained separate sequential steps for manufacturing large structures from thermosetting composites. Consequently there are significant challenges related to inherently low processing rates, high volumes of defects and limited process flexibility"

Executive Summary

This study investigates the feasibility of using Layer by Layer (LbL) curing to deliver a step-change improvement in the processing speed of large, high value structures (see Figure 1). This new strategy is applicable in process setups where whole layers are placed sequentially, or in variants such as AFP/ATL in which local placement is carried out. Numerical simulations of the LbL curing process have been conducted to achieve a compromise between inter-laminar properties and process efficiency, in addition to experimentally implementing the whole layer variant of the process to assess the quality of laminates produced.

The investigation was carried out using a highly exothermic prepreg system (Hexcel 913/glass). The cure and consolidation behaviour of the prepreg were characterised and captured in appropriate constitutive models and the coupled simulation was executed for scenarios of the whole layer and ATL variants of the process. The simulation was used to optimise the curing of a 40 mm thick laminate for both the LbL process and the conventional cure process, subject to the same temperature overshoot constraints. Results indicate that a component can be cured by the LbL process within approximately 1 h 20 min, in comparison to about 3 h for the optimised conventional process. This significant improvement is accomplished within the deposition stage of the material, therefore assuming the duration of the consolidation stage is similar to the curing stage means that the overall LbL process can be completed in less than one quarter of the duration of the conventional process. Furthermore, LbL curing offers suitable process flexibility to enable thick laminates (up to 40mm) to be cured with moderate or low temperature overshoots. The LbL process can exploit process time savings offered by eliminating the thermal mass (heat up/down) of tooling by processing at isothermal conditions. This is not possible during conventional curing of reactive thermosetting polymers at this level of thickness.

The process was implemented using a servo-hydraulic machine equipped with heated plates (see Figure 2). The setup produced specimens of 40 mm thickness (see Figure 3) with acceptable temperature overshoot in agreement with the simulation. Furthermore, the temperature distribution evolution measured during the process and the thickness of the consolidated part matched those predicted by the simulation, proving the validity of the modelling analysis and optimisation results. The quality of the LbL laminates was investigated using microscopy and was found to be adequate with low levels of porosity similar to conventional processing. The mechanical performance of materials produced using the LbL route was compared with that of conventional laminates. Inter-laminar shear strength (ILSS) and mode I fracture toughness of laminates produced using LbL curing matched those of conventional laminates.

Overall the feasibility study delivered a 75% reduction in process time without degrading product quality, achieving equivalent inter-laminar properties and porosity levels.

Key Findings/Notable Achievements

This work has demonstrated that it is possible to manufacture composite laminates by placing and partially curing sub-laminates sequentially in an additive manner. This allows the manufacturing of thick structures to be carried out significantly faster compared to current processes.

The main challenge addressed was to find an optimal compromise between accelerating the process and preserving the adherence of adjacent layers. This was achieved through a LbL curing study, by the development and application of a dedicated simulation methodology for the process and the characterisation of interfacial behaviour as a function of processing parameters. This was demonstrated at the laboratory level through process trials.

The main outcomes of the project are:

- Simulation and experimental demonstration showed that the new LbL process proposed is feasible.
- Manufacturing of thick and ultra-thick laminates can be carried out at a fraction of the time required in conventional processing, with the cure stage accelerated by 50% and the overall process accelerated by ~75%.
- The LbL process allows sufficient compaction and removal of porosity.
- The degree of pre-cure in a sub-laminate after its placement and consolidation can be adjusted to a level around the gelation degree of cure of the matrix to achieve inter-laminar properties equivalent to those of standard laminates.
- The new concept can operate in currently inaccessible regions of the processing landscape in terms of thickness, cure time and temperature overshoot. Its capability for fast curing and to merging the consolidation/cure stages can find uses in the context of AFP and ATL.

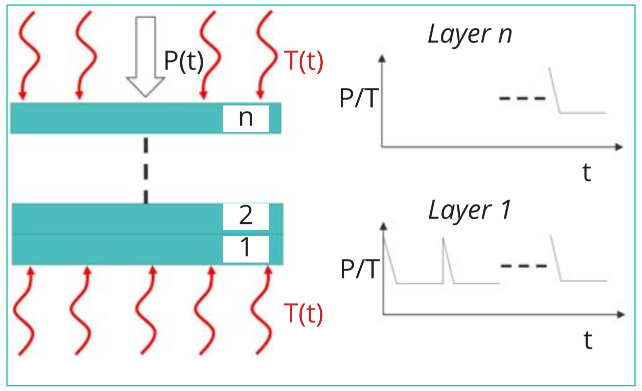


Figure 1. Layer by layer process concept.

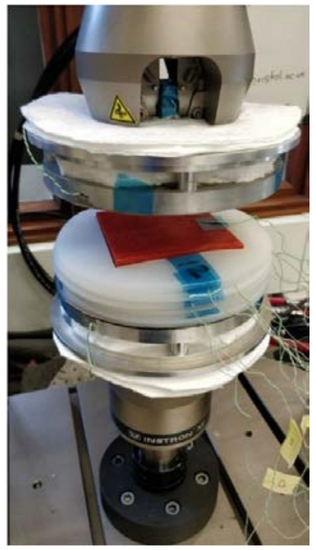


Figure 2. Servo-hydraulic testing frame equipped with heated plates to conduct LbL laboratory trials.

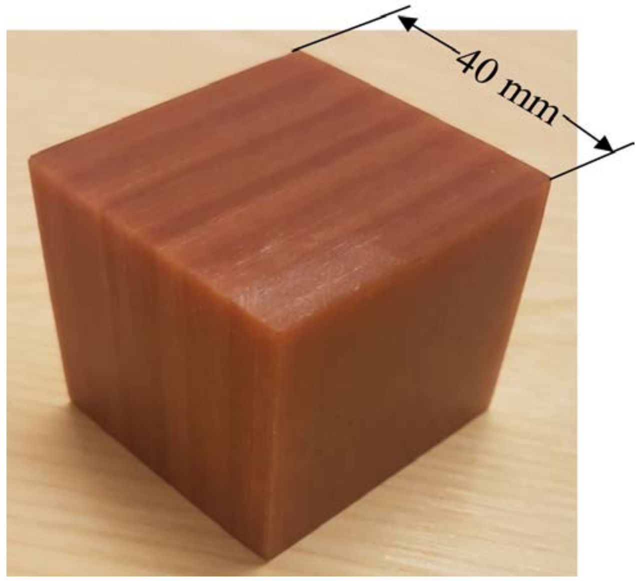


Figure 3. Ultra-thick laminate produced using the layer by layer process.

Simulation of forming 3D curved sandwich panel

Start Date:	01/01/2018 End Date: 30/06/2018
PI:	Dr Shuai Chen (University of Nottingham)
Co-I(s):	Dr Lee Harper (UoN), Prof Nick Warrior (UoN)
Project Partners:	Gordon Murray Design

"Composite sandwich panels offer considerably higher bending stiffness than a monolithic panel of similar mass. It is challenging to produce complex geometries without extensive machining of the core, which is expensive and generates significant material wastage."

Executive Summary

Composite sandwich forming is an affordable, high volume process developed to manufacture 3D panels with complex curvatures and varying thickness, using flat feedstock. The core material is deformed by a combination of bending, shearing and local crushing using matched tooling, avoiding the need to CNC machine the core prior to forming. A simulation tool has been developed to predict the forming behaviour of complex composite sandwich panels, to assist process development and component design. This study fits within the Hub's "High rate deposition and rapid processing technologies" and "Design for manufacture via validated simulation" priority areas.

An existing fabric forming model has been extended to incorporate the forming behaviour of the core into a process simulation for sandwich panels. The compressive, tensile, shear and friction behaviour of the core was characterised using standard test methods, to provide input data for the numerical model and to improve the fundamental understanding of the material behaviour during forming. A multi-scale modelling scheme was used where meso-scale and macro-scale models were correlated to provide a balance between simulation accuracy and computational efficiency. Results from the meso-scale indicate that, the formability of the core for components with complex curvature is mainly derived from in-plane deformation, while the through-thickness core crushing provides the formability for variable thickness. A macro-scale model was developed to predict the homogenised forming behaviour. Mechanical field variables, such as nominal strains were adopted as defect indices based on observations taken from the meso-scale simulations.

Overall the feasibility study delivered a 75% reduction in process time without degrading product quality, achieving equivalent inter-laminar properties and porosity levels.

Key Findings/Notable Achievements

The successful delivery of this project has demonstrated the feasibility of forming curved panels directly from 2D feedstock. As shown in Figure 1, the cell walls of the honeycomb core buckle or fold around the compression surface providing the formability of variable thickness, which has a negligible effect on the core material outside the punch area. Crushing starts at the top of the specimen in contact with the punch surface and propagates through the thickness towards the base of the specimen. Minimal crushing can be observed at the bottom surface of the specimen. The simulation results are in good agreement with the deformation modes exhibited by experimental specimens.

The FE model has been employed to simulate the forming process for a generic demonstrator part, which highlights one of the critical defects commonly observed in the experimental components (see Figure 2). Whilst no out-of-plane wrinkling occurs in either of the skins, cross-sections taken from the formed component indicate resin rich regions in the thickest region of the core. During forming, the fabric skins become trapped due to high frictional forces, causing the fabric to bridge the concave regions of the tool. The high in-plane tensile forces in the fabric cause the core to locally crush, creating channels along the edges of the geometry, resulting in resin-rich areas during moulding.

The developed simulation tool will reassure designers that defect-free components can be made using this process, before tooling is cut. The simulation can also be used to optimise the forming process, including initial blank shape, to avoid unnecessary material wastage.

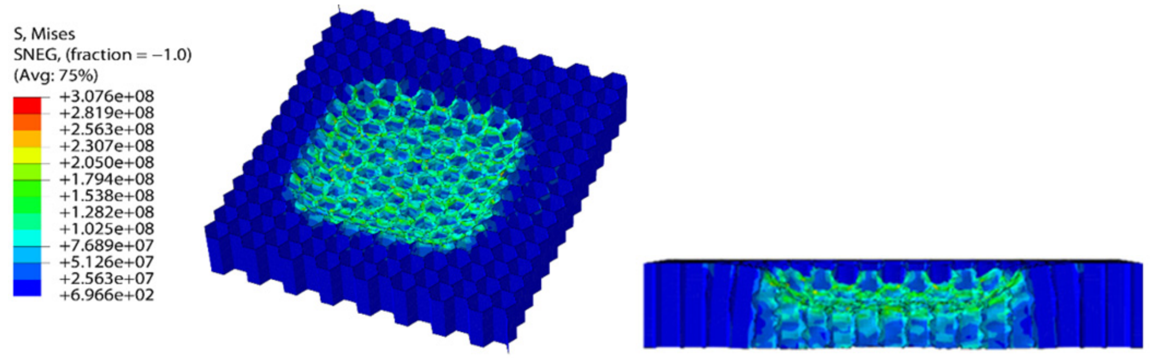


Figure 1. Simulation of the core crushing mechanism to produce different local thicknesses (von Mises stress, scale in Pa).

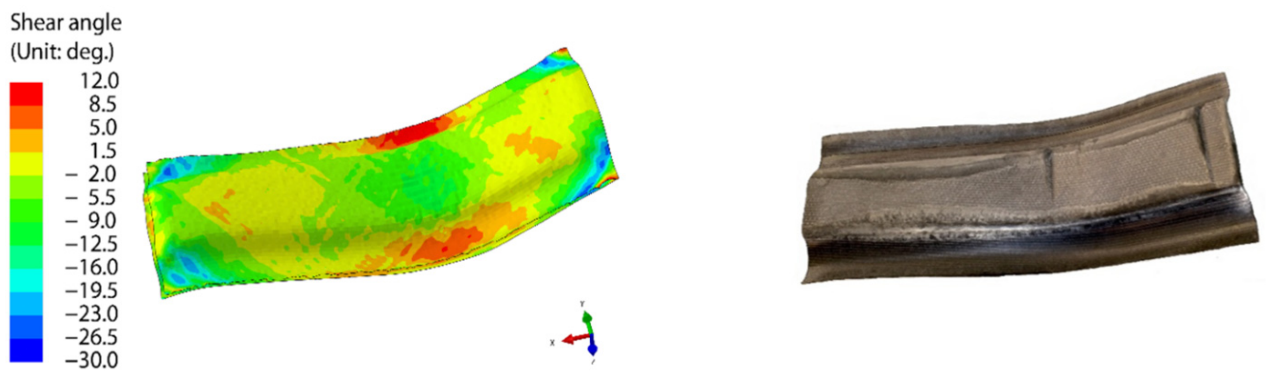


Figure 2: Sandwich panel forming behaviour from simulation and experiment for a demonstrator component.

Manufacturing thermoplastic fibre metal laminates by the *in situ* polymerisation route

Start Date:	15/10/2017 End Date: 14/04/2018
PI:	Dr Dipa Roy (University of Edinburgh)
Co-I(s):	Prof Conchur O Bradaigh (UoE), Prof Vasileios Koutsos (UoE)
Researchers:	Dr Dimitrios Mamalis (UoE)
PhD students:	Wini Obande (UoE)
Project partners:	FAR-UK, Arkema, Eirecomposites

"Primary structures within the aerospace sector require materials which combine high strength, high stiffness, low density, toughness and fatigue resistance. Fibre reinforced composites satisfy almost all these demands, but offer limited fracture toughness due to the brittleness of the fibres and matrix."

Executive Summary

Integrating thin metal sheets and fibre-reinforced materials to create Fibre Metal hybrid Laminates (FMLs), combines the superior specific properties of composites with the ductility of a metal phase, offering unique mechanical properties. Thermoplastic FMLs exhibit higher inter-laminar fracture toughness compared to thermosets, and provide potential routes for repair and material recycling. However, processing thermoplastic FMLs to produce large structures is challenging due to the high pressure and temperature requirements, which can lead to high residual stresses and delamination at the polymer/metal interface due to the mismatch in CTE.

