ACM5

AUTOMATED COMPOSITES MANUFACTURING

Fifth International Symposium **on Automated Composites Manufacturing**

Conference Programme

NATIONAL COMPOSITES CENTRE

University of BRISTOL

Bristol Composites Institute

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Prof. Ole Thomsen, Co-Chairman, University of Bristol
Dr Enrique Garcia, Co-Chairman, National Composites Centre

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Dear ACM5 attendees,

I'd like to welcome you all, to the event and to this collection of extended abstracts - alongside my Co-Chairs Ole Thomsen of Bristol Composites Institute and Enrique Garcia of the National Composites Centre. ACM has been a very positive contribution to the composites conference landscape since its inception in 2013, ably developed by Suong van Hoa and his team at Concordia University. We were originally intending to hold the conference in 2021, but like the rest of the world's scientific community we have had to rely on virtual meetings for the last two years due to the global COVID pandemic. Whilst we did all manage to keep things moving, I'm sure that, like me, most of you have been missing the chance to meet in the real world for the discussions and relationship building that is really the lifeblood of scientific research. We have conference participants with 19 different nationalities attending this conference, demonstrating the breadth of interest in the technology across the world.

The two main UK organisations supporting Composites Manufacturing research from academia through to industrial application are the EPSRC Future Composites Manufacturing Research Hub (previously the EPSRC Centre for Innovative Manufacture in Composites – or CIMComp) and the National Composites Centre (NCC), both of which are now past their 10th birthday and focussed heavily on the automation of composites manufacture and you'll hear from both organisations during the conference. I'd like to think that the presentations and discussions taking place over the next two days will help to identify future research directions for both organisations and for the wider composites manufacturing community. It will be our pleasure to welcome you to the NCC and to the city of Bristol, to demonstrate what has been achieved here and introduce you to the range of its capabilities.

Lastly, whilst great strides have been made in automating composites manufacture there are still some areas where we need to up the game to open up new applications and new markets in support of achieving a sustainable low carbon future. I would encourage all of you to put these issues at the centre of your discussions and the new relationships that will be forged during this conference. Please enjoy the next couple of days and leave us ready to move on to the next phase of the composites manufacturing story.

Kevin Potter
Professor of Composites Manufacturing and Design
Chair for ACM5

With thanks to our sponsors and exhibitors at this year's conference.

Baker Hughes

Baker Hughes is an Energy Technology Company who develop and deploy technology to help meet the world's demand for energy and to advance industry and take energy forward, making it safer, cleaner, and more efficient for the people and the planet.

We are working to drive new technology into an industry that is reluctant to change, and composites are the new disruptive technology for the industry. We have formed a strong partnership with NCC to develop suitable technologies within the sector, and automation of the manufacturing processes will be key to the successful utilisation of composites in this field.

CIMComp
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Manufacturing Research Hub

The Future Composites Manufacturing Research Hub is a £10.3m investment by the EPSRC to engage academics from across the UK to deliver a step-change in the production of polymer matrix composites. The Hub is driving the development of automated manufacturing technologies to deliver components and structures for demanding applications, within the aerospace, transportation, and renewable energy sectors. The vision is to develop a national centre of excellence in fundamental research for composites manufacturing – delivering research advances in cost reduction and production rate increase, whilst improving quality and sustainability. Our aim is to underpin the growth potential of the UK composite sector by developing the underlying manufacturing process science.

CORIOLIS

Coriolis Composites develops, makes and markets robotic and gantry cells for automated fiber placement. We are mainly using a standard robot enabling the laying of continuous or discontinuous fibers, in all directions and on complex geometrical surfaces.

Our objective is to develop and supply automated solutions for the manufacture of composite parts. The aim is to enhance mechanical performance thanks to low costs and an energy efficient, reliable technology that enables layup using a variety of composite materials.

Coriolis provides: Machines, software and Composites engineering services as well as maintenance support for machines in operation.

CONTENTS

SESSION 1
AUTOMATED FIBRE PLACEMENT 1

SESSION 2
AUTOMATED FIBRE PLACEMENT 2

SESSION 3
FORMING TECHNOLOGIES 1

SESSION 4
FORMING TECHNOLOGIES 2

SESSION 5
DEVELOPING TECHNOLOGIES

SESSION 6
ROBOTICS AND MOULDING TECHNOLOGIES 1

SESSION 7
ROBOTICS AND MOULDING TECHNOLOGIES 2

POSTER PRESENTATIONS

ACM5 Overview & Preliminary Programme

Venue: National Composites Centre, Bristol & Bath Science Park, Emersons Green, Bristol BS16 7FS

Day 0 – Tuesday 5 April 2022.

Time	
16.00-17.00	**Tour of National Composites Centre (NCC)** Bristol & Bath Science Park, Emersons Green, Bristol BS16 7FS
17.00 -18.30	**Registration & Welcome reception** NCC, Bristol Poster session
	BUS TRANSPORT from Bristol city centre (hotels) to the NCC and Bus return to Bristol city centre after welcome reception **Collection point in city centre:** Collection at College Green, BS1 5UY 15:20 (leaving College Green by 15:30). Arrival at National Composites Centre (NCC) by 16:00. Return to College Green, BS1 5UY Leaving NCC at 18:45-19:00. Arrival at College Green around 19:15 – 19:30

ACM5 Preliminary Oral Presentations Schedule

Day 1 – Wednesday 6 April 2022.

Time	Speaker	Title
9.00	Kevin Potter, BCI/University of Bristol & Enrique Garcia, NCC, UK	**Opening remarks and welcome**
	Session 1. Automated Fibre Placement 1. Session chair: Sayata Ghose, Boeing	
9.15	**Suong Van Hoa, Concordia University, CA**	**Keynote 1. Recent Advances and Challenges in Automated Composites Manufacturing**
9.45	Yi Wang, University of Bristol, UK	A simulation platform for the influence of process conditions on steering-induced defects in automated fibre placement (AFP)
10.05	Xiaochuan Sun, University of Bristol, UK	On-the-fly Process Control in Automated Fibre Placement
10.25	Lars Brandt, TU DLR, D	Introduction of 3-dimensional process simulation for thermoplastic AFP for enhanced process parameter identification
10.45	Iryna Tretiak, University of Bristol, UK	Cyclic Compressive loading of Carbon/Epoxy Prepregs: Novel Challenges and Model Requirements
11.05	**Tea and Coffee break**	
	Session 2. Automated Fibre Placement 2. Session chair: Anoush Poursartip, University of British Columbia, CA	
11.20	Ralf Schledjewski, Montanuniversität Leoben, A	Improved layup quality during automated thermoplastic tape layup – Inline detection of consolidation force and tape geometry

11.40	Yi Wang, University of Bristol, UK	A modelling framework for the evolution of prepreg tack under processing conditions
12.00	Daniël MJ Peeters, TU Delft, NL	Predicting the formation of gaps and overlaps due to width variations of dry-fiber tapes during automated fiber placement
12.20	Anthony Evans, University of Nottingham, UK	Developing a Testbed for Automated Fibre Placement Technologies
12.40	Evangelos Zympeloudis, iCOMAT, UK	Fibre Steering for the manufacture of next generation advanced composites
13.00	**Lunch and Poster Session**	
Session 3. Forming Technologies 1. **Session Chair: Sean Cooper, NCC, UK**		
14.30	**Malin Åkermo, Royal Institute of Technology, S**	**Keynote 2 Composites Manufacturing in Future Light Weight Design**
15.00	Byung Chul Kim, University of Bristol, UK	Fibre-Steered Forming Technology for High-Volume Production of Complex Composite Components
15.20	Chrysoula Aza, University of Bath, UK	Fibre length effect on the design of formable laminates for complex geometries
15.40	Long Bin Tan, A-star, SG	Development of Machine Learning Model for Composites Thermoforming Process
16:00	**Tea and coffee break**	
Session 4. Forming Technologies 2. **Session Chair: Eric Kim, BCI/University of Bristol, UK**		
16.15	Anoush Poursartip, University of British Columbia, CA	Forming Process Simulation and Experimental Validation
16.35	Carl Scarth, University of Bath, UK	Stacking sequence selection for defect reduction in forming of long composite spars
16.55	Steven Roy, NRC, CA	AFP Inspection: From OCT A-Scans to the Digital Twin
17.15	**End of session remarks**	

Time	**Conference Banquet, Bristol**
19.30-	Avon Gorge by Hotel du Vin, Sion Hill, Clifton, Bristol BS8 4LD (by Clifton Suspension Bridge) Pre-dinner drinks from 19:30. Dinner 20:00. **BUS TRANSPORT:** Collection at National Composites Centre at the end of conference at 17:15pm. Collection point outside South Gate Reception. Brief drop off at College Green, BS1 5UY to allow you to return to hotels to change if required Collection from College Green, BS1 5UY to travel to The Avon Gorge Hotel, Clifton. 19:00 (Leaving by 19:10) to arrive at hotel at 19:20 Return to National Composites Centre, BS16 7FS including a drop off at College Green, BS1 5UY for people staying centrally at approx. 11:15pm.

Day 2 – Thursday 7 April 2022.

Time	Speaker	Title
Session 5. Developing Technologies **Session Chair: John Summerscales, University of Plymouth, UK**		
9.00	**Ed Findon, LM Wind Power, DK**	**Keynote 3. Challenges in the manufacture of large wind turbine blades**
9.30	**Nicholas Warrior, University of Nottingham, UK**	**Keynote 4. Automation projects within the EPSRC Future Composites Manufacturing Research Hub**
10.00	**Tea and Coffee**	
10:15	Andrea Codolini, University of Cambridge, UK	Influence of tool orientation on the drapeability of unidirectional non-crimp fabrics.
10.35	Marco Bogenschütz, University of Hannover, DE	Determination and impact of fiber angle deviations in automated processing of carbon fiber non-crimp fabrics
10.55	Narongkorn Krajangsawasdi, University of Bristol, UK	Highly Aligned Discontinuous Fibre Composite Filaments for Fused Deposition Modelling: Printability investigation
11.15	Lourens Blok, Lineat, UK	Exploring commercial use cases for aligned short fibre composites
11.35	Laura Rhian Pickard, University of Bristol, UK	Manufacturing of novel hierarchical hybridised composites
11.55	Tim Searle, Composite Integration, UK	From Resin Confusion to Resin Infusion – Understanding, Process Control & Automation
12.15	**Sponsor & Exhibitor Presentations**	
12.35	**Lunch and Poster Session**	
Session 6. Robotics and Moulding Technologies 1 **Session Chair: Stephen Hallett, BCI/University of Bristol, UK**		
14.15	**Philippa Glover, CNC Robotics, UK**	**Keynote 5. Applications of robots across composites manufacture**
14.45	Goran Fernlund, Convergent, CA	Data mining and science-based analytics for automation of composites processing
15.05	James Streatfield, Loop Technology, UK	High rate composite deposition for large scale aerostructures
15.25	Rachael Weare, WMG, UK & Andy Bools, Expert Technologies Group, UK	Automated Stamp Forming of CF-Prepreg Materials
15:45	**Tea and Coffee**	
Session 7. Robotics and Moulding Technologies 2		

Session Chair: James Kratz, BCI/University of Bristol, UK		
16.05	Andrew J Parsons, University of Nottingham, UK	Enhanced Characterisation and Simulation Methods for Thermoplastic Overmoulding – ENACT
16.25	Julien van Campen, TU Delft, NL	The Effect of Multi-Patch Laminate Design on the Manufacturing Efficiency of Composite Plates
16.45	Joe Summers, Airborne, UK	Design For Automation: Lessons from a High Rate Development Project
17.05	Per Saunders, NCC, UK	Low-cost photogrammetric control for automated trimming of composite preforms
17.25	**Closing remarks & end of conference**	

ACM5 Poster Presentation listing

Author	Title
Yannick Willemin, 9T Labs, DE	Seamless solution for industrial-grade continuous carbon fibre 3D-printed composites
Andre Mendes Florindo, TU Delft, NL	Robotic sequential ultrasonic spot welding for a full-scale thermoplastic fuselage demonstrator
Francesca Stramandinoli, Raytheon Technologies, USA	Collaborative Composite Sheet Layups for Complex Geometry of Small Plies
Christoph Frommel, DLR, DE	Automated Inspection in Thermoplastic Automated Fibre Placement
Peter A Arrabiyeh, TU Kaiserslautern, DE	Wet Fiber Placement – Additive Manufacturing with Fiber Bundles Impregnated with Thermoset Resin
Ngoc Anh Vu, University of Twente, NL	Yarn interaction in an enhanced kinematic model of the triaxial overbraiding process
Daniël MJ Peeters, TU Delft, NL	How smart is smart manufacturing?
John Summerscales, University of Plymouth, UK	In situ polymerisation during monomer infusion under flexible tooling
Peter Lascelles, Heraeus, UK	AFP Layup of CF-LM PAEK Fuselage Skin using a Pulsed Xenon Flashlamp System with an Optical-Thermal Simulation Tool
Francesco G. Morabito, University of Bristol, UK	Wraptor composite truss structures: Continuously Wrapped Tow Reinforced Truss Beams
Mehrshad Moghadamazad, Concordia University, CA	Temperature gradients in thermoplastic composites made by automated fiber placement
Jia Ge, Queen’s University Belfast, UK	Multi-objective optimization for drilling of cf/pekk composite
Machar Devine, University of Edinburgh, UK	Recyclable acrylic-glass composites for marine and tidal energy applications
Matthew Thompson, University of Nottingham, UK	Effect of winding twist on multilayer braided composites
Charles P. Macleod, University of Bristol, UK	Fibre-waviness characteristics of fibre-steered laminates produced by Continuous Tow Shearing process
Michelle Rautmann, University of Bristol, UK	Advanced continuous tow shearing

Guy D Lawrence, University of Nottingham, UK	The effects of Inter-Ply Friction for a Dry Bi-Axial Non-Crimp Fabric during Automated Preforming
Gert Schouterden, KU Leuven, B	Testing setup for sensitivity analysis-based component optimisation of membrane-shaped MR-based draping tools
Matt Hardman, NCC, UK	Achieving ultra high rate automated composite deposition
Philip Druiff, NCC, UK	Machine Learning for Data Driven AFP
Matt Hardman, NCC, UK	Whitepaper: The need for material and process standards for Automated Fibre Placement

SESSION 1
AUTOMATED FIBRE PLACEMENT 1

A SIMULATION PLATFORM FOR THE INFLUENCE OF PROCESS CONDITIONS ON STEERING-INDUCED DEFECTS IN AUTOMATED FIBRE PLACEMENT (AFP)

Yi Wang[1], Sarthak Mahapatra[1], Jonathan P. H. Belnoue[1], Dmitry Ivanov[1] and Stephen R. Hallett[1]

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Keywords: Automated Fiber Placement, Process Modelling, Prepreg Tack, In-plane Shear

ABSTRACT

In the last 10 years or so, digitalisation has revolutionised the manufacturing sector, allowing more intelligent, efficient and less wasteful processes. This was enabled by recent advances in in-situ sensing and data analytics. Hence a combination of high-volume data collection, processing and analysis allows real-time monitoring of the process and on-the-fly adjustment if needed. The composite industry is however characterised by its high value and low throughput nature and has somehow been left behind in this trend. It is often argued that this lack of physical data could be supplemented by the production of synthetic data produced by physics-based models. In the specific case of the Automated Fibre Placement (AFP process), this would rely on the existence of simulation tools that are good enough to capture the influence of a number of process parameters (e.g. temperature of the lamp, roller compaction force, machine speed etc) on preform quality. However, up to recently, models for the prediction of defects produced in the AFP process, in particular when the tape is steered along a certain radius, have been more qualitative than quantitative.

In the present contribution, a route for increased accuracy of numerical models for the AFP steering process is proposed, as shown in Figure 1. The work starts from the characterisation of prepreg tape under key mechanisms that are known to affect wrinkle formation, i.e. prepreg tack, in-plane shear [1,2] and bending. Constitutive models for each deformation mechanisms are then derived and implemented in the form of material and contact subroutines for commercial finite-element packages that are further integrated into a full AFP simulation platform. The proposed framework was validated against real-life data available in the literature [3]. Very promising results on the model's ability to capture the effect of process conditions on preform quality was demonstrated. The work can provide insights on how AFP system settings affect the deposition quality and enable a true digital twin of the AFP steering process for advanced composites part manufacture.

This work is funded by the Engineering and Physical Sciences Research Council (EPSRC) through the Centre for Doctoral Training in Advanced Composites Collaboration for Innovation and Science (grant no. EP/L016028/1) and the EPSRC project "Simulation of new manufacturing Processes for Composite Structures (SIMPROCS)" (grant no. EP/P027350/1).

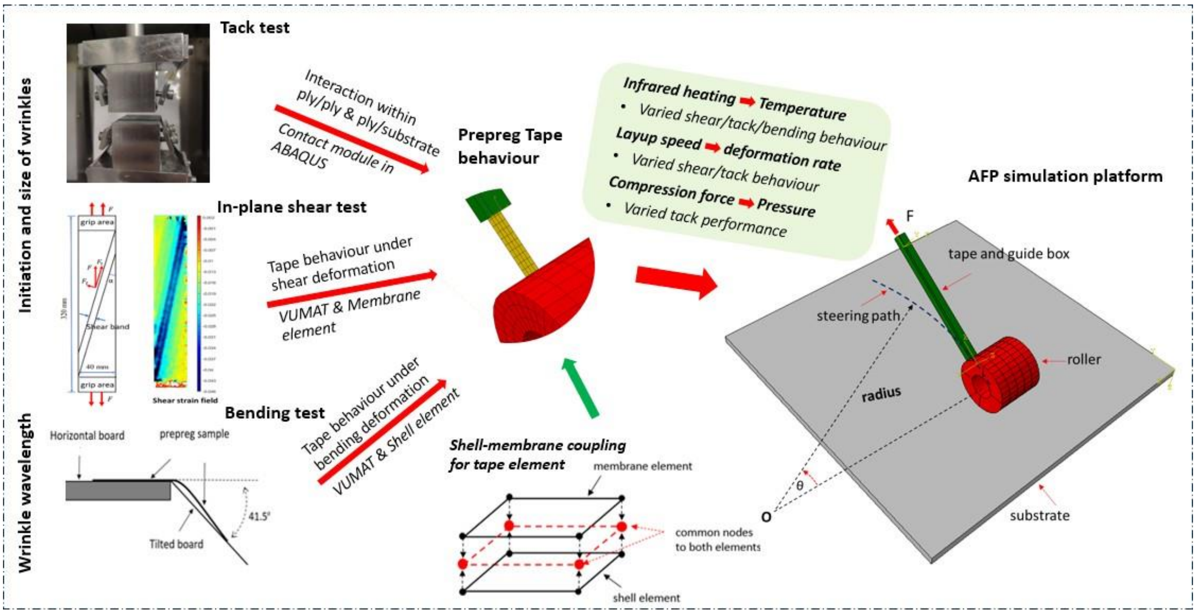

Figure 1: A route for modelling Automated Fibre Placement steering process under varied conditions.

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ON-THE-FLY PROCESS CONTROL IN AUTOMATED FIBRE PLACEMENT

Xiaochuan Sun[1], Jordan Jones[1], Yusuf Mahadik[1], Duc Nguyen[1], Iryna Tretiak[1] Mario Adrian Valverde[1], James Kratz[1*]

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Keywords: Automated fibre placement, Online process control, Real-time measurement, Smart manufacturing, Functional tooling

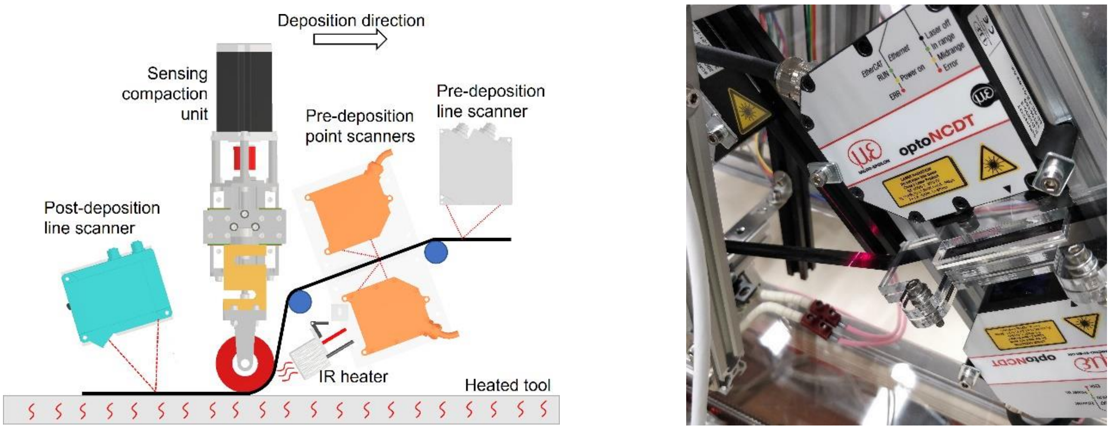
ABSTRACT

Automated Fibre Placement (AFP) technology has been widely recognised as one of the most advanced manufacturing processes for composite structural components across many key industries. Compared to hand lay-up processes, AFP offers considerably higher robustness, repeatability, and productivity, and it is ideally suited for large thin parts with simple geometry [1,2]. As capabilities to process different material systems, process wider tapes and achieve higher process rates are key performance indicators for the most state-of-the-art AFP machines, an intelligent system process control, that makes the machine aware of what it is processing, is in high demand and deserves further exploration.

Current AFP process control has focused on producing defect-free parts with advanced mechanical performance by fibre trajectory design, course monitoring and optimisation of key processing parameters i.e. deposition rate, heating/melting temperature, uniformity of compaction pressure. These parameters are normally determined through averaged off-line material measurements, off-line process condition measurements combined with trial-and-error manufacture iterations, often requiring heavy machine operator intervention with prolonged machine downtime (up to 40%), which makes the cost for AFP and sequential post-processing for large thick parts significantly high [3]. In addition, current process control can be considered as a passive system where in-coming material properties and in-process conditions has no effect on machine actions. While recent advancements have automated defect detection and online quality assurance [4], a lack of real-time material measurements and active process control based on 'live' data during AFP remains. Therefore, deviations between the as-designed and as-manufactured part are inevitable as a-priori determination of 'ideal' processing parameters fail to account for the stochastic nature of the deposited material (i.e. prepreg tape properties and its dimensions).

This research aims to enable on-the-fly fine tuning of the key AFP manufacturing parameters using real-time measurements of both material and active processing conditions. To prove the concept, a novel AFP testbench, named as real-time AFP (RT-AFP), is firstly constructed consisting of multiple sensors to measure material properties and processing conditions in real-time. Figure 1a & b show a schematic of the current design of RT-AFP and pre-deposition sensing unit, respectively. Incoming prepreg material firstly enters pre-deposition sensing region where a laser line sensor and a pair of laser point sensors are located, from which material width and thickness are measured; any defects caused by upstream processing can also be captured. These 'live' sensor data (material dimensional information) and material quality (as a binary indicator) are monitored and fed into a master control system implemented via LabView, which consists of a set of closed-loop controllers that 'tune' the compaction force, temperature and process rate on-the-fly. A post-deposition line scanner simultaneously measures the thickness and width of the material that has been laid down, including current tape(s) and overall thickness of laminate, to confirm the previous intervention from real-time AFP process control. In a class with other online inspection systems, defects detected during deposition can also be measured and assessed by the post-deposition sensor.

Monitoring these key processing variables and up/down stream material dimensions in real-time allows operators to be fully aware of what is going in and out under what conditions during AFP process, which allows ‘in-situ’ control of incoming material and the key process conditions, the quality and thickness control of the final un-cured laminate may be improved, which provide parts are more closely aligned with design requirements and constraints.



(a) (b)

Figure 1: (a): Schematic of real-time AFP (RT-AFP) testbench; (b): real-time material measurement unit located prior to deposition during AFP process with a pair of point sensors (RHS) and single line sensor (LHS). Note that other processing modules such as material unwinder and feed unit are ignored in (a).

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INTRODUCTION OF 3-DIMENSIONAL PROCESS SIMULATION FOR THERMOPLASTIC AFP FOR ENHANCED PROCESS PARAMETER IDENTIFICATION

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Keywords: Thermoplastic AFP, Process Simulation, Heat transfer, CFRP, CF/PEEK, CF/LM-PAEK

ABSTRACT

One step Thermoplastic Automated Fiber Placement (TP-AFP) is on the verge of being industrialized. Reliable, powerful and controllable heat sources enable faster layup rates and increased quality in terms of consolidation and porosity. Thus, mechanical knock down factors as compared to post-consolidated references are decreasing for steadily improving AFP processes. Single step in-situ consolidation of CFRP parts for high volume products such as single aisle commercial aircrafts are becoming a viable opportunity to standard thermoset production. This is especially the fact, as post-consolidation in ovens and autoclaves with their inherent size limitation and high recurring costs from vacuum bagging can be avoided. Today process set points for new materials are commonly found by trial and error with mechanical testing of test specimen. This is both time and cost intensive. A more sensible approach is to use process simulations fed with material characteristics to find optimal manufacturing parameters.

In general, for TP-AFP the pre-impregnated tape is supplied from individual material spools and transported to the nip point region. The tape and substrate are both heated over their melting temperature. Under the compaction roller, the surface asperities are smoothed out and intimate contact is established. This enables polymer self-diffusion and the tape is bonded on to the substrate. This process is repeated until the laminate is build.

Simulation of thermoplastic AFP with laser heating started in the late 1980s. Grove showed a two-dimensional analytical simulation considering reflection of the laser [7]. Beyeler and Güçeri introduced a model based on finite elements method [3]. Nejhad and Agarwal adapted and improved the simulation [1, 8]. Recent research focused on near infrared diode lasers with one consolidation roller. Grouve established a simple optical process model calculating the reflection and determining the laser heat flux to tape and laminate, it feeds into a subsequent heat transfer model [6]. Stokes-Griffin and Compston used a three-dimensional optical model and modelled the CFRP tape as half cylinders and fed the results into a two-dimensional heat transfer simulation [9]. Fricke showed a simulation with lagrangian frame and resulting residual stresses in the laminate [5]. Most work neglected heat transfer in the tape width direction due to the mass flow while layup. Optical models have not been applied to a three-dimensional simulation yet. In general, applied assumptions led to a lack of accuracy compared to the real process. Moreover, model complexity went back and forth to find an optimal representation and simulation tools are optimized for legacy equipment.

In this work a new modelling approach is shown for laser assisted AFP. A fully 3-dimensional simulation models the mechanical, optical and thermal physics of the process. This is realized in an integrated software chain and the simulation is validated via extensive thermocouple measurements for the AFP process. In order to facilitate the usage of the model in a working process, a reduced version of the model is presented in this paper that helps to understand the effects of parameter variations with a consistent machine setup. This will reduce the need for iteration cycles for setting up the process, enhance process knowledge and thus promote industrializability.

Process simulation and validation is done with an infrared diode laser with a wavelength range of 980-1040 nm on a multi tow layup machine supplied by AFPT GmbH. The layup machine is mounted on a standard articulated robot.

The simulation is based on an eulerian frame that is fixed on the consolidation roller and moves along with the machine. This results in a steady simulation with mass flows for tape, substrate and tooling. The system boundaries are chosen to resemble the most common case during tape placement: a tape is laid down next to an already consolidated one. In width the consolidation roller acts as boundary. In tape length direction the heat zone resembles the start and cooling zone end of the simulation.
For the optical model ray tracing was conducted. The laser and its optics were simplified as quadratic ray source that is diverged by an equi-concave lens. A precise representation of the real laser irradiation was reached by simulating four million rays.

Heat conduction into the tooling was simulated with standard aluminum thermal properties attributed to the meshed bulk material. Material properties for CFRP tape and laminate are modelled dependent on temperature as well as orthotropic for in-fiber and perpendicular direction. The coefficients can be found in literature [4]. These are defined for CF/PEEK, however, recent research found that values also apply for CF/LM-PAEK [2]. Heat conduction between roller and tape/substrate is modeled with a thermal resistance. Varying laminate structure can be simulated due to the implementation as individual geometries per ply. Design of the simulation and meshing are depicted in figure 1.

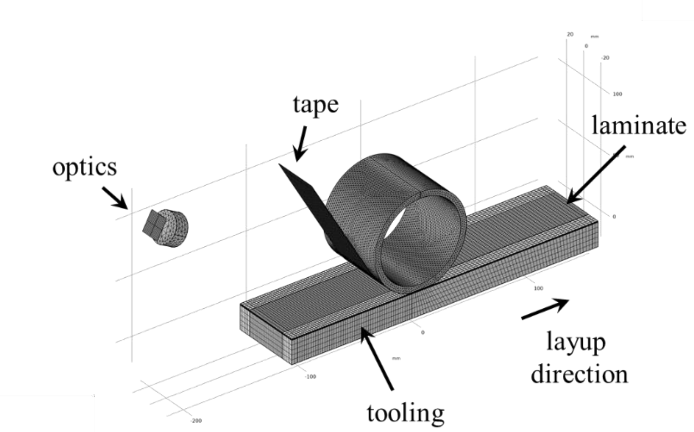

Figure 1: Simulation design and mesh.

Validation of the simulation was conducted using k-type, thin thermocouples that were placed onto a substrate of five placed UD layers, in order to rule out heat dissipation effects to the metallic tooling. Tracks of 3 x 1/2” CF/LM-PAEK tape were placed on top of the thermocouples and measurements were done for three consecutive layers in total. The layup speed was set to 125 mm/s. Thermal gradients measured were compared to the simulation and showed good correlation. Shadowing of the compaction roller can be seen within the simulation results, however not in the measurements. This is attributed to the sampling time (100 Hz) of the used data logger.

For practical implementation on the equipment the simulation results for various parameter sets are prepared and stored in a simplified application. This tool gives easy access to temperature distribution and gradients for different layup velocities, laser power, laser incident angles and consolidation pressures. Future work will comprise a prediction of quality factors like expected laminate void content and crystallinity based on the 3D simulation model.

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CYCLIC COMPRESSIVE LOADING OF CARBON/EPOXY PREPREGS: NOVEL CHALLENGES AND MODEL REQUIREMENTS

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Keywords: Automated Fibre Placement (AFP), compaction, springback

ABSTRACT

The growing demand for more cost and labour effective production of large, lightweight, and geometrically complex composite structures has led to the replacement of traditional manufacturing processes, such as hand lay-up and vacuum bagging, with automated processes such as Automated Tape Laying (ATL) and Automated Fibre Placement (AFP).

These automated processes involve robotic deposition of prepreg strips, in a sequential manner, onto a mould to produce a bespoke lay-up using a deposition head that consists of a heating source and a compaction roller.

Although these manufacturing processes have made significant progress in improving the manufacturability of large-scale composite parts, the occurrence of defects remains a significant challenge to the production of parts for high performance applications. The various process parameters, such as heating temperature, placement speed and compaction pressure have a significant effect upon the introduction of defects. The variability in material behaviour during manufacture, in regard to its dependence on the process parameters, has been investigated by Nixon-Pearson et al. [1] where the compaction behaviour of the uncured prepregs has been investigated under different processing conditions.