In this investigation, Elium®, an infusible liquid thermoplastic (TP) resin, glass fibre reinforcements and metal sheets (Al 6082-T6) were used to fabricate low-cost FMLs at room temperature. Different surface treatments were explored to enhance the interfacial bonding between the metal and the thermoplastic composite (TPC), which plays a vital role in the performance of the FML.

The objectives were to:

- Prepare the surface of the metal sheets with suitable chemical or physical treatments to achieve an acceptable level of interfacial bonding with the TPC.
- Manufacture FMLs using the vacuum assisted resin infusion route.
- Investigate the mechanical properties of the FMLs in comparison to an equivalent Elium® based reference laminate (FRP) with no metal interlayer.

Key Findings/Notable Achievements

- Suitable surface treatment conditions were identified for the Al alloy sheets (10% NaOH treatment for 20 min, atmospheric plasma treatment with 2 mm/s scan speed, 1 scan and source (nozzle)-to-substrate distance 0.5 mm).
- VARTM manufacturing of the TPC-FMLs was successfully carried out using Elium® liquid thermoplastic resin.
- Test samples were successfully extracted from the TPC-FMLs for mechanical testing without any debonding at the TPC-metal interface.
- Reference FRP and TPC-FMLs were characterised for their flexural and interlaminar shear strength properties. The measured properties were comparable to published values.
- Mode-I Interlaminar fracture toughness of the thermoplastic FML (Elium® resin/glass fibre and alkali treated metal interlayer) was found to be (~170%) higher than the reported value of epoxy based thermoset FMLs.

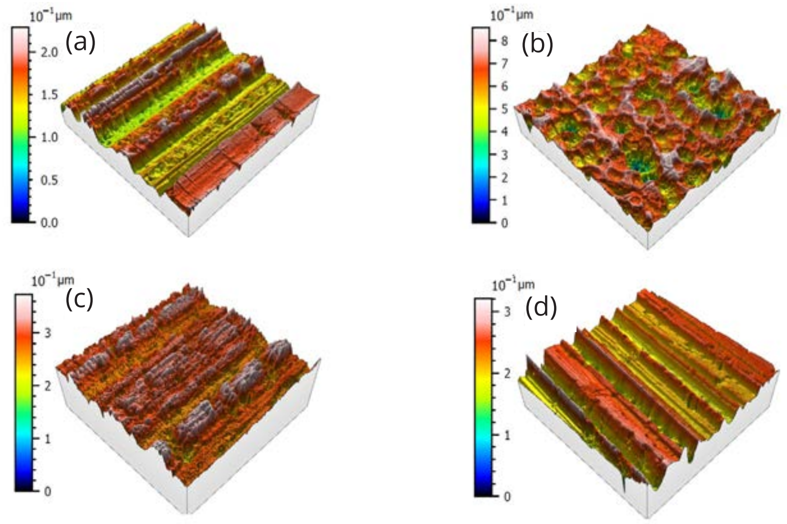


Figure 1. Surface topography images of the (a) degreased-only Al alloy samples, (b) after alkaline etching for 20 min, (c) after acid treatment for 20 min, and (d) after plasma exposure.

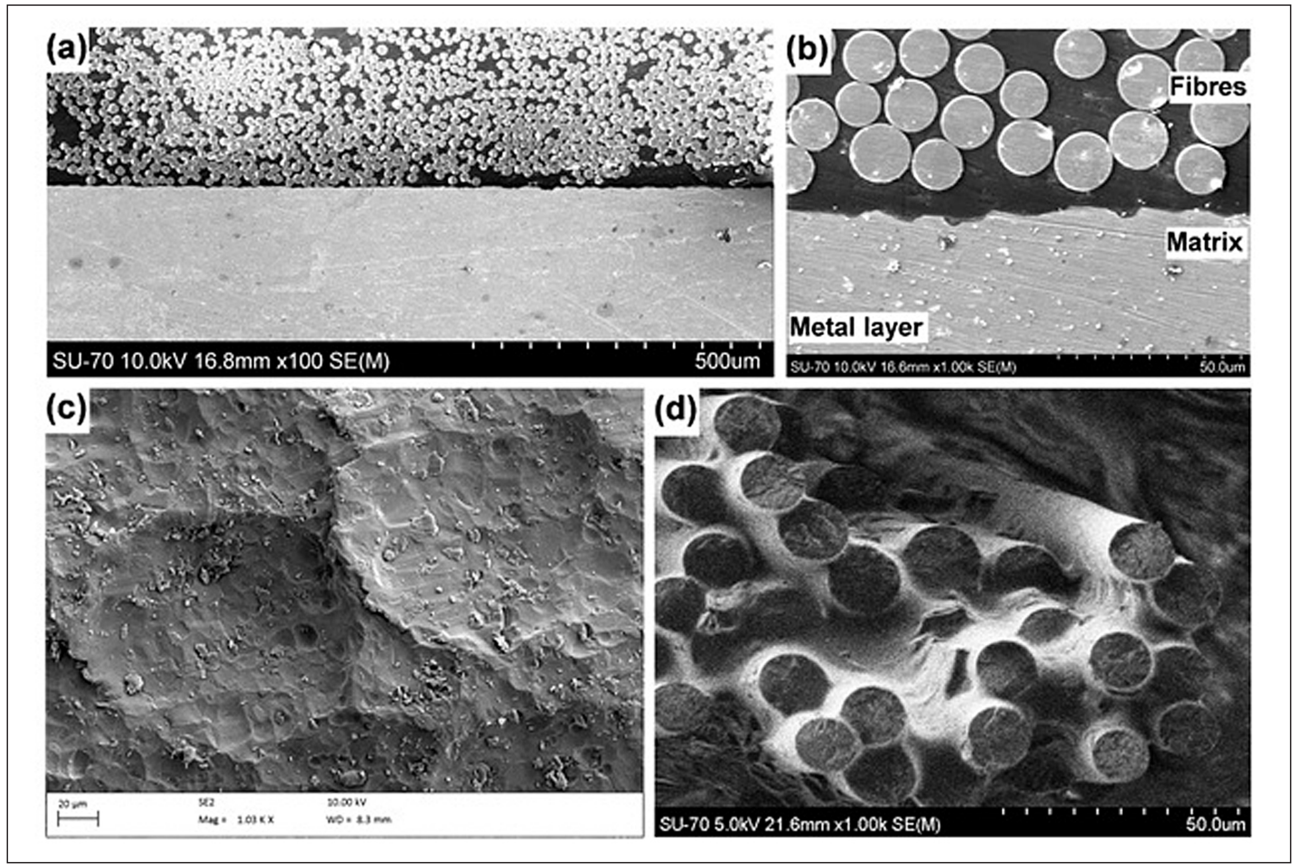


Figure 2. (a) Low and (b) high magnification SEM micrographs taken at the composite/Al alloy interface. (c) Debonded Al alloy surface after flexural testing. (d) Flexural/fractured surface of the GF-Elium® under bending mode.

Feasibility Studies

Active control of the RTM process under uncertainty using fast algorithms

Start Date:	01/02/18 End Date: 30/09/18
PI:	Prof Michael Tretyakov (University of Nottingham)
Co-I(s):	Prof Andy Long (UoN), Dr Marco Iglesias (UoN)
Researchers:	Dr Mikhail Matveev (UoN), Dr Andreas Endruweit (UoN)
Project partners:	ESI Group, LMAT, National Composites Centre

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

Executive Summary

Occurrence of voids and deviations from the designed mould filling time and flow pattern are caused by stochastic variability in the material and process parameters, which cannot be realistically fully eliminated. Active Control Systems (ACSs) have been successfully implemented in other manufacturing fields, such as injection moulding, to deliver repeatable products. However, they have not reached sufficient maturity to be widely used in composites manufacturing, due to the complexity and variability of the RTM process.

This study investigated the feasibility of using novel mathematical and numerical techniques to quantify uncertainty in an ACS, where a very fast response was required. The aim was to develop a system to exploit the information collected during RTM mould filling to estimate the distribution of permeability online and perform predictions of the mould filling time and dry spot formation. This novel system not only accounted for uncertainties in the simulation, it also aimed to reduce them by means of Bayesian Inversion.

The project achieved its original objectives to:

- Develop and test a Bayesian Inversion Algorithm to estimate local permeability and porosity (defects) in fibre preforms.
- Estimate mould filling time in real time using information about defects.
- Implement ACS to control RTM mould filling.

Key Findings/Notable Achievements

A novel Bayesian Inversion algorithm (BIA) was implemented to estimate local permeability and porosity of a preform using in-process information. The approach was validated using virtual and laboratory experiments, where the in-process information (pressure at a limited number of locations and front positions) was collected during mould filling. Ansys Fluent© was used to simulate the RTM process and the BIA was implemented in MatLab©. There was generally good agreement between the experimental data and the simulations when incorporating controlled defects in the preform to simulate the effect of mould filling. This study confirmed that it is feasible to recover the locations and shapes of defects using the BIA approach (see Figure 1), which consequently can become an integral part of a non-destructive evaluation (NDE) for composites.

The Active Control System was implemented at the laboratory scale using an RTM tool equipped with pressure transducers, flow front sensors and controllable pressure gates, (See Figure 2). The experiments demonstrated that the ACS is feasible in this setup, providing adequate control over mould filling.

It was assumed that the flow front propagation over a small distance can be described by a pseudo-1D model, enabling a very fast pseudo-1D BIA to be used to estimate the local permeability and porosity in real time. New injection pressure values at the resin inlets were computed to ensure the flow front matched the reference flow front at the next observation time. The project demonstrated that it is feasible to use an ACS based on the BIA to ensure repeatable RTM production cycles.

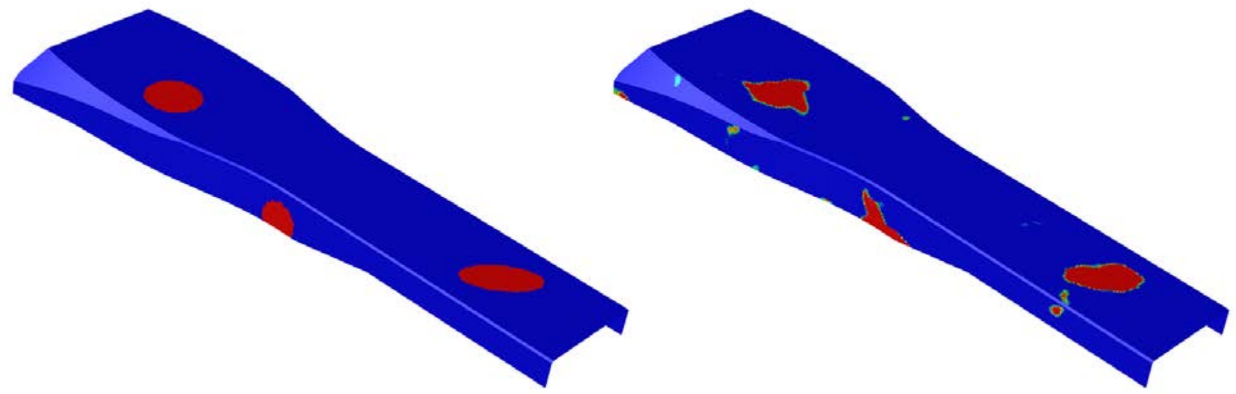


Figure 1. Restoring permeability and porosity in 3D virtual experiments. The Bayesian Inversion Algorithm can predict the position and shape of defects using in-process data collected in real-time. (Left) Virtual experiment on 3D preform with defects (Right) Restored porosity.

Figure 2. Lab implementation of the Active Control System based on Bayesian Inversion Algorithm.

Feasibility Studies

Microwave heating through embedded slotted coaxial cables for composites manufacturing

Start Date:	01/02/18 End Date: 31/07/18
PI:	Dr Mihalis Kazilas (Brunel University London)
Researchers:	Dr Wenbo Duan (BUL)
PhD Students:	Mr Dimitris Fakis (BUL)
Project partners:	KW Special Projects, Loiretech

"Microwave heating has the potential to create considerable energy savings and significantly increase heating rates compared to conduction or convection heating. Commercial microwave solutions for composites rely on oven cavities, but the resulting temperature distribution in the component is below the required standard for curing conventional thermoset resins."

Executive Summary

When a carbon fibre composite is heated through MW radiation, electromagnetic (EM) energy is absorbed by the carbon fibres and converted to heat. The heating process is volumetric and instantaneous. The resin matrix is subsequently heated through conduction.

This study investigated the use of microwave (MW) heating for composites manufacturing without the need for a dedicated MW oven. Initially, it was proposed that the composite would be subjected to the microwave energy via slots in the tool containing coaxial cables to act as MW applicators (waveguides). In the Feasibility Study it was shown that these did not produce an acceptable thermal profile, as local temperature variations were too high. Alternatively, MW applicators were produced as printed circuit boards (PCBs), which were slotted inside the tooling. Their design can be easily tailored to suit the size and shape of the composite being heated. The concept was validated by producing a number of composite laminates that were of similar quality to laminates produced in a convection oven.

Key Findings/Notable Achievements

The potential for faster curing of composites has been shown compared to current manufacturing processes, offering time and energy savings without a loss in laminate quality. Consequently there are new market opportunities for MW-suitable RTM and infusion tooling that can process composites at faster rates compared to existing tooling.

- Slotted cables did not produce a uniform temperature distribution in the composite: The combinations tried in the Feasibility Study resulted in temperature variations higher than 15°C. Further optimisation of the slotted cable distribution may result in a more uniform temperature profile.
- A fractal antenna was manufactured on a PCB board and slotted into a ceramic tool. The resulting temperature distribution of cured laminates was within 10°C through the thickness of the laminate. With further optimisation, this distribution is expected to fall within ±5°.
- The laminates manufactured using MW heating had the same glass transition temperature as laminates manufactured using a conventional oven, indicating that the degree of cure was the same.
- The heating rates achieved using MW radiation were between 7°C/min - 9°C/min. This was almost double the 4°C/min achieved using a conventional oven.
- Potential energy savings were calculated to be 68% compared to a conventional convection oven (however this value largely depends on tool and component size).

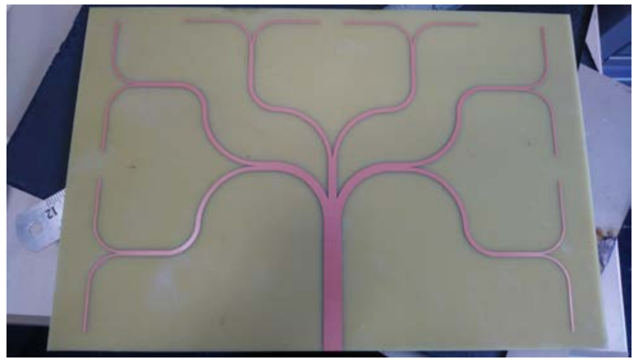


Figure 1. Fractal antenna used as microwave applicator.

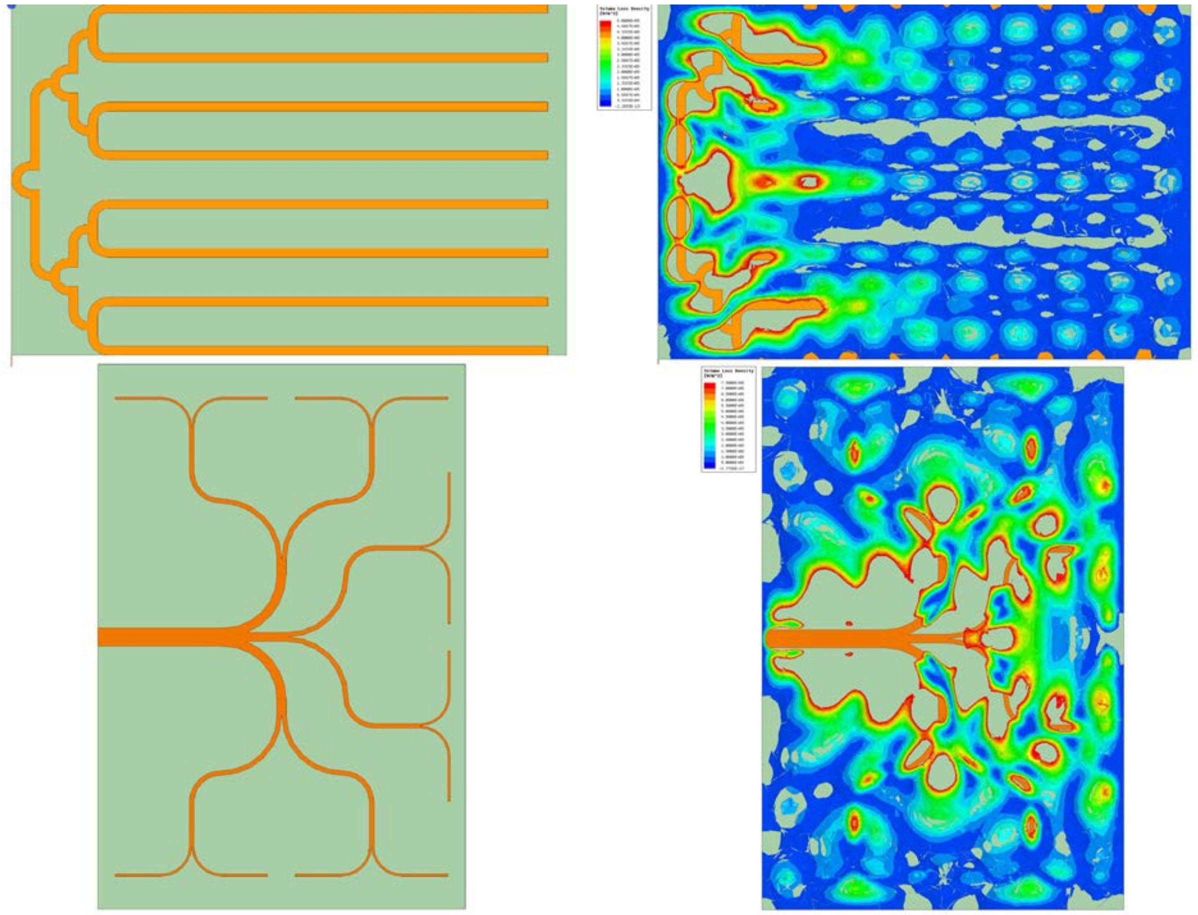


Figure 2. Monopole (top) and fractal (bottom) arrays alongside electromagnetic energy loss distribution.

Acceleration of monomer transfer moulding using microwaves

Start Date:	01/03/18 End Date: 30/09/18
PI:	Prof Derek Irvine (University of Nottingham)
Co-I:	Dr Chris Dodds (UoN)
Co-I Researchers:	Dr Andrew Parsons(UoN)
Researchers:	Dr Alex Ilchev, Research Fellow (UoN)
Project partners:	Betime Nuhiji at AMRC

"Due to the high melt viscosity of thermoplastic matrices, successful infusion into fibre reinforcement is challenging and requires the use of complex and costly processes such as prepregging or co-mingling."

Executive Summary

Monomer Transfer Moulding (MTM) is an effective method of producing fibre reinforced thermoplastic composites from dry fibre that exhibit good fibre/matrix interface quality. It is a derivative of RTM, using very low viscosity monomers that can infuse fibre forms easily at low injection pressures. The cure cycle is not initiated until after the mould is filled, so there are no issues concerning resin curing too quickly and failing to fill the mould cavity. The main limitation is that the polymerisation process takes several hours.

This project investigated the feasibility of using microwave heating to accelerate in-situ polymerisation sufficiently, so that monomer solutions could be used directly to make composite components. Microwave heating can both greatly increase the speed of polymerisation and overcome undesirable thermal gradients within the reaction media by heating the reagents volumetrically. Thus the application of microwave heating to MTM delivers the potential to (a) reduce cycle times from hours to minutes (b) remove the need for heating ovens, significantly reducing space requirements, mould complexity/cost and increase process flexibility and (c) reduce energy requirements.

The project successfully established the benefits of using microwave heating for (a) removing moisture during glass fibre preparation and (b) the production of glass fibre reinforced polymer composite panels. The benefits relating to the preparation of composites from a monomer pre-solution rather than a polymer resin precursor system were defined. A mould design was successfully delivered to account for the requirements/restrictions of both MTM and microwave heating, taking into consideration manufacturing limitations due to material choice. Some small scale components were produced via microwave polymerisation, defining manufacturing parameters for further studies.

Key Findings/Notable Achievements

- It was confirmed that microwave heating was suitable as the sole heat source in an in-situ polymerisation reaction for a composite component.
- Dielectric measurements indicate a 60 mm microwave penetration depth for glass fibre/polycaprolactone materials, suggesting a ~120 mm thick component could be cured.
- Extremely rapid heating is achieved (+60 °C/min) up to the cure temperature and this temperature is maintained throughout the reaction.
- Microwave assisted pre-drying of glass fibres is extremely effective, resulting in a higher final molecular weight.
- Processing options are limited by the behaviour of the monomer – e.g. poor fill under vacuum related to surface tension/viscosity. Positive pressure filling is preferred.
- Heat loss profile is different from conventional heating and is affected more by the presence of the fibre. Control of the EM field was limited and therefore requires further optimisation to control temperature distribution within the laminate.

Figure 1. The Vötsch microwave curing oven at AMRC measures 1.8m x 2.8m, and provides heating at 450°C.

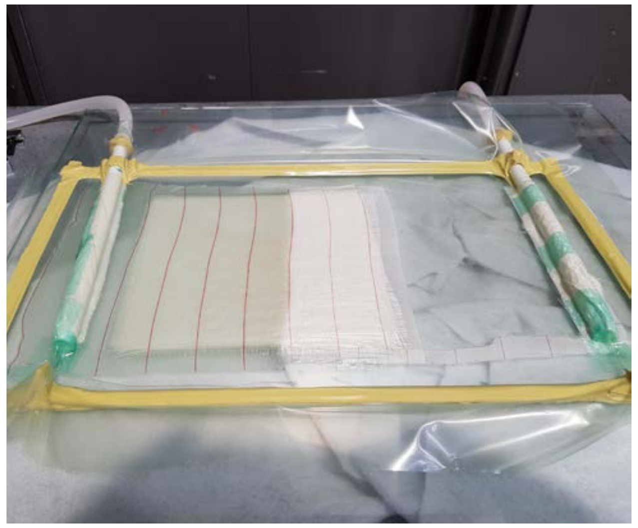


Figure 2. Vacuum infusion of caprolactone into woven glass, using both pressure control and a very narrow exit channel to constrain flow and improve fill. Caprolactone monomer has a very low viscosity and had a tendency to racetrack along the bag surface rather than penetrating the fabric.

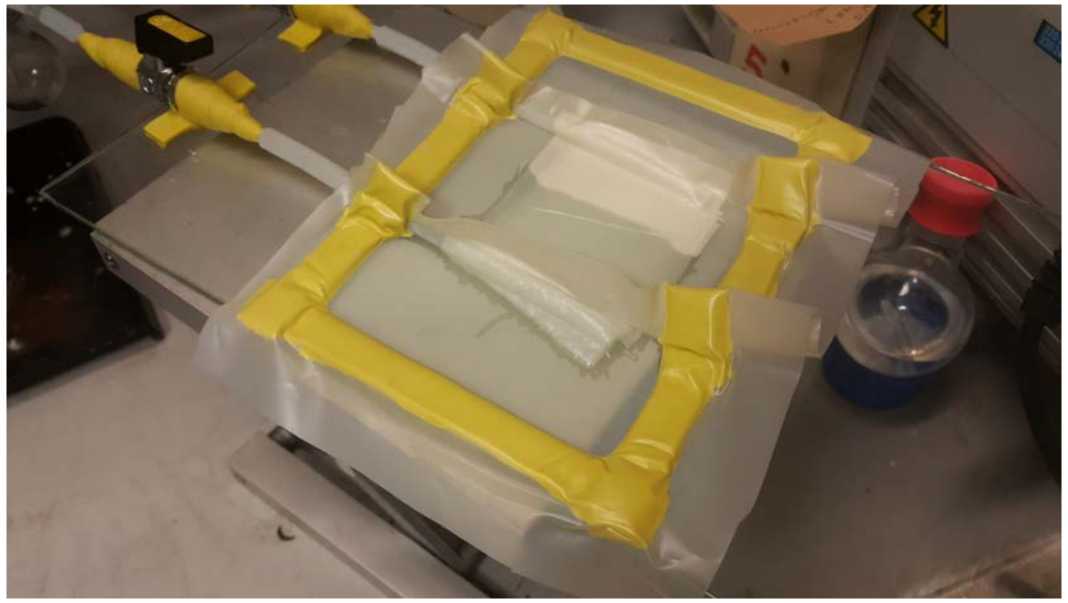


Figure 3. Vacuum infusion of caprolactone into woven glass, using a Schlenk line. The reaction of caprolactone is highly moisture sensitive and the Schlenk line enabled careful control of moisture in the system, as well as providing a backwards and forward flush to eliminate any trapped gas and improve fill.

Platform Grant Research

Developing automated manufacturing technologies for composite laminate structures

Platform Fellow:	Dr Michael Elkington
Institution:	University of Bristol
Project Partners:	Bristol Robotics Laboratory (University of Bristol, University of West England)

"Hand laminating of complex composite structures is a skilled manual process, which cannot currently be replicated by robots. Automation of the prepreg laminating process requires developments in the compaction of the composite material – requiring significant application of force - and in the continual assessment of the quality of the structure, preventing and correcting potential structural defects during the layup process."

Collaborative layup of complex composite structures

This aspect of the project investigates potential opportunities of introducing collaborative human-robot working (cobotics) to composite laminating. This approach has been successfully implemented elsewhere in other manufacturing environments to increase productivity and reduce worker fatigue in tasks that have proved difficult to fully automate.

A new laminating process has been demonstrated where a human and robot work together to layup prepreg composite materials onto complex mould shapes, combining the cognition and awareness of a human worker with the mechanical capabilities of a robotic system.

A range of complex composite layups were completed by a laminator and a six axis robot working sequentially, taking turns to work on the layup. In the first round of trials the robot took over the majority of the compaction duties, pressing the prepreg onto the mould, relieving the human of this repetitive, high force action. The human completed the remaining elements of layup, primarily aligning and deforming the ply to the mould shape. The result was a significant reduction in human-prepreg contact time and much of the intensive physical effort being removed from the process. A second round of trials are currently in process where the human and robot operate simultaneously in the same workspace. The robot supplements the laminator by acting as a 'third hand', taking on a range of layup tasks while the human is still fully engaged in the layup with both hands.

This work has demonstrated collaborative layup of complex components using pre-preg materials. The possibilities for combining the best aspects of humans and robots have been demonstrated. This has reduced both the human-prepreg contact time and the physical effort significantly without compromising the capabilities of hand layup to make the most complex high quality components.

Figure 1. Manufacture of a composite component by collaboration between laminator and robot.

Figure 2. Laser projection ply placement verification coupled with cobotic laminating.

Tactile sensing of defects during composite manufacture

During traditional manual layup, skilled laminators use tactile sensing to constantly gather feedback of what is happening to the prepreg beneath their fingers. Out of plane defects such as wrinkles or bridges can be detected and the laminator uses this information to make minor adjustments to correct the developing defects and ensure part quality is to the required standard. Current automated processes lack any tactile sensing and rely on visual feedback once a ply has been laid up, at which point it may be difficult or impossible to correct the defect.