During AFP processing, the deposited material undergoes cyclic mechanical loading and unloading induced by sequential passes of the compaction roller. However, the number of compaction cycles experienced by each ply will vary, with the bottom ply experiencing all compaction cycles whilst the top ply is typically subjected to only a single compaction cycle. This can cause significant variation in the through-thickness geometry, which has a knock-on effect to the overall behaviour of the parts. This behaviour can also be observed in thick industrial-sized structures, where debulking is typically applied once for every 4 additional plies laid-up. In this case, whilst each block of 4 plies is exposed to cyclic pressure loading, each individual block experiences a different number of cycles. Thus, the bottom plies experience greater compaction than the upper plies, thereby leading to deviation from the expected thickness and architecture of the plies, and subsequently the structural and material properties.

The behaviour of the material under cyclic compaction becomes much more complex for material systems where hysteresis and permanent strain is an issue. [2], [3]. Furthermore, springback has been observed in dry fibre systems [4], and it is expected that the springback effect in other material systems will differ and result in further complexities.

In this work, an investigation of the mechanical response to cyclic compressive loadings of toughened carbon/epoxy prepregs is undertaken. Two aerospace grade prepreg systems, namely IM7/8552 and IMA/M21 (developed by Hexcel®) were investigated. In the IM7/8552 carbon fibre/epoxy system a thermoplastic toughening phase is dispersed within the plies throughout the bulk of the resin, whilst in the IMA/M21 carbon fibre/epoxy system includes an extra layer of thermoplastic particles dispersed as a distinct ‘interlayer’ between the plies. The presence of the toughening thermoplastic particles

introduces an extra phase to the material; thus, it will increase the complexity and behaviour of the material system.

Custom-made heater plates have been developed to simulate the loading and unloading conditions that may be experienced by a material system during AFP and ATL (Figure 1). With this experimental setup, a testing program has been implemented in which the springback of these material systems is investigated at different constant temperatures by varying the dwell time in the unloaded position of a repeated cyclic loading regime. The effect upon the thickness of the material system, and the variation of the plies therein, is subsequently determined.

For both material systems, springback decreases with each successive cycle. However, the largest springback was observed at different compaction temperatures for each material system. The experimental outcomes were used for further development of an existing state-of-the-art phenomenological material model. The acquired experimental data sets new requirements for the model to include a springback response during load relaxation and provides information for extensive validation.

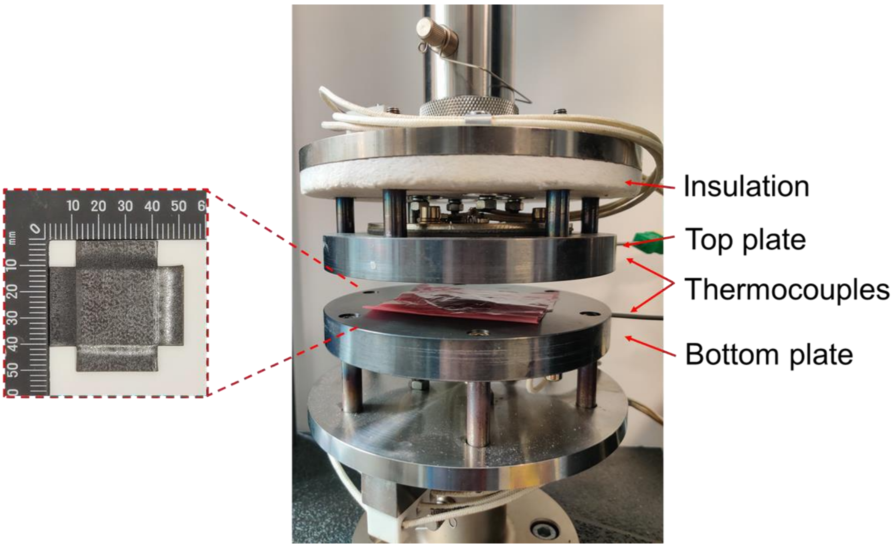

Figure 1: Experimental test set-up.

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SESSION 2
AUTOMATED FIBRE PLACEMENT 2

IMPROVED LAYUP QUALITY DURING AUTOMATED THERMOPLASTIC TAPE LAYUP – INLINE DETECTION OF CONSOLIDATION FORCE AND TAPE GEOMETRY

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Keywords: Automated Tape Layup, Thermoplastic, Inline monitoring, Consolidation force, Control

ABSTRACT

Among the various processes used for composite manufacturing, automated tape layup (ATL), offers the possibility of precise layup of large parts having high areal weights with increased productivity and reduced material wastage. The process has been widely used for unidirectional prepregs in aerospace, automotive and renewable energy industries and examples of manufactured parts include wing skins, tail planes and the centre wing box of the A380 [1].

Commonly used for thermosets, ATL has been continuously adapted for thermoplastics due to the various advantages they offer. Some of them being, more chemically and fatigue resistant, tougher and the possibility of in-situ consolidation, wherein, no post-processing is required such as autoclaving. Even after constant development, thermoplastic material suffers from a variety of problems: tape uniformity (edge, width, thickness), fibre-volume content, surface roughness, which gives rise to material variability at the slit-tape level. The complex, nonlinear multivariable processing conditions contributes to additional variability in layup conditions inevitably generating defects [2]. The most common positioning defects being gaps and overlaps. These defects can lead to pronounced effect on the strength and failure development of the final laminate [3].

Process monitoring and control is needed to rectify these defects during manufacturing to improve process reliability, dimensional accuracy and mechanical performance. Numerous inline monitoring techniques based on visual, optical, acoustic and infrared thermography approaches exist to detect these defects [2, 4]. However, width variation using inline force adaptation to rectify these defects does not exist so far. This research works serves as the first step towards such a control system.

The major process parameters that influence the quality of the consolidated bond are heat, speed of placement and force [5]. Given that a required minimum force is maintained, it is found to have the least impact on the overall quality of the bond [6]. Consolidation force can thus be varied inline without drastically affecting the layup quality.

Light section sensors operating on laser triangulation detect the contour of the tape before and after layup. These sensors serve two purposes: prediction of gaps and overlaps based on material variability detected by the first sensor; quality inspection by detecting gaps and overlaps after layup manifesting as a result of process variability, detected by the second sensor.

A 6-axis force sensor placed directly above the consolidation roll measures the force applied on the laminate during the running process. Static and dynamic system behavior identification and validation tests are performed using pressure sensitive foils (Prescale from Fujifilm) and pressure mapping films (Tekscan). The forces measured by the force sensor placed above the roll are in good agreement with measurements from pressure sensitive films and pressure mapping films placed below the roll. The consolidation force is applied via a pneumatic system, which is converted to a dynamic set-point specification. This now enables the resultant force applied through the pneumatic pressure cylinder to be varied in-line. The flexibility of both on the fly and static programming are enabled. Specified tests

are carried out to characterize width before layup and after layup with varying force. Empirical model is formulated based on these correlations using which force can be varied in accordance to width spread requirements.

A novel approach for defect control is utilized, where inline force variation is used to obtain desired width increment. The present work focuses on thermoplastic CF-PA6 and flash lamp heating, humm3® system. A realistic use case of such a system would be for complex shaped tools and variable stiffness composites where gaps and overlaps are a common occurrence due to either steering restrictions for curvilinear fibers or ply drops for tapered laminates. Optimized width spread and force application based on a priori knowledge of path planning can help alleviate these defects.

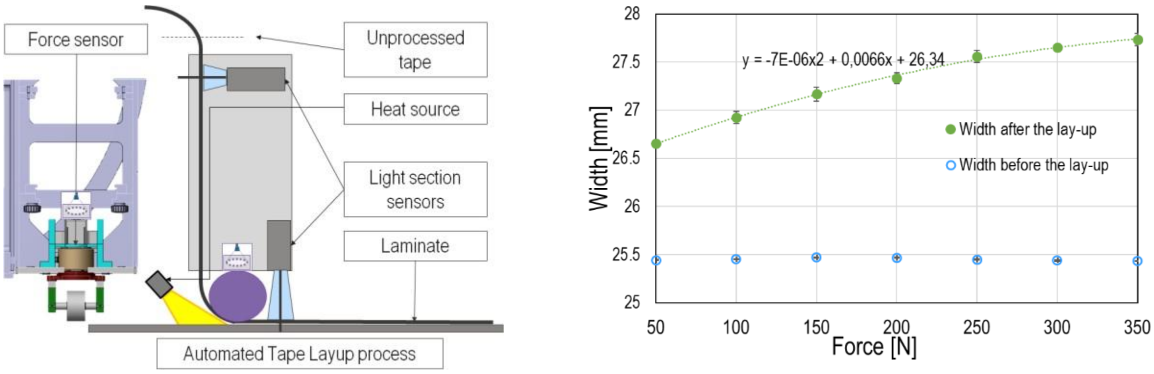

Figure 1: Modified layup head with force sensor placed above the consolidation roll (left), width and force correlation for a specific heat output (right)

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A MODELLING FRAMEWORK FOR THE EVOLUTION OF PREPREG TACK UNDER PROCESSING CONDITIONS

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Keywords: Prepreg Tack, Modelling Framework, Automated Fiber Placement

ABSTRACT

Tack, which is an expression used to characterise prepreg's stickiness, is one of the key material parameters controlling product quality in automated composites manufacturing. More specifically in the automated fibre placement (AFP) process, the tack level of prepreg directly affects the generation of defects, i.e. a higher tack value can provide a larger resistant force to out-of-plane deformation and tape buckling. Hence, the number of defects, such as wrinkles, could be mitigated if prepreg's tack performance could be adjusted. Therefore, a better understanding of tack is fundamental to the digitalisation of the AFP process which would lead to the production of parts of better quality and higher production rates.

However, despite its significance, there are no standard characterisation methods and the modelling frameworks for tack are few and far between. There is even a disagreement within the community on what physical quantity needs to be measured. This is, in part, due to the complexity of the phenomenon as highlighted in the literature (i.e., prepreg tack depends on a number of variables such as temperature, pressure, deformation rate and the measured quantities, namely peak traction and separation energy, are associated with large variability levels).

In the present contribution, a comprehensive prepreg tack modelling framework (inspired by Gutowski [1] and Forghani [2]) is proposed (as shown in Figure 1). A modified probe tack test is developed to perform the experimental characterisation of prepreg tack at different test conditions consistent with the AFP process. The obtained database forms the basis of the proposed modelling framework. The results demonstrate the model's ability to capture the non-monotonic evolution of tack with process conditions. This provides one of the building blocks for the development of an AFP simulation platform.

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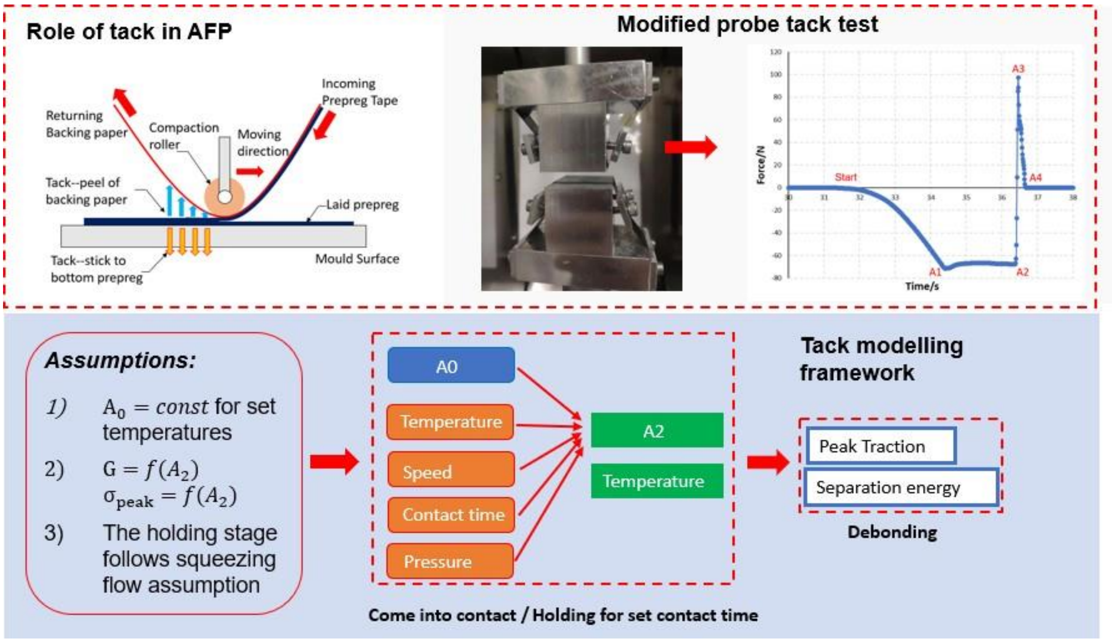

Figure 1: A comprehensive framework for prepreg tack modelling under processing conditions.

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PREDICTING THE FORMATION OF GAPS AND OVERLAPS DUE TO WIDTH VARIATIONS OF DRY-FIBER TAPES DURING AUTOMATED FIBER PLACEMENT

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Keywords: Dry Fibre Placement, Defect prediction, Predictive quality, Tapes, Virtual Manufacturing

ABSTRACT

In order to meet the expected increase in production volumes in the aerospace sector, more efficient and cost-effective solutions for the production of composite components are currently being investigated [1]. Up to now, 80 % of all composite components in the aerospace sector are manufactured with prepreg materials [2]. The subsequent autoclave consolidation of prepreg materials is time and cost intensive and therefore represents the bottleneck in the production chain. Dry fibre placement (DFP) in combination with liquid composite moulding (LCM) processes such as vacuum infusion or resin transfer moulding (RTM) offers the possibility of out-of-autoclave (OOA) production of composite components. DFP is closely related to automated fibre placement (AFP). In DFP, instead of prepreg tapes, spread tows without matrix material with a small amount of a polymeric binder material are used. The binder material ensures the necessary stability of the material and the adhesion of the plies during deposition.

However, compared to prepreg tapes, binder-fixated, dry-fibre tapes cannot be slit as accurately for means of width toleration [3,4]. They lack the matrix material that keeps the cut edges together after slitting. Therefore, dry-fibre tapes exhibit excessive fibre fray after slitting, which can cause problems during DFP processing (fuzz balls, filament accumulation on guiding elements etc.). Without slitting however, dry-fibre tapes show higher variations in width than their slit prepreg counterparts. The width variations can be as high as 10 - 15 % of the nominal width [4]. They are caused by varying spreadability of the tow due to inconsistent filament entanglement, sizing distribution and variations in the width and thickness of the raw fibre material.

During deposition in the DFP process, these width variations lead to gaps and overlaps between adjacent tows, which in turn compromise the mechanical properties of the component [5]. Approaches towards online inspection of the AFP process [6,7], which have been developed in recent years, aim to detect these defects during deposition. However, this does not prevent the defects from occurring, as they are only detected once they have been deposited. In the case of critical errors, production downtimes and scrap still occur.

The presented work aims at predicting the locations of possible gaps and overlaps by using the width profile of the tape, measured during tape manufacturing by online quality inspection, and by considering the robot trajectories, including the run-in and run-out lengths. By combining this information, an accurate prediction of gap and overlap locations can be made (see figure 1). This prediction is validated by determining the true gap locations from laser-line scanning images obtained after placement. In the next step, virtual test coupons are extracted at specific positions from the considered ply lay-up. This geometric information is then combined with the defect layer method to predict the stiffness of all coupons.

This work is a first step towards virtual manufacturing, where the as-manufactured structure can be modelled before manufacturing. By anticipating defect formation before production is started,

countermeasures such as changing the layup strategy or completely removing the faulty material sections can be taken in advance. This prevents production scrap and avoids machine downtime.

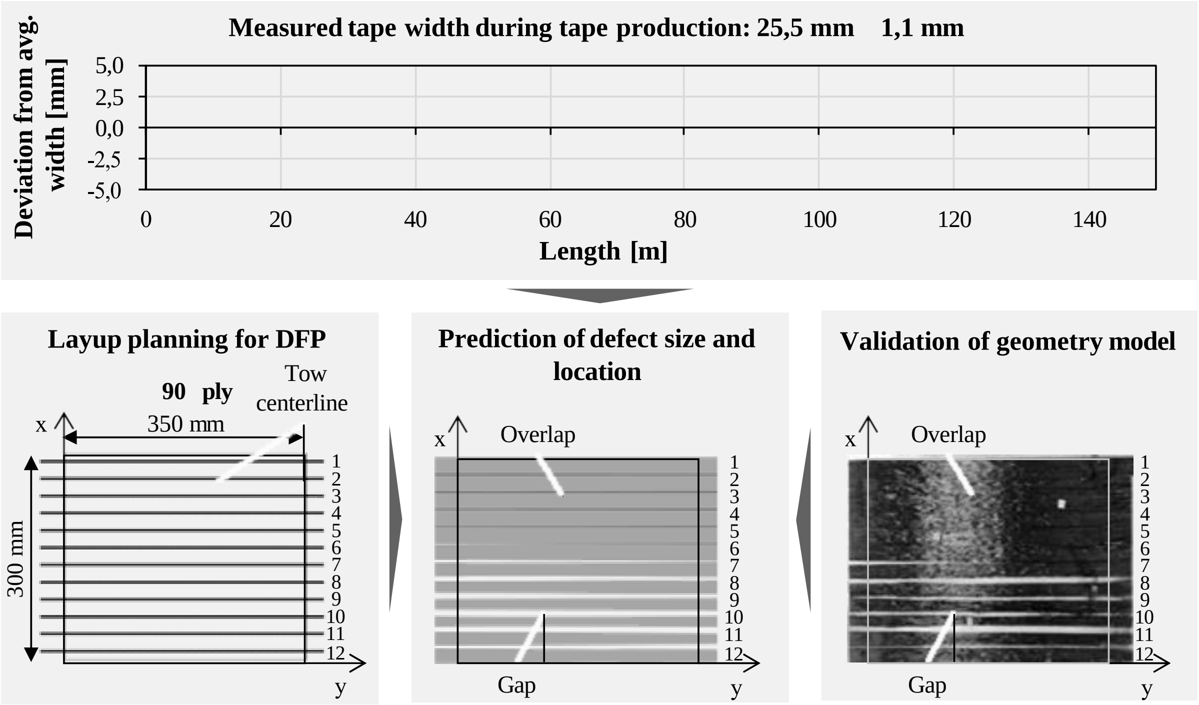

Figure 1: Prediction of the defect size, position in the laminate and subsequent FEM simulation of the defect-affected part behavior

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DEVELOPING A TESTBED FOR AUTOMATED FIBRE PLACEMENT TECHNOLOGIES

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Keywords: Automation, Fibre Placement, Digital Twin, Machine Design

ABSTRACT

Automated fibre placement (AFP) technologies are increasing in popularity in the aerospace industry for their repeatability and high production rates. Consequently, dry fibre alternatives, automated dry fibre placement (ADFP), are considered to reduce the material cost compared to the prepreg slit tapes. However, this sector demands strict quality regulations, and for large-scale parts, such as wing skins and fuselages, manufacturing defects can be expensive in terms of the waste, finance and time. This is especially true if they not detected until post-production quality inspection. It is consequentially critical that the ADFP process is fully understood, and sufficient in-process inspection is implemented, to ensure consistently high-quality manufacturing. Commercial AFP machines are vastly expensive, with very little in terms of closed-loop control. This means they rely entirely on a priori manufacturing simulations using bespoke software to control process parameters, such as motion commands and heating power. The very high cost and space requirements inherently limit the ability to investigate these manufacturing process within a lab environment.

This presentation therefore details the development of a lab scale 4-axis ADFP rig, capable of producing 2D preforms with steering and orientation control. The purpose of the machine is to enable high level investigation within a research environment of the machine, processing, and material parameters at high-deposition rates. To achieve this the development of the machine has focussed on data acquisition, via sensors, encoders, and control systems. From this, the machine can generate a “Digital Twin”, a digital representation of the real manufactured component, including design information and part data with respects to manufacturing information, inspection and simulations. The Digital Twin must be automatically generated and used-by a corresponding physical system without the need for manual intervention from the operator [1]. This requires automated exchange of information, duplex in nature, to enable manufacturing processes to be analysed and adjusted in-situ and in real time. With the generation of the large data set, this rig will explore methods of data visualisation, and extracting the important information from the raw data and the generation of a HDF5 digital twin.

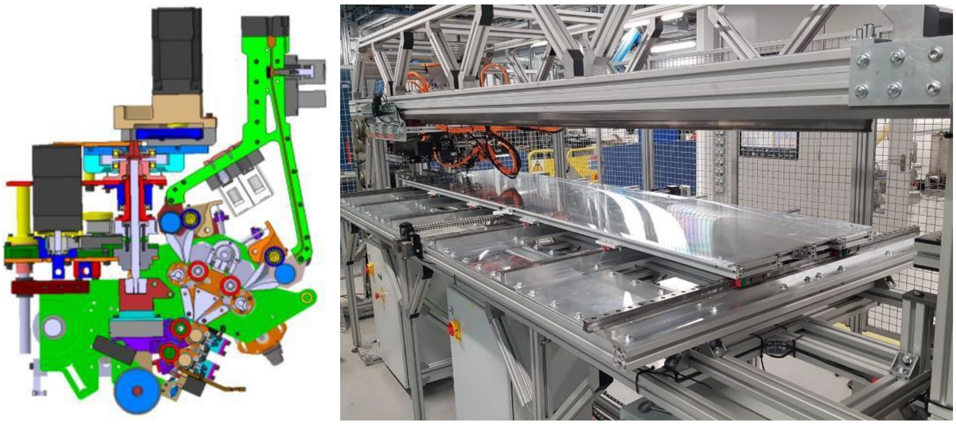

Figure 1: Lab scale, high speed rig for 2D automated dry fibre placement of carbon fibre.

The system is capable of simultaneously depositing four ¼" carbon slit-tapes at rates up to 3m/s (Fig. 1), greater than existing commercial AFP and ADFP processes which are often restricted to 1000mm/s [2, 3]. The tape's binder coating is melted by Joule heating as the electrically conductive carbon tapes pass over a pair of copper rollers allowing a current flow. Integrated into the machine is an array of sensors: IR thermometers, a 6-axis forces/torque sensor, positional micrometre and a laser line scanner and temperature information. Additionally, 13 servo motors provide positions, velocities and torque values in real-time for the machine axes, fibre delivery system and cutters, which provide an accurate mechanism with which to control tape tension and cutting precision.

In order to process the data, an Industrial PC (IPC) uses EtherCAT technology to establish communication between a human-machine interface (HMI), data server, the PLC, physical inputs and outputs (I/O), and Numerical Control (NC). This enables real-time data monitoring and logging to an external PC. The HMI and server are operated within a PC. This is the backbone of the developed rig, simultaneously performing cyclic loops at a base rate of 0.1ms and performing cyclic tasks offset from one another to prevent latency. Although the EtherCAT technology allows for short sampling rates, hardware such as the various sensors and servo drives are limited. These sampling inconsistencies have an effect on the adjustments during the high speed deposition processes. For example, travelling at 3m/s, as little as 2ms between samples suggests that the minimum travel distance before a change will be made is 6mm. Therefore, selecting a control system that can exceed the limitations of the connected hardware to prevent a 'bottle-neck' as the data is processed and exchanged between devices. This data is streamed and processed in real time to a developed HMI that both provides a visualisation of the data (Fig. 2) and writes data to a digital twin in the format of a HDF5 file. High rates of communication transfer large quantities of data from the machine or from a virtual machine (simulation) while PLC and external-programs can be used to develop and implement closed-loop control, such as real-time pressure and temperature control. The freedom to manipulate machine parameters and the abundance of information enables high fidelity evaluation during the ADFP process.

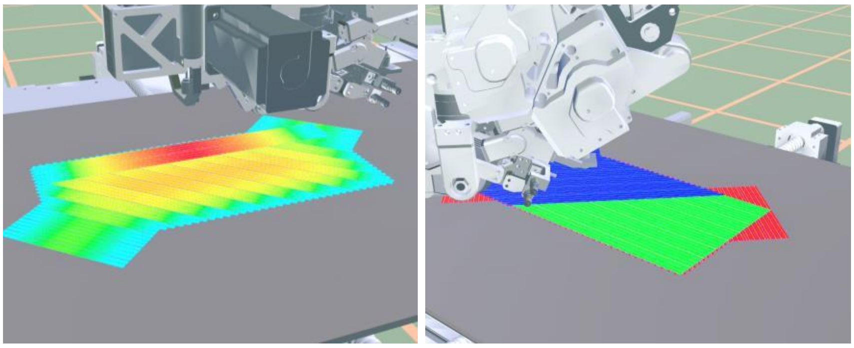

Figure 2. Data visualisation in the HMI of the ADFP manufacturing process showing deposition velocity (left) and orientation (right)

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FIBRE STEERING FOR THE MANUFACTURE OF NEXT GENERATION ADVANCED COMPOSITES

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Keywords: Automated deposition, Fibre-steering, Manufacturing process

ABSTRACT

iCOMAT (Bristol University spin-out) has developed Rapid Tow Shearing (RTS), the world's first automated composites manufacturing process (patented- GB2492594, 4 patents pending approval) that can steer fibres without generating defects, drastically expanding the design space of composite components. Effective fibre-steering is imperative to achieve low-cost lightweight parts, given the complex shape/load paths required in aerospace and automotive. Current state-of-the-art in composites manufacturing (Automated Tape/Fibre Placement - ATL/AFP) has very limited capability in achieving steering [1], which in turn limits designs to conventional laminates essentially comprising UD layers. As composites are anisotropic (stiff/strong along fibres), designing with curved fibres offers much greater flexibility with opportunities to follow the load path and the geometry of components resulting in tailored and efficient designs [2]. RTS offers the unique capability to steer without defects and can enable improved structural integrity to be achieved with considerably fewer composite layers minimising the use of raw material and in turn production costs and environmental footprint.

iCOMAT has successfully led a series of InnovateUK and ATI projects demonstrating the benefits of RTS against current state-of-the-art across aerospace and automotive applications. In specific, a lower wing skin panel was designed and manufactured achieving 65% weight reductions compared to conventional AFP, while maintaining structural integrity, whilst a series of hybrid SMC/UD automotive parts were manufactured outperforming straight-fibre parts in terms of quality, cost, rate and weight savings (30%). Additionally, iCOMAT recently designed and manufactured a thin-walled cylinder for a contract with the UK-Space-Agency (UKSA) and European-Space-Agency (ESA) achieving a weight reduction of 20% as well as an increase in buckling load and stiffness of 24% and 8% against traditional straight-fibre cylinders, respectively (Figure 1). iCOMAT, recently became the first/only UK automated composites manufacturing machine supplier by securing its first contract for a machine placement to an automotive Tier1 to produce a series of parts for a leading UK OEM.

Figure 1: iCOMAT aerospace grade fibre-steered cylinder (left), straight-fibre cylinder (right).

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SESSION 3
FORMING TECHNOLOGIES 1

FIBRE-STEERED FORMING TECHNOLOGY FOR HIGH-VOLUME PRODUCTION OF COMPLEX COMPOSITE COMPONENTS

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Keywords: Fibre steering, Continuous Tow Shearing, Automated Fibre Placement, Short-fibre composite, Forming

ABSTRACT

The automated fibre placement (AFP) process has been widely used to produce large and complex composite aerostructures, and is attracting attention from other industries as a solution for automating manual lay-up processes to improve the quality and productivity. Furthermore, it enables fibre-steered designs with structural performance superior to straight fibre designs. However, when the part geometry is small and highly complex, the advantages offered by AFP cannot be realised. As the lay-up paths become too short to accelerate the head, the machine can never reach its maximum lay-up speed. And the geometry would require fibre-steering with tight steering radii, which results in defects such as tape buckling, gaps, and overlaps. This is a significant challenge in enhancing the automation level in composites manufacturing and realising novel fibre-steering concepts.

In this work, a novel automated manufacturing technology for high-volume production of small and highly complex composite parts was developed by combining three cutting-edge technologies (material, manufacturing, simulation) developed in the Bristol Composites Institute. As shown in Figure 1, the Fibre-Steered Forming (FSF) technology developed starts from designing a flat fibre-steered preform through a Virtual Unforming simulation. In this simulation, from a target 3D preform as an input, a flat preform pattern with fibre steering paths, which can be turned into the target 3D fibre paths after forming, is obtained by reversely forming the target preform. The flat fibre-steered preform is produced by CTS (Continuous Tow Shearing) process and then formed into the target shape using a double-diaphragm forming process. The FSF process works for both continuous fibre prepregs and highly-aligned short fibre prepregs produced by HiPerDiF (high performance discontinuous fibre) process, and its feasibility and production qualities were compared numerically and experimentally.

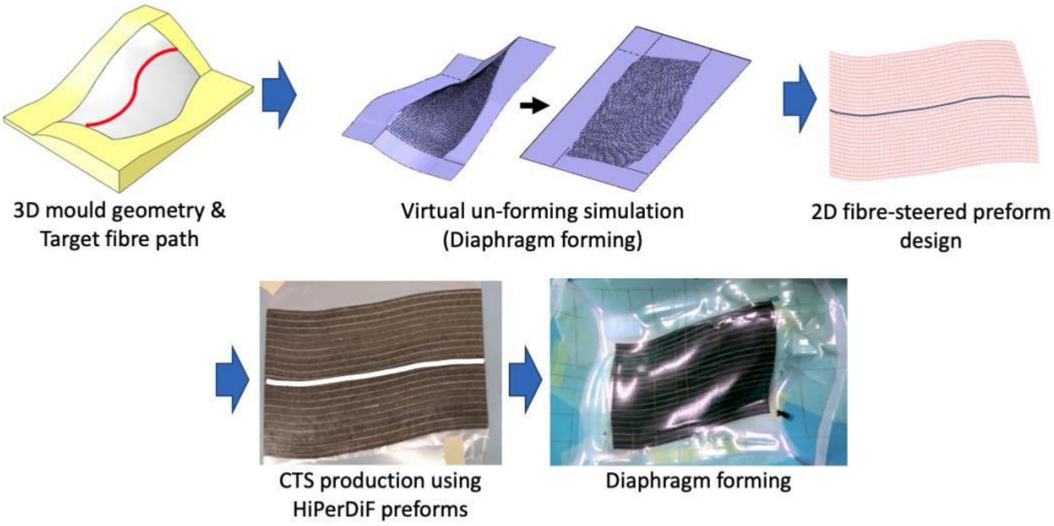

Figure 1: Process flow of the Fibre-Steered Forming Technology.

The Virtual Unforming was realised by directly reversing the forming process. An initial double-diaphragm forming simulation was first performed with a surrogate preform model with simplified material properties to extract the nodal displacement histories of the diaphragm models. Then an as-designed 3D preform model with target fibre paths was replaced with the surrogate model, and the nodal displacement histories were reversed to deform the diaphragms back to the original flat states [1]. A hybrid element, which is a shell element superimposed with a membrane element, was used to represent out-of-plane bending and in-plane material properties of the preform, respectively. Figure 2 shows the overall process of deriving a representative fibre path from the 3D target preform. After the unforming simulation, 100 mm wide carbon/epoxy prepreg tapes were steered along the representative path using the CTS process to produce the 2D fibre steered preform, as shown in Figure 3 (a) [2]. The produced preform was formed in a bespoke double-diaphragm forming rig, and the forming quality of the preform on a doubly-curved complex surface was analysed using a 3D coordinate measurement system. HiPerDiF tapes were tested in the same test framework. HiPerDiF tapes made with 3 mm long carbon fibres were used to produce fibre-steered preforms and their formability on a complex geometry tool was assessed comparatively with the continuous fibre steered preform. As shown in Figure 3 (b), it was found that the stretchability of the HiPerDiF preform offered superior formability over the continuous fibre preform.