This aspect of the project has developed an automated layup process which has real-time tactile feedback capabilities. It is based around the TacTip sensor developed at Bristol University by the Bristol Robotics Laboratory (BRL). The device uses a flexible rubber membrane which deforms around the surface of the objects being probed. A camera captures the deformation by recording the movement of small 'pins' protruding from the inner surface off the membrane. A combination of image analysis and statistical data processing uses this data to 'feel' the surface below the sensor.

Initial trials with the Tactip demonstrated that it was capable of detecting a wide range of typical composite layup defects, ranging from wrinkles and foreign objects to trapped backing film or misaligned plies. However, the existing TacTip uses a soft gel core, preventing it from applying any significant compaction force.

Within the project a range of stiffer and more robust TacTip versions were developed to simultaneously apply layup pressure while sensing for defects. The most successful version replaced the gel core with an elastomer enabling over 40 times more force to be applied while retaining the tactile sensing properties. This new sensor has been demonstrated to repeatedly and reliably detect a range of typical layup defects while compacting prepreg onto curved mould surfaces

This is believed to be the first example of combining tactile sensing with significant force application. Wrinkles, bridging, incorrect material types, stray bagging film and other defects have all been reliably detected while simultaneously compacting prepreg materials onto complex mould surfaces.

Tactile sensing can provide a powerful new quality assurance tool for automated processing, checking for defects with every application of the layup end effector. Tactile feedback allows defects to be detected at the earliest possible stage in the manufacturing process, allowing corrections to be made and avoiding potentially lengthy inspection, rework or scrappage later in the manufacturing process.

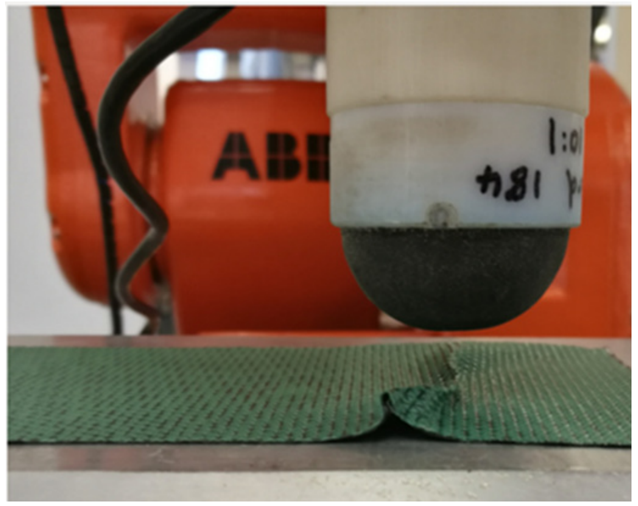


Figure 3. Developed 'Tactip' sensor simultaneously detects defects while applying consolidation pressure to a composite prepreg laminate using a 6-axis robot.

Significance of Work

- Potential to reduce layup times, increasing the productivity of a workforce.
- Potential to increase quality by reducing defects and reducing costs related to repair of defects.
- Reductions in Musculoskeletal System Diseases (MSD), a major cause of absenteeism in manual manufacturing industries.

Platform Grant Research

International permeability benchmarking exercise

Platform Fellow:	Dr Andreas Endruweit
Institution:	University of Nottingham
Project Partners:	Hexcel, Saertex, National Physics Laboratory, 30 international academic institutions

"Fabric permeability is one of the key parameters influencing succesful resin infusion in liquid composite moulding processes. A range of methods and approaches have been developed to determine the permeability tensor for fibrous reinforcement, but there is significant scatter in the data and no test standards exist."

Executive Summary

Platform funding enabled the University of Nottingham to participate in international activities on benchmarking of experimental techniques for characterisation of reinforcement processing properties.

Background

In Liquid Composites Moulding (LCM) processes, a dry textile reinforcement structure is preformed and impregnated with a liquid resin system. Subsequently, the resin is cured at high temperature to obtain a solid composite component. LCM processes are commonly used in mid- to high-volume production of composite components, e.g. for lightweight automotive applications. Ongoing efforts aim to consistently produce components at sufficiently high quality to replace more expensive autoclave processes for structural aerospace components.

In production of composite components applying LCM-technology, the quality of impregnation of the reinforcement with the matrix material and the cycle time depend on the fabric permeability. The permeability is a measure for the velocity with which an injected resin impregnates a reinforcement. The permeability of fibrous reinforcements depends on the fibre volume fraction and the geometrical arrangement of fibres, both of which depend on the level of reinforcement compaction. To characterise the permeability of reinforcement textiles, a wide variety of experimental methods has been developed. Most address measurement of the in-plane permeability, which is of high relevance to LCM, since composites are most frequently processed in thin shell-like structures.

Since permeability characterisation is a prerequisite for process design and optimisation, there is a lot of demand from the composites industry. The University of Nottingham has been providing experimental permeability characterisation as a service to the UK industry for more than 10 years. However, there is a complete lack of standardisation for measurement of the reinforcement permeability. It is well known that permeability data obtained using different methods are not necessarily consistent, which affects the usefulness of the data.

Benchmark Exercises

Two previous worldwide exercises on benchmarking of permeability measurement have been conducted (with participation of the University of Nottingham). The first one gave a general overview of measurement systems and approaches, the second focused on permeability tests employing the linear flow technique. Results were published in 2011 and 2014, respectively.

Following discussions within the composites community, also involving the National Composites Centre, the need for further joint activities in the field of permeability characterisation was identified. The University of Nottingham organised a special session at the 13th International Conference on Flow Processes in Composite Materials (Kyoto, 2016), where an overview of previous activities was given and plans for further benchmarking and standardisation efforts in measuring permeability and compressibility of reinforcement textiles were proposed and discussed. It was agreed that two new studies would be launched:

A. Measurement of in-plane permeability, focusing on the radial flow technique; led by Institut für Verbundwerkstoffe, Germany;
22 participating institutions worldwide. This study was to complement the previous activities on characterisation of the in-plane permeability of reinforcements. Advantages of the radial flow technique over the linear flow technique are that only one test (rather than three) is required for in-plane textile characterisation and that the possible error sources (race-tracking) can be avoided.

B. Measurement of through-thickness permeability and compressibility; led by National Physical Laboratory, UK;
30 participating institutions worldwide. This study followed the same approach as previous activities, but focused on measurement of the through-thickness permeability and of the reinforcement compressibility, which is related to the permeability. As no previous work had been carried out towards standardisation of through-thickness permeability and compressibility measurement, the aim was to get an overview of the methods in practical use, the range of results obtained implementing these methods, and to identify sources of variation.

Prof Andy Long and Dr Andreas Endruweit (University of Nottingham) were nominated as members of the steering committee for both studies. The studies were supported by Hexcel and Saertex, who provided reinforcement fabrics for the test series.

Platform funding paid for one Research Fellow (Dr Andreas Endruweit) to work part-time on:

- helping with formulation of guidelines for experimental procedures, which were then distributed to all participants;
- carrying out series of radial in-plane permeability tests, through-thickness permeability tests and fabric compaction tests; documenting and reporting the experimental work;
- evaluating and compiling data acquired by other participants;
- contributing to preparation of manuscripts and presentations.

Both benchmark exercises are now completed.

Dissemination

- Announcements were made public on the JEC Composites website.
- Workshops were held at international conferences:
  - 21st International Conference on Composite Materials, Xi'an, 2017.
  - 14th International Conference on Flow Processes in Composite Materials, Lulea, 2018.
  - 18th European Conference on Composite Materials, Athens, 2018.
- One manuscript summarising results of one of the studies was accepted for publication in Composites Part A – Applied Science and Manufacturing. One more journal publication is still under preparation.

Significance of Work

The concluded benchmark studies gave valuable new insights into sources of uncertainty in fabric permeability and compressibility testing. This is a prerequisite for standardisation of material test methods (National Physical Laboratory).

Involvement in joint activities allows the University of Nottingham to maintain a leading position in the worldwide composites research community.

Technology

Overview of the Technology Pull-Through (TPT) Programme

The NCC Technology Pull-Through (TPT) programme is an initiative supported by UK Government Catapult funding to transfer suitably mature technologies from universities into the National Composites Centre (NCC), Bristol. The NCC use their capabilities to industrialise lab-based technologies and increase their appeal to potential commercial users. The programme runs on an open call process, issued annually; proposals are assessed and selected through the input of NCC technical experts, supported by the Knowledge Exchange Committee of the CIMComp Hub.

The programme was successfully piloted in 2017 with 9 projects from the University of Bristol (UoB). It was then extended to all universities under the EPSRC Future Composites Manufacturing Research Hub in 2018. 7 proposals were received in Round 2, with 3 projects successfully chosen. For the 2019/20 programme, the initiative has been opened to all UK universities: 18 proposals were submitted with 6 successful applications and ~£750k of Catapult funding committed. To date, the number of proposals received has increased year on year; the expectation is that the number will continue growing as the programme matures and dissemination within the community improves.

The objective of the TPT programme is to identify technologies at TRL3 with high potential for industrial application. Funding can be awarded from NCC and HVM Catapult to support projects developed at NCC in close collaboration with the Academic Principal Investigators (APIs) from the respective universities. The application process is articulated in two stages:

Stage 1 is based on the provision of high-level, short proposals submitted by the APIs which are then reviewed by two bodies: the Hub's Knowledge Exchange Committee and the NCC's TPT Committee (formed by NCC staff identified by the NCC Technology Board). The outcome of Stage 1 is a down-selected list of proposals approved to submit to the next stage.

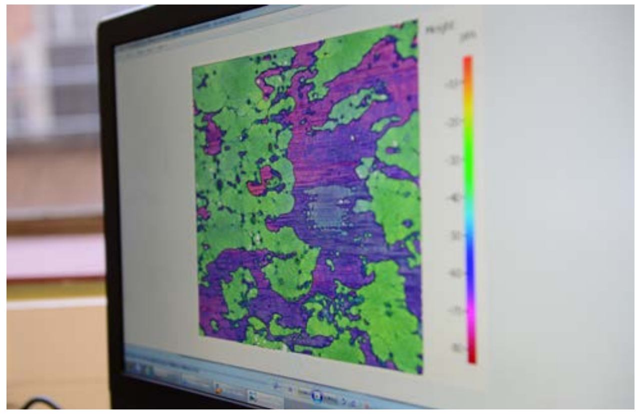
Stage 2 requires the approved applicants to submit a fully detailed proposal, compiled with the support of an NCC Champion and NCC Technology Project Manager, identified by the NCC TPT Committee. Stage 2 proposals are reviewed by the NCC TPT Committee and the output is a final list of funded projects.

SimpleCure

An example of a successful TPT project is SimpleCure. As part of the 2017/18 NCC TPT Programme an in-house cure simulation software called SimpleCure was developed in collaboration with UoB. SimpleCure is an Excel based 1D FEA heat transfer solver that can predict the degree of cure and temperature distribution through the thickness of the manufactured part.

Challenge: The academic community has extensive experience developing cure schedules that produce fully-cured composite laminates in the shortest possible time without generating an exotherm. This is achieved by cure modelling using finite element codes and high-fidelity material models. However, process modelling is still not widely used in a good portion of current industrial applications (especially in the SME world), leading to significant amount of scrap with considerable cost implications. In addition, there is currently no standardised methodology for cure kinetics characterisation and modelling.

Solution: To address these issues a set of guidelines detailing best practice on cure kinetics characterisation and modelling was produced. Furthermore, an Excel based 1D cure simulation model was developed. The model is user friendly and its implementation does not require any modelling/ programming expertise.
Impact: The outcome of this work can contribute towards the optimisation of the manufacturing process and thus can considerably help accelerating decision making around cure scheduling improving NCC or others responsiveness. A team of NCC engineers have already been trained to use the software, while a further group of industry representatives will be trained in March 2019.



Round 2 Summary - Hub Partners

Braid winding - University of Manchester: A technology that combines braiding and filament winding combining beneficial properties from both capabilities

DiSenC - Cranfield University: linear and woven dielectric sensors that can be used for flow and cure monitoring respectively in liquid moulding processing carbon fibre thermosetting composites.

Nanowebs - Queens University Belfast: Scale up and assessment of carbon nano web technology for the purpose of anti-icing/de-icing relevant composite structures.

Announcement of New Projects

SimpleCure2 - University of Bristol: Feasibility study of using a portable device that scans a material's fingerprint, defines a robust cure cycle and automatically programs the production equipment controller.

Braiding Simulation - University of Bristol: Validated modelling capability for mapping local permeability in braided preforms.

Dismantleable Joints - Oxford Brookes University: A solution to the irreversibility of structural adhesives using either additives or chemically reversible polymers.

HiPerDiF - University of Bristol: Scale up of a manufacturing process for highly aligned, discontinuous fibre reinforced composites.

Polarisation imaging – University of the West of England: Development of a machine vision-based inspection system for verification of composite materials, fibre angle measurement and defect detection.

3D Printing of Ceramic Matrix Composites - Imperial College London/ Loughborough University: supporting MSc projects while increasing internal capability.

Next Steps

The next steps for the TPT programme includes the dissemination of completed projects and the kick-off of the 2019/20 projects. The dissemination process may include the exploitation of technologies into trademarked brands, showcasing demonstrators and processes at engineering shows (i.e. JEC) and integrating the technology into industrial applications through CR&D / privately funded projects. As part of this dissemination process, the successful projects are advertised to the NCC's Tier 1&2 members at the monthly Research Committee meetings. This creates a seamless communication channel across the 'valley of death' between the academic innovators and the industrial users.

The accepted new projects have had an accurately resourced and financed project plan ready to kick off from the 1st April 2019. The variety of projects are destined to fit within the NCC's future technology road map, ensuring that academic research will be contributing to the UK's future focus of engineering and technology.

Training

EPSRC Industrial Doctorate Centre in Composites Manufacture

> "Training postgraduate industry-supported Research Engineers who aspire to key leadership positions in the UK composites industry"

- EPSRC funding: £7.5M to 2023, with over £1.9M industry cash contribution to date.
- Industry-led and industry-based research projects starting on day 1 of the 4 year programme.
- Underpinning specialist technical units and business skills training provided.
- Continuing collaboration between the Universities of Bristol (lead), Cranfield, Manchester and Nottingham.
- Scholarships still available for suitable industrial projects, starting at any time of the year.

The new intake in 2018 has seen the proportion of our female Research Engineers increase to 31%, a welcome trend that we continue to encourage. We were also pleased to widen our industry sponsor base by new projects starting up at Airbus, QinetiQ , Heraeus and the Offshore Renewable Energy Catapult (ORE-Catapult).

Our academic focussed events have included a "Composites Manufacturing Masterclass" by Professors Binetruy (Ecole Centrale Nantes, France) and Advani (Univ of Delaware, USA) delivered at the NCC in March 2018. This was designed to give our REs an appreciation of different academic approaches to the topic of 'composites manufacture' and many University and NCC staff also joined in the experience. Current REs also participated in the Hub Open Day at the University of Nottingham in July, directly preceding the ICMAC 2018 international conference. The 'rapid fire' introductions to the poster session gave a good overview of the breadth of coverage of the topic we now achieve as a group.

One highlight of the year has to be the Queens' Award for Enterprise: Innovation 2018 gained by Jo-Bird & Co. Ltd, based to a significant extent on their EngD project carried out by Laxman Sivanathan with the support of UoB's Dr Carwyn Ward.

Cohort building is an important aspect of the IDC, enhancing support and improving the research environment for our student members. The Student Committee organised an outdoors activities weekend in the Brecon Beacons, including white water rafting and waterfall jumping, providing opportunities to enhance their teamwork, leadership and communication skills. The IDC group also participates in all Hub organised researcher events, ensuring growing cohesion between the IDC EngD and the Hub PhD students.

There is widening international participation, brought about by involvement in international conferences, (7th International Symposium on Aircraft Materials, France, April 2018; 18th European Conference on Composite Materials, Athens, June 2018; 8th International Symposium on Composites Manufacturing for High Performance Applications, Netherlands, November 2018, and Offshore Wind R&D Conference, Germany, November 2018), the Study Tours element of the EngD programme as well as the Hub support for international secondments. Recent Study Tour trips have included a stay at IRT Saint Exupery in Toulouse by Vincent Gill and Oli Parks visited the Netherlands-based parent company of his UK industrial supporter, AEL Airborne. Nikita Budwal has made frequent trips to the US this year and Alex Cochrane is currently on a paid secondment to the new Lightweight Manufacturing Centre (LMC) as an Assistant Manufacturing Engineer.

Outreach activities have included Petar Zivkovic's contribution to the Inside Track Lectures at the University of Bristol; "Is a PhD right for my career: a guide to engineering PhDs?". Preetum Mistry, registered at the University of Nottingham, is involved in the 'Eighty Eight Pianists' project led by the University of Cambridge. This hopes to inspire young people with the ultimate STEM outreach opportunity to break a world record, where engineering is fused with art. A number of the REs are in their final year, busy writing up, soon to join the growing alumnae group.

"Thank you for setting up the Industrial Doctorate Centre in Composites Manufacture. Together with all the academics, university members of staff, and the sponsoring companies, you have created a stimulating four-year programme that gave me the skills, competencies and confidence to take on a leadership position at NCC and now to move into a commercial role..." *Dr Mattia di Francesco*

"It has been a pleasure to watch the programme mature over a period of 5+ years. The content has evolved from the tentative plans for the initial modules to become a full programme of learning, ideal for students undertaking a doctorate in this area. I really do rate the programme in terms of the range of material covered, the various assessment types, the development opportunities afforded to the students. The provision is amongst the top handful offered nationwide in terms of postgraduate taught material in composites." *External Examiner report by Professor Paul Smith, 2018*

The taught component of the programme continues to train our REs in the range of skills and knowledge required by a well-rounded R&D professional in the sector, whilst also supporting our affiliated Hub PhD students and forming a basis for a newly developing national curriculum of M-level training in composites. The next IDC dissemination event is scheduled for the 11th June 2019 at the University of Bristol and we look forward to welcoming both existing and potential future industrial and academic supervisors.

Practical session hosted by Jo-Bird& Co.Ltd as part of Unit 7 of the EngD taught component

Partnerships

Academic Partners

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

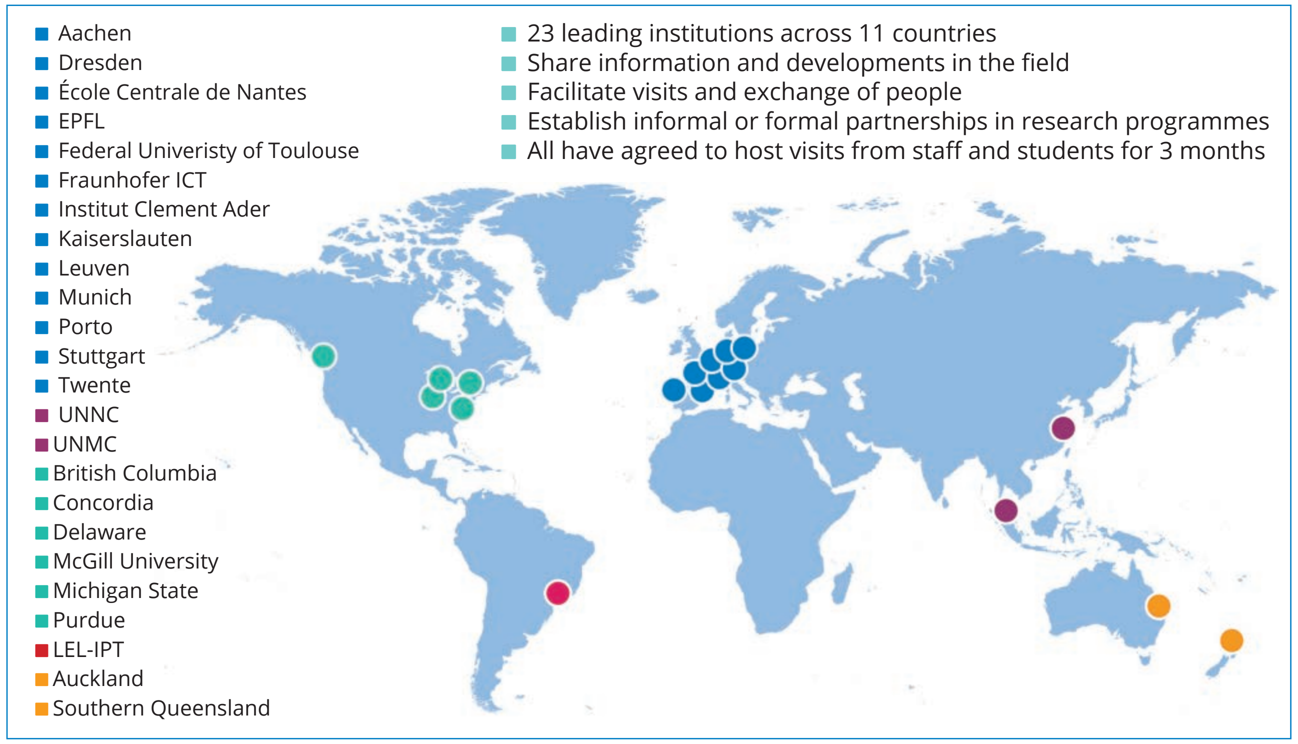
The Hub is pleased to announce the following new partners joining in 2019:

Industrial Partners

Our industrial partner network is critical in ensuring that the research undertaken within the Hub is aligned with industry needs and seeks to overcome barriers faced throughout the industrial supply chain. Their involvement in Hub projects also provides a key pathway to impact as we develop technologies that will form the aerostructures or automotive components of tomorrow. Of particular importance are the involvement of four High Value Manufacturing Catapult Centres (NCC, AMRC, MTC, and WMG) who are able to refine and scale up technologies for commercialisation and industrial exploitation.

International Partners

As part of our aim to produce a step-change in composites manufacturing, it is important to ensure that we engage with and learn from experts both within and outside of the UK. The Hub is uniquely placed to facilitate this international community and have developed a network of twenty three leading institutions across twelve countries. This is particularly important in our training aspirations, as Hub postgraduate students will have the opportunity to spend a three month secondment at one of these institutions, accessing new expertise and facilities and developing their personal networks.



Partner Engagement

CIMComp were delighted to welcome Professor Byron Pipes from the Composites Manufacturing and Simulation Center at Purdue University, Indiana, USA, to the University of Nottingham to conduct a seminar on "Composites Extrusion Deposition Additive Manufacturing". The seminar explored the challenges of the geometric principles and time scales that are present in the simulation of additive manufacturing, with a focus on the polymer composites extrusion deposition process. An end-to-end simulation application for this the process of Additive Manufacturing was presented. Professor Pipes placed particular emphasis on the highly anisotropic character of carbon fibre-reinforced polymer composites and the development of a successful approach to this challenging simulation scenario. The seminar generated a significant amount of interest and was well attended by students and academics at the university. Professor Pipes also extended his visit to several other Hub member universities including the University of Bristol and the University of Edinburgh, to explore collaboration opportunities and to strengthen links with the Hub's International Student Exchange Scheme.

Professor Pipes is the author of over one-hundred archival publications, including four books and has served on the editorial boards of four journals in his field. He received his doctoral degree in mechanical engineering from the University of Texas at Arlington and the MSE from Princeton University. He holds Fellow rank in ASC (American Society for Composites) and ASME (American Society for Mechanical E ngineers) and SAMPE.

"To anyone considering whether an international placement is worth the effort – I would highly recommend it. My experience visiting the University of British Columbia (UBC) in Vancouver has been great so far. The people behind the Composites Research Network (CRN) have been more than welcoming. I am very thankful to the Composites Research Hub for giving me this opportunity, and would like to encourage others to draw on the Hub's extensive links into this close-knit composites community."

Vincent Gill, University of Bristol

International Exchange Visits

The International Exchange Programme provides an opportunity for PhD Candidates, Research Engineers (EngD's) and Postdoctoral Researchers funded by the Hub to undertake a three month visit to one of the twenty-three International Partner Institutions. This ensures that Hub personnel are exposed to the latest technologies championed by leading academic and research institutes throughout the world.

Benefits

Members taking part in the scheme undertake joint research activities with the International Partner giving access to expert knowledge and specialist equipment while fostering relationships, potentially leading to further collaborations. Exchanges between Hub members and the Partner Institutions are bi-directional to maximise research outcomes and dissemination. Leveraging resources between members can provide a "critical mass" typically resulting in joint research publications or internationally funded proposals.

How to Become Involved

Applications to the scheme can be made using the online form within the Partners area of The EPSRC Future Composites Manufacturing Research Hub website (https://cimcomp.ac.uk). The Partner Institutions are listed along with their key research strengths. Interested candidates should establish which Institution they wish to visit, having made prior contact with them through their local supervisor. A work programme is to be agreed with the Institution and the expected outcomes of the interaction. A budget comprising travel and accommodation costs should be included with the application for funding.

Current Participants

Sponsorships have been granted to 3 candidates to date covering transportation and accommodation costs. Exchanges will take place between the following institutions:

1. University of Bristol, UK to the University of British Columbia (UBC), Canada - April 2019. A study into high speed impact on composites to simulate bird strike events will be undertaken. UBC has specialised delivery and measurement capabilities within their Composite Research Network (CRN) facility.

2. University of Edinburgh, UK to the University of Auckland, NZ - July 2019. An investigation into the impact behaviour of carbon fibre reinforced thermoplastic composites will be undertaken. Equipment within the Centre for Advanced Composite Materials (CACM) including high speed camera recording of impact will permit a detailed study into damage initiation and progression.

3. University of Southampton, UK to the Defence Science and Technology (DST), Melbourne, Australia – July 2019. Characterisation of damage using a strain-based, non-destructive evaluation approach will be undertaken on composite structures. The DST incorporates an integrated Thermoelastic Stress Analysis and Digital Image Correlation.

Trade mission to the USA

In October 2018, the Hub Director Prof Nick Warrior was invited to participate in the Innovate UK KTN Composites Global Expert Mission to the USA. The purpose of the mission was to gain a greater understanding of the US composites materials landscape as part of the UK's National Composites Materials Centre addition to the National Composites Centre and High Value Manufacturing Catapult.

Nick represented the UK academic community alongside industry experts, members of the HVMC, Innovate UK and BEIS. The group spent two days in Dallas at CAMX, the largest composites focused exhibition in the US, before travelling to the Oakridge National Laboratory, NASA and the Institute for Advanced Composites Manufacturing Innovation (IACMI).

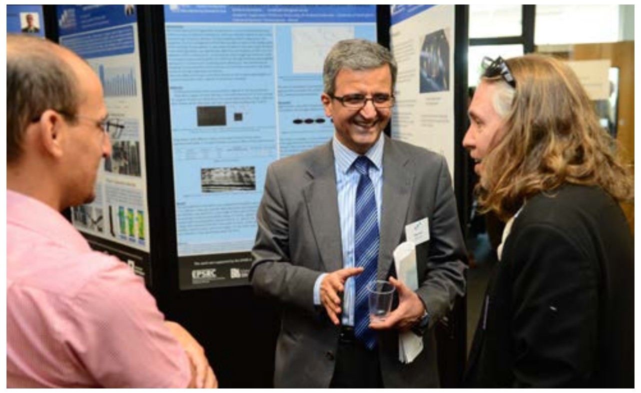
Outreach

Events

Hub Open Day, July 2018

The Hub hosted it's first annual Open Day in July 2018, which was a great opportunity to celebrate the first year and showcase achievements to both academia and industry. The celebrations were well received by an attendance of over 120 delegates from UK and international academic institutions and companies. The Hub was delighted to welcome two keynote speakers to the event: Dr Turlough McMahon from Airbus UK who presented the manufacturing challenges for future composite aerostructures; and Andy Smith from Gordon Murray Design who spoke about using composite sandwich panels in volume automotive applications. The event also recognised the work of 35 Hub-affiliated PhD and EngD students as they conducted poster presentations and delivered two minute summaries of their research, conveying that the future really is bright for composites and manufacturing. The posters were judged by attendees and prizes were awarded to the top three during a drinks reception following the event.