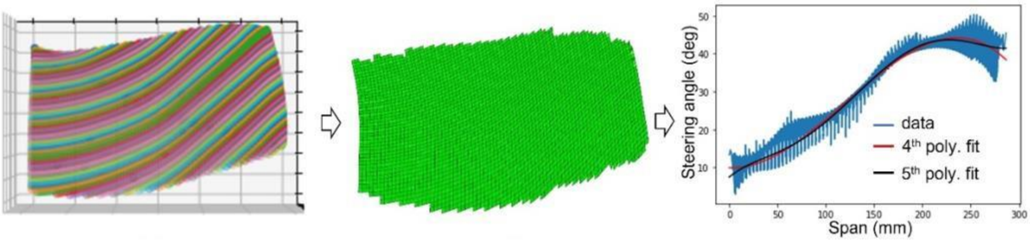

Figure 2: Overall process of deriving steering fibre path: (left) 3D ‘as-designed’ fibre orientation in code framework, (middle) 2D flattened preform after the ‘un-forming’ simulation, (right) averaged fibre angle variation along the span for CTS production.

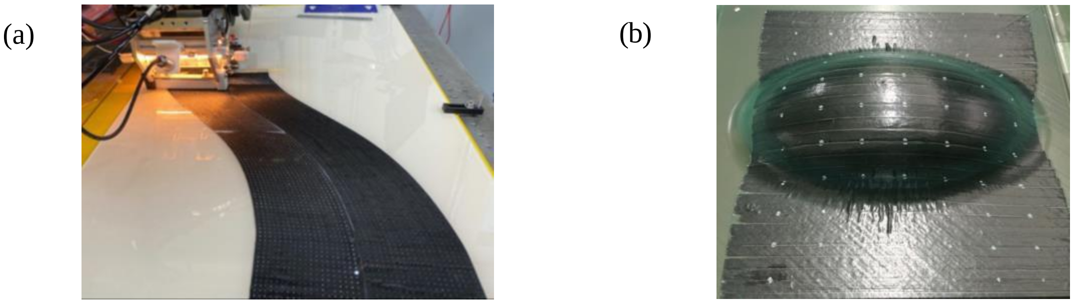

Figure 3: (a) Fibre-steered preform production using CTS process, (b) a single ply HiPerDiF preform formed on a doubly-curved surface.

ACKNOWLEDGEMENT

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FIBRE LENGTH EFFECT ON THE DESIGN OF FORMABLE LAMINATES FOR COMPLEX GEOMETRIES

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Keywords: Forming, Defects, Design, Geometry effect

ABSTRACT

Manufacturing defects, such as wrinkles, can easily occur in the forming of multi-layer laminates over complex geometries. Research has shown that besides the forming process control variables, such as temperature and vacuum pressure, the laminate stacking sequence itself has significant influence on the formed parts quality. While an index has been previously suggested to enable design of tailored stacking sequences for defect-free forming of complex geometries [1], the challenge of associating geometric features and fibre orientations with the formation of wrinkles during forming remains. Experimental results from a diaphragm forming (DF) with various stacking sequences onto a complex tool geometry with the same geometric feature, but of different lengths, suggest that the fibre length affects formability and the occurrence of defects [2].

This work introduces a simplified semi-analytical approach to assess the length effect in the formation of wrinkles during forming. A one-dimensional model is developed based on the forming kinematics (Figure 1a,b) of a flat laminate along the longitudinal direction of a spar geometry with a central recess area identical to that of [1]. Driven by the atmospheric pressure p acting on the laminate during forming, the initially flat laminate gradually contacts the tool surface in the ramped region. This results in a curvature of radius R in the laminate and the development of a membrane force T. The tangential tension T is proportional to the radius of the curvature, $T = pR$, and changes as the value of the R of the curvature changes over time as the forming progresses until the laminate reaches full contact with the tool surface.

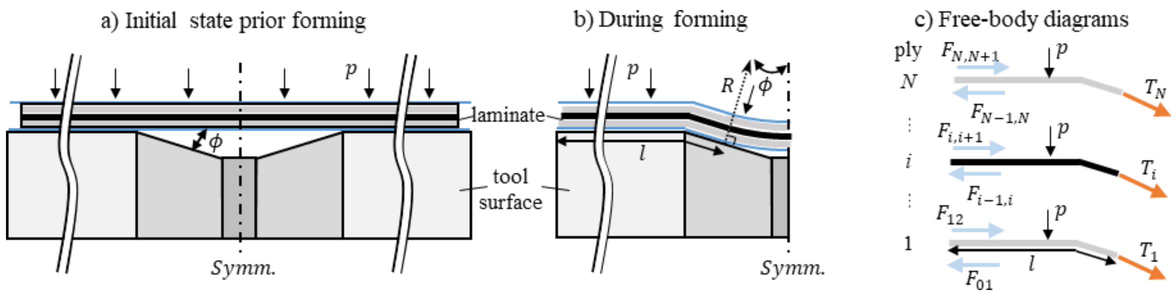

Figure 1: a-b) Schematic of forming kinematics in the longitudinal direction of a laminate; c) Free-body diagrams for each ply.

The initial flat state of the laminate suggests an infinite radius, leading to high tension T causing the laminate to slip over the tool, but over time the value of T decreases as the radius decreases. To prevent wrinkling, friction between layers must be overcome to introduce effective slip mechanisms and allow the layers to conform to the tool geometry. Considering the free-body diagrams for each ply (Figure 1c), the tension force is reacted by the inter-ply friction and laminate-diaphragm/tool friction. Assuming the curvature remains constant across the laminate thickness, for slip to occur in the i^{th} ply, the following inequality must be satisfied:

$$T_{\mathrm{h}} > F_{i-1,i} - F_{i,i+1} \quad \text{, for } i = 1 \tag{1}$$

$$F_{i-2,i-1} > 2F_{i-1,i} - F_{i,i+1} \quad \text{, for } i = 2 \ldots N \tag{2}$$

where N is the number of plies, T_{h} the horizontal component of T_i and F_{jn} the frictional force in the interface between the j^{th} and n^{th} layer, calculated as $F_{jn} = \mu_{jn}\, p\, l$, where l is the length of the fibres in contact with the tool/ply and μ_{jn} the coefficient of friction of the interface.

While inter-ply slip is desirable for the laminate to conform to the geometry creating book-ends, in this case it will also lead to excess material in the recess area, which is likely to cause wrinkling. To avoid the formation of wrinkles, the excess material will require to move either i) by inter-ply slip towards the ends, or ii) through in-plane shear in the transverse direction. Herein we investigate the former.

The wrinkling problem can be considered equivalent to the buckling of a plate of unit width on an elastic foundation [3,4]. A total potential energy can be calculated based on the combination of elastic strain energy, energy stored in the elastic foundation and work by applied loads. A critical buckling load, P_{cr}, can be obtained by minimising the potential energy with respect to the amplitude, A, of the wrinkle. Assuming deflection solutions, w, of periodic form $w = A(1 - \cos(2\pi x/\xi))$, the P_{cr} is determined by:

$$P_{cr} = 4\hat{D}\frac{\pi^2}{\xi^2} - \frac{p}{2A}\frac{\xi^2}{\pi^2} + \frac{3k}{2}\frac{\xi^2}{\pi^2} \tag{3}$$

where $\hat{D} = E_f I$ is the bending stiffness of the lamina with I its second moment of area [3] and E_f the fibre elastic modulus, k is the stiffness of the elastic foundation and ξ is the wavelength of the wrinkle.

On the hypothesis that an equivalent load to the critical buckling load that creates a wrinkle is required to remove it. This load will need to be higher than the friction developed between the ply interfaces, to enable inter-ply slip and the wrinkle not to form. Rearranging the inequality, a critical length is derived:

$$l < \frac{P_{cr}}{(\mu_{i-1,i} + \mu_{i,i+1})p} \tag{4}$$

Assuming E_f = 231 GPa, I = 2.63e-4 mm^4/mm (obtained as in [4] with fibre radius r_f = 3.5 μm for a single 0° ply), p = 0.1 MPa, k = 0.225 N/mm^3 [3], A = 0.4 mm [2], ξ = 18.3 mm and μ = 0032 [5], the model suggests that for a single ply of 0° fibre orientation not to wrinkle, a length l < 2,250 mm is required. This can justify the experimental results in [2] for spar geometry of 6 m length and the wrinkling developed in laminates with 0° plies.

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DEVELOPMENT OF MACHINE LEARNING MODEL FOR COMPOSITES THERMOFORMING PROCESS

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Keywords: Thermoforming, Machine Learning, Optimization, Artificial Neural Network

ABSTRACT

Thermoforming is a process where the laminated sheet is pre-heated to the desired forming temperature before being pressed and cooled between the molds to give the final formed part. Defects such as wrinkles, matrix-smear or ply-splitting could occur to the formed part if the process is not optimized [1]. Traditionally, for thermoforming of fiber reinforced composites, engineers would either have to perform numerous physical trial & error experiments or to run a large number of high fidelity simulations in order to determine satisfactory combinations of process parameters that would yield a defect-free part. Such methods are very expensive in terms of equipment & raw material usage, mold fabrication cost, and man-hours. In recent times, Machine Learning has been utilized across many different industries. In engineering & manufacturing, a properly trained Artificial Neural Network (ANN) can be used to develop design guidelines or provide optimized solutions that would substantially reduce the design cycle time.

For our work, the double-dome geometry is chosen as it is widely used by research groups [2,3] as a suitable benchmark for investigating of forming behavior. To build the dataset, 120 thermoforming cases were simulated using AniForm^{TM}. Varying processing parameters, such as laminate orientation, spring tensioner stiffness, preload, and grip size were analyzed. In this paper, two applications of ANN are presented. The first is the use of ANN to analyze images from simulation so as to predict the process parameters resulting in the quality of the formed product (inverse problem). Metrics such as the slip-path length (SPL) and intra-ply shear angle (SA) results were used to evaluate the quality of the thermoformed part. The slip-path length is defined as the total slip that was encountered by a certain point at the tool-ply interface as the laminate needs to slide along the tooling during press forming [1]. The magnitude of this length could give an indication of the duration a particular region was exposed to a colder tooling surface, which will give a higher possibility of surface defect as shown by Figures 1 and 2, where in-house experiments and simulations, for the thermoforming of 4- ply 2x2 Twill Carbon-Fiber Reinforced Thermoplastic (CFRTP), show good correlation between this metric and the location of matrix smearing defect.

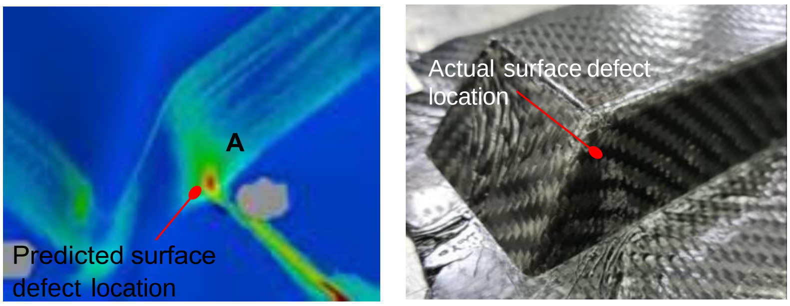


Figure 1: Good correlation of SPL parameter with actual surface defect found from thermoformed CFRTP trapezoidal profiled part

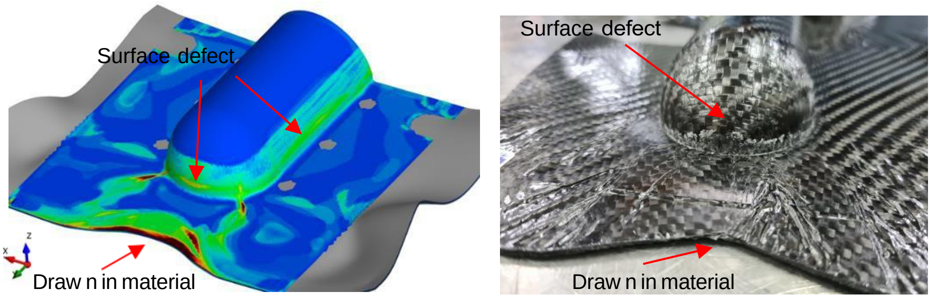
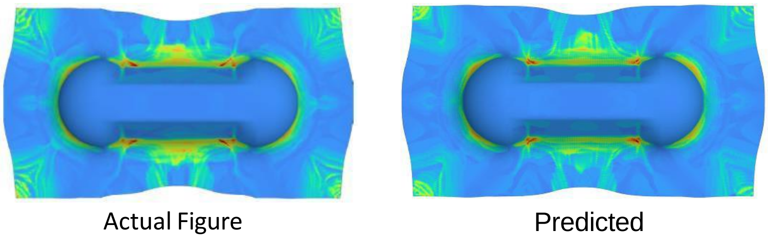
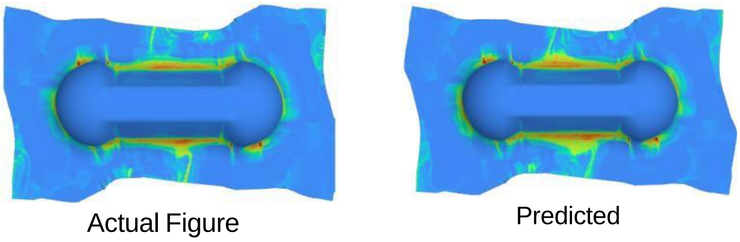


Figure 2: Good correlation of SPL parameter with actual surface defect found from thermoformed CFRTP dome profiled part

Contour images of thermoformed laminate are collected as input data. The novelty of this work is that it is the first to report image-analysis method of approach in ML/NN related to Thermoforming CFRTP composites. This method can be extrapolated to use actual photos of parts post-formed or during in-situ process via incorporation of computer vision. The Convolutional Neural Network (CNN) is used to process the images to extract features as inputs for the machine learning. The predicted parameter outputs are used to rerun the Thermoforming process simulation in AniForm^{TM} in order to obtain the SPL contours for visualization comparison. Figure 3 shows some cases of relatively good prediction of process parameters from the ANN.



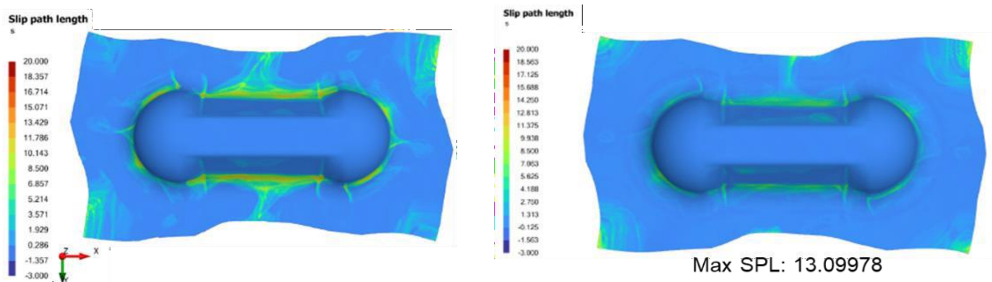
Actual parameters: **45/45** Laminate, S0.25, PL8, Point (Grip0)
NN prediction: **45/45** Laminate, S0.27 PL6, Grip4



Actual parameters: **15/15** Laminate, S0.5, PL8, Grip8
NN prediction: **15/15** Laminate, S0.49, PL5, Grip8

Figure 3: Comparison of predicted process parameters from ML versus actual parameter used and the resulting SPL contour plots from AniForm^{TM} simulations.

Besides having lower maximum slip path length, it is also desired for greater ply shear angle coverage of the formed parts to be within the criteria of 40 to 50 degrees, so as to promote better laminate formability and reduce possibility of wrinkling. The second application is the use of ANNs to predict the process parameters that would result in minimal slip path length and also to optimize/maximize the proportion of nodes that have the ply shear angles between 40 to 50 degrees. Figure 4 shows the best cases in the original dataset and the optimized cases using the ANN predicted parameters. The optimized outputs from ANN are used to re-run the AniForm^{TM} simulation to visually validate that the overall SPL contour has indeed been reduced or that the shear angle coverage has indeed increased.

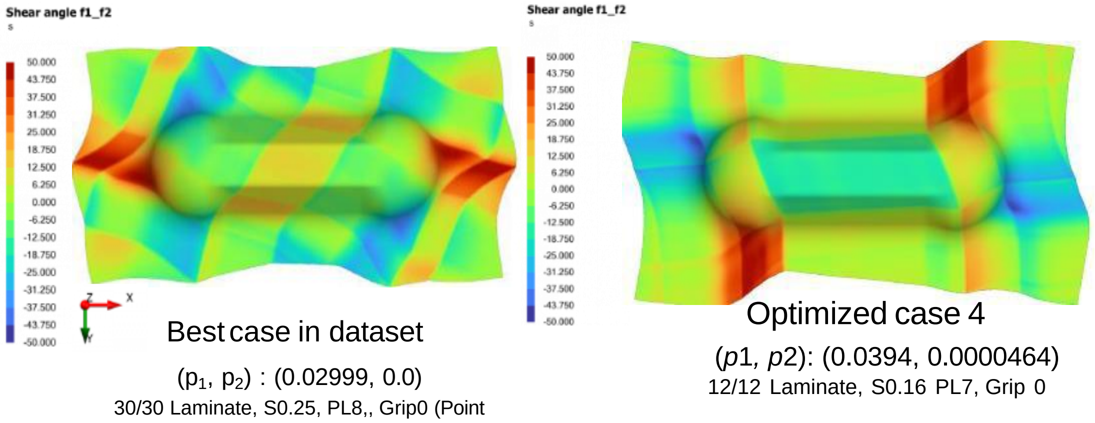


Best case in dataset

-30/-30 Laminate, S0.5, PL2, Grip8

Optimized case

34/34 Laminate, S0.18, PL1, Grip6



Best case in dataset

(p_1, p_2) : (0.02999, 0.0)

30/30 Laminate, S0.25, PL8,, Grip0 (Point

Optimized case 4

($p1$, $p2$): (0.0394, 0.0000464)

12/12 Laminate, S0.16 PL7, Grip 0

Fig.4 Comparison of contours plots for optimized parameters versus best case parameters in dataset.

The ML models are shown to be able to predict relatively well the process parameters yielding the final SPL contours, as well as in effectively optimizing the process parameters to form a better quality product. Data-driven models seems to tell us that the optimized laminate orientation is not at 0 or 90 degrees, and neither at 45 degrees. It is slightly less than 45 degrees. Secondly, lower preload and a mid-size grip seems to correspond to a lower possibility of surface defect, while a larger preload and point grips seem to correspond to better ply shear angle coverage.

The ANN code and capability has been developed in IHPC. To the best of the authors' knowledge, the approach presented here is novel as there is no prior reported work on applying image analysis method in Machine-Learning for composite thermoforming. This opens up the possibilities of using photos from physically formed parts for the manufacturing optimization process. This pioneer work would help lay the foundation for further research to consider other challenging aspects of data driven models and robustness.

We acknowledge the thermoforming experimental results provided by SIMTech (A*STAR) for simulation correlation. The work is made possible through an Industry Alignment Fund on the Polymer Matrix Composites Programme (PMCP), with grant no. A19C9a0044.

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SESSION 4
FORMING TECHNOLOGIES 2

FORMING PROCESS SIMULATION AND EXPERIMENTAL VALIDATION

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Keywords: Forming, Prepreg, Process Simulation, Finite Element Analysis, Manufacturing Defects

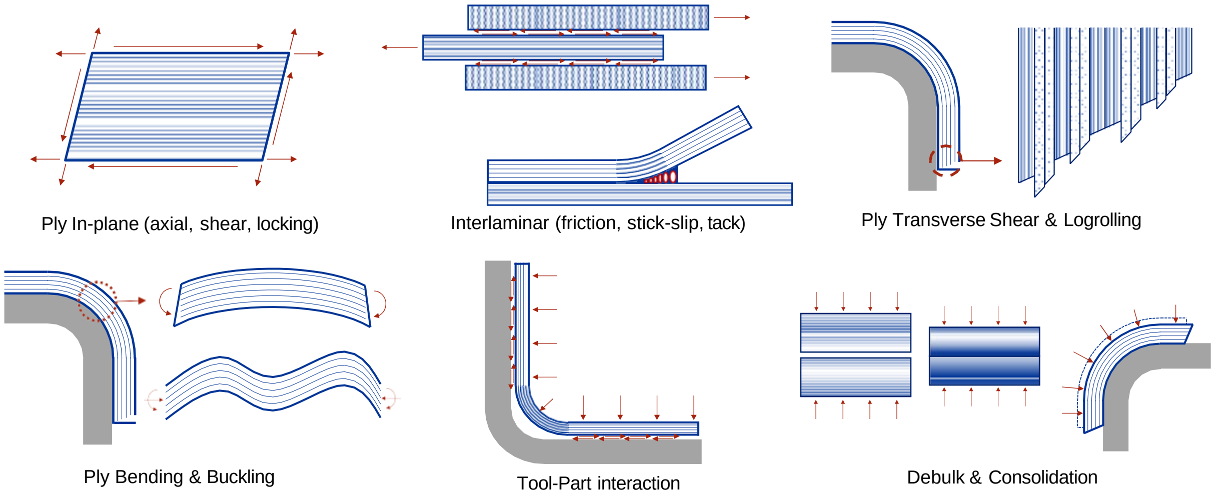
ABSTRACT

Forming of composite materials is an attractive manufacturing option for aerospace primary structures but often presents challenges in terms of defects, including fibre wrinkling, buckling and waviness. The National Research Council Canada has developed a suite of forming processing technologies that feature knowledge of resin rheological and cure behaviour, and inter-ply migration and defect avoidance strategies. These are facilitated by thermal and deformation management through the use of localized and accurate manipulation of viscosity and ply movement. Ongoing efforts are applying process simulation to aid integration of the technology within automation cells.

Convergent Manufacturing Technologies is speeding the digital transformation of the process for efficient, high quality part production through the application of simulation tools. Convergent's forming solution includes a comprehensive set of materials characterisation which feeds physics-based forming simulation using COMPRO/Abaqus modelling platform. The material characterisation covers the key aspects of prepreg deformation and ply interactions during the forming process including ply bending, in-plane shear, transverse shear and inter-ply tack [1] (Figure 1 and Figure 2.a).

Convergent has developed two levels of Finite Element based forming simulations: shell-based, and shell+solid-based representations [2]. The shell-based approach, which is common in forming simulation, represents plies (or a stack of plies) using shell elements. This approach allows for efficient modelling of ply bending, in-plane shear and ply-to-ply interaction. The shell+solid ply representation offers a more refined description of intraply transverse shear and through-thickness consolidation. This approach is required when consolidation driven wrinkles are among the outcomes of interest. COMPRO's forming simulation solutions can predict the effect of tool and part geometry, as well as process conditions on part formability and defects formation.

Forming trials have been performed on a typical airframe hat stiffener and C-shaped spars. Laminate thickness, lay-up, debulk conditions and forming temperature are among the parameters that were investigated. Embedded tracers, profilometry, sectioning, microscopy and x-ray imaging were used to measure laminate deformation and ply movements. Outcomes of these tests are used for model validation, where laminate deformation, relative ply movements and defects (e.g. wrinkles) are compared to simulation predictions. The processing window was developed based on the material matrix key parameter, preferred ply migration, corresponding thermal strategies, and deformation mechanisms, while process robustness is validated through repeated trials.


Ply In-plane (axial, shear, locking)

Interlaminar (friction, stick-slip, tack)

Ply Transverse Shear & Logrolling

Ply Bending & Buckling

Tool-Part interaction

Debulk & Consolidation

Figure 1: Key deformation mechanisms in forming process

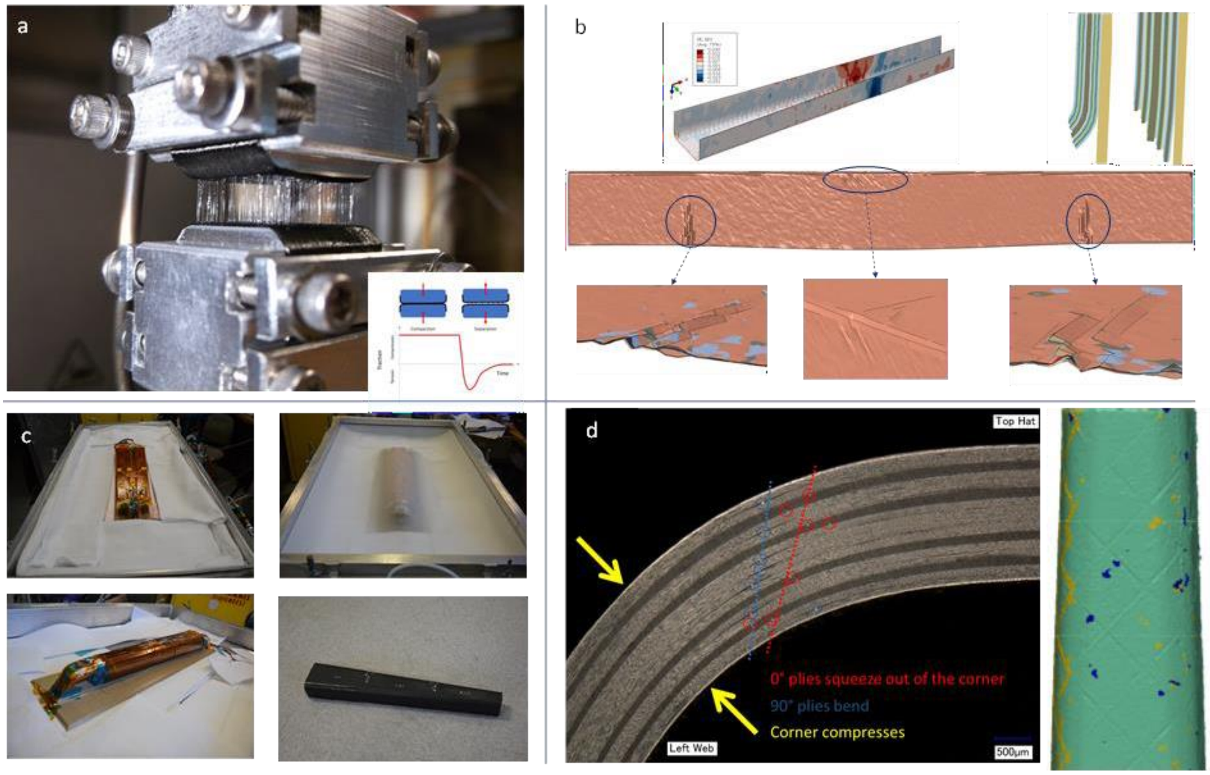


Figure 2: a) Characterisation, b) Forming simulation, c) Forming trials, d) Evaluation

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STACKING SEQUENCE SELECTION FOR DEFECT REDUCTION IN FORMING OF LONG COMPOSITE SPARS

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Keywords: Diaphragm Forming, Length-effect, Design for manufacture, Non-standard ply angles

ABSTRACT

Future aerospace composites will need to be manufactured at high rates to meet the demands of new markets. Recent aircraft such as the Airbus A350-XWB and the Boeing 787 are manufactured using Automated Fibre Placement to control quality in regions of complex curvature such as wing spars. The cost and rate of production for these aircraft will not be suitable for new platforms. Productivity can be increased by automating the forming of parts from flat laminates of dry or pre-impregnated plies if defects, such as fibre wrinkling can be eliminated or reduced to within acceptable limits.

Studies (e.g. [1,2]) have shown that the laminate stacking sequence has a strong influence on formability, as the interaction between adjacent plies can restrict shear, causing wrinkling if inter-ply slip is constrained. While the tendency of wrinkles to occur in different stacks can be accurately predicted using Finite Element simulations (e.g. [3]), such simulations have unsuitably high run time for design applications. A rapid analytical metric, the "Compatibility Index" (C_{max}) [1], has been developed for assessing the formability of different stacks based upon the compatibility of resin- dominated deformation modes across adjacent plies. This index was validated by achieving good correlation with levels of wrinkling observed in laboratory-scale (0.5m) spars, manufactured via Double Diaphragm Forming over a male tool with a central, recessed “joggle” feature. This metric has yet to be assessed in application to longer, industrial-scale components.

Three 6m long spars using the same joggle feature as [1] have been manufactured, with tool geometry illustrated in Figure 1. It is proposed that forming long spars containing 0° plies into the joggle will lead to more wrinkling than in shorter spars due to a “length effect”, wherein high inter-ply friction prevents slip, leading to compressive forces in the fibres of the 0° plies which cannot change length to conform to the tool surface. Using non-standard ply orientations in place of the commonly used 0°, ±45° and 90° plies, may mitigate against this effect, as such plies can deform into the joggle via in- plane resin-dominated modes, and forming is therefore less reliant upon inter-ply slip. The layups of the three spars are shown in Table 1, with compatibility index [1] used to predict formability based upon small-scale trials. Two stacks are comprised of standard-angle plies: i) with low C_{max} indicating poor formability and, ii) with a higher C_{max} indicating good formability. The ply angles in Spar iii) are chosen to match the in-plane stiffness of Spars i) and ii) [4], with layup which maximises C_{max}.

The spars were manufactured using Single Diaphragm Forming (SDF) of flat, 6.0m × 0.3m 24-ply stacks of a Cycom HTS 977-2 prepreg, using a highly extensible Stretchlon® 200 membrane as the support diaphragm, with the entire rig contained within an outer vacuum bag. Forming was undertaken at 90°C, with a vacuum drawn in the cavity between the outer bag and the base of the forming rig causing the laminate to conform to the tool surface. Each forming operation was completed in the region of 10 minutes following application of this vacuum. Following forming, metrology scans were undertaken using a Hexagon 7-axis laser scanning arm to inspect the geometry of the formed spars. Thickness maps generated from this metrology data are shown in Figure 2.

Wrinkles were observed in the centres of Spars i) and ii) after forming, whereas no clear wrinkles were observed in Spar iii). Spar ii) was the most heavily defected, with the largest wrinkle having amplitude

0.879mm, whereas in Spar i) the largest wrinkle had amplitude 0.435mm. The discrepancy between predicted and observed formability in Spar ii), which was had a higher C_{max} value than Spar i), could be indicative of the length effect, although further trials are advised to ensure this result is repeatable. The marked improvement in the quality of Spar iii) compared with Spars i) and ii) is, nevertheless, a clear indicator of the benefits of using non-standard ply angles in the forming of long spars.

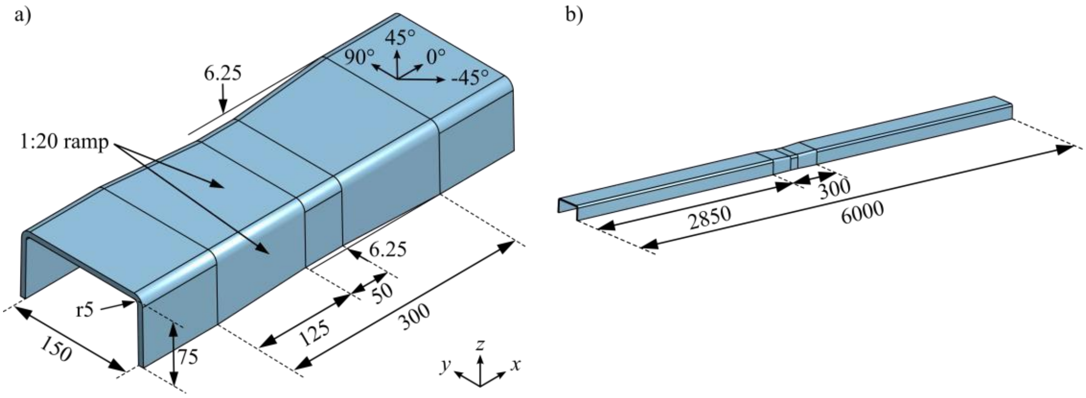

Figure 1: Geometry of forming tool: a) detail of central recessed “joggle”, b) overall spar geometry.