> "It was an amazing and useful experience. The projects presented were really interesting and they offered points of constructive discussion."



11th International Conference on Manufacturing of Advanced Composites, July 2018

The EPSRC Future Composites Manufacturing Research Hub hosted the 11th International Conference on Manufacturing of Advanced Composites (ICMAC11) on 11th-12th July 2018. The conference was organised on behalf of the British Composites Society (a division of the Institute of Materials, Minerals and Mining) and was held in the brand new Advanced Manufacturing Building at the University of Nottingham. ICMAC11 brought together composite manufacturing scientists, engineers and end users from academia and industry to hear about the latest developments from pioneers and emerging leaders in the composites field.

The extensive programme was attended by over 120 delegates and featured 40 oral presentations across two parallel sessions, with a further 12 papers presented in a dedicated poster session. There was a truly international feel to the conference, with delegates travelling from as far as New Zealand, Japan and USA to present papers. Stimulating keynote presentations were delivered at the beginning of each day, inspiring and captivating attendees.

The first was from Prof Remko Akkerman, University of Twente, who shared new thermoplastic processing developments at TPRC in the Netherlands. The second was from Prof Simon Bickerton, University of Auckland, who presented his work on preform quality assessment conducted during his 3 years at BMW, Munich.

A full programme followed, with sessions focusing on areas such as Advanced Fibre Placement, Sensing and Inspection and Emerging Processes. Interactive workshops were held in the afternoon sessions, including training on TexGen, the University of Nottingham's Textile modelling software led by Dr Louise Brown, and a round-robin discussion on resin shrinkage measurement led by Dr Nicholas Boyard (Nantes).

Networking opportunities were abundant and were formally recognised as a key motivating factor for conference attendance from the feedback received. The conference included an evening dinner reception at the Nottingham Council House, one of the region's most iconic buildings — which offered an opportunity for further networking, surpassed by the opportunity to watch England lose their World Cup Semi-final match against Croatia.

JEC World, March 2018

In March 2018, Hexcel Reinforcements exhibited an automotive seat demonstrator component at JEC World in Paris, part of a collaboration with the University of Nottingham. This was the result of a Feasibility Study funded by CIMComp in 2013, which aimed to develop a forming simulation tool for complex 3D preforms manufactured from multiple plies of non-crimp fabric. The outcome from this work was further developed during an Innovate UK-funded project called ALPA (#101879), involving Hexcel and the University, which saw the simulation tool used to develop more drapeable fabrics. The seat demonstrator and the simulation output was shown to over 40,000 visitors at the JEC event, the largest composites trade show in the world.

Advanced Engineering Show, October 2018

The Hub's Management Group and a selection of researchers attended the Advanced Engineering Show 2018, held on 31st October – 1st November at the NEC, Birmingham. This event is the UK's largest annual engineering and manufacturing event that connects OEMS, Tier 1 manufacturers and supply chain partners. It is also the primary networking and showcasing opportunity for CIMComp to engage with the industrial community within the UK.

With an attendance of 15,000 visitors over the two days, the Hub was pleased to exhibit the most recent developments during the one-hour open forum session, where project leads, researchers and postgraduates delivered their research to a full auditorium. The Hub was delighted to welcome Guy Atkins, Managing Director of Jo Bird & Co Ltd, who discussed their collaboration with the University of Bristol's Industrial Doctorate Centre (IDC). Jo Bird and Co currently sponsor Laxman Sivanathan, an EngD student who has been instrumental in helping them to win their second Queen's Award for Enterprise in 5 years.

The event was also the ideal opportunity to launch the Hub's new video, which provided an excellent backdrop for the exhibition stand and created lots of interest from passing delegates.

SAMPE Conference, September 2018

Prof Andy Long chaired the annual SAMPE UK and Ireland Conference in September 2018, which was held in Southampton in conjunction with SAMPE Europe. The theme was "Large Structures in Composites Engineering" and a number of Hub members from the Universities of Nottingham, Cranfield, Bristol, Edinburgh and Southampton presented their work to an audience of 120 people. The Hub supported the event with an exhibition stand, which was an effective way to distribute copies of the recently published annual poster book to the UK community. It was also nice to see some of our international partners in attendance, including RWTH Aachen University, The Lehrstuhl für Carbon Composites (LCC) in the Technical University of Munich (TUM) and KU Leuven.

SAMPE (the Society for the Advancement of Material and Process Engineering) has been operating for 75 years and has an annual event for the promotion of technical excellence in materials and process engineering.

Farnborough Airshow, July 2018

In conjunction with colleagues at the University of Nottingham's Centre for Aerospace Manufacturing and Institute for Aerospace Technology, CIMComp was 1 of 1500 exhibitors that were invited to showcase at the Farnborough International Airshow 2018. With over 70,000 trade and public visitors over 7 days, Farnborough is the most significant aerospace event in the world, with impressive flight demonstrations and exhibits from Tier 1 suppliers and OEMs, as well as live STEM related activities, it provides an excellent opportunity to promote CIMComp and the work of our member institutions and partners.

Student Outreach

Researcher Network Events

Long-lasting, informal connections between Hub researchers are very important for the success of the Hub, as well as for the future of the UK composites community. The Researchers' Network (RN) aims to promote research collaborations by organising regular social and professional events. The RN is steered by members from several Hub universities (Bristol, Manchester, Nottingham and Southampton) and is open to organising new exciting events and activities.

"Great Composites Bake Off"

An event, which included elements of lab training and a manufacturing challenge, was organised for the Hub researchers and saw more than 30 people coming to the University of Nottingham in July 2018. The researchers took part in a 'resin infusion challenge' for which they had to work in teams to layup and infuse a complex composite part within two hours (dubbed the Great Composites Bake Off). A panel with the least defects was selected by the peers and the winning team (a mix of Bristol, Cranfield and Nottingham researchers) was awarded small prizes. The event received very positive feedback from the participants and more competitions of this kind will follow in the future.

Visit to the Imperial War Museum, Duxford

Hub researchers visited the Imperial War Museum, Duxford, to see inspiring examples of composite materials used on iconic aircraft such as Concord. The event was organised by the Researchers' Network in February 2019, gathering together almost 30 researchers from Bristol, Cambridge, Cranfield, Manchester, Nottingham and Southampton, including the new cohort of Hub PhD and EngD students. The researchers were shown how the aerospace industry adopted filament winding for the Polaris missile in the 1960s, through to extensive use of carbon fibre composites on the Eurofighter Typhoon. The event concluded with dinner, providing an excellent opportunity for the group to network and reflect on their visit to the museum.

STEM Events

An EngD student from Nottingham has been involved in a high profile STEM initiative to fuse engineering and art together, in an attempt to encourage more school pupils to consider a career in engineering. Preetum Mistry has been working on the "88 Pianists" project to try and break the current world record for the greatest number of people to play a single piano. Led by the University of Cambridge, the project is a collaboration involving numerous academic institutions across the UK to design mechanical fingers to enable 88 people to play the piano at once. Preetum has been involved in co-ordinating four half-day outreach sessions to Year 5 and 6 students at local schools, focusing on design, engineering and music. The project involves 2000 pupils from 35 schools throughout the UK, all trying to design mechanical methods to play the piano from 5 metres away. Preetum was a member of the selection panel and is currently working on building the winning designs into full-size mechanisms.

"I believe it is really important to get involved in engineering outreach events. This has been a fantastic STEM project to really interact, engage and inspire younger children."
Preetum Mistry, University of Nottingham

School Outreach Programme

Dr Michael Elkington at the University of Bristol has led an outreach activity designed to promote engineering and higher education to secondary school students. A full one day programme was developed, enabling students to gain hands-on experience with a mini project to design and build a rocket. Alongside the practical work, students were introduced to engineering and pathways to higher education. The event has been running for 3 years with a range of state schools across the Bristol area, involved 11 Hub PhD and EngD students.

Future Plans

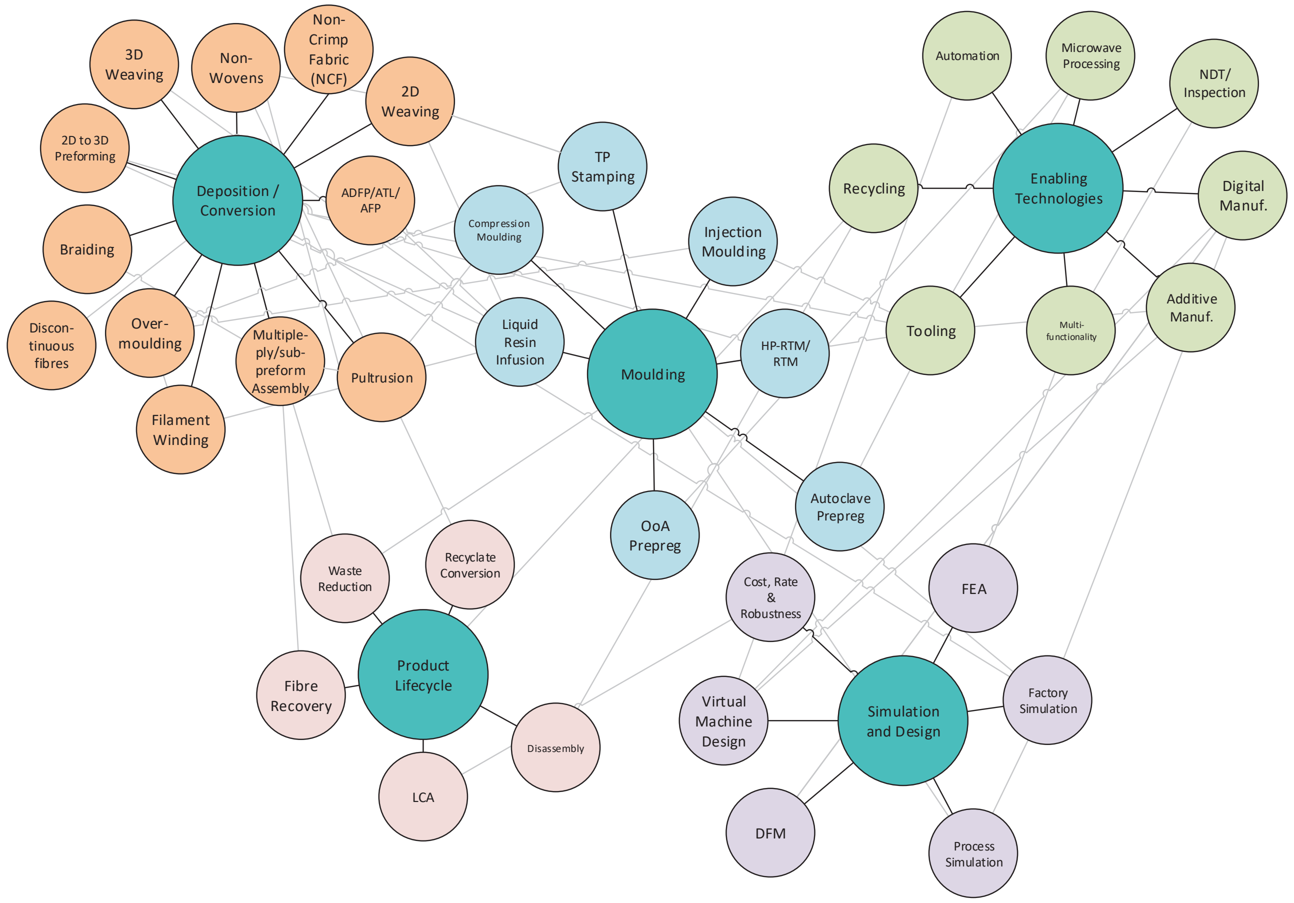
The RN plans to maintain the current schedule of two events a year with both professional and social components. The Hub has allocated funding to the Research Network to support and enhance their research and enable their small independent projects. The fund will be managed by the RN and details will be released by summer 2019.

Shaping the Future

Hub Roadmapping

The Hub's roadmapping activities describe a number of strategic activities which will provide a cornerstone for future Hub activity, including thematic funding calls, opportunities for collaboration and strategic direction. This is currently made up of four areas:

- Core Project route mapping
- Hub research challenge mapping
- UK academic capability register
- UK research funding register



Core Project Route Mapping

Our three flagship Core Projects are long-term programmes with two University partners and a number of industrial and Catapult collaborators. In order to make sure that the work being undertaken within these projects is contextualised, high-level route maps have been developed to quantify outcomes against industry requirements.

Hub Research Challenge Landscape

The Hub plays a key role in funding fundamental composites manufacturing research in the UK. This is done in line with our five research priority themes and two grand challenges. However, in order to ensure that we are funding the most critical and needed research we need to remain up to date with research trends. Our challenge landscape map is written by academics for academics with endorsement from industrial partners and other stakeholders, collating low-TRL challenges which act as a barrier to step-changes in composites manufacturing. We hope that this will also enthuse researchers, and inspire them to solve some of the most pressing problems in this sector.

UK Academic Capability Register

In order to grow composites manufacturing in the UK, we first need to know what research is being undertaken, and who is delivering it. The Hub capability register identifies centres of expertise whether engaged with the Hub or not and captures specific institutional strengths and key research areas.

UK Research Funding Register

The UK funding register helps us to coordinate a view on what areas of research are supported by UK and EU funding bodies and what trends are evident. Focusing specifically on composites manufacturing, this register uses keywords to provide insights into industry sector relevance, manufacturing processes and materials utilised, and the Technology Readiness Level (TRL) of projects. This complements and expands upon a previous exercise undertaken during the Centre for Innovative Manufacturing in Composites (CIMComp) which recorded funded projects between 2008 and 2014.