Spar	Layup	C_{max}
i) Benchmark	$[\pm45/90/0/\mp45]_{2S}$	0.69
ii) Optimised Standard angle	$[(\pm45)_4/(0/90)_2]_S$	0.91
iii) Optimised Non-standard angle	$[(27/-63)_3/(-27/63)_3]_S$	0.94

Table 1: Stacking sequences and values of C_{max} for each of the spars from the forming trials.

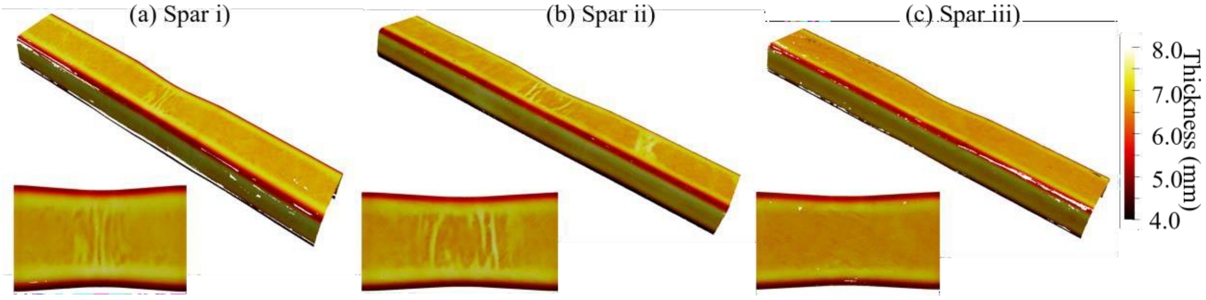

Figure 2: Thickness maps of spars, measured from the metrology scans undertaken after forming.

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AFP INSPECTION: FROM OCT A-SCANS TO THE DIGITAL TWIN

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Keywords: AFP, In-Process Inspection, OCT

ABSTRACT

In addition to the traditional, finished part dimensional verification and quality reports, the AFP process requires a ply-by-ply inspection of the as-built laminate to ensure that each layer in the ply stack conforms with the manufacturing allowable specifications. This requirement introduces complexity and significant overhead to the layup process.

To address this problem, Fives and the National Research Council Canada have proposed an In- Process Inspection system based on Optical Coherence Tomography (OCT) technology that can perform high-resolution surface profilometry simultaneous to layup and automatically align the as- manufactured measurements to the as-designed engineering model. Accurate surface profile measurements and a rigorous sensor spatial calibration procedure are key enablers to compare fabrication data to the CAD design reference. Once these two datasets are matched, the differences can be analysed to differentiate features inherent to the AFP process and detect manufacturing defects using robust disposition criteria. This work describes the technology and methodology enabling the analysis pipeline from individual depth measurement points to course, ply, and laminate level aggregations.

OCT technology is extensively used in medical applications for its ability to sense through the thickness of biological tissues using interferometry, providing a high-resolution through-depth measurement called an A-scan. Scanning this beam enables the reconstruction of complex 3D objects. In the current work, this technology is used for surface profilometry, where a peak in the A-scan signal corresponds to the position of the measured surface. The scanning head, mounted on the AFP machine behind the compaction roller (Figure 1), sweeps this beam laterally to acquire measurements across the compaction roller width, referred to as profiles. As the sensor is mounted on the AFP head, it scans along the course during material deposition, enabling full In-Process Inspection.

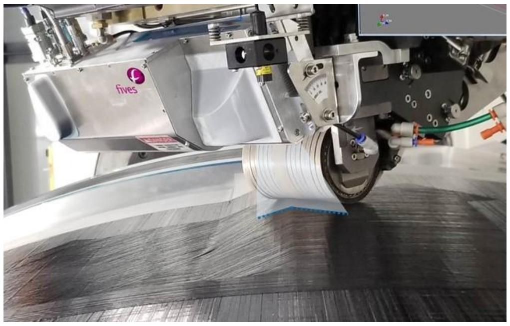


Figure 1: Scanning head mounted on a Viper 4000 Automated Fibre Placement Machine

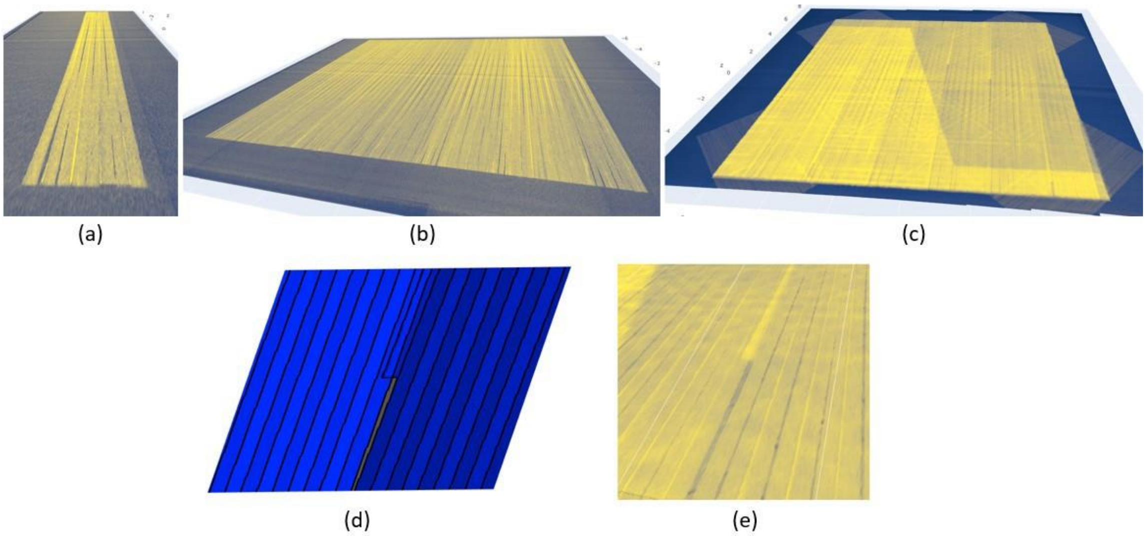
Accurate surface reconstruction is enabled with precise characterization of the following:

1. Scanning head position with respect to the machine Tool Centre Point (TCP).
2. Machine TCP position and orientation during the process and transformation of the as-installed tool location to the design.
3. Synchronization between the inspection system measurements and machine motion.

Measurements originate in the Sensor reference frame, as mounted behind the compaction roller. A methodology was developed to find the scanning head position with respect to the TCP (Fig 1), utilizing the inspection system's own capabilities as a surface profilometer. By scanning an alignment plate with known geometric features, the 6 degrees of freedom (3 translations, 3 rotations) required to express the scanning head position relative to the TCP can be calculated.

With knowledge of scanning head position with respect to the TCP, the measurements can also be described in the TCP reference frame. Furthermore, as the TCP reference frame and tool surface position and orientation are known throughout the process (see 2 and 3 above), the measurements can be described in any reference frame to facilitate comparison with the Design Intent.

The Digital Ply book contains information about both the Design Intent and Manufacturing Allowables. For example, the Design Intent contains the programmed tow add / drop location with specific tolerances for all tow lanes of the band being deposited. The inspection system compares the located measurement data with the Design Intent and uses Manufacturing Allowables to evaluate discrepancies between them. This analysis is performed during material deposition, evaluating a number of possible discrepancies such as gaps, laps, tow add or drop position, etc. In addition to the current course being deposited, because the data is automatically transformed to a common reference frame, the precisely located 3D point cloud can be evaluated for Ply-level and Laminate-level allowable criteria, such as splice density per area (considering previous plies). Measurements of a flat component at various stages of completion is shown in Figure 2, with an example of Design Intent.



(a) (b) (c)

(d) (e)

Figure 2: Course (a), Ply (b) and Laminate (c) measurements during fabrication.
Design intent with 50% coverage (d), corresponding measurements (e).

The methodology described enables the accurate positioning of measurements from a head-mounted sensor for evaluation with the Digital Ply book. The In-Process Inspection system described is paving the way for long-desired digital twin for the Automated Fibre Placement process.

SESSION 5
DEVELOPING TECHNOLOGIES

INFLUENCE OF TOOL ORIENTATION ON THE DRAPEABILITY OF UNIDIRECTIONAL NON-CRIMP FABRICS

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Keywords: Forming Defects, Uniaxial Non-Crimp Fabrics, Gapping, Design for Manufacturing

ABSTRACT

The automation of out-of-autoclave processes, such as Liquid Composites Mouldings (LCM), has become an attractive solution to reduce the extensive manufacturing costs of composite parts enabling the implementation of high-volume production. However, the automation of LCM is currently held back by the high cost of preforming, in part due to the limited understanding of the manufacturing defects in dry fabrics forming. Among dry fabrics, non-crimp fabrics (NCF) have attracted the attention of the composite industry due to their outstanding mechanical performance and ability to drape onto three-dimensional shapes [1]. NCF materials consist of single (uniaxial NCF) or multiple (multiaxial NCF) layers of fibrous yarns stitched together by warp knitting. The forming defects, such as out-of-plane wrinkles, of multiaxial NCFs were found by Viisainen et al. [2] to be highly dependent on the geometrical features of the tool. Geometries with fewer sharp corners produced fabric preforms with less defects. For uniaxial NCFs, the characterisation of their draping mechanism has been limited to single-layer draping of hemisphere-like geometries [3]. Due to the geometrical isotropy of the tool, the draping behaviour was independent of the orientation of the uniaxial (UD) NCF. The draping behaviour of UD NCFs for anisotropic geometries has not been fully understood yet. Therefore, the present work aims to assess the drapeability uniaxial NCFs on corner-like geometries that are found in wing spar forming, where the fabric orientation varies with respect to the tool primary direction.

The draping behaviour of the uniaxial NCF FCIM356 with carbon tows and glass yarns stitched together by polyester yarns in a tricot pattern was investigated using the experimental set-up in Fig.1. Round specimens with 380 mm diameter were formed over a male-only punch at a constant speed of 1 m/s. A triangular prism punch of 75 mm forming height was used to enable the control of the relative angle between the fabric and the tool. The direction of the fabric was defined by the orientation of the carbon tows. The primary direction of the tool was governed by the orientation of the edge that connects the apices of the side triangles. Three forming configurations were investigated: 0° when the carbon tows were initially parallel to the tool direction; 90° when the carbon tows were initially perpendicular to the tool direction; 45° was the intermediate configuration to assess the anisotropy behaviour of the fabric material. The deformations of the fabric surface were measured by an Aramis 3D-DIC system mounted on the top of the test rig frame. Since the carbon fibres changed orientation during the tests, the strain map was calculated in the material coordinate system.

A gapping defect was the predominant forming defect observed during draping due to the severe transverse extension applied to the carbon fibre tows in forming the material. By correlating the DIC images with the strain calculations, it was observed that gapping initiated at a transverse strain of around 0.08. For all configurations, transverse strains localised near the apices of the triangular faces but their intensity differed according to the relative angle between the carbon fibres and the tool direction, as shown in Fig. 2a. The 45° configuration exhibited the largest transverse strains. However, the 0° configuration produced the widest gapping area, as for large punch displacements (greater than 40 mm) gapping initiated near the top and bottom edges of the prism base. When the UD NCF was oriented at 90° with respect to the tool direction, the largest draping loads acted along the direction of the fibres and small strains were measured in the transverse direction. Therefore, gapping was only observed in the sharpest corners of the prism, near the apices of the triangular faces.

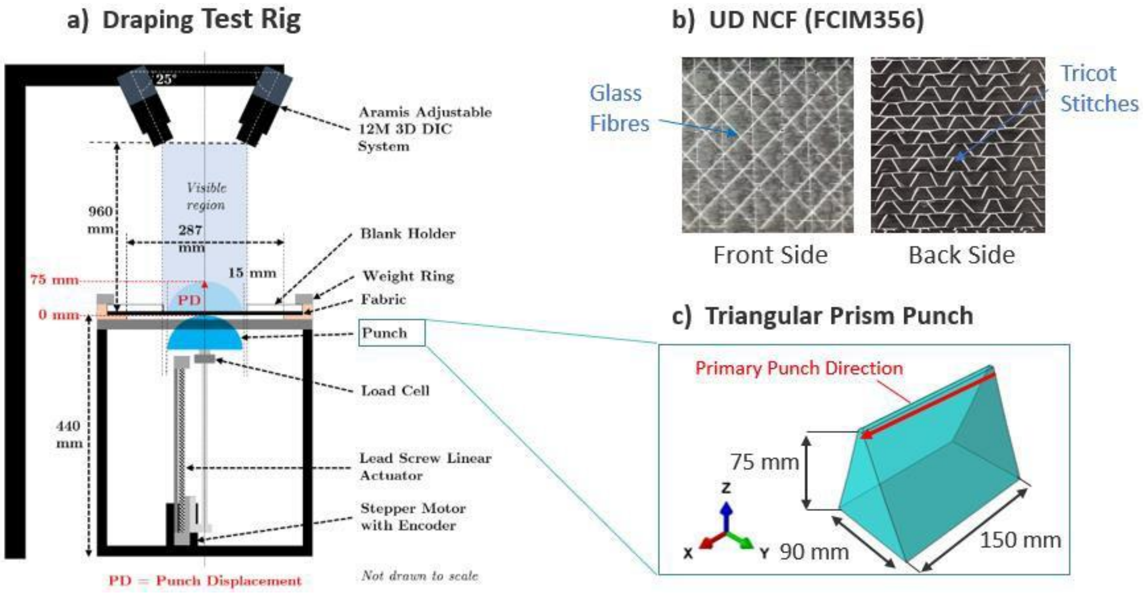

Figure 1 Experimental draping set up: a) test rig designed by Viisainen et al. [2], b) unidirectional dry fabric material and c) nominal dimensions of the punch.

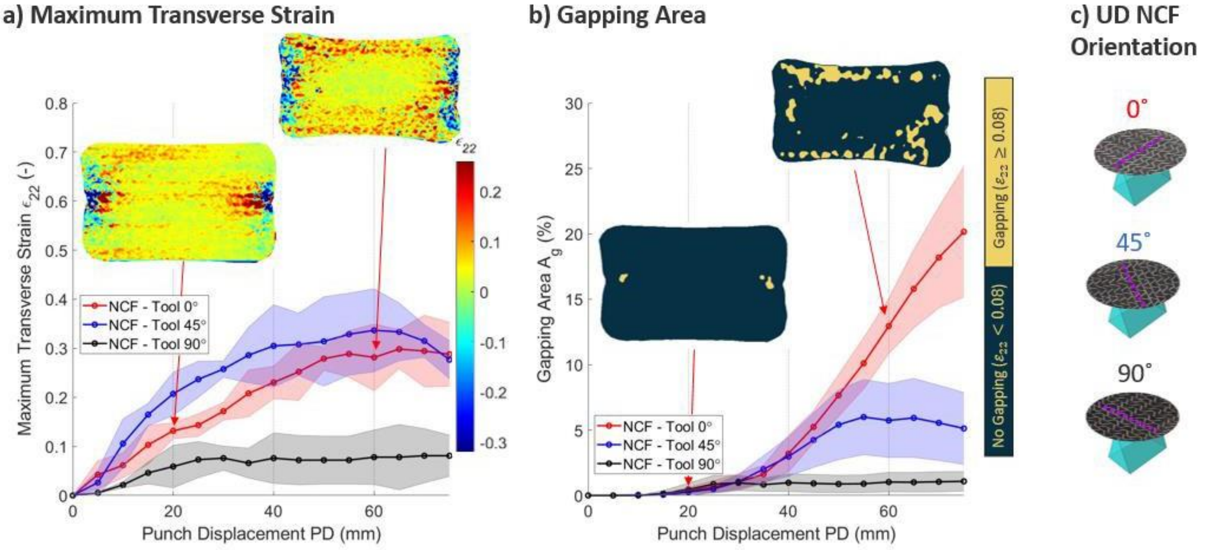

Figure 2: Evolution of a) maximum transverse strain and b) gapping area during draping tests for c) unidirectional NCF orientated at 0°, 45° and 90° with respect to the punch primary direction. Standard deviation plotted as a shaded area. Images of transverse strains and gapping area maps were displayed for 0° orientation at PD=20 mm and PD=60 mm.

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DETERMINATION AND IMPACT OF FIBRE ANGLE DEVIATIONS IN AUTOMATED PROCESSING OF CARBON FIBER NON-CRIMP FABRICS

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Keywords: CFRP, non-crimp fabrics, fiber angle, continuous wet draping, rotor blade

ABSTRACT

Automated production technologies such as draping are increasingly being used to produce dry fibre preforms for structural components made of carbon fiber reinforced plastics (CFRP). The manufacturing advantage over prepreg processes lies in the formability of the dry fibres and textile semi-finished products and thus in the possibility of complex shaping. However, this flexibility is accompanied by a change of fibre orientation during processing, which in turn significantly determines the mechanical properties of the composite material. Even small fiber angle deviations of a few degrees can have a significant impact on the mechanical properties of the final component. Consideration of this variance can so far only be taken into account to a limited extent in the development of fibre composite components, as the relationships between manufacturing effects and the mechanical properties are not comprehensively known [1].

In the automated processing of dry non-crimp fiber fabrics (NCF), fiber angle deviations are caused by the draping process on double curved surfaces and by influences of the production technology. While state of the art draping of NCF materials especially onto 3D surfaces is dominated by a large amount of manual labor, the in-house developed continuous wet draping (CWD) [2] offers an automated method of processing.

The presented research work deals with the determination of fiber angle deviations in the CWD process and an estimation of their impact on mechanical component properties. Investigations are carried out in a novel automated production process for small rotor blades used in tidal power plants. Based on a near-process 3D scan fiber angle deviations are determined (Figure 1 a) of the draped fiber material of each individual layer. Since NCF have a characteristic surface waviness due to the aligned rovings, the fiber paths can be identified by analysing the surface topography. A draping and process simulation (Figure 1 b) is used to estimate the fiber angle distribution and fiber deviations resulting from drape on a complex 3D surface. Accordingly, by comparing both sets of data, conclusions can be drawn about production-related fiber angle deviations (Figure 1 c).

In order to determine their impact on the final component's mechanical properties, a Finite Element structural model (Figure 1 d) with variable fiber trajectories is developed. In most FE simulations, the fibre directions in the NCF are assumed to be initially uniform with the design direction, neglecting any variability in fiber orientation [3]. In order to map the real fiber orientation more accurately an interface is used to import captured fiber angle deviations into the model.

Stress calculations and the comparison to a reference model indicate the impact of the fiber angle deviations on the mechanical properties. Thus, the investigations on the rotor blade have shown an 8 % decrease in bending stiffness and a 5 % decrease in component safety. This reduction in strength is caused by the change in fibre architecture during the draping process. The evaluation of simulation and measurement data results in an averaged fibre angle deviation of 4 °, compared to the fibre direction in the designed component. In perspective, with the knowledge gained about the strength and stiffness reductions, the FE-model can be used to analyse and compare different compensation measures e.g. by adding additional laminate layers.

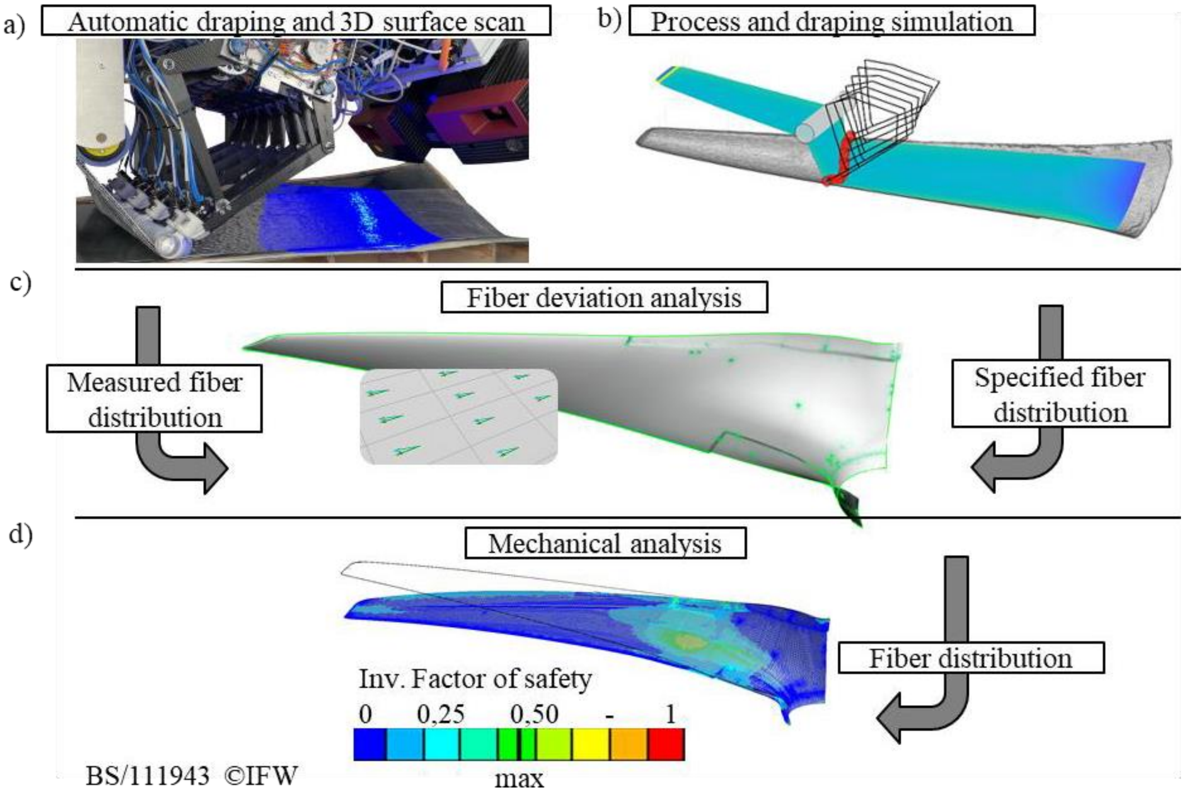

Figure 1: a) Automatic draping process and 3D surface scan b) Process simulation with included draping simulation c) Fiber deviation analysis d) FEM-Model for mechanical Analysis

With regard to future work, the measurement procedure and the analysis methodology as presented here for the CWD can also be transferred to other manufacturing processes for dry fibre preforms. This would make it possible to compare different manufacturing processes and their impact on mechanical properties. Further investigations are conceivable in order to apply the approach simultaneously in the manufacturing process.

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HIGHLY ALIGNED DISCONTINUOUS FIBRE COMPOSITE FILAMENTS FOR FUSED DEPOSITION MODELLING: INVESTIGATING THE EASE OF PRINTING

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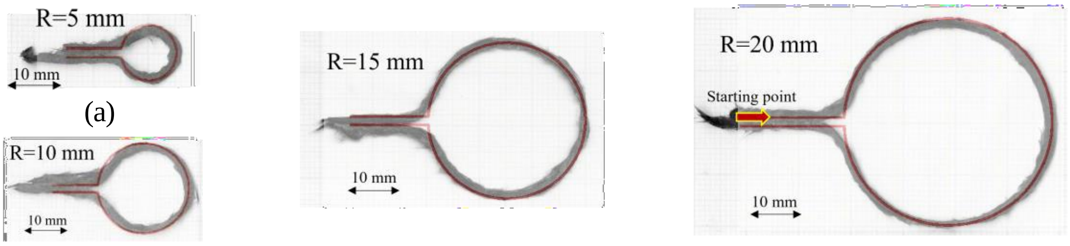
Keywords: Aligned discontinuous fibre composites, fused deposition modelling, thermoplastic composites, additive manufacturing, 3D printing.

ABSTRACT

Fused deposition modelling (FDM), a thermoplastic, layer-by-layer, additive manufacturing technique, can quickly build complex geometries, reducing design limitations and production costs compared to conventional manufacturing methods. Using a fibrous reinforcement strengthens the thermoplastic matrix, allowing FDM to be used in the manufacture of small and complex structural components. Aligned discontinuous fibre composites (ADFRC) incorporate a high-performance reinforcement architecture that, owing to a sufficient fibre length and high level of alignment, results in mechanical performance compared with those of continuous fibre composites. Moreover, it can offer higher formability and reduce manufacturing defects. ADFRC preforms, produced with the High Performance Discontinuous Fibre (HiPerDiF) technology, were impregnated with poly(L-lactic acid) (PLA) and then hot-rolled into an FDM filament, with a circular cross section, using a purposely built semi-automated roller moulding and pultrusion device. The resulting circular filament with a 1-mm diameter can be fed into any general 3D printer with a simple machine modification, *i.e.* nozzle replacement. Single-layer tensile specimens were 3D-printed with this filament, with a fibre content between 35 and 42% by volume, and show superior tensile properties compared to other 3D printed PLA composites from the literature. As a result of the high formability of the HiPerDiF reinforcement, the filament can be 3D-printed to certain complex geometries, *e.g.* a braced aerofoil shape. Moreover, the finer filament diameter, when compared to thinner and wider conventional composite tapes, allows for the fabrication of small scale parts that cannot be produced with automated tape layup. In this work, the steering limitation of the filament is studied by printing different radii of curvature to identify the printing procedure that allows it to achieve the smallest printing radius.

High Performance Discontinuous Fibre (HiPerDiF), a novel fibre alignment technology, invented and patented by the University of Bristol, allows for the production of aligned discontinuous fibre preforms which may be used to reinforce various types of polymeric matrices, *e.g.* thermosetting, thermoplastic, or vitrimeric [1-3]. In this study, there are two constituents: commercial 3 mm chopped C124 carbon fibre and poly(L-lactic acid) (PLA). After passing the fibre through the HiPerDiF process, the HiPerDiF preform and thin PLA 3D printed film were consolidated into a composite tape using heat and compression. Then, the tape was bulked up by feeding it through the tuned gap between two heated rollers to make a square-like cross section. Finally, the square filament was pultruded through a convergent nozzle to make a filament with a circular cross section of approximately 1 mm diameter.

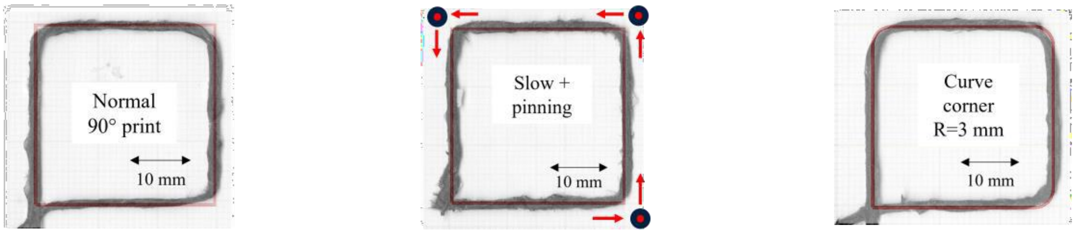
The printability of the filament was initially evaluated with a circle printing path with different radiuses, *i.e.* 5 mm, 10 mm, 15 mm, and 20 mm. The printed rasters of the different radii, obtained with a constant printing speed of 300 mm/min, along with the defined path are shown in Figure 1. The printing path starts from the top left straight line, reaches the changing corner where it turns upwards before entering the circular section. Overall, the printed raster follows the defined path even with a radius as small as 5 mm. However, poor printing was found at the changing corner as the material cannot adhere sufficiently to the bed.



(a) (b) (c) (d)

Figure 1. Printing trial of a circular path with different radii: (a) 5 mm; (b) 10 mm; (c) 15 mm; (d) 20 mm, showing that the printed rasters following the circular path.

The sharp corner steering was further investigated by printing a 30 mm x30 mm square path with three 90° corners. With a constant printing speed of 300 mm/min the sharp 90° corner defined by the printing path cannot be achieved due to poor bed adhesion at the sudden direction change as shown in Figure 2 (a). Printing precautions were implemented to increase the bed adhesion at the sharp corner, *e.g.* slowing the printing speed to 200 mm/min at 5 mm before and after reaching the corner or moving downward (in Z direction for 0.1 mm) to pin the raster at the corner before continuing the normal printing; however, even if both methods slightly improve the printing quality, a perfect 90° sharp corner could not be achieved (Figure 2 (b)). A 3-mm radius was inserted in the printing path instead of the sharp 90° corner, to allow the raster to change its direction more gently, as shown in Figure 2 (c). In this way, the printed raster seems to be more repeatable and to better follow the defined path even if with small deviations due to poor bed adhesion. The poor bed adhesion may be the result of the high fibre volume content in the filament. Future work will include the production of filaments with different fibre volume fractions and investigations of their printability along with a campaign to identify the smallest printable corner radius.



(a) (b) (c)

Figure 2. Square printing of 30 x 30 mm to investigate the 90° corners with different printing precautions: (a) normal printing; (b) printing with slow down and pinning at the corners; (c) curve corners with a radius of 3 mm.

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EXPLORING COMMERCIAL USE CASES FOR ALIGNED SHORT FIBRE COMPOSITES

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Keywords: Aligned, Discontinuous, Fibre, Composite, Forming

ABSTRACT

The performance and lightweight benefits of fibre composite materials are offset by a heavy cost and manufacturing burden. Typical manufacture is expensive, both due to high material costs and complicated manufacturing processes involving slow lay-up procedures that limit production rate. A fundamental cause is the inextensible nature of continuous fibres that complicate draping operations without wrinkles and fibre bridging, often incurring additional reserve factors due to manufacturing uncertainties.

Lineat produces highly aligned discontinuous fibre pre-preg tapes using the hydrodynamic HiPerDiF technology developed in the University of Bristol ((UoB) [1]. This new engineered fibre architecture enables composite forming capability as individual fibres can slide relative to each other during manufacture. This greatly simplifies the shaping actions required during composite manufacture. Due to the high level of alignment, the full strength of the fibres can be reached giving a better trade-off between performance and processing of composite materials. By changing from continuous fibre to an aligned discontinuous fibre architecture, an improved material format is created that is suited for automated manufacture of complex shapes and can vastly reduce defects and the overall production burden.

To date, most manufacturing work on highly aligned discontinuous fibre composite has been performed in the academic environment showcasing the performance with different fibres types and over various composite recycling loops. However, relatively little work has been performed on characterising the manufacturing behaviour of aligned fibre composites. Development in Lineat focuses on informing potential commercial users of aligned fibre composites how to process these novel materials. Two areas are highlighted here, the consolidation and compaction behaviour of aligned fibre composites and the tape handling and forming characteristics.

Early manufacturing work in Lineat utilizing the 3rd gen UoB HiPerDiF (HPD3) prototype highlighted different consolidation behaviour compared to traditional continuous fibre composites. Initial vacuum (1bar) and autoclave processing (7bar) of Lineat-HPD3 50gsm 3mm Toho Tenax C124 fibre with 50gsm epoxy resin film resulted in dry areas on the laminate indicating insufficient resin was present. A survey was done on the compaction behaviour of short fibre composites which have been well described by Liu et al. [2] and recently reported by the University of Delaware. Figure 1 shows the collated compaction curves of different aligned fibre materials in comparison with uni-directional virgin continuous fibre tapes.

From this, the Lineat-HPD3 compaction curve was predicted and new tapes with a 20 gsm fibre preform and 50gsm epoxy resin film was processed using oven curing under vacuum pressure giving a fully wetted laminate. The higher required consolidation pressures on Lineat-HPD3 tapes were attributed to a thin layer (estimated at ~20% per ply thickness) of misaligned fibres due to water pooling, ultimately causing resin rich areas in the composite. This is being upgraded with new alignment plate manufacturing Lineat has developed to minimise pooling and increase alignment expected to match or exceed the TuFF and 3mm Nottingham alignment.

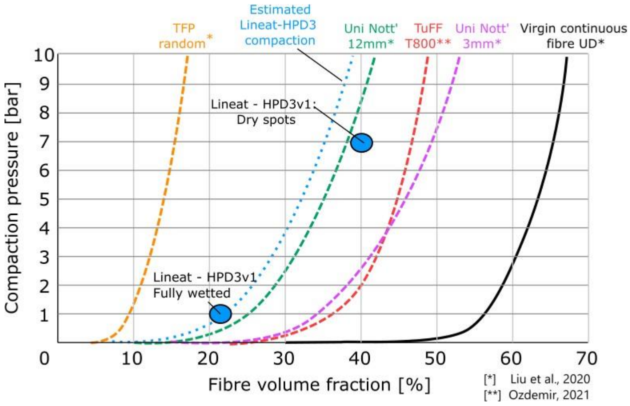

Figure 1: Compaction pressure versus fibre volume fraction of different fibre architectures.

The tensile strength of dry aligned fibre tapes, stabilized tapes and pre-pregged tapes was assessed (all 30mm wide, 20gsm fibre preform). The performance of dry aligned fibre tapes could not be assessed and essentially is 0N. An undisclosed binder was added at 3% mass content of fibres within the hydrodynamic alignment process mixture to stabilize the tapes and increased the tensile load carrying capacity to 1.4N. Pre-pregged tapes with a 50gsm resin film were able to hold a load of 12N, however, pre-pregging was performed single sided under minimal pressure to aid release from the processing belt due to a lack of cooling, and this is to be improved on next generation Lineat machines.

Aligned fibre preform blanks ($[0/90/0]_s$ - 20gsm 3mm fibre tapes with 50gsm epoxy resin film) were prepared to perform initial forming trials on a female shell mould. For comparison, a continuous fibre preform of ($[0/90/0]_s$ - 50gsm fibre with 2x100gsm epoxy resin film) was prepared. The preforms were heated to 40 °C and formed into the mould using vacuum pressure and Stretchlon bagging film. Figure 2 shows the moulded preforms, demonstratin the vast improved forming capability of the aligned fibre preform, with a maximum extensional strain of 22%.

Figure 2: Shell mould (left) and formed preforms; aligned fibre (centre) and continuous fibre (right).

Future development work in Lineat consists of building the first automated fibre alignment machine with improved alignment and developing the tape to commercial quality and formats. The aim is to replace the current manual lay-up procedures with automated preform preparation from aligned fibre tapes, such that tailored aligned fibre blanks can be used to replace multiple lay-up steps with a single operation before final consolidation.

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MANUFACTURING OF NOVEL HIERARCHICAL HYBRIDISED COMPOSITES

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Keywords: Fibre-reinforced composites, pultruded rods, compression, overbraiding, hybridisation

ABSTRACT

Inspired by natural composites such as bamboo (Figure 1) or bone, the NextCOMP programme seeks to improve compressive performance through a novel, hierarchical approach to advanced composites. Features designed to improve compressive performance are introduced at multiple length scales. Novel fibres and resins are under development, along with new approaches at the ply level.

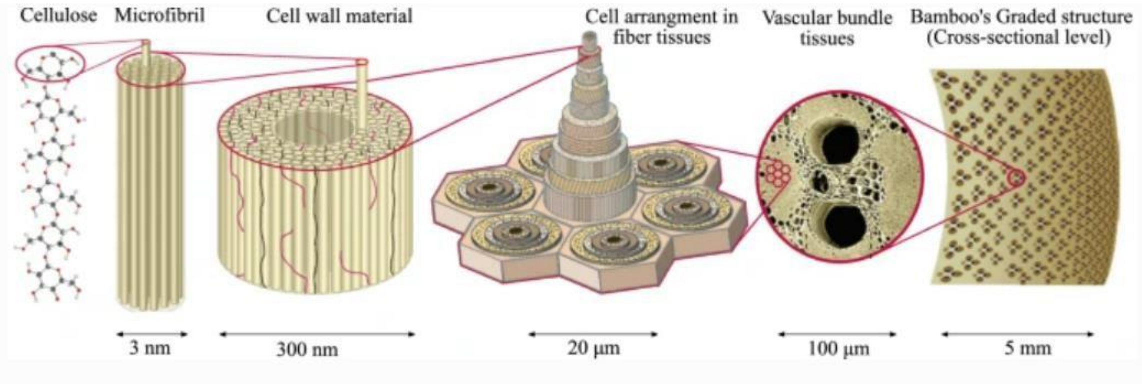

Figure 1: Illustration of hierarchical structure of bamboo. Reproduced from [1].

This new approach to composites brings its own manufacturing challenges, combining multiple methods both automated and manual.

Cylindrical struts, consisting of carbon-fibre epoxy pultruded rods of circular cross section plus an infused resin, have previously been manufactured [2] and subjected to compression after impact testing [3]. Struts overwound with Kevlar to confine the kink bands exhibited greater compressive strength than comparable struts without overwinding. X-ray CT images (Figure 2) show multiple smaller kink bands in the former case compared to a single large kink band in the latter.

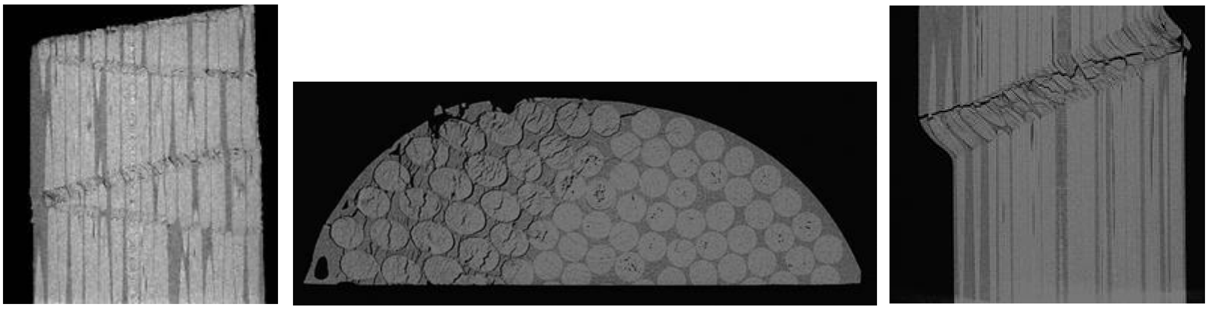

Figure 2: Slices from XCT reconstructions of samples from experiments reported in [2]. Strut with overwind shown left with multiple smaller kink bands, strut without overwind shown right and centre with single kink band.

In the hierarchical approach overbraiding of individual rods is employed, introducing hybridisation where rod and overbraid fibres differ. Various materials and geometries are under test (Figure 3), including a range of rod cross section shapes and areas. These overbraided rods are then integrated into larger structures, including but not limited to cylindrical struts.

Figure 3: Circular cross section carbon fibre-epoxy rods overbraided with Toray T300 carbon (left), Teijin high modulus Zylon (centre) and Teijin Twaron 2200 aramid (right).

This presentation focuses on our latest investigations into the design, manufacture and compression testing of single and hierarchical composite overbraided architectures. Optimisation of overbraiding for different test cases will be explored. The work is placed in context regarding what this new approach to composites may mean for manufacturing, with a look towards future challenges and opportunities.

The authors kindly acknowledge the funding for this research provided by UK Engineering and Physical Sciences Research Council (EPSRC) programme Grant EP/T011653/1, Next Generation Fibre-Reinforced Composites: a Full Scale Redesign for Compression in collaboration with Imperial College London.

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FROM RESIN CONFUSION TO RESIN INFUSION – UNDERSTANDING PROCESS CONTROL & AUTOMATION

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Keywords: Resin Infusion, Technology Readiness Levels, Automation, Performance Validation

ABSTRACT

The precise automation of manufacturing methods for composites is challenging. This must be preceded with a clear understanding of the science behind the process variables and the competent techniques required to produce successful material. This paper explores a wide-ranging journey to understand the key process variables and the methods to implement and control these. This in turn, delivers high quality infused composite for a variety of sectors including wind energy, aerospace and marine.

In addition to this understanding, a fundamental and sometimes overlooked requirement is the simple skill of being very good at making composite parts. This is central to the work at Composite Integration. Whether it is the skillful manufacture and realisation of detail in small components (figure 1) or the logistical organisation of large infusions (figure 2), it is this focus that ties together the following key steps:

1. Understanding the process variables.
2. Determination and design of an automated system to control and monitor the process.
3. Successful multi-sector infusions.

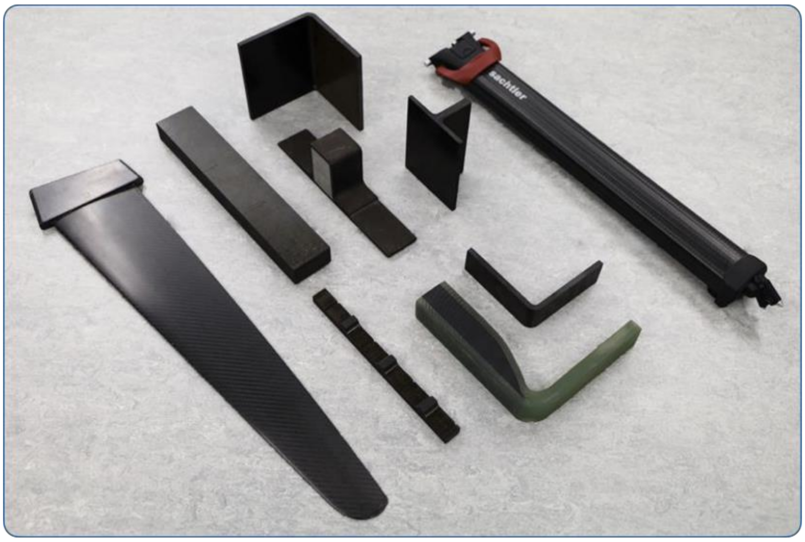

Figure 1: Typical examples, all with complex elements that require excellent manufacturing skills.

Figure 2: A typical large-scale infusion at Princess Yachts – heavily reliant on an understanding of process variables and an automated system to handle these.

In order to successfully work through these steps two important things are needed. Firstly, tightly focused laboratory work where routine and expertly manufactured composite is produced with comprehensive and appropriate data gathered. Secondly, an understanding and experienced capability is brought to bear on Technology Readiness Levels 3 to 7; this is often referred to as the "Valley of Death". The approach to the work described in this paper seeks to bridge this neglected gap robustly. Figure 3 illustrates these steps, and the presentation expands on these areas in detail.

Figure 3: Composite Integration's approach to a comprehensive improvement of automated infusion.

Where possible each step is explained in the presentation, with data sets that demonstrate the automation precision that has been developed to enable high quality infused composite to be produced consistently at both small and large scales in demanding production environments.

In 2012 Composite Integration introduced "Direct Infusion" which was largely pioneered in the marine sector for large hull infusions. This is now the industry standard and has found its place in the aerospace and wind energy markets. In conclusion, the paper will also consider some of the next technical challenges that must now grasped which will take the Industry to Direct Infusion 2

SESSION 6
ROBOTICS AND MOULDING TECHNOLOGIES 1

DATA MINING AND SCIENCE-BASED PREDICTIVE ANALYTICS FOR AUTOMATION OF COMPOSITES PROCESSING

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Keywords: Processing, Data mining, Analytics, Statistics, Probabilistic models.

ABSTRACT

This paper addresses the use of data mining and science-based predictive analytics in a composites aerospace factory where a multitude of parts/tools are cured together in batches, using a variety of cure recipes and autoclaves. Lead and lag thermocouples (TC’s) are currently installed on all parts/tools to monitor and control the autoclave cure process. One of the main goals with this project was to reduce the number of TC’s monitored during cure, while ensuring that all parts meet process specifications. Nine years of production data was cleaned-up, aggregated, and systematically reviewed. Based on the review, two key areas where the process can be automated, and value extracted were identified: “Process analytics” and “Smart load”.

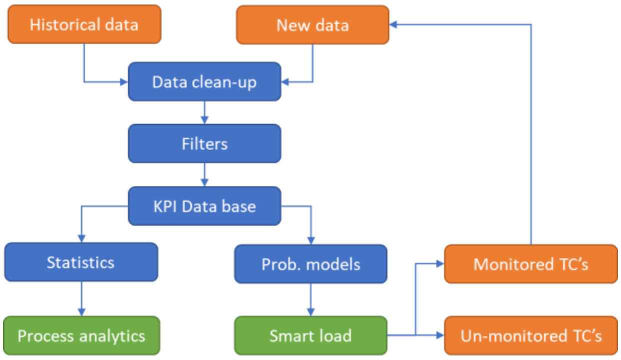

Figure 1: Data mining and predictive analytics workflow.

The workflow is as follows. Historical thermo-couple (TC) data is automatically cleaned-up, filtered, aggregated and key performance indices (KPI’s) calculated for every cure, part, cure recipe, and autoclave. The KPI’s are then stored in a KPI data base that allows easy access and efficient storage for all key metrics of these large data sets. As new data is generated in the factory, data is automatically processed and added to the data base, creating a self-updating data repository. The KPI data base is then utilized in two main ways:

By applying descriptive statistics to the metrics in the KPI data base, relevant process data, statistics and analytics is automatically generated. This data gives a strong situational awareness of current factory assets and how performance is changing over time, automating and simplifying dispositioning, scheduling, and evaluation of factory performance.

In the current process, many tools and parts are loaded and cured together in the autoclave. There is a requirement that the parts/tools that are the slowest heating up (lagging) must be monitored with thermocouples as they are used to control the autoclave and ensure that all parts in the load gets fully cured. Because variability in how the autoclaves are loaded, and the number of parts in different cures, and other factors, there is a large variability in the thermal response of parts/tools from cure to cure. Figure 2 shows an example of the normalized time to enter dwell (time to reach 10F below the dwell temperature) for parts cured with a specific recipe, in a specific autoclave. Although some parts/tools are on average thermally heavier than others, there is a large variability in the measured thermal response from load to load.

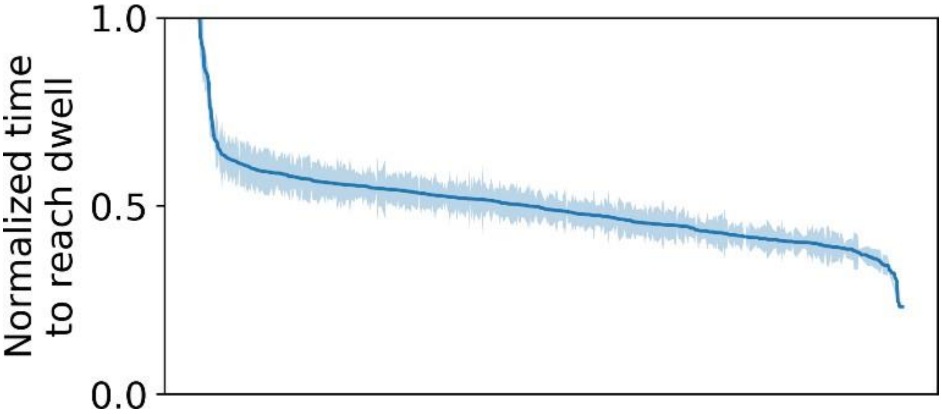

Figure 2: Historical data of normalized time to enter dwell for different parts cured with a specific cure recipe in one autoclave. Solid blue line represents mean response, and light blue bars represent one standard deviation [1].

To reduce the number of parts that are monitored in each cure, a probabilistic simulator was built that with statistical certainty can predict which parts are most likely to be the lag of the load and require TC monitoring. Several different models were evaluated but for accuracy, robustness and interpretability, a sampling based probabilistic Bayesian hierarchical model (BHM) was selected [2] and used to predict which parts are most likely to be the lag of the load. The BHM model was trained using historical data from the KPI data base. When back testing model prediction against historical data it was shown that a reduction of TC monitoring of up to 80% is possible without spec failures.

The data mining and predictive analytics approach presented is the first step in better utilizing historical data and applying science-based predictive analytics and probabilistic models to automate and improve composites aerospace processes.

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HIGH-RATE COMPOSITE DEPOSITION FOR LARGE SCALE AEROSTRUCTURES

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Keywords: Kitting, Deposition, Layup, Inspection.

ABSTRACT

A key challenge facing aero structure manufacturers is how to produce components at high quality and at sufficient rate to satisfy the production targets of the next generation of single isle passenger aircraft. This presentation highlights a number of innovative production technologies explicitly targeting high-rate deposition of composite materials on large scale aero structures such as flight control surfaces, wing covers and spars.

The proposed approach utilises gantry or robot deployable end effectors and peripheral equipment to nest, cut, sort and kit composite plies before depositing them into mould tools, inspecting and tacking in an effort to achieve rates in excess of 150 kg/hr. The approach acknowledges there is no one-size-fits-all for the wide variety of geometries encountered in composite component manufacture and instead utilises an array of end effectors and a common deployment platform to achieve optimal rates for a given target application.

Two deposition approaches are considered, conformal pick and place and roller. While pick and place is advantageous for complex ply shapes that need to be placed to a high tolerance, roller deposition scores in terms of compactness. The strengths and weaknesses of the two technologies will be explored along with key performance capabilities and target application examples.

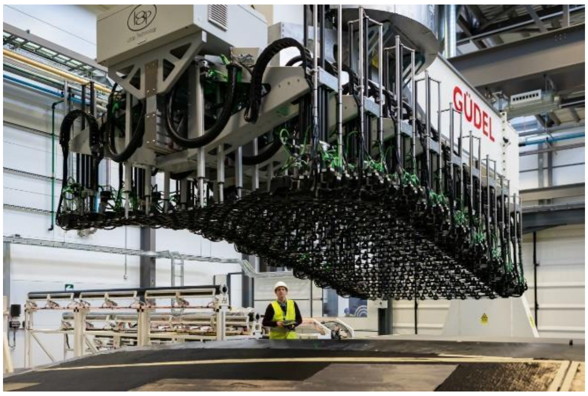

Figure 1. FibreFORM™ 4 m variant.

FibreFORM™ has evolved into highly conformable pick and place end effector. Designed with fuselage sections, wing skins and engine nacelles in mind, it is capable of picking composite plies from a flat surface and forming it into a double curvature surface. Achievable shapes include concave, convex and omega profiles, as well as handling flat ply sheets.

Overall, FibreFORM™ is capable of achieving up to 800 mm of stroke (or more with an adapted design) over the mould surface. An arm, as shown in figure 2, provides up to 500 mm of stroke. Each arm consists of a number of hands, each containing a wrist unit capable of rotating through 140°. The wrist units rotate in such a way as to form the basic shape of the spline which is further adjusted by mid-mounted linear actuators that push or pull the middle zone of the spline to assist in forming the final shape.

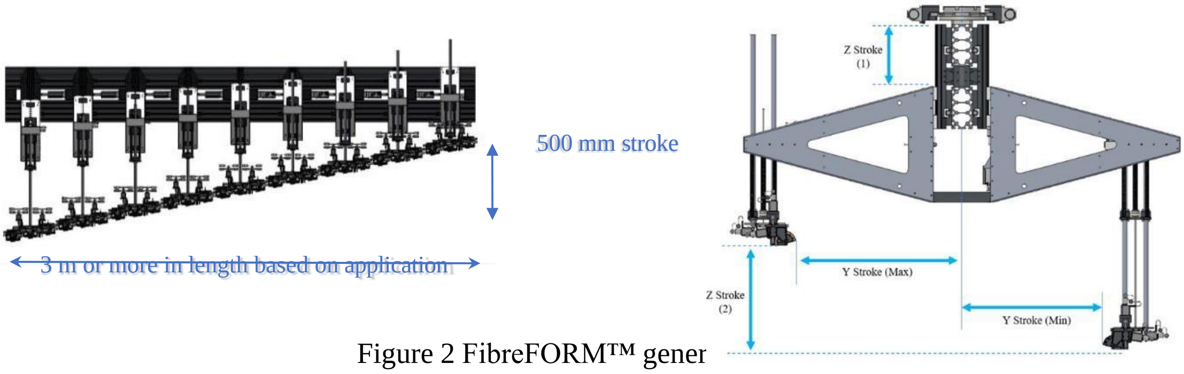

Figure 2 FibreFORM™ gener

To aid the transfer of the ply to the mould tool surface, the FibreFORM™ end effector can also be rotated up to 15 ° from horizonal to meet the average surface normal of the mould. This feature is reliant on the length of the end effector and the deployment method used. This precise level of movement at multiple levels enables FibreFORM™ to achieve +/-0.5 mm of repeatability in ply deposition, depending on the material type and geometry.

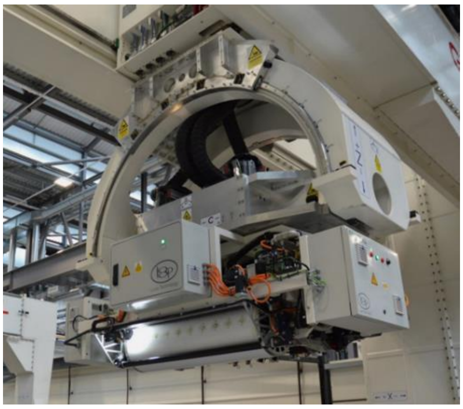

Figure 3. A 1.3 m FibreROLL system, gantry mounted

FibreROLL is a scalable twin roller storage and deposition system for dry fibre composite plies. The tool picks and loads plies onto interchangeable storage rollers or can place them directly onto the workpiece. This is combined with a vision system that monitors ply edges during layup for verification and positional correction.

FibreROLL can handle a wide range of materials and sizes including high porosity materials such as woven or NCF composite plies. The modular design allows FibreROLL to handle widths from 0.5m to 5m, with the basic design modified to suit each application.

Due to its vacuum cup layout along the main roller, it is limited to basic ply shapes. However, the roller-based design allows the transfer of large plies with a smaller footprint than other automated deposition systems, handling plies up to 20m long or more.

Due to the ply being rolled up and fed onto the storage system, some movement and twisting can be observed. This can result in the overall accuracy being reduced when compared to other pick and place processes such as FibreFORM.

AUTOMATED STAMP FORMING OF CF-PREPREG MATERIALS

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Keywords: Stamp-forming, Automated, Zero-tack, Automotive, Prepreg Forming.

ABSTRACT

Composite materials offer solutions to address the need for vehicle lightweighting, provided they are affordable and suited to automation. This paper provides an insight into the innovative industrial research carried out at WMG, facilitated by Expert Technologies, in the form of structural composite body and chassis applications for passenger and commercial vehicles.

As the global demand for ever lighter vehicles increases with the pressures of environmental legislation, the extension of electric vehicle range and increased customer content, manufacturers are looking to composite solutions for lightweight body and chassis systems. Replacing existing vehicle structures with CFRP (Carbon Fibre Reinforced Plastic) offers the largest mass reduction potential and could achieve a 30% weight saving over current aluminium assemblies. The absence of affordable materials and high-volume manufacturing methods has slowed adoption, with CFRP applications limited primarily to the low volume luxury car sector. Automation is key to industrialising any high- volume manufacturing process, which means that materials and processes must be selected or developed according to their suitability for automation. Mixed fibre architectures also offer a solution to mitigate the cost of increased CFRP use, combined with the benefits of part consolidation.

Aston Martin Lagonda, Expert Tooling & Automation and WMG, University of Warwick collaborated on two Innovate UK funded projects, 'InterCOMP' and 'CADFEC', the latter being a UK-US collaboration including DowAksa, to address the need for affordable light-weighting of vehicle body structures using carbon fibre composites. During InterCOMP, a double-diaphragm stamp forming process was investigated as a means to develop a cost-effective automated manufacturing solution. Prepreg ply cutting and blank assembly was carried out in an automated manner and integrated with a single stage double-diaphragm forming/moulding step to demonstrate a fully automated manufacturing process suitable for high volume automotive applications.

CADFEC further developed the design of the Aston Martin Rapide floorpan (Fig. 1) demonstrated on InterCOMP, to combine both discontinuous and continuous materials in a single forming and co-moulding process using WMG's Automated Composites Manufacturing (ACM) line, upgraded by Expert Technologies with a direct material gripping system. An innovative and unique material offering from DowAksa, enabled the consortium to tackle several critical automation issues including

out-life, preform stability and tack, to adopt a ‘right material, right place’ design and manufacturing strategy.

The technology has since been used for low-cost production representative prototyping; WMG manufactured components for Innovate UK funded, Ford led commercial vehicle project CHASSIS. The open edge prepreg compression moulding process was used to produce prototype volumes of upper and lower panels for a front sub frame from a single mould, with quality, cost and cycle time benefits.

Figure 1: Prototype floor pan produced on InterCOMP (left) and CADFEC (right).

The authors acknowledge the assistance of Aston Martin Lagonda, Ford Motor Company, Gestamp Chassis and DowAksa for their commitment to these projects. Furthermore, the authors gratefully acknowledge the financial support of Innovate-UK and the Fund for International Collaboration.

SESSION 7
ROBOTICS AND MOULDING TECHNOLOGIES 2

ENHANCED CHARACTERISATION AND SIMULATION METHODS FOR THERMOPLASTIC OVERMOULDING – ENACT

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Keywords: Thermoplastic, Overmoulding, Structural

ABSTRACT

Increasing the uptake of composites in the high-volume automotive market requires reduced production times through fast, automated processes, using cost-efficient materials with minimum wastage. This can be achieved by using thermoplastic composites, which are currently used in a range of non-structural parts, offering additional benefits such as chemical and heat resistance and the potential for closed-loop recycling. Thermoplastic Overmoulding (TPO) is an emerging manufacturing method combining high-speed, low-cost injection moulding of complex shapes with the structural support of strategically located continuous fibre elements. Effective implementation of this technology requires detailed knowledge of interface development during manufacture[1], the fibre orientation distribution created by the flow of injected material[2] and the effect of injection conditions on the continuous element[3,4]. Control of stress transfer is critical between the continuous and discontinuous elements.

The supply chain requires an improved understanding of optimised material combinations and confidence in the capability of computer aided engineering (CAE) design tools for TPO to be more widely adopted. The ENACT project has built on outcomes from the previous TOSCAA project[5] to deliver a novel set of processes and technologies to support the wider uptake of thermoplastic overmoulding (TPO) for the automotive sector. The adopted approach combines material characterisation, process simulation and tooling instrumentation to offer novel design methods to support light-weighting of automotive components. The main focus of the work was to deepen the understanding of the anisotropic material properties that are induced by the process, to positively influence the performance of the final component.

Figure 1 shows simulation data demonstrating the use of a graduated geometry around the edges of a continuous fibre element that acts to shift high stresses away from the edges. In doing so the stress within the high-performance continuous fibre element can be increased, making more efficient use of this reinforcement. This presentation will show more data from these simulations, related mechanical testing and aspects of manufacturing to demonstrate that this is an effective means of managing the stress transfer in the interface region. It will also show the development of a demonstrator component (shown in Figure 2) and future activities linked to the project outcomes.

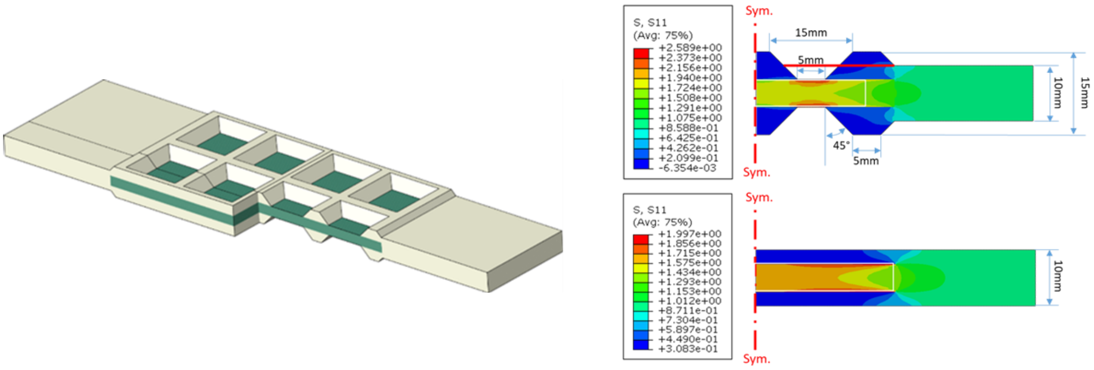

Figure 1: Managing stress transition between dissimilar materials with geometrical solutions (left: modified geometry with cut through for internal detail, right: comparison of stress distribution between plain and modified geometry)

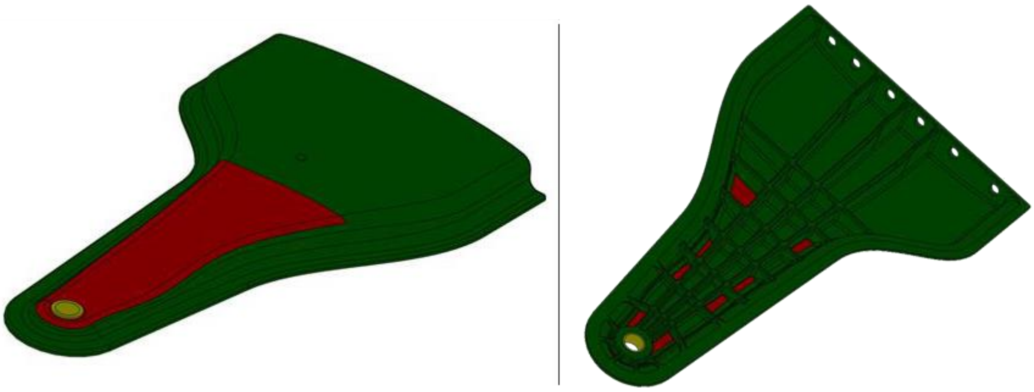

Figure 1: CAD images of the demonstrator component (continuous element in red)

This work was funded by Innovate UK [Project Reference: 105799] as part of the, “UK and USA: innovation in global composites market” Competition and by the Engineering and Physical Science Research Council [Grant number: EP/P006701/1], through the, “EPSRC Future Composites Manufacturing Research Hub”.

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THE EFFECT OF MULTI-PATCH LAMINATE DESING ON THE MANUFACTURING EFFICIENCY OF COMPOSITE PLATES

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Keywords: Laminate Blending, Automated Fibre Placement, Automated Tape Laying, Variable Stiffness, Manufacturing Efficiency

ABSTRACT

Spatially tailoring the stacking sequence of a composite laminate can be used to obtain significant improvements in the mechanical response of a structure. Buckling load improvements of 50-75% for simply-supported plates under in-plane compression have been reported in literature [1]. The improvement in buckling load is attributed to load redistribution within the laminate. In recent work we have demonstrated that it is possible to achieve variable stiffness laminate designs by means of laminate blending and patching operations, instead of fibre steering (Fig. 1). This results in a straight- fibre variable stiffness (SFVS) laminate. Stacking sequence continuity is assured by enforcing relaxed generalized blending guideline [2]. The developed method is computationally efficient. Preliminary results show similar improvements in buckling load improvement as have been reported in literature for fibre-steered variable stiffness laminates. The advantage of the proposed design method is that variable stiffness laminates can be achieved by a wide range of manufacturing techniques.

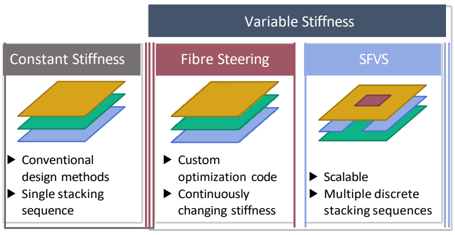

Figure 1: Straight-fibre variable stiffness laminates

We consider the application of automated tape laying (ATL) or automated fibre placement (AFP) to be a viable option to manufacture medium to large scale SFVS laminates. In the most generic case, both manufacturing methods result in a jagged edge of a deposited layer of material. This is of no concern for most conventional applications where the edge of the manufactured structure can be trimmed. The concern for SFVS laminates is that the jagged edges of the manufactured patches cannot be trimmed, leading to the accumulation of manufacturing defects on the edges of the regions of the SFVS laminate. In the presented work we investigate the effect of minimum cut-off length (MCL), cutting strategy and tow width on the accumulation of defects in the transition zones of an SFVS laminate. The transition zone is defined as the zone in between two regions of the laminate where gaps and overlaps are predicted.

The starting point of the current work is the output of the design method for SFVS laminate for a plate of 600mm x 400mm divided in 5x5 design regions. This output consists of several patches of given orientation (selected from the set {0˚,15˚,30˚,45˚,60˚,75˚,90˚}) and their stacking order. The design is balanced and symmetric. The fibre paths for each patch have been generated for three options: a path is terminated s.t. 1) the entire patch falls within the design region, 2) the centre line of the path is terminated on the edge of the design region, 3) the entire design region is covered by the patch. Or in other words: 1) no overlap, 2) alternating gaps and overlaps, 3) only overlaps. After generation of the paths, the local thickness build-up in the laminate is sampled (Fig. 2).

The results show that a reduction of MCL will reduce the surface area of the laminated affected by gaps and/or overlaps significantly (Fig. 3). Furthermore, cutting strategy 2 and 3 are found to give favourable results.

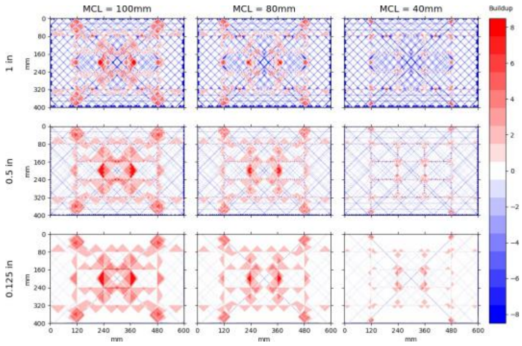

Figure 2: Thickness build-up in SFVS laminate as function of tow-width and minimum cut-off length (MCL) for option 2, alternating gaps and overlaps.

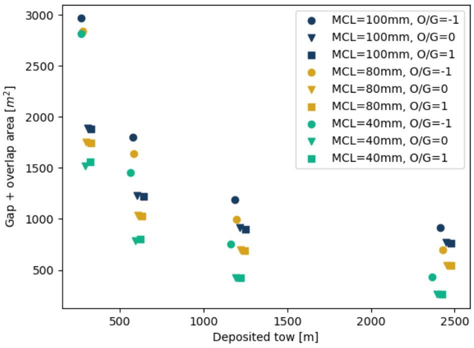

Figure 3: Area with gaps and/or overlaps as function of deposited tow length.

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DESIGN FOR AUTOMATION: LESSONS FROM A HIGH RATE DEVELOPMENT PROJECT

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Keywords: Forming, Automation, Process simulation, Design process

ABSTRACT

Traditionally, the composite development process has required the interaction of design, materials and manufacturing engineers to a far greater extent than with other materials. The more complex the component, the greater the level of interaction required. It is generally accepted that for composites to become widespread, automation and digitalisation will need to be adopted. This adds a crucial function: automation engineering. Whilst one approach is to attempt to automate production of a component or assembly that has already been designed and is currently being manufactured, greater gains in efficiency and cost can be achieved when automation is considered as a key factor during design stages.

Using an ongoing collaborative R&D project to design an automotive component and develop an automated solution to preform the components at high rate using recycled carbon fibre as a case study, the concurrent development process of a component and an automated solution is detailed. Competing drivers of cost, sustainability, performance and weight are mapped against the interactions required between the design, materials and processes and automation teams.
Through mapping the interactions required within the development process, this work shows how considering automation as a key factor in the design process influences the multiple driver trade-offs.

Generally there are two separate design processes for components and for automation solutions. An efficient design framework for composites has been suggested by (1), and is shown in Figure 1. Automation solutions generally follow a systems engineering approach such as the Vee Model (2).

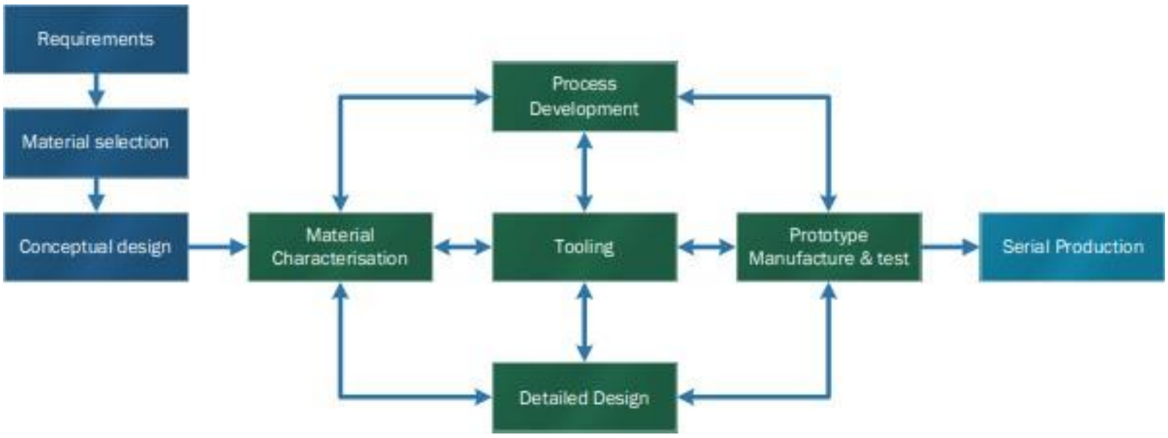

Figure 1: Composites design process and interaction framework

In a linear design process, automation may only be considered after the initial prototype production, which can lead to high cost changes and become difficult to certify in certain industries (3). This can also lead to a more complex automation system as it would need to be designed around an already existing component. To minimise the complexity and cost the automation should be considered at an initial stage along side the design of the component. A proposed concurrent design approach can be seen in Figure 2.

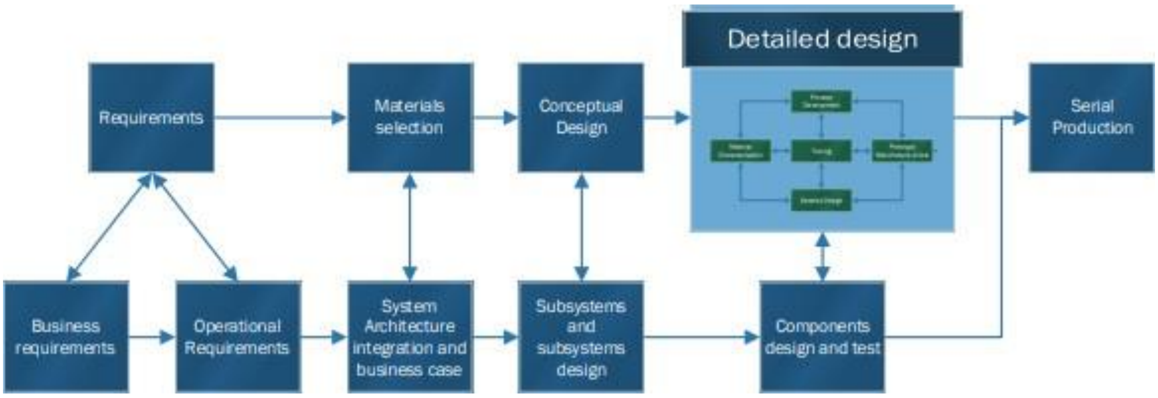

Figure 2: A Suggested design and automation design concurrent engineering framework

In this summary paper, progress in the automation of a high production rate automotive component will be described, alongside an augmented concurrent design process to aid in the reduction of costs and improvement in quality for the development of automated manufacturing solutions. Creation of effective automation and a detailed understanding of the process are the key first steps to enabling digitalization of the manufacturing process, thereby future proofing production and democratising composites for future mobility.

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LOW-COST PHOTOGRAMMETRIC CONTROL FOR AUTOMATED TRIMMING OF COMPOSITE PREFORMS

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Keywords: Photogrammetry, Robotics, Measurement, Automation, Composites

ABSTRACT

In many manufacturing processes, composite preforms require trimming. At this stage, substantial costs will have been incurred through manufacturing resources and time, and it is crucial that errors are avoided. Trimming sometimes causes a bottleneck in the manufacturing chain, so the operation also needs to be performed rapidly.

Automating the trimming process can result in a fast and high-quality cut. For example, at the National Composites Centre (NCC) an ultrasonic cutting knife is used on a robot (Fig. 1). Controlling the knife through the robot provides the flexibility to trim complex shapes and has been shown to give good results once it is set up. However, after a changeover, or before an important cut, the question needs to be asked: "Is the robot about to cut in the right position and orientation?"

In response to questions like this, a project was initiated at the NCC to further mature a low-cost photogrammetric system developed at University College London [1-2]. Robotic control was added and demonstrated on the ultrasonic trimming process. A network of 6 cameras was deployed around the working area to form a measurement system. Photogrammetry is used to track the path of the knife in relation to a cutting table (Fig. 2). This information is communicated to the robot controller so that the path can be adjusted.

During the development of a system to meet the requirements of the case study, several task-specific decisions were made to ensure robustness and accuracy. Key amongst these were the choice of camera lenses, their location with respect to the working area, and the design of suitable target holders both to provide a reference system and to track the robot end-effector. For example, in the ultrasonic trimming process, targets were mounted close to the knife tip whilst maintaining line of sight to as many cameras as possible when cutting. Additionally, a customised knife mount was developed to allow for precise setting of the knife orientation.

Whist the detailed system design is specific to the process being studied; the technology could be applied to a large variety of automated composite manufacturing applications. Robotics are already a step change from hand-operations. Adding the ability to monitor and improve the accuracy of robots at a low cost will further increase the use of composite materials.

This project was supported by funding from the NCC's annual Technology Pull-Through programme with supports the transfer and further development of academic technologies into industrial and commercial environments.

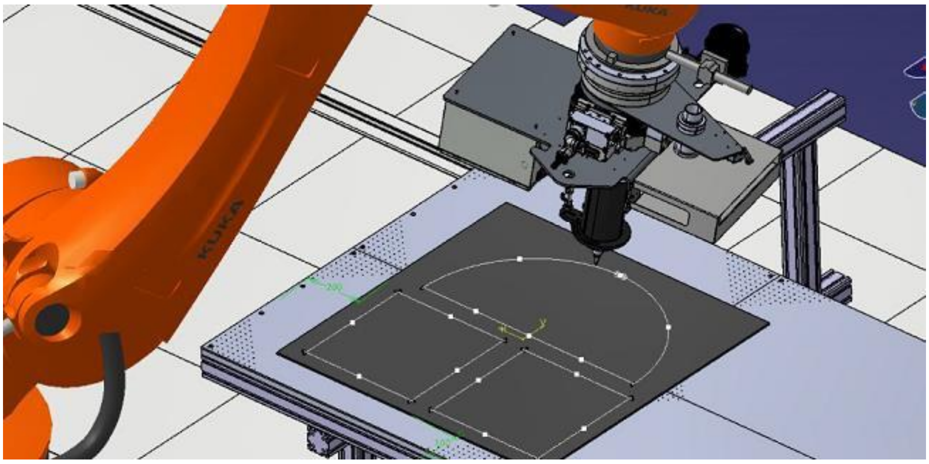

Figure 1: Simulation of an ultrasonic knife cutting a composite preform

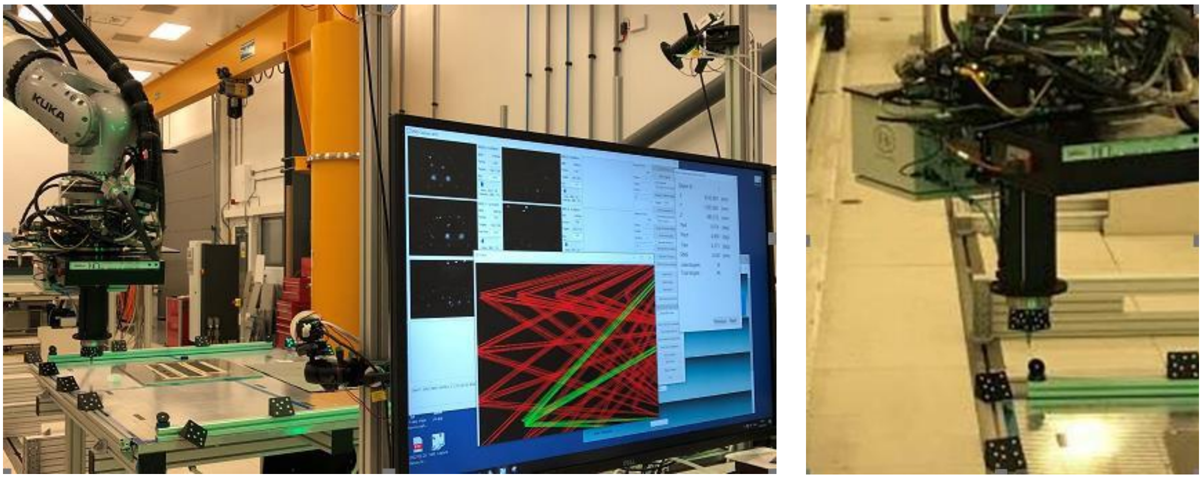

Figure 2: Tracking the knife through low-cost photogrammetry to facilitate monitoring and control

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POSTER PRESENTATIONS

SEAMLESS SOLUTION FOR INDUSTRIAL-GRADE CONTINUOUS CARBON FIBRE 3D-PRINTED COMPOSITES

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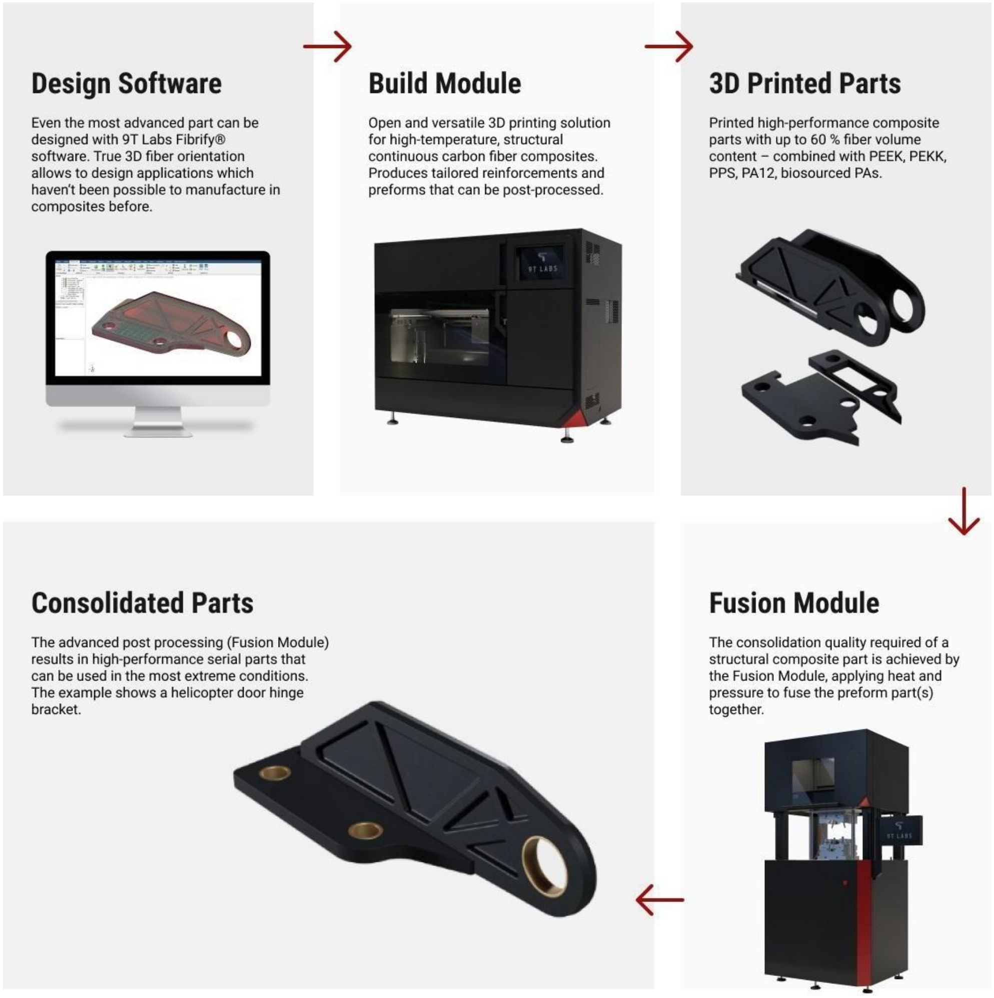
Keywords: 3D printing; structural composites, serial/series production, carbon composites; aesthetics

ABSTRACT

High performance composites possess excellent mechanical and chemical characteristics, making them applicable for various industries such as aerospace, medical and leisure. Remouldability and high fracture toughness of thermoplastic based matrix systems led to new applications with short cycle times in production and high damage tolerance. However, the comparably high costs associated with carbon fibre composite parts to its aluminium or steel contenders, remain a constraining factor. A higher degree of freedom to optimise the part geometry and the fibre layup in combination with increased automation in manufacturing will reduce the current constraint.

3D printing, an additive manufacturing technology, is believed to deliver on those demands for manufacturing. A competitive 3D printing approach for the manufacturing of composite parts in series production requires the understanding of the material (high fibre volume contents), the required part quality (low void content) and the cost structure. 9T Labs' radically new approach on 3D printing of performance composites considers all three aspects by introducing high fibre volume content (>50%) materials, ensuring part quality by introducing appropriate consolidation steps and scalability through parallelization of affordable printing units.
9T Labs is pursuing applications in fields including aerospace (e.g., hinges, brackets), medical (e.g., surgical instruments), industrial automation (packaging machines), and leisure/luxury (e.g., motorsports, watches, eyewear).



Design Software

Even the most advanced part can be designed with 9T Labs Fibrify® software. True 3D fiber orientation allows to design applications which haven't been possible to manufacture in composites before.

Build Module

Open and versatile 3D printing solution for high-temperature, structural continuous carbon fiber composites. Produces tailored reinforcements and preforms that can be post-processed.

3D Printed Parts

Printed high-performance composite parts with up to 60 % fiber volume content – combined with PEEK, PEKK, PPS, PA12, biosourced PAs.

Fusion Module

The consolidation quality required of a structural composite part is achieved by the Fusion Module, applying heat and pressure to fuse the preform part(s) together.

Consolidated Parts

The advanced post processing (Fusion Module) results in high-performance serial parts that can be used in the most extreme conditions. The example shows a helicopter door hinge bracket.

Figure 1. Additive fusion technology consists of advanced design software, a 3D printer that produces (near-)net-shape preforms, and a compact compression press equipped with matched metal dies in which preforms are heated, shaped, and consolidated.

Results showed that 3D printing can be a cost effective alternative to conventional manufacturing technologies while increasing the specific mechanical performance. The cost analysis showed that cost advantages are balanced between initial manufacturing equipment costs (CAPEX) and cost savings derived from automation by reduced manual labour. 3D printing in combination with appropriate consolidation steps proved to be the solution to bridge the gap between high equipment costs for in-situ printing and the required printed part quality for series production, providing significant cost advantages in production of small and medium sized parts at quantities of 100 to 10’000 parts.

The bracket shown above is for a structural application that can be produced in an optimised way using 9T Labs’ technology. It comes from an aluminium part that has been topology optimised to save weight by orienting carbon fibres according to the load case. Additionally, it saves costs because of the lower amount of carbon fibre used versus other composites processes while complying with the same loadcases.

9T Labs’ all-in-one solution proved to be economically viable with up to twenty times lower development costs and up to ten times lower production costs through the seamless integration of software, 3d-print module, and consolidation module. Furthermore, this innovative approach allows up to 50% more lightweight design vs. metal for serial parts withstanding the required loadcases.

ROBOTIC SEQUENTIAL ULTRASONIC SPOT WELDING FOR A FULL-SCALE THERMOPLASTIC FUSELAGE DEMONSTRATOR

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Keywords: Thermoplastic composites, Fusion bonding, Ultrasonic welding, Automated assembly

INTRODUCTION

Multi-spot sequential ultrasonic welding is a promising joining technique for thermoplastic composites in an overlap configuration. Laboratory-scale multi-spot welds have been demonstrated to exhibit a comparable load-carrying capability as well as a smaller and more localized damage on failure when compared to mechanically fastened joints of similar size [1]. In this project, sequential ultrasonic welding has been developed for joining of structural components using an automated sequential welding process, based on previous work [2]. The technology is being demonstrated on a full-scale thermoplastic composite fuselage section of 8 m length and 3 m shell radius as part of the Clean Sky 2, Large Passenger Aircraft – Platform 2 [3], where the fuselage skin will be joined to circumferential frames through the use of welded clips, in the lower shell of a fuselage demonstrator (see Figure 1).

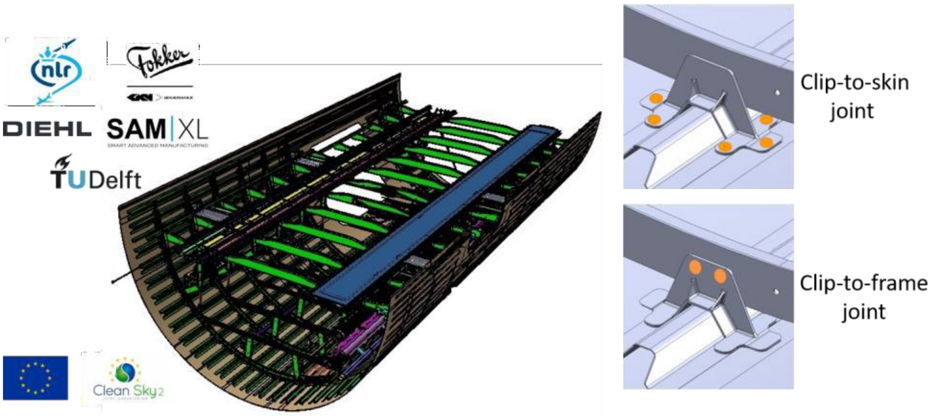

Figure 1: Lower shell of the thermoplastic composite fuselage demonstrator (left) and joint configuration/weld spot locations (right)

Figure 2: Robotic End-Effector for Clip-To-Skin (left) and Clip-To-Frame (right) Ultrasonic Welding

TECHNOLOGY DEVELOPED

At SAM|XL and TU Delft, sequential ultrasonic welding technology has been developed in preparation for the sub-assembly of the fuselage demonstrator. Figure 2 shows the hardware consisting of an end-effector that can be equipped with two different tools that shall be used to join structural clips to the fuselage skin and stringer, configuration named Clip-To-Skin (CTS), and the frames, configuration named Clip-To-Frame (CTF). In the CTS tool, the welding stack is actuated vertically normal to the part to be welded and a weld jig. In the CTF tool, the welding stack is actuated horizontally and is coupled with an integrated anvil to provide back pressure on the frame during the welding process. Feedback from the ultrasonic generator as well as displacement and pressure sensors integrated in the end-effectors are used to control the welding process.

RESULTS & CONCLUSIONS

Welding trials were conducted in representative joint configurations (CTS and CTF) with the material configuration as in the demonstrator i.e. short-fibre composite welded to continuous-fibre composite. Welding parameters were based on previous work [2]. Weld quality was assessed based on lap shear strength of the joints, cross-sectional images of the interface as well as ultrasonic scans of the weld as presented in Figure 3. Average single-lap shear strength of 30 MPa (COV 1.8 %) was achieved.

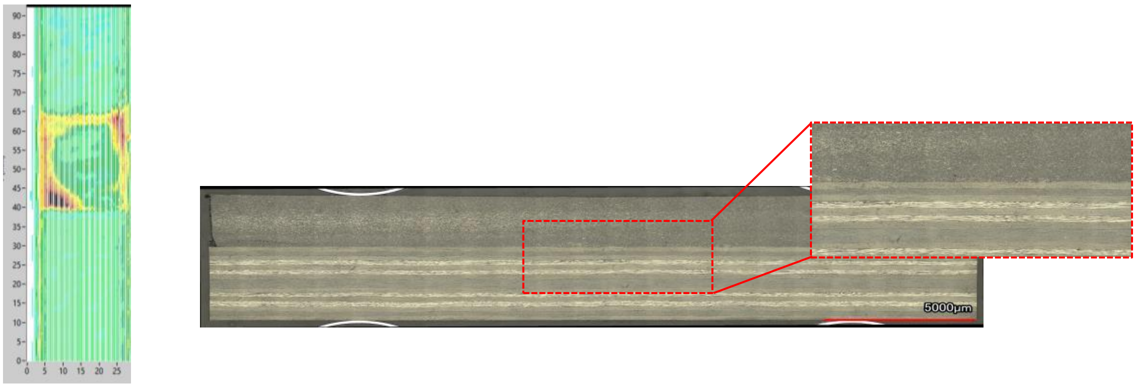

Figure 3: Ultrasonic scan of approximately circular spot welded single lap joint (left) and cross- sectional micrograph of the welded joint (right)

The following conclusions can be drawn from the results obtained through experimental trials with the robot-based welding tools developed for the joining of the skin and stringer to the circumferential frames through welded clips in the thermoplastic fuselage demonstrator.

- The concept and the functionality of robot-based welding tools in both configurations was experimentally tested and demonstrated for sequential spot welding.
- High spot weld quality is achieved during welding trials.
- The tools can be utilized for joining of the thermoplastic composite skin to stringer and frames in the fuselage demonstrator through 208 welded clips in an automated welding process.

ACKNOWLEDGEMENT

This project has received funding from the Clean Sky 2 Joint Undertaking (JU) under grant agreement No 945583. The JU receives support from the European Union’s Horizon 2020 research and innovation programme and the Clean Sky 2 JU members other than the Union.

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COLLABORATIVE COMPOSITE SHEET LAYUPS FOR COMPLEX GEOMETRY OF SMALL PLIES

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Keywords: Automating manufacture of complex structures, human-robot collaboration, human intent prediction, robotic planning, execution monitoring

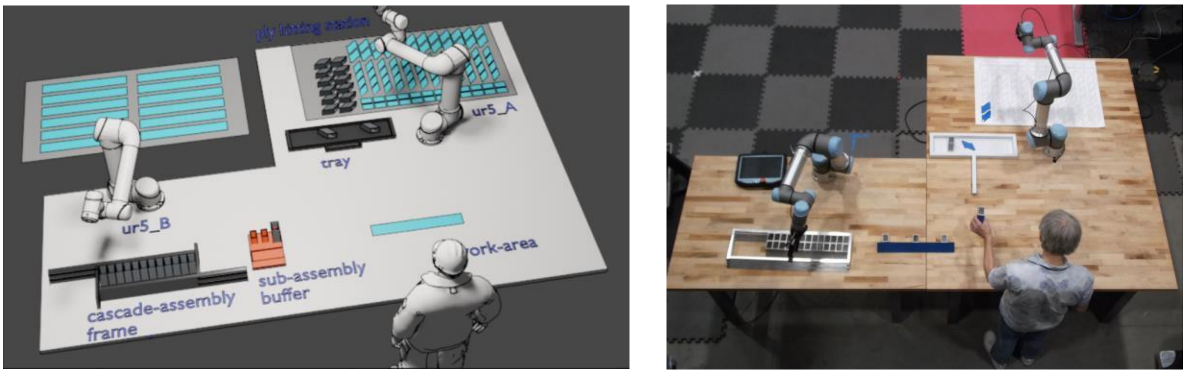
ABSTRACT

Polymer Matrix Composites (PMCs) are structural materials consisting of fiber reinforcements embedded within an engineered polymer matrix. High specific strength and stiffness make PMCs well suited for aerospace applications. Currently prepreg sheet-based composite manufacturing requires a high degree of manual labor, starting from assembling a prepreg ply kit, all the way to autoclave cure and finishing. During a typical composite layup process, the workers are moving and handling the plies, working together to place plies on a complex-geometry tool, inspecting ply layup quality, performing necessary repair, and then bagging and placing plies in an autoclave to cure. Manual processes such as this often lead to high ergonomic risk exposure, low throughput, and high labor costs. In modern manufacturing systems, these challenges can be addressed through an increasing focus on collaboration and workspace-sharing among robots and humans. Systems with the collaboration and coexistence of humans and robots in shared workspaces offer the repeatability and precision of robots together with human intelligence, flexibility, and dexterity. In the context of composite manufacturing, robots can perform simple tasks with high precision while human collaborators can handle complex sheet manipulation operations required in composite fabrication that are beyond the current capability of robotic systems.

Our approach was to leverage robots that may take on some repetitive actions to help alleviate fatigue-related ergonomic stresses; robots and a human may work together to place a ply on the tool with one of them being the leading partner and the other a follower depending on the specific layup tasks and their capabilities. Through our research we developed an integrated framework for human-robot collaboration to address the labor-intensive nature of sheet-based composite manufacturing. The manufacturing of thrust reverser composite cascades for aircraft engine nacelles was the identified use case for the technology development. Based on the composite fabrication process, a modular workstation design approach was selected. Three modular workstations, namely a kitting station, subassembly station, and final assembly station were installed (Figure 1). The human and two robotic arms collaborated to manufacture a thrust reverser composite cascade prototype for aircraft engine nacelles. A typical composite cascade unit uses ~1,000 plies of prepreg sheet. Each thrust reverser typically has 16 cascade units. In one aircraft engine, the number of plies can amount to ~16,000 plies. The main processing steps include 1) prepreg ply kitting, 2) applying the plies on small rectangular- shaped compartment tools (i.e., mandrels) to form sub-assemblies, each one with unique geometric feature, and 3) position the sub-assemblies in a large tool and applying additional large/long plies to create the full cascade assembly.