University of Nottingham

Group leader	Prof Nick Warrior
Email address	nick.warrior@nottingham.ac.uk
Key academics	Prof Andy Long, Prof Shuguang Li, Prof Steve Pickering, Prof Arthur Jones, Dr Lee Harper, Dr Andreas Endruweit, Dr Tom Turner, Dr Mike Johnson, Dr Dimitrios Chronopoulos, Dr Davide de Focatiis
Academics	10
Postgrads	7
PDRA	15
Capability overview	Process development, composite forming, multiscale modelling, FEA, damage & fatigue, recycling, textile composites, biocomposites, resin infusion, 3D textiles
Process expertise	Preforming, preform assembly, overmoulding, braiding, ADFP, NCF, discontinuous

Grant Awards

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

HEFCE Composites Curriculum Development Project

This is a £200k programme to develop an understanding of how a complete Master's level composites training curriculum can be developed. A group of academic institutions has been brought together in a project led by Bristol and Plymouth Universities and are working towards identifying the detailed curriculum requirements in terms of a large number of specific units arranged in a structure of ten thematic blocks. The taught element of the IDC in Composites Manufacturing covers part of the total requirement and is being used as the basis for the development of some of the curriculum. A number of these units are being fully developed and will be trialled at the NCC.

Certification for Design – Reshaping the Testing Pyramid

This is a collaborative programme led by Ole Thomsen of Southampton University, involving the universities of Bath, Bristol and Exeter, with a total value of £6.9M. The Bristol input focuses on Manufacturing, Manufacturing Simulation and Advanced Inspection. The project aims to enable more structurally efficient and lightweight airframes that are essential for meeting future fuel and cost efficiency challenges. It also aims to maintain and enhance the UK's international position in the aerospace industry by providing a route for lessening regulatory constraints, moving towards a more cost/performance optimised philosophy. Industry partners are Airbus, BAES, GKN, RR, NCC, CFMS and the Alan Turing Institute.

Additional Leveraged Funding

NCC Technology Pull Through Fund, Nov 2018 – March 2019, £23,556. Braid-winding. PI: Prasad Potluri, University of Manchester.

EPSRC EP/S016996/1. Feb 19 – Jan 22, £940,000. Investigation of Fine-scale Flows in Composites Processing. PI: Tom Rendall, Other Investigators: Kevin Potter, Raf Theunissen, James Kratz. Project partners: University of Bristol, BAES, Dantec, NCC, Rolls Royce PLC, SHD Composites.

EP/R023247/1. Feb 18 – Jan 21, £518,156. Advanced Continuous Tow Shearing in 3D (ACTS3D): Advanced Fibre Placement Technology for Manufacturing Defect-free Complex 3D Composite Structures. PI Eric Kim. CIs, Kevin Potter, Stephen Hallett, Paul Weaver. Project partners: ABB, Airbus, BAES, NCC.

EP/R021597/1. Feb 18 – July 19, £101,082. Achieving a Predictive Design for Manufacture Capability in Composites by Integrating Manufacturing Knowledge and Design Intent. PI Carwyn Ward. Project partner: NCC.

Innovate UK 103362. 2018 – Jan 21, £164,998. Composite Hybrid Automotive Suspension System Innovative Structures (CHASSIS). PI: Nick Warrior, Ford UK, NCC, Gestamp, University of Nottingham.

EP/P027393/1. Dec 17 – Dec 20, £1,036,426. High Performance Discontinuous Fibre Composites - A Sustainable Route to the Next Generation of Composites. PI Ian Hammerton, CIs Kevin Potter, T Rendall. Project partners: Airbus Group Limited, BAE Systems, Coriolis Composites UK, Hexcel Composites Ltd, National Composites Centre, Hitachi, Toyota, Oxford Advanced Suraces, Solvay, ELG Carbon Fibre Ltd.

European Office of Aerospace Research and Development (EOARD), Sept 2017 – Sept 2020, £393,000. Damage Tolerance and Durability of Structural Power Composites. PI: Emile Greenhalgh. Project partners: Imperial College London, Chalmers University, KTH University.

EP/P027288/1. July 17 – June 19, £101,114. Novel Tow Termination Technology for High-quality AFP Production of Composite Structures with Blended Ply Drop-offs. PI Eric Kim. Project partners. Airbus, BAES, NCC, RR.

EP/P027350/1. May 17 – April 22, £1,115,704. SIMulation of New Manufacturing PROcesses for Composite Structures (SIMPROCS). PI Stephen Hallett, Cis, Ivana Partridge, Dmitry Ivanov, Kevin Potter, Carwyn Ward, Luiz Kawashita, Eric Kim, James Kratz. Project partners: Airbus, BAES, Bombardier, ESI, GKN, JLR, LMAT, NCC, RR.

EPSRC EP/P007465/1. Feb 17 – July 2020, £836,406. Beyond Structural; Multifunctional Composites that Store Electrical Energy. PI: Emile Greenhalgh, Other Investigators: Milo Shaffer, Alexander Bismarck, Anthony Kucernak, Project partners: Imperial College London, Chomorat, Hexcel, BAE Systems, Sigmatex UK Ltd, EADS Airbus, Qinetiq Ltd.

H2020 CS2 738085, Feb 2017 – Jan 2020, £511,000. Structural pOweR CompositEs foR futurE civil aiRcraft (SORCERER). PI: Emile Greenhalgh, Project partners: Imperial College (Project Coordinator), Chalmers University of Technology, KTH Royal Institute of Technology and IMDEA Materials Institute.

EU Clean Sky 2: £591,000. 2017. Multiscale Analysis of Airframe Structures and Quantification of Uncertainties System (MARQUESS). Investigators: I A Jones, D Chronopoulos, C Hyde, S Li, A C Long, S McWilliam, S Triantafyllou, T Turner.

Publications

Journal papers

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

1. 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. In-Plane Permeability Characterization of Engineering Textiles Based On Radial Flow Experiments: A Benchmark Exercise, accepted for publication in Composites Part A, 2019.
2. Mamalis, D.,Obande, W., Vasileios, K., Blackford, J., Ó Brádaigh, C., Roy, D. (2018) Novel Thermoplastic Fibre-Metal Laminates Manufactured by Vacuum Resin Infusion: The Effect of Surface Treatments on Interfacial Bonding, Materials and Design,162, 331–344.
3. Veldenz, L., M. Di Francesco, P. Giddings, B.C. Kim, and K. Potter. (2018) Material Selection for Automated Dry Fiber Placement using the Analytical Hierarchy Process. Advanced Manufacturing: Polymer & Composites Science, 2018. 4(4): p. 83-96.
4. Di Francesco, M., Veldenz, L., Dell'Anno, G., Potter, K. (2017) Heater Power Control for Multi-material, Variable Speed Automated Fibre Placement, Composites Part A: Applied Science and Manufacturing, (2017) 101, p. 408-421.

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5. 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.
6. Yan, S., Zeng, X., Long, A.C. (2019) Meso-scale Modelling of 3D Woven Composite T-joints with Weave Variations, Composites Science and Technology,171, 171-179.

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7. Endruweit, A., Zeng, X., Matveev, M., Long, A. (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, 139-150.
8. 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. https://doi.org/10.1177/0021998318818245.
9. 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.
10. 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.

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11. Akonda, M., Stefanova, M., Potluri, P., Shah, D. (2017) Mechanical Properties of Recycled Carbon Fibre/ Polyester Thermoplastic Tape Composites, Journal of Composite Materials 51 (18), 2655-2663.
12. Atas, 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.
13. Belnoue J., Tassos, M., Nixon-Pearson, O., Kratz, J., Ivanov, D., Partridge, I., Potter, K., Hallett, S. (2017) Understanding and Predicting Defect Formation in Automated Fibre Placement Prepreg Laminates, Composites Part A: Applied Science and Manufacturing 102 (1), 196-206.
14. Corbridge, D., Harper, L., de Focatiis, D., Warrior, N. (2017) Compression Moulding of Composites with Hybrid Fibre Architectures, Composites Part A: Applied Science and Manufacturing 95 (1), 87-99.
15. Gautam, M., Katnam, K., Potluri, P., Jha, V., Latto, J., Dodds, N. (2017) Hybrid Composite Tensile Armour Wires in Flexible Risers: A Multi-scale Model, Composite Structures 162, 13-27.
16. Göktaş, D., Kennon, W., Potluri. P. (2017) Improvement of Model Interlaminar Fracture Toughness of Stitched Glass/Epoxy Composites, Applied Composite Materials 24 (2), 351-375.
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24. Prabhu, V., Elkington, M., Crowley, D., Tiwari, A., Ward, C. (2017) Digitisation of Manual Composite Lay-up Task Knowledge using Gaming Technology, Composites Part B: Engineering 112 (1), 314-326.
25. Roy, S., Potluri, P., Soutis, C. (2017) Tensile Response of Hoop Reinforced Multiaxially Braided Thin Wall Composite Tubes, Applied Composite Materials 24 (2), 397-416.
26. 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.
27. 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.
28. 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.

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

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2. Mills, A. Affordable Thermoplastic Matrix CFC / Metallic Framework Structures Manufacture, 8th International Symposium on Composites Manufacturing for High Performance Applications, November 2018, Netherlands.
3. 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.
4. Jiménez-Fortunato, I., Bull, D.J., Dulieu-Barton, J.M., Thomsen, O.T. Toward Combining Imaging Techniques to Characterise Defects and Damage in Composite Dtructures, SAMPE Conference on Large Structures in Composite Engineering, Southampton, 2018.
5. 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.
6. 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.
7. 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).
8. Roy, D. Out of Autoclave Processing of Composites : Challenges and Opportunities, Innovate UK, 15th March 2018, Titanic Belfast, Belfast, United Kingdom.
9. Roy, D. Intelligent Composite Design and Manufacture, Sampe UK and Ireland chapter annual seminar and SME table top exhibition, 7th of February 2018, Nottingham, United Kingdom.
10. Elkington, M., Gandhi, N., Libby, M., Kirby, A., Ward, C. Collaborative Human-Robotic Layup, December 12th -14th 2017, CAMX, Orlando.
11. Radhakrishnan, A., Hamerton, I., Shaffer, M., Ivanov, D. Localised Control of Composite Properties using Liquid Resin Printing, poster presentation, Bristol Composites Institute conference, Bristol, 15 November 2017.
12. 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.

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

1. 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.
2. 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.
3. Harrison, P. Multi-step Thermoforming of Multi-cavity Multi-axial Advanced Thermoplastic Composite Parts, 11th International Conference on Manufacturing of Advanced Composites Nottingham, ICMAC July 2018, Nottingham, UK.
4. 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.
5. 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.
6. 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.
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18th European Conference on Composite Materials, Athens, Greece, 2018

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4. 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.

75th Annual Conference of the Society for Experimental Mechanics, USA, 2018

1. Bull, D.J., Dulieu-Barton, J.M., Thomsen, O.T. High-fidelity Testing and Integrated Modelling of Composite Substructures and Components, 75th Annual Conference of the Society for Experimental Mechanics, USA, 2018.
2. Bull, D.J., Dulieu-Barton, J.M, Thomsen, O.T. Understanding Heterogeneity in Discontinuous Compression Moulded Composite Materials for High-volume Applications , 75th Annual Conference of the Society for Experimental Mechanics, USA, 2018.
3. Jiménez-Fortunato, I., Bull, D.J., Dulieu-Barton, J.M., Thomsen, O.T. Towards Integrating Imaging Techniques to Assess Manufacturing Features and In-service Damage in Composite Components, 75th Annual Conference of the Society for Experimental Mechanics, USA, 2018.

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

1. 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).
2. Jiménez-Fortunato, I., Bull, D.J., Dulieu-Barton, J.M., Thomsen, O.T. Towards Combining Imaging Methods to Evaluate Defect and Damage in Composite Sub-structures, International Conference on Modern Practice in Stress and Vibration Analysis (MPSVA 2018), Cambridge, 2018.

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

1. Bull, D.J., Dulieu-Barton, J.M., Thomsen, O.T., Butler, R., Rhead, A.T., Fletcher, T.A., Potter, K.D. Reshaping the Testing Pyramid: Utilisation of Data-rich NDT Techniques as a Means to Develop a 'High Fidelity' Component and Sub-structure Testing Methodology for Composites, 21st International Conference on Composite Materials, Xi'an, 20-25th August 2017.
2. Koncherry, V., Patel, 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.
3. 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.
4. 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.
5. Yan, S., Long, A.C., X Zeng. Design Optimization of 3D Woven T-joint Reinforcements, Proceedings 21st International Conference on Composite Materials (ICCM-21), Xi'an, 20-25th August 2017.
6. 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.

International Symposium on Automated Composites Manufacturing, Montreal 2017

1. 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.
2. Veldenz, L., Di Francesco, M., Atwood, S., Giddings, P. Kim, B.C., Potter, K. Assessment of Steering Capability of Automated Dry Fibre PlacementTthrough a Quantitative Methodology, International Symposium on Automated Composites Manufacturing, Montreal, 2017.