For the selected application, where a human and robots work together to kit and assemble composite subassemblies for installation in an overall product assembly, effectiveness and safety is ensured by integrating human early action prediction generated by a visual perception framework into the robot motion planner so that the planner can produce safe motions proactively, instead of relying on frequent

re-planning. More in details, a perception-based analytics system that couples generative and discriminative models estimates the current and future class of an action taking place [1]. In this approach, current and prior human joint positions are captured and used by machine learning models to generate a prediction of future joint positions, consumed by a discriminative network to then determine the probability of the action that will next be performed. This prediction drives the behavior of the robot so that it can anticipate and respond to what it expects the human to do next [2]. An execution monitoring layer was leveraged to track the cell state and prevent errors. A contingency planner for altering tasks and motion plans for the agents to enable safe and efficient operations were developed.



a) b)

Figure 1: Hybrid cell setup: a) design; b) physical setup.

The developed technologies were demonstrated to support collaboration among robots and humans in the layup of the composite cascade prototype. The assessment of the system performance was done with respect to Key Performance Parameters (KPPs) that among other included (i) the ergonomic exposure of human operators, measured as the time spent on repetitive layup process, (ii) the direct labor required, as the number of human operators needed during layup process, and (iii) the throughput rate, as assembly time. The current manual process for the layup of thrust reverser composite cascades was considered as the baseline for the evaluation. Our assessment demonstrated that human ergonomic exposure and direct labor were reduced by 50%. About the layup assembly time, we considered that a human operator would take ~4 minutes to create a mandrel sub-assembly and ~9 minutes to create a long ply sub-assembly (i.e., baseline). Our objective was to achieve 30% improvement (i.e., 2.8 minutes for the mandrel sub-assembly and 6.3 minutes for the long ply sub-assembly). Through our approach we were able to achieve a total time for sub-assembly kit of 1.2 minutes for the mandrel sub- assembly and 1.6 for the long ply sub-assembly, only ~42% and ~25% of the time objective respectively.

ACKNOWLEDGMENT

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AUTOMATED INSPECTION IN THERMOPLASTIC AUTOMATED FIBRE PLACEMENT

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Keywords: Thermoplastic CFRP, Automated fibre placement, Thermography of moving objects, Profilometry, Air coupled ultrasound

ABSTRACT

Automated Fiber Placement (AFP) involves the deposition of hundreds of meters of tape. After every layer the production is commonly stopped and the entire layer is inspected. Thermoplastic fibre placement generally aims at in-situ consolidation. Thus, inspection of the deposited tape concerning gaps, overlaps, twists, foreign objects and further defects is of utmost importance, as well as inspection of the tape's consolidation. We examined the feasibility of making such measurements "in-line", without stopping the production. For the experiment a laying machine supplied by AFPT GmbH is used that places 3x1/2" tapes. It is manipulated by a high precision KUKA robot. Figure 1 shows the tape laying machine mounted on the robot, plus a schematic representation of the process. Before the consolidation roller built in sensors measure nip point temperature. Additionally, pressure of the roller, laser incident angle and power are controlled. After the roller, three quality assurance methods were used to examine external as well as internal features of the laminate.

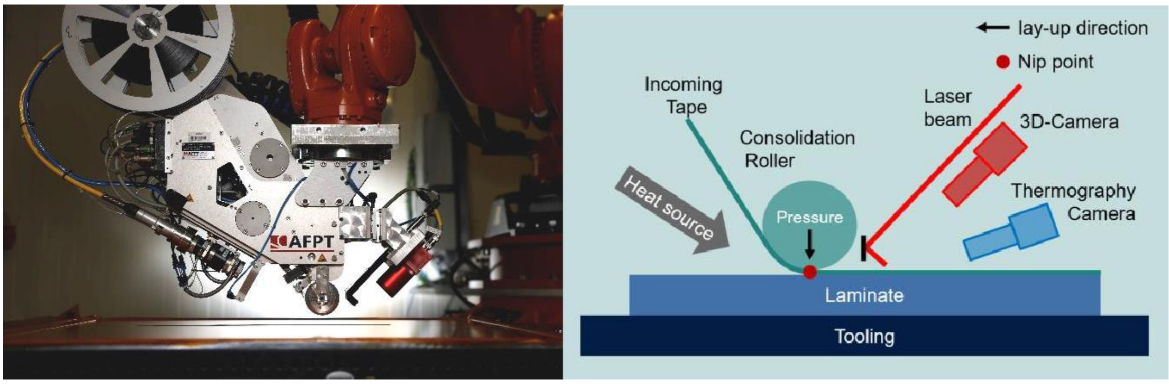

Figure 1: AFP System mounted on robot and schematically process description with integrated quality assurance.

For external inspection a 3D-camera profilometer was installed behind the consolidation roller. By triggering the system via the robot's software encoder in 0.4 mm intervals, large amounts of high-resolution position-based height profiles across all tows and neighbouring tracks were generated. A database stores the automatically uploaded data. All relevant data is attached per track, consisting of 3D position data, raw data (height profiles) plus metadata and calibration info. For evaluation the height profiles are smoothed with a mask to eliminate background noise. Afterwards, all four tow borders in each profile are calculated with help of the gradients and curve fitting of the profile. The main goal is to find gaps and overlaps as well as missing tapes or foreign objects like small cut pieces of tape. Figure 2 (left) shows a visualization of the data from an aircraft skin structure where a gap between two tracks was measured.

First trials where conducted to evaluate thermography as quality method using an infrared camera mounted directly behind the tape laying machine. It measures the temperature of the placed tape. A wide-angle camera lens allows to record a larger area of the tape and selection of a region of interest (ROI) with a higher than average temperature. Due to the movement of the robot the ROI with the potential defect is moving through the picture in accordance with the robot speed. By evaluating the temperature information in several consecutive pictures, a cooling curve can be plotted for each pixel. In theory the cooling behaviour of undisturbed laminate differs from the one with a defect. Defects like porosity, foreign body inclusion or twisted tape leads to a drift in thermal gradients due to changed heat transfer. The measurement of a plate with artificial defects induced during production showed that the defects were visible on the images without image processing and could be tracked over a certain period of time. The cooling curve from the defect differs largely from the undisturbed laminate. Figure 2 (middle) shows two pictures were the ROI with defect moved through the picture and has sufficiently cooled down during the motion. This verified the feasibility to detect defects via inline thermographic imaging of the moving object. Design of the tape laying head and the mounting of the camera resulted in a gap between camera field of view and consolidation roller. Thus, the cooling process could not be recorded in its entirety. For example, the undisturbed laminate used as reference had almost finished cooling to environmental temperature when entering the picture. This behaviour could probably prohibit the evaluation by methods used like in pulse thermography measurements since the initial temperature under the pressure roller and in the gap is unknown. Also, the ROI moves out of focus of the camera when measuring curved surfaces.

Additionally, on the fly internal inspection of the laminate was attempted via an air coupled ultrasound system. Air-coupled ultrasonic inducers were used for the excitation of Lamb waves in the laminate. To generate Lamb waves the mechanical properties of the laminate are considered in the arrangement of the inducers. If mechanical properties differ from design or surface irregularities occur Lamb wave generations is disturbed resulting in lower or no amplitude measures. Due to the highly dynamic process and changing temperatures directly behind the roller, the excitation of Lamb waves was not possible during production. Therefore, a plate with artificial defects was produced and the system was used, after a layer was completed, in a separate process to examine the quality of the laminate. Figure 2 (right) shows the C-scan of the plate. The artificial defects could be detected even though material consolidation was not optimal. Data shows that the air-coupled ultrasonic inspection is feasible for internal inspection as long as the tape laying head is not interfering with the measurement.

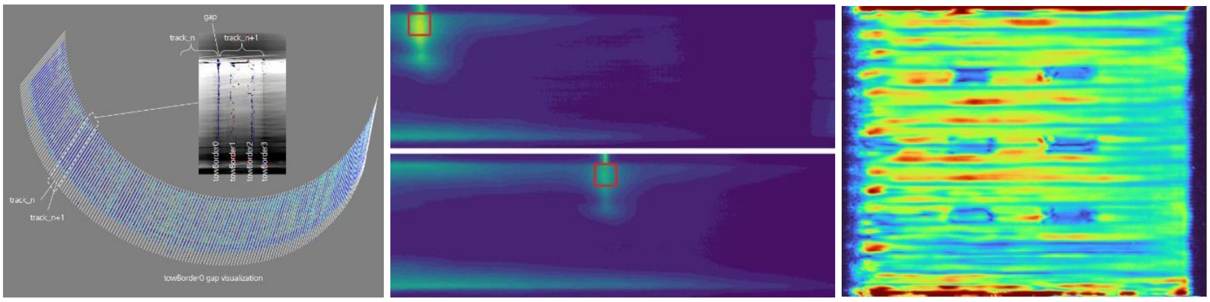

Figure 2: Visualization of measured gaps with profilometer (left), visualization of thermographic measurement of moving defect (middle) and C-scan of air-coupled ultrasonic inspection (right)

The conducted experiments showed that in the current development state, profilometry and thermography are capable of in-line quality assurance of the AFP process. External features can be detected precisely with the profilometer. Internal features and defects can be detected with thermography of the moving object as well as air-coupled ultrasonic inspection. This could make the downstream quality assurance methods obsolete which in turn saves production time and potentially decreases costs. However, in the current development state only the profilometer measurement can be used quantitatively. Although further improvement of the evaluation algorithm as well as the database storage are required. The thermography measurements could be improved by using a different camera and a change in experimental setup to move the camera field of view next to the consolidation roller. Additional actuators could be used to guide the camera when curved surfaces are measured. This enables the usage of advanced thermography evaluation methods due to more accurate tracking of the moving object. Ultrasonic inspection could be conducted in-line with the help of additional actuators to measure the previously deposited track instead of the actual one. This would require modifications of the robot movement for each track but would make the downstream approach of ultrasonic inspection obsolete.

WET FIBRE PLACEMENT – ADDITIVE MANUFACTURING WITH FIBRE BUNDLES IMPREGNATED WITH THERMOSET RESIN

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Keywords: Wet fibre placement, Resin impregnation, Automation

ABSTRACT

Additive manufacturing (AM) is considered to be a key technology in modern times; future developments of these processes will allow to replace entire storage facilities with a variation of 3D printers, which are capable of printing any required replacement part. 3D printing with plastics has established itself to the point where hobbyists can buy an entire 3D printing unit at starting prices as low as 100 Dollars. 3D printed plastic products are light and cheap to produce, but the mechanical properties are often insufficient. In this context, new AM processes, that combine fibrous material with a polymer matrix are gaining attention, as they allow parts that are both, light and have high mechanical performance. The matrix systems mostly include thermoplastics, but also UV-light curable thermosets [1]. On the other side, conventional, thermally cured thermoset resins, are difficult to use for AM with fibre-reinforced polymer composites (FRPC), as most resins are in a viscous liquid state and cannot be quasi-instantly hardened after being placed. Wet fibre placement (WFP) [2] is an additive manufacturing technique, that in-situ impregnates fibre bundles with thermal-cure resins, in order to lay them almost tensionless into tooling moulds. Fig.1 shows a schematic of the process. After placement, the structure is consolidated and cured in a heated press, making it a bridging technology between “classic” AM with often-insufficient part quality on the one side [1] and the material inefficient “classic” prepreg compression moulding [3] with textile-based prepregs on the other side. [4]

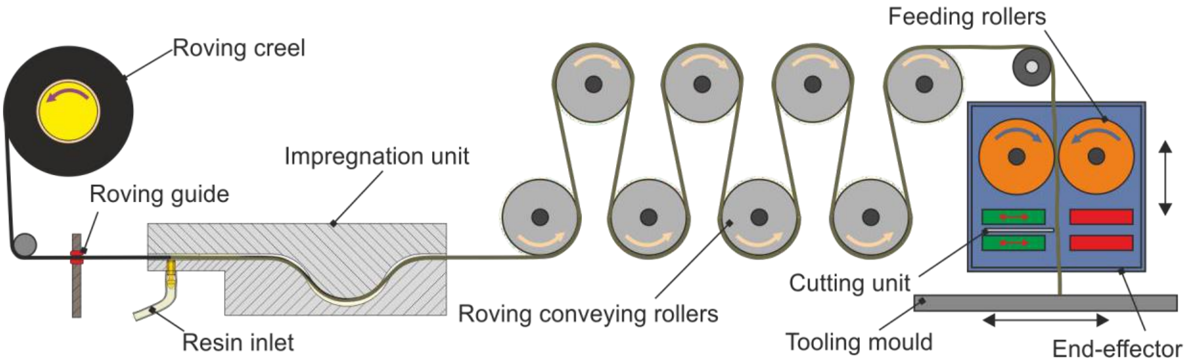

Figure 1: Schematic of the wet fibre placement setup

A major challenge for WFP is to securely convey the fibre bundles from the creel to the tooling mould without damaging the roving or squeezing out the resin. Among other things, the WFP system comprises several partially, independently driven rollers in a conveying unit, an end-effector mounted to a rotational axis that is fixed to a traversing Z-axis, and a tooling mould that is mounted to a X-Y- axis – Fig. 2 shows an image of the newly built-up WFP system at the Leibniz-Institut für Verbundwerkstoffe GmbH (IVW). The end-effector contains two feeding rollers, a cutting unit and position sensors. For accurate fibre placement, a complete synchronization of all moving elements is required, which is a unique challenge, given the high number of system elements. The rotational axis and the X-Y-axes are synchronized to ensure a unidirectional fibre orientation while laying radii and other shapes along the X-Y-axes. Dancer units regulating different electrical drivers are installed, to keep a constant roving conveying feed rate throughout the system. Also, a dancer unit is installed between the roving conveying rollers and the end-effector and a second one is located inside the end- effector. The poster illustrates the major challenges of the WFP automation and how they were solved in order to achieve a robust and efficient process.

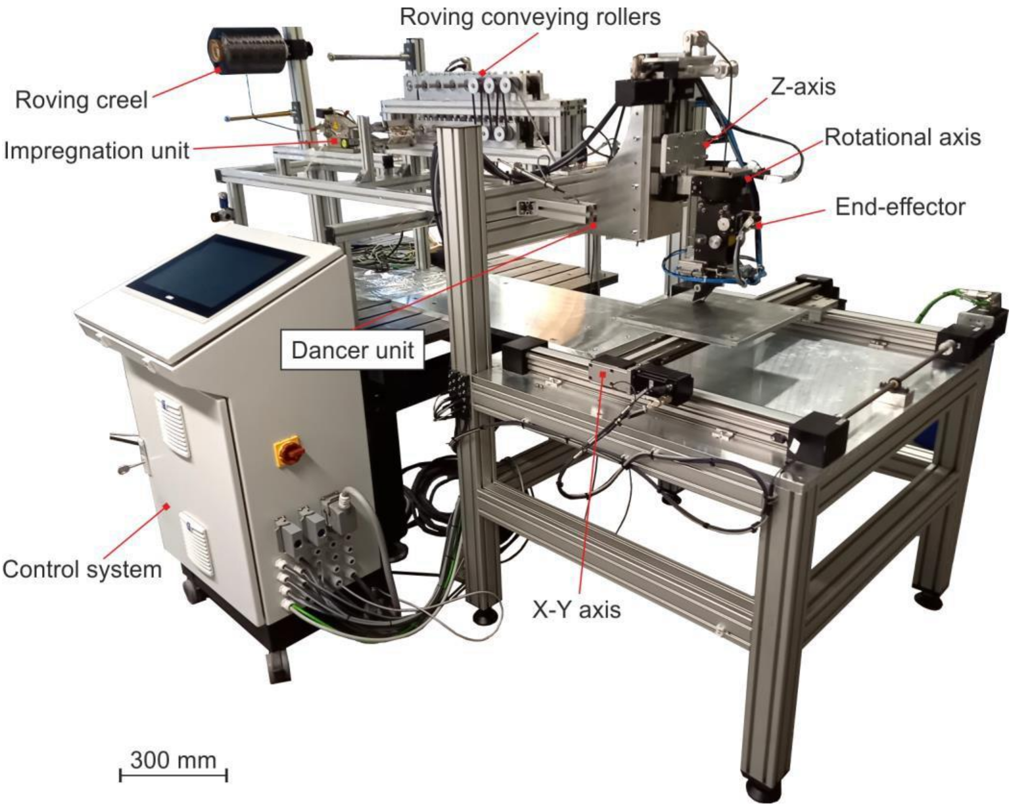

Figure 2: Image of newly commissioned WFP system [5]

ACKNOWLEDGEMENT

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YARN INTERACTION IN AN ENHANCED KINEMATIC MODEL OF THE TRIAXIAL OVERBRAIDING PROCESS

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Keywords: Overbraiding, Yarn interaction, Frontal approach, Preform, Simulation.

ABSTRACT

Overbraiding is a manufacturing process for tubular preforms that can be used in for example Resin Transfer Molding. The preform reinforcement structure can be either biaxial or triaxial. In the case of a triaxial braid, the additional longitudinal stem yarns significantly improve the axial and bending stiffness of the final structure. Structural design of braid reinforced products requires prior knowledge of the fibre distribution, in terms of the braiding angles, fibre density, and the cover factor. Process simulations are useful to predict this distribution for complex geometries. A kinematic model offers fast computation, which, however, does not account for yarn interaction, causing a loss of accuracy of the model predictions [1]. This especially holds for triaxial braids, considering the huge number of additional contact points involved by including the stem yarns. Therefore, the objective of the current work is to develop a new triaxial overbraiding model that includes yarn interactions for complex mandrel shapes.

Figure 1 illustrates a single interlaced point formed between a warp and a weft yarn. Assuming inextensible yarns, the position of the contact point can be determined from force equilibrium:

$$\mathbf{F}_a^c + \mathbf{F}_e^c = \mathbf{0}. \tag{1}$$

Two more Eulerian degrees of freedom, θ_e and θ_a, are added to describe possible sliding between the yarns. The stick-slip stages are distinguished based on a slip criterion using Amonton's friction. The system of equations can be written as:

$$\Psi_s(\theta_e,\theta_a) = \|\mathbf{F}^t(\theta_e,\theta_a)\| - \mu\|\mathbf{F}^n(\theta_e,\theta_a)\| \quad \text{and} \quad \Psi_s(\theta_e,\theta_a) \begin{cases} < 0 \text{ during stick} \\ = 0 \text{ during slip} \end{cases} \tag{2}$$

Here, $\mathbf{F}^t(\theta_e,\theta_a)$ and $\mathbf{F}^n(\theta_e,\theta_a)$ are the tangent and normal force components of the contact forces, respectively and μ is coefficient of friction.

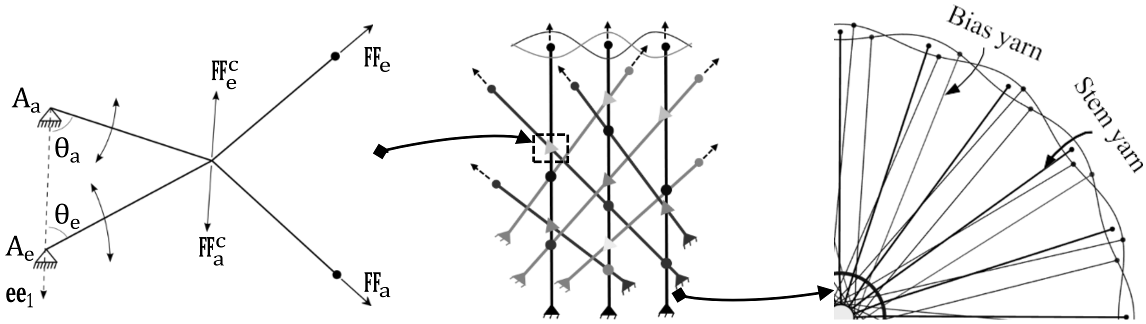

Figure 1: Triaxial overbraiding model, from left to right: a single contact point mode, definition of row of contacts in frontal procedure, front view of triaxial overbraiding simulation using a cylindrical mandrel.

To avoid solving a large system of equations, a fast iterative frontal procedure is utilized to model the multiple interlaced points of the braids. An adapted frontal approach, as presented in Ref.[2], is used to calculate the solution of multiple interlaced points. The procedure has forward and backward scanning steps between rows to iteratively update the contact point positions. The algorithm was implemented in MATLAB® for numerical studies.

Table 1: Parameters for the triaxial overbraiding simulation.

Braiding parameter	Value
Target braid angle [°]	44.5
Spool plane radius, [m]	1.382
Mandrel radius, [m]	0.05
Guide ring radius, [m]	0.17
Friction coefficient of yarns and yarn-to-ring	0.1

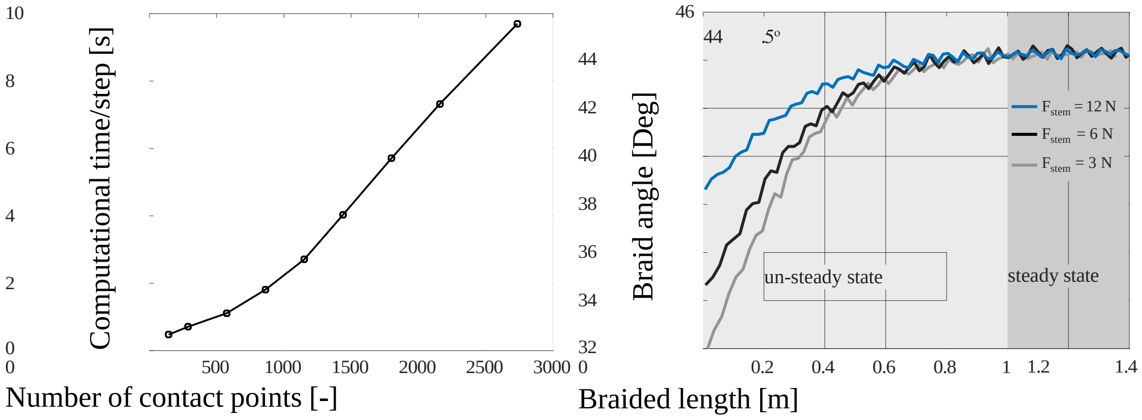

Figure 2: Numerial study of the triaxial overbraiding simulation, right: computational time with increasing number of contact points, left: simulated braid angle as a function of braided length.

A triaxial overbraiding machine with 20 carriers and a circular guide ring is used to virtually overbraid a cylindrical mandrel. The parameters used for the process are listed in Table 1. The tension force applied on stem yarns is varied between 3 N, 6 N, and 12 N, while the tension on the bias yarns is kept constant at 5 N, to study the effect of stem yarn tensioning on the resulting braid angle.

As shown in Figure 2, the computational time is approximately proportional to the number of contact points. Additionally, the computational times lie in the order of only seconds, even for a large number of contact points with the current MATLAB® implementation. As the tension force on stem yarn increases, the initial braid angle increases. The braid angle converges to the target braid angle when reaching steady-state. For the future research, more relevant experiments are needed to validate these simulation results.

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HOW SMART IS SMART MANUFACTURING?

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Keywords: Automated fibre placement, defect prediction, virtual manufacturing

ABSTRACT

One of the current trends in automated fibre placement is the use of ‘smart manufacturing’. One of the defects that could possibly be avoided are the small gaps/overlaps that occur due to the tape not being of the exact same width everywhere, as shown in the left of Figure 1. Using a ‘scan-and-plan’ approach the tape already placed is scanned and the next tape is placed adjacent. While this approach does eliminate gaps and overlaps, a new problem occurs: the tape is locally steered, and thus the layer does not have the fibre angle it was designed for, as shown in the right of Figure 1. This effect so far has not been investigated, but it is important to check that we are not creating a new problem trying to solve another one.

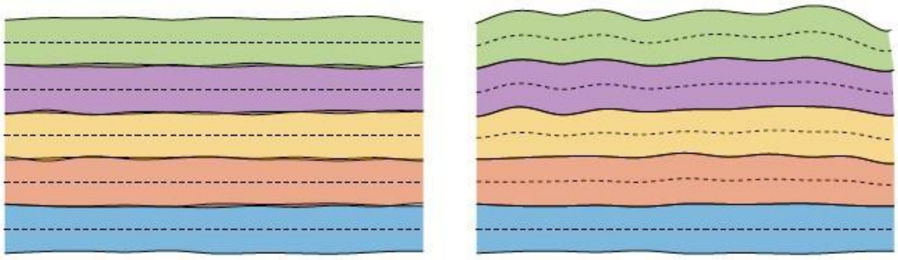

Figure 1: ‘standard’ manufacturing on the left; ‘smart’ manufacturing on the right.

The variation in tow width was randomly generated to obtain a smooth and representative variation of each fibre width [1]. Later on, this methodology can be used with input of actual measurements of fibres as well. Initially, it was attempted to lay the fibres perfectly next to each other, but it was found that when laying down many fibres next to each other, the radius could become so small that the radius of the outer layer becomes negative, leading to self-intersection of the edges, which is of course not realistic. This is shown in Figure 2.

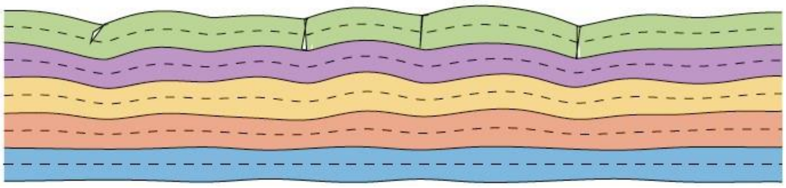

Figure 2: self-intersection of the outer edges.

To avoid the self-intersection of the outer edges, a minimum steering radius was implemented. The downside is that it is not possible to completely avoid gaps/overlaps this way anymore. A wide range of minimum steering radii were tried to find the limitations. The results are shown in Table 1, where it can be observed that the largest steering radius leads to almost no change in angle, but a relatively high percentage of gaps and overlaps. The opposite is true for the smallest steering radius: the maximum angle deviation is large than 10 degrees, which could have major implications for the mechanical behaviour of the structure, and a relatively lower percentage of gas and overlaps.

Minimum steering radius [mm]	Percentage of gaps/overlaps	Maximum angle deviation [deg]
50	0.98%	11.9
200	1.29%	6.1
800	1.59%	1.9
6400	1.84%	0.5

Table 1: Results for different minimum steering radii.

To assess the effect of the angle variations and gaps and overlaps, the defect layer method [2] was used to model a 500 by 500 mm panel under uniform compression, with a quasi-isotropic layup. Both the fibre deviations and the influence of gaps/overlaps are taken into account. The results with local fibre steering are obtained using a minimum steering radius of 400 mm. For the traditional manufacturing, multiple options are checked: in order to minimise gaps or overlaps, the offset between layers can be increased/decreased by the standard deviation σ. The results are shown in Figure 3, where it can be observed that local fibre steering does not improve the buckling load or effective stiffness by a lot compared to an offset equal to the tow width. However, often overlaps are being avoided by increasing the offset, which would not be necessary with local fibre steering. Hence smart manufacturing can have advantages, but

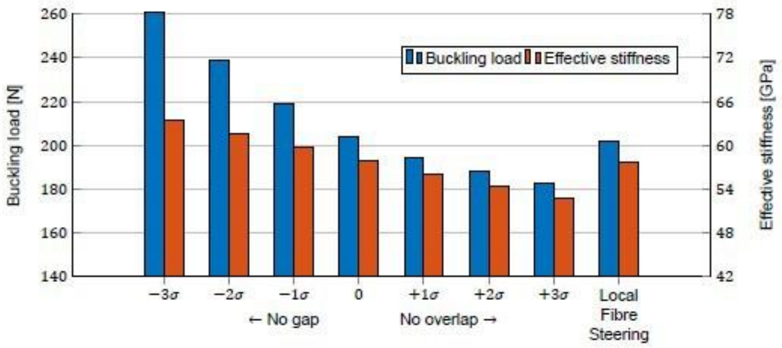

Figure 3: Buckling and effective stiffness as a function of manufacturing strategy.

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IN SITU POLYMERISATION DURING MONOMER INFUSION UNDER FLEXIBLE TOOLING (MIFT)

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webpage: https://www.plymouth.ac.uk/research/materials-and-structures-research-group/composites-engineering

Keywords: *in situ* polymerisation (ISP), Large structures, Marine environment, Monomer Infusion under Flexible Tooling (MIFT), Thermoplastic matrix.

ABSTRACT

A significant majority of large fibre composite structures in the marine environment currently use a thermoset resin matrix. These materials have excellent durability in the sea, but are difficult to dispose of at end-of-life. After a rigorous selection process [1], methyl methacrylate and lactide monomers have been identified as potential thermoplastic matrix systems which can be manufactured using in situ polymerisation (ISP) during composite manufacture by liquid composite moulding (LCM) processes. LCM includes resin transfer moulding (RTM) for components up to about 3 m square, then Infusion under Flexible Tooling (RIFT for resins, or MIFT for monomers). The acrylic is a "drop in" for polyester resin, but lactide requires elevated temperature processes. At end of life, acrylic is lower in the recycling hierarchy.

INTRODUCTION

With the increasing concerns over environmental issues, natural fibres and thermoplastic matrices attract increasing interest by composite engineers. As a method of Liquid Composite Moulding (LCM), Resin/Monomer Infusion under Flexible Tooling (RIFT/MIFT) has been widely used for the production of large and complex composite structures with high mechanical properties [2, 3]. Acrylic methyl methacrylate (MMA) and lactide monomers were reported to be suitable to produce thermoplastic matrix marine composites using in situ polymerisation (ISP) by LCM [1]. In this study, flax fibre reinforced thermoplastic composites were made (by MIFT via ISP) and flexural tested to guide the future production and application of large marine composite structures.

MATERIALS, SAMPLE PRODUCTION AND TESTING

The acrylic MMA resin used in this work is Elium® 188 XO catalysed with benzoyl peroxide. The L-lactide was catalysed with Tin(II) 2-ethylhexanoate. The natural fibre reinforcement was a 2x2 twill weave flax fabric with areal weight of 200 g/m^2. The schematic of the MIFT for production was shown in Fig. 1. As elevated temperature is required for the process of MIFT of L-lactide monomer, polylactic acid (PLA)-flax composites were produced in the oven at 170 °C for 3 hours. The flax fibre volume fractions were ~31% for both PLA-flax and Elium®-flax composites. The mechanical properties of the sample were investigated by three-point flexural testing. The sample geometry for flexural tests is 80 x 10 x 3 mm^3 (cut from the composite plate). The test span and speed in the flexural testing were 48 mm and 1.28 mm/min respectively according to ASTM D790 standard [4].

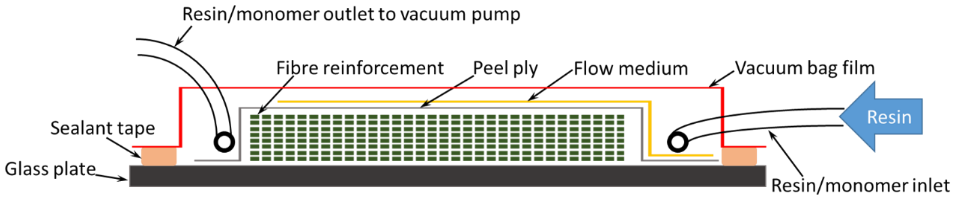

Figure 1. Schematic of the MIFT.

RESULTS AND CONCLUSIONS

The experimental results from the flexural tests and theoretical prediction (by rule-of-mixture equations [5, 6]) are shown in Table 1. Although acrylic resin (Elium®) is lower in the recycling hierarchy at end-of-life, it can be seen Elium®-flax shows better flexural properties than PLA-flax composites. In addition, except for the flexural strength of Elium®-flax, all experimental results are significantly lower than the theoretical prediction values.

Table 1 Flexural properties for PLA-flax and Elium®-flax composites.

Composite	Flexural strength			Flexural modulus		
	Experimental Mean ± SD (MPa)	Prediction (MPa)	E/P* (%)	Experimental Mean ± SD (GPa)	Prediction (GPa)	E/P* (%)
PLA-flax	56.98±9.58 (16.8%)	91.7	62.1	3.66±0.31 (8.5%)	9.86	37.1
Elium®-flax	123.73±4.96 (4.0%)	119.3	103.7	4.98±0.42 (8.4%)	9.45	52.7

*E/P represents the ratio between experimental value and prediction.

This study produced flax fibre reinforced thermoplastic composites by MIFT via ISP, but further work is required to optimise the ISP processes, and to develop coupling agents which enhance the fibre- matrix interface and improve the composite mechanical properties.

ACKNOWLEDGMENT

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AFP LAYUP OF CF-LM PAEK FUSELAGE SKIN USING A PULSED XENON FLASHLAMP SYSTEM WITH AN OPTICAL-THERMAL SIMULATION TOOL

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Keywords: Thermoplastics; AFP layup; xenon flashlamp; ray tracing; FEA

ABSTRACT

Xenon flashlamps have emerged as an alternative heat source to the laser in Automated Fibre Placement (AFP) of thermoplastics. These systems are showing sufficient promise to be selected as the fuselage skin layup solution via the AFP process for the Clean Sky II project FRAMES. A Xenon Flashlamp system, consisting of a flashlamp, reflector and quartz light guide, has been shown to reach the temperatures required to process thermoplastic composites in a similar response time to a laser with reduced safety burden. To determine good pulse parameters for CF-LM PAEK for the FRAMES project, an opto-thermal simulation model has been created based on experimental characterisation.

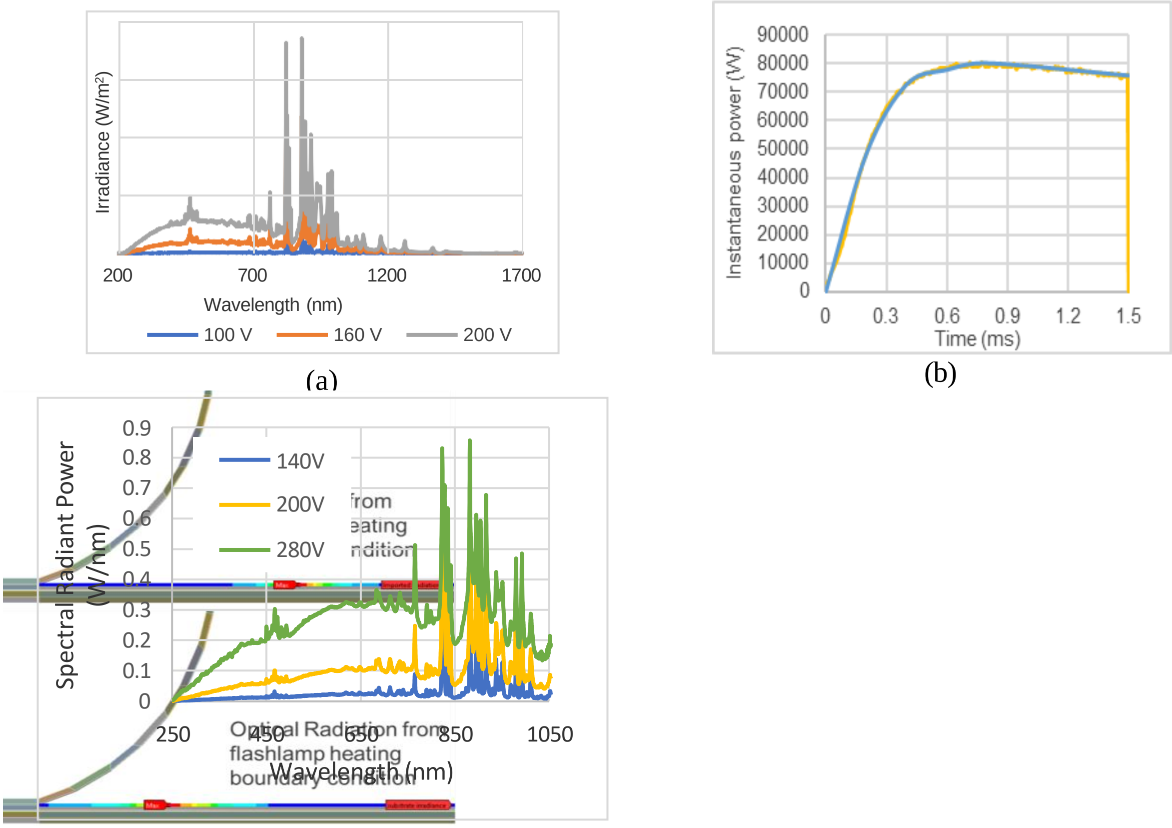
A full optical ray tracing simulation model of the pulsed xenon flashlamp system is required to determine the distribution of energy exiting the light guide and being absorbed by the CF-LM PAEK tapes. Firstly, the xenon plasma source was characterised using spectral irradiance and goniometric measurements. The spectral irradiance measurements in figure 1 (a) show the expected behaviour for a Xenon source, with the measurements at specific voltage ranges used by the pulsed flashlamp system. Furthermore, the goniometric measurements showed the flashlamp can be approximated as a Lambertian emitter for this application. This characterisation data was used to build a source model for the xenon flashlamp within optical ray tracing software and supplemented with literature and datasheet data to complete the optical flashlamp system simulation.

The next step was to determine the energy levels of the pulses entering and exiting the flashlamp system, this was achieved by measuring the electrical pulse energy entering the flashlamp and the optical energy exiting the system light guide. The electrical energy entering a flashlamp was measured using an oscilloscope, with a plot of this shown in figure 1 (b), and the area under the curve giving the energy value. The energy exiting the system light guide was determined using an integrating sphere, with the area under the graph once again giving the energy value, with some of the results shown in figure 1 (c). Based on the measurements in figure 1 (b) and (c), it is possible to calculate the electrical to optical energy conversion efficiency and control energy levels within the simulation tool. Since the optical aspect of the simulation was well characterised, its irradiance profile was transferred to the thermal simulation as shown in figure 1 (d).

Analysis showed that an additional radiative heating process originates from the quartz light guide, which heats up whilst the system is powered, and the resultant heat to the composite tapes via radiation. It is possible to experimentally measure this effect with thermocouples on the surface of a composite tape and build a 3D finite element simulation of this effect, which produced a similar looking thermal curve. The heat flux within this simulation was captured and transferred to the main thermal simulation as a boundary condition, as shown in figure 1 (d).

A finite element analysis (FEA) technique developed in [1] was used to predict the resultant processing temperature within a transient thermal ANSYS simulation. To provide the simulation with its necessary pre-requisite parameters, the thermal diffusion parameters of the CF-LM PAEK material were measured using the DSC and LFA techniques by an external laboratory. In parallel, AFP layup trials were performed, with thermocouples used to provide actual thermal measurements during

processing. The pulse energies used in the trials, with an example shown in figure 1 (b), were measured and scaled to the measured energy curve with the calculated energy efficiency. This data was used to determine optical energy heat flux boundary condition and was programmed to pulse within the simulation. The IR radiation was also scaled and included in runs of the simulation tool for comparative purposes. This simulation tool, as a result, accurately captures the physics behind the two mechanisms heating the CF-LM PAEK tape, but further thermal measurements of the quartz light guide are required to improve the radiative aspect.



(a) (b)

(c) (d)

Figure 1: (a) Spectral irradiance measurements of xenon flashlamp used in system, (b) oscilloscope measurement of electrical energy entering the system from a single pulse, (c) integrating sphere measurement of energy exiting the system light guide, and (d) heat flux boundary conditions imported into the transient thermal FE simulation for both optical energy from flashlamp and IR radiation from heating of the light guide.

Acknowledgements: This project has received funding from the Clean Sky 2 Joint Undertaking under the European Union’s Horizon 2020 research and innovation programme under grant agreement No 886549.

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WRAPTOR COMPOSITE TRUSS STRUCTURES: CONTINUOUSLY WRAPPED TOW REINFORCED TRUSS BEAMS

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Keywords: Truss structure, Composites, Continuous Manufacturing

ABSTRACT

Recent developments in ultra-efficient composite truss structures have shown very high structural efficiency through the combination of truss geometry, composite material properties, and the use of scalable manufacturing processes [1]. However, efficient use of material is not enough to minimise structural costs, if that efficiency comes at the expense of a complex manufacturing process. Therefore, cost-effective production processes must be developed synergically with new structural designs. Although filament winding-based approaches such as the WrapToR (Wrapped Tow Reinforced) process allow for simpler machine design compared to other manufacturing techniques such as braiding or pultrusion, the process is limited to batch production of truss beams with limited lengths [2]. In this work we present a novel process for continuous high-throughput production of WrapToR truss beams (Figure 1a) by continuously winding the web members. Similar to other examples of continuous formation of beam-like truss structures [3, 4], our concept resembles an extrusion process; therefore, we have named the process "Trusstrusion" with a "Trusstruder" as the central mechanical component developed for this purpose (Figure 1b).

Conventionally, WrapToR trusses are obtained utilising a modified filament winding machinery. The longitudinal pultruded chord members of the trusses are held in place on a mandrel while the winding head moves back and forth over the entire truss length to wind the FRP tows of the shear web members. In order to achieve a continuous process, a novel winding machine (the Trusstruder) runs along the longitudinal members of the WrapToR truss itself, which are held in place using an internal supporting mandrel. Since the shear web members of WrapToR beams are wound in two directions (clockwise and counter-clockwise) with respect to the beam axis, a coaxial counter- rotating winding head wraps multiple pre-wetted tows in opposite directions around the continuously extruded longitudinal members. In this way it is possible to achieve a fully wound truss structure in one passage, avoiding the need for the reciprocating motion of conventional winding machines.

The continuous Trusstruder concept consists of a *Feeding* and a *Winding* system, with internal modules which perform the various tasks in the WrapToR truss winding process; see Figure 1c. The *Feeding* system deals with the feeding and driving of the unidirectional (UD) pultrusions; an initial module holds the corner rods in place and the second houses the motors and control board, which drive the pultrusions into the *Winding* system. Here, the corner rods are held in place by a series of pulleys which maintain the correct cross-sectional shape of the truss during winding and consolidation. The currently designed modules can produce trusses with the cross-sectional properties and materials listed in Table 1.

In summary, trading process and geometry versatility for standardisation and production rate, this new machine concept moves towards high throughput, continuous production of WrapToR truss beams.

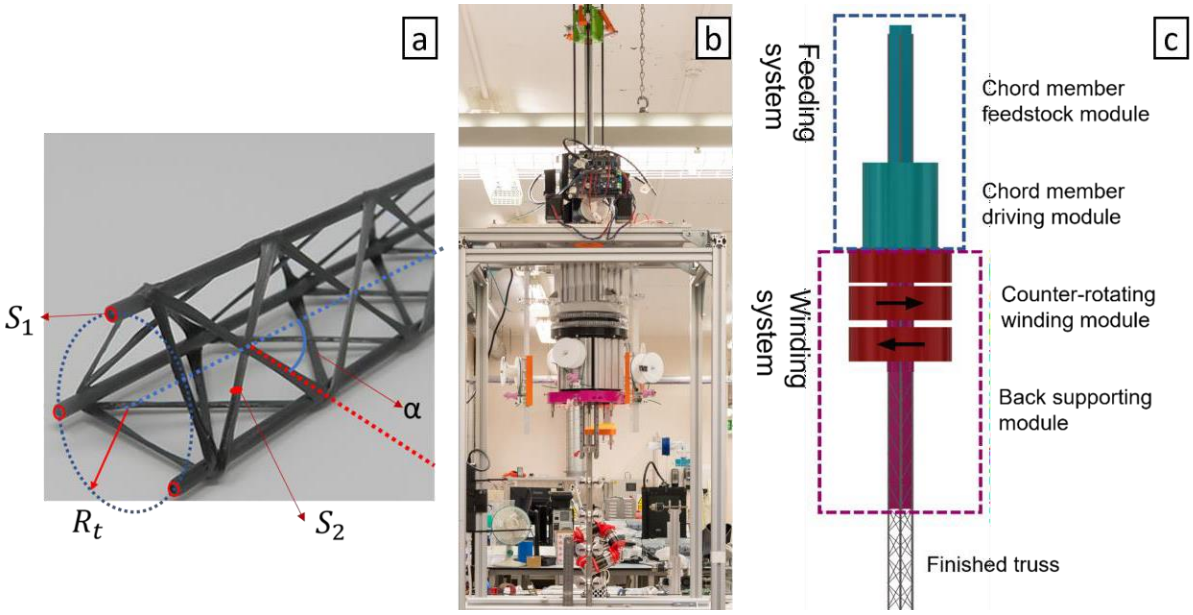

Figure 1 a) WrapToR truss beam produced with the Trusstruder. b) The current version of the Trustruder at the Bristol Composites Institute Laboratories. c) Schematic representation of Trusstruder's modules arrangement.

	Property	Symbol. [unit]	Value / Range
R_t	Truss radius	R_t [mm]	40
α	Shear web angle	deg [-]	[15, 60]
S_1 - Chord member	R external	R_{ext} [mm]	6
	R internal	R_{int} [mm]	n.a.
S_2 – Shear web member	Web radius (6K to 48K)	R_{web}[mm]	[0.8, 1.25]

Table 1 Characteristics of the truss beams produced with the current version of the Trusstruder

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TEMPERATURE GRADIENTS IN THERMOPLASTIC COMPOSITES MADE BY AUTOMATED FIBER PLACEMENT

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Keywords: Automated Fiber Placement, Thermoplastic Composites, Heat Transfer Analysis, Temperature Gradients

ABSTRACT

Automated fiber placement (AFP) is a suitable process for the manufacturing of thermoplastic composites. This is because the process can be used to make composite structures with different sizes (in contrast with processes such as compression molding, thermoforming, or thermo-stamping where only samples of small sizes can be made). Another reason is the in-situ consolidation of the materials during the process, and it may not be necessary to perform secondary process such as autoclave treatment. However, in practice it is not certain that thermoplastic composite structures with high quality (minimum amount of void, proper interlaminar shear strength, distortion free) can be made without secondary treatment after material deposition using AFP. Our experience shows that thermoplastic composite structures without free edges (such as those with cylindrical shape) can be made very well using AFP. This is due to the constraint provided by the non-existence of free edges. On the other hand, structures with free edges (such as flat plates, curved panels etc.) exhibit distortion even during the manufacturing process of unidirectional plates [1, 2]. The reason for this is due to the thermal gradients developed within the structure during the material deposition process.

In this paper, we developed models for the determination of temperature distributions in unidirectional thermoplastic composite (carbon/PEEK) plates during and after material deposition using AFP machine with a hot gas torch [3]. From these temperature distributions, the temperature gradients were determined as functions of time and space. The results show that large temperature gradients arise during and after the process. The temperature gradients vary from location to location within the laminate. They also depend on the thermal conductivity of the mandrel. Figures 1 and 2 show some typical results of the temperature distributions and temperature gradients. These temperature gradients explain the reason for the distortion of the laminates. The temperature gradients can be used to determine the residual stress distributions in the laminate. Figures 1 and 2 indicate temperature and temperature gradients developed in a unidirectional thermoplastic (carbon fiber/PEEK) laminate with a length of 508mm (20 inches) during the deposition of layer 10.

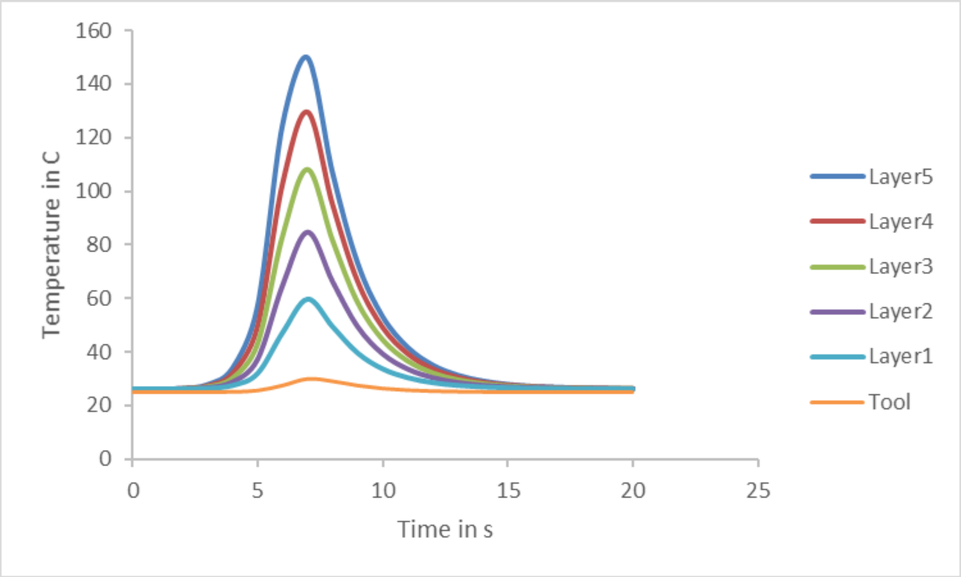

Figure 1: Temperature distribution of the laminate (aluminum tool).

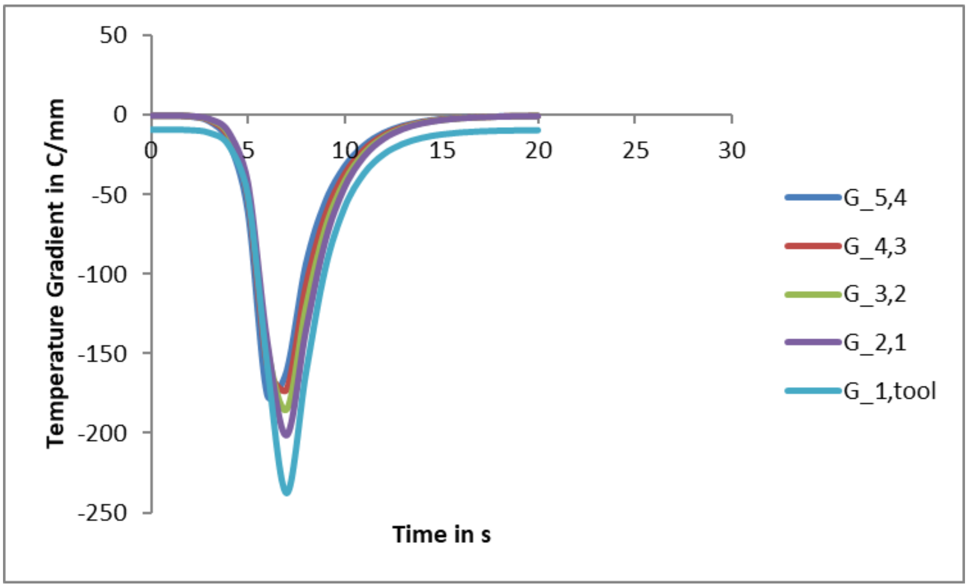

Figure 2: Temperature gradients of the laminate (aluminum tool).

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MULTI-OBJECTIVE OPTIMIZATION FOR DRILLING OF CF/PEKK COMPOSITE

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Keywords: CFRTP, Drilling, Multi-objective optimization, NSGA-II

ABSTRACT

Adoption of carbon fibre reinforced plastic (CFRP) in aeronautical structures has enabled significant weight reduction, less fuel consumption and higher performance of new generation aircrafts. In aircraft assembly, joining of CFRP panels with metal frames is mainly accomplished by riveting through assembly holes created by drilling. This present additional challenges as CFRP hole damage (i.e. delamination, microstructural damage and thermal damage) can be easily induced with use of improper machining parameters. To date, most drilling optimization studies were focused on conventional thermoset CFRP (CF/epoxy) [1,2]. The relevant research on drilling parameter optimization of the emerging carbon reinforced thermoplastic composites (CFRTP), particularly carbon fibre reinforce polyetherketoneketone (CF/PEKK), is absent. Considering the unique thermal- mechanical properties thermoplastic CF/PEKK [3], optimizing drilling parameter for CF/PEKK is highly desirable for its practical aircraft assembly applications.

In this work, full factorial experiment has been carried out for conventional drilling of thermoplastic CF/PEKK. The drilling parameters (spindle speed and feed rate) are the input variables, while the drilling performance indices obtained from physical experiments (thrust force, machining temperature, delamination damage factor and material removal rate (MRR)) are selected as response variables. The measured thrust force data is plotted in Fig.1. Data analysis including analysis of variance (ANOVA), second-order polynomial regression and multi-objective optimization. The objective functions and constrains for the optimization can be expressed as follows:

$$\text{Minimize } \mathrm{F}(\mathrm{S},\mathrm{F}) = f_F(S,F),\ f_D(S,F),\ -f_{MRR}(S,F) \tag{1}$$

Subject to $f_D(S,F) \le 1.5$, $f_T(S,F) \le T_g$

$$S \in [1327,5308], F \in [0.025,0.2]$$

where f_F, f_D, f_{MRR}, f_T are functions for thrust force, delamination factor, MRR and hole wall temperature, respectively. Pareto front was obtained from the optimization and decision making following previous study [4].

Second order polynomial regression was used to express the responses variables as a function of the input drilling parameters. Multi-objective optimization using Non-dominated Sorting Genetic Algorithm (NSGA-II) was conducted in search of the trade-off between the hole quality and the drilling efficiency. The global convergency and spacing distance of the obtained pareto front were inspected to ensure the reliability of the optimization. The optimization results were then validated by experiment, where an ideal trade-off between different objectives can be achieved. The optimization results is expected to provide parametric guidance for practical manufacturing of advanced CF/PEKK composites.

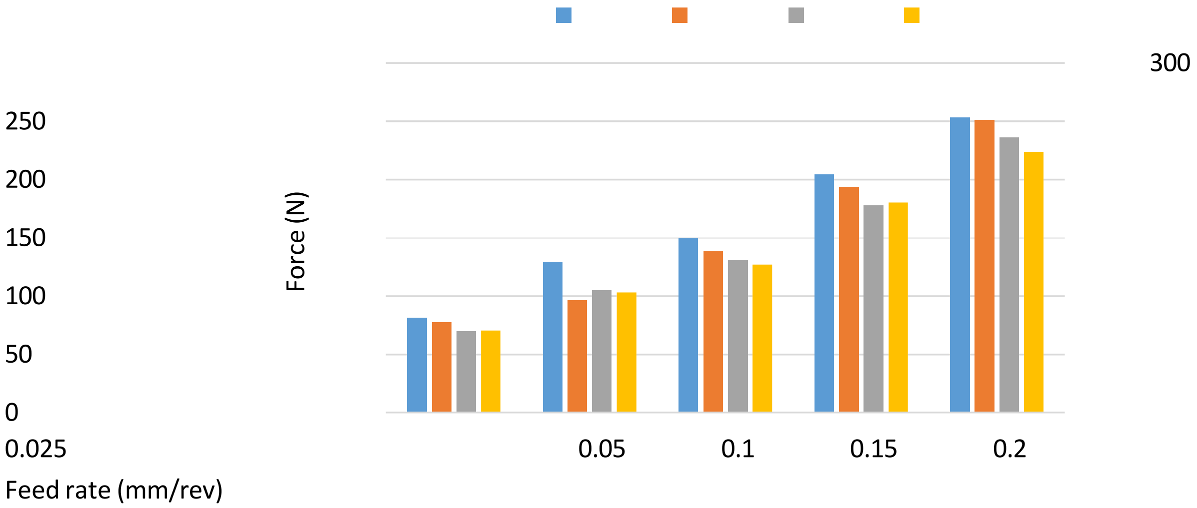

Fig. 1 Thrust force in drilling of CF/PEKK under various parameters

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Spindle speed: S1327 S3654 S3981 S5308

RECYCLABLE ACRYLIC-GLASS COMPOSITES FOR MARINE AND TIDAL ENERGY APPLICATIONS

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Keywords: Sustainability, Acrylic Thermoplastic, Mechanical Properties, Ageing Studies

ABSTRACT

Polymer matrix composites will play a key role in meeting global sustainability targets, and as a result demand is expected to grow in various sectors [1]. The onshore wind turbine blade industry alone is expected to accumulate 43 million tonnes of composite waste worldwide by 2050 [2], but if current practices of using non-recyclable thermoset matrices continue, most of this waste will be incinerated or landfilled.

For the manufacture of large composite structures, liquid acrylic monomeric resins are a recyclable alternative to thermosets. The resins have a low viscosity and polymerise at ambient temperatures, allowing them to be processed in the same way as typical thermosets. Moreover, acrylic polymers are thermoplastics, allowing them to be thermoformed, dissolved, or melted for recycling. On the other hand, acrylic polymers have a low solvent resistance, reducing their suitability for applications involving exposure to fuels, cleaning solutions and lubricants. The recent development of a thermoformable acrylic-poly(phenyl ether) (PPE) hybrid matrix with improved mechanical characteristics provides a solution to the problem of solvent resistance [3].

The present work includes a comparative study of the mechanical properties of acrylic/glass, acrylic-PPE/glass and epoxy/glass composites before and after ageing in seawater at 50°C for 3 months, with the aim of determining their suitability for tidal turbine blades and shipping applications.

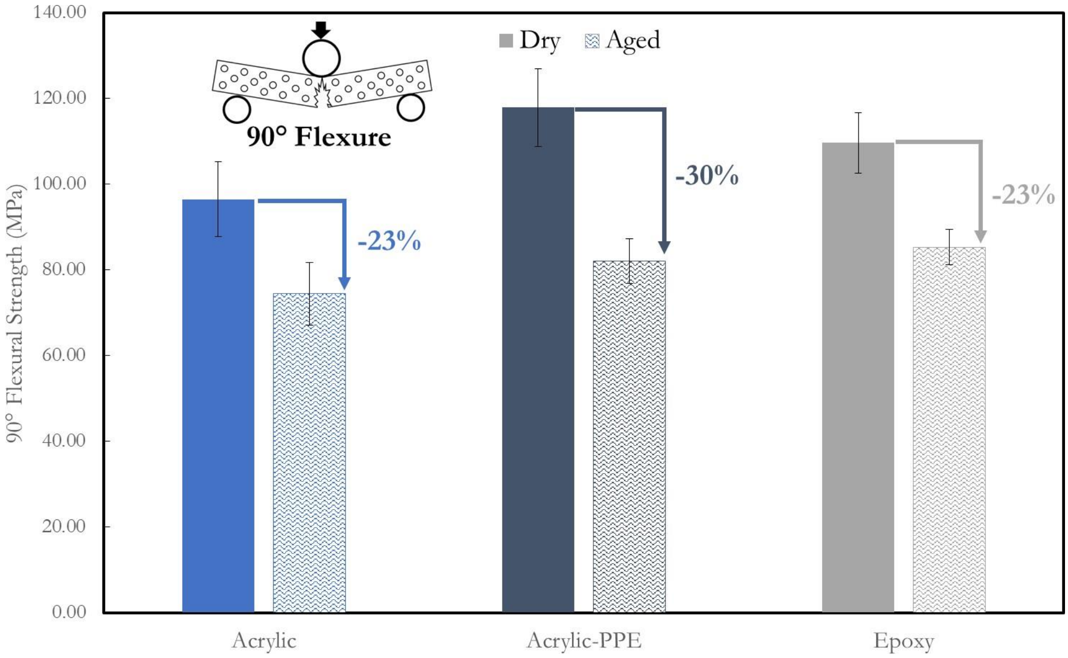

Figure 1: Flexural strength of 90° specimens before (solid) and after (hashed) seawater ageing. The percentage reductions in strength are highlighted with arrows.

The effect of water absorption on the 90° flexural strength of specimens prepared with each matrix is reported in Figure 1. The acrylic-PPE composite outperformed both unmodified acrylic and epoxy, with the flexural strength of dry specimens increasing by 22% compared with unmodified acrylic.

Ageing caused a greater decrease in the 90° flexural strength of the acrylic-PPE composite than the unmodified acrylic and epoxy, however even after ageing the strength of the acrylic-PPE specimens remained 10% higher than unmodified acrylic. Modification of acrylic with PPE therefore results in enhanced matrix flexural strength in both dry and aged samples.

The fracture surfaces of the samples were investigated using scanning electron microscopy (SEM), and a comparison of the tensile side of the fracture of acrylic-PPE composites before and after ageing is displayed in Figure 2. The role of the fibre-matrix interface in composite strength—and the weakening effect that water has on it—is made clear by the contrast in the quantity of matrix remaining attached to the fibres after fracture.

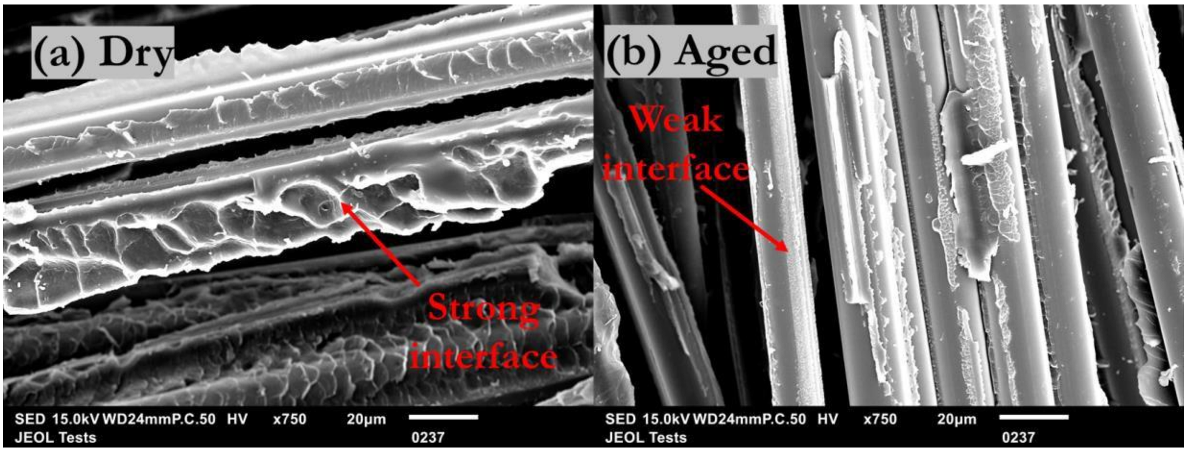

Figure 2: SEM images of the fracture surfaces of 90° flexural acrylic-PPE composite specimens. Matrix remains attached to the fibres in the dry specimens (a) whereas bare fibres are exposed in the aged specimens (b).

To conclude, acrylic modified with PPE combines the recyclability of a traditional thermoplastic with the ease of processing and solvent resistance of a thermoset. Compared to pure acrylic, the hybrid matrix has enhanced flexural strength both before and after accelerated seawater ageing. In addition to the results presented here, further SEM images of the three different matrices before and after water ageing will be discussed.

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EFFECT OF WINDING TWIST ON MULTILAYER BRAIDED COMPOSITES

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Keywords: Braiding, Winding, Twist

ABSTRACT

Applying a measured level of twist to fibres during the winding process has been recommended by manufacturers but little literature