Other presentations and events

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

1. Belnoue, J., Sun, R., Cook, L., Tifkitsis, K., Kratz, J., Skordos, A. A Layer by Layer Manufacturing Process for Composite Structures, Project poster at ICMAC, July 2018, University of Nottingham, academic and industrial audience, size: >100.
2. Elkington, M., Gandhi, N., Libby, M., Kirby, A., Ward, C. Collaborative Human-Robotic Layup, Project poster at ICMAC, July 2018, University of Nottingham, academic and industrial audience, size: >100.
3. Harrison, P., McGookin, E., Mulvihill, D., Richards, D., Campbell, I. Multi-step Thermoforming of Multi-cavity Multi-axial Advanced Thermoplastic Composite Parts, Project poster at ICMAC, July 2018, University of Nottingham, academic and industrial audience, size: >100.
4. Mamalis, D., Obande, W., Koutsos, V., Ó Brádaigh, C., Roy, D. Novel Infusible Thermoplastic Matrix in Fibre Metal Laminates, Project poster at ICMAC, July 2018, University of Nottingham, academic and industrial audience, size: >100.
5. Bethany Russell, Embedding Vascular Networks into Thick Composite Parts as Thermal Management Tools for Cure Processing, Project poster at ICMAC, July 2018, University of Nottingham, academic and industrial audience, size: >100.
6. Sutcliffe, M., Zhou, J., Viisainen, V. Wrinkle Formation Characterisation During the Forming of Non-crimp Fabrics, Project poster at ICMAC, July 2018, University of Nottingham, academic and industrial audience, size: >100.
7. Sutcliffe, M., Zhou, J., Viisainen, V. Can a Composite Forming Limit Diagram be Constructed? Project poster at ICMAC, July 2018, University of Nottingham, academic and industrial audience, size: >100
8. Tretyakov, M., Long, A.C., Iglesias, M., Endruweit, A., Matveev, M. Active Control of the RTM Process Under Uncertainty using Fast Algorithms, Project poster at ICMAC, July 2018, University of Nottingham, academic and industrial audience, size: >100.
9. Veldenz, L., Di Francesco, M., Giddings, P., Kim, B.C., Potter, K. Overcoming Challenges in Manufacturing Complex Structures with Automated Dry Fibre Placement, Project poster at ICMAC, July 2018, University of Nottingham, academic and industrial audience, size: >100.
10. Warrior, N.A., Chen, S., McGregor, O., Harper, L. Forming Simulations for 3D Curved Sandwich Panels, Project poster at ICMAC, July 2018, University of Nottingham, academic and industrial audience, size: >100.

Advanced Engineering Show 2018: Oral Presentations

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

Bristol Composites Institute Conference 2018 Poster presentations

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

Oral Presentations

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

Patents

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

Esteem Indicators

Appointments

- Professor Prasad Potluri, University of Manchester, appointed as a Visiting Fellow at AMRC with Boeing.
- Professor Kevin Potter, University of Bristol, awarded a visiting Professorship at Zhejiang University.
- Dr Andreas Endruweit appointed as an Associate Professor in the Composites Research Group at the University of Nottingham, March 2019.
- Dr Lee Harper appointed as an Associate Professor in the Composites Research Group at the University of Nottingham, March 2019.
- Dr Michael Elkington appointed as a Platform Fellow at the University of Bristol, Jan 2019.

Awards

- Mr Verner Viisainen commended at the Vice-Chancellor's Social Impact Awards Ceremony, University of Cambridge, February 2019.
- Caroline O'Keeffe, University of Bristol, awarded the recipient of the Colston Research Society Travel Award, 2019.
- Laxman Sivanathan, EngD student in the IDC in Composites Manufacture, and Dr Carwyn Ward, Laxman's academic supervisor, University of Bristol, received the Queen's Award Commemorative Crystal Bowl on behalf of JoBird Ltd. for the Enterprise: Innovation 2018 prize.

Invited Lectures

- Professor Kevin Potter, University of Bristol, invited to give a plenary lecture at the 4th China International Composites Technology Conference 2019 (28th-30th Nov 2019), Guandong, China.
- Professor Kevin Potter, University of Bristol, invited to give a keynote lecture at CANCOM 201, 22-25 July 2019, Kelowna, Canada.
- Professor Andy Long, University of Nottingham, invited to give a plenary lecture at ICCM-22 (11th – 16th August 2019, Melbourne, Australia, approximate audience of 1000 people.
- Professor Andy Long, University of Nottingham, invited as a keynote speaker for TexComp, 17th-19th September 2018, approximate audience was 100 people.
- Dr Marco Iglesias, University of Nottingham, invited speaker at a workshop on Frontiers of Uncertainty Quantification 2018 (FrontUQ18), Italy, approximate size of audience was 40 people.
- Dr Mikhail Matveev, University of Nottingham, invited speaker at the 14th International Conference on Flow Processing in Composite Materials, Lulea, Sweden, May 2018, approximate audience of 150 people.
- Dr Daniel Mulvihill, University of Glasgow, chaired the IMechE PostGrad Researcher Conference in Glasgow on the 6th and 7th of December 2018.

Committee memberships

UK's Composites Leadership Forum

- Professor Mike Hinton, Director of Research and Technology Partnerships for the High Value Manufacturing Catapult and Chair of the Hub's Advisory Board, is a member of the Composites Leadership Forum.
- Craig Carr, Composites Technology Manager – GKN Aerospace and member of the Hub's Advisory Board, is Chair of the Aerospace Industry Group.
- Dr Enrique Garcia, Chief Technology Officer at the NCC and member of the Hub's Advisory Board is Chair of the Technology Working Group.
- Professor Nick Warrior, University of Nottingham, is a member of the Composites Leadership Forum and the Automotive Industry Group.
- Dr Lee Harper, University of Nottingham, is a member of the Technology Working Group.
- Brett Hemingway, Head of Composites Technology at BAE Systems and member of the Hub's Advisory Board, is a member of the Technology Working Group.

Society for the Advancement of Material and Process Engineering (SAMPE)

- Tim Wybrow, Application Research Manager at Solvay and member of the Hub's Advisory Board is Chair of the UK Chapter.
- Andrew Mills, Cranfield University, is Deputy Chairman of the UK Chapter.
- Dr Lee Harper, University of Nottingham, is a committee member.
- Dr Carwyn Ward, University of Bristol, is a committee member.
- Professor Conchur O'Bradaigh, University of Edinburgh, is a committee member.

Other

- Professor Kevin Potter, University of Bristol, is a member of the International Advisory Board of the Japanese Structural Materials for Innovation Programme and the Advisory Committee for the ACM4 conference, Montreal April 2019.

Editorials

- Professor Ole Thomsen, appointed as editor of Composites Part B: Engineering and is a member of the editorial board for Composite Structures.
- Dr Carwyn Ward is the assistant editor for Advanced Manufacturing: Polymer & Composites Science.
- Professor Ivana Partridge is a member of the editorial board for Advanced Manufacturing: Polymer & Composites Science.
- Professor Kevin Potter is a member of the editorial board for Advanced Manufacturing: Polymer & Composites Science and the editorial board for Composites Part A: Applied Science and Manufacturing.
- Professor Andy Long is a member of the editorial board for Advanced Manufacturing: Polymer & Composites Science, a member of the editorial board for Composites Part A: Applied Science and Manufacturing and a member of the editorial board for Journal of Composite Materials.
- Professor Michael Sutcliffe is a member of the editorial board for Journal of Composite Materials.

Key People

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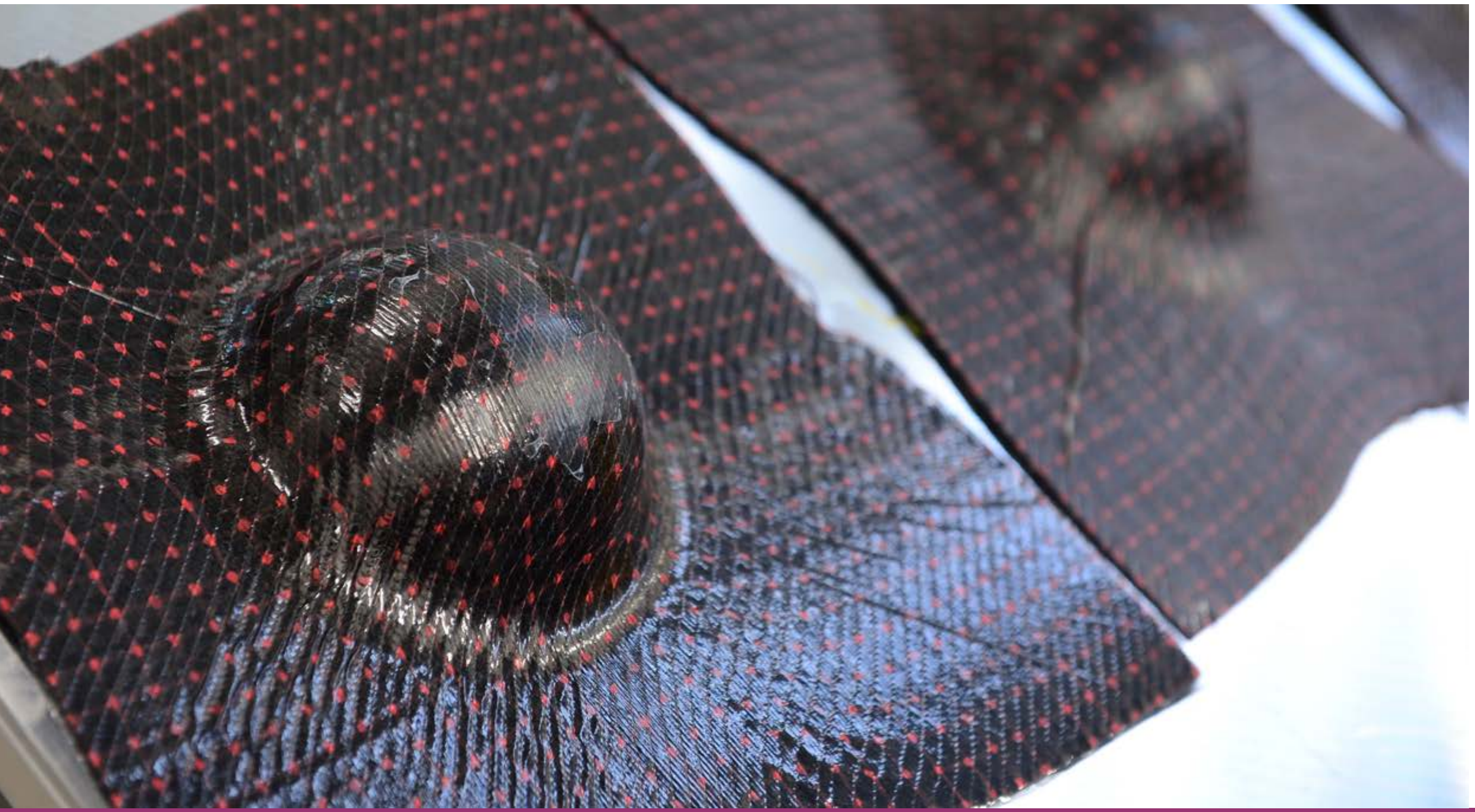

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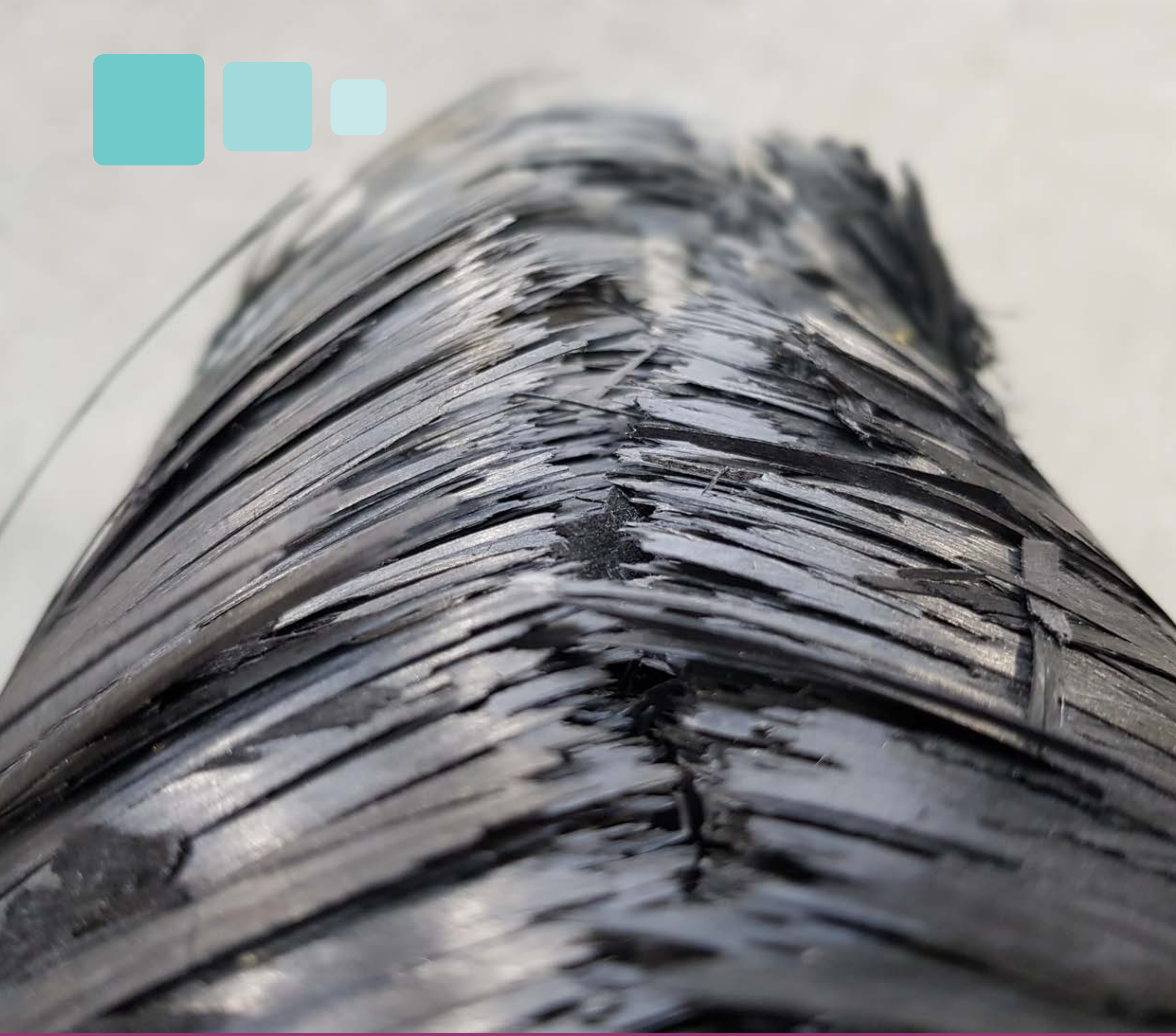

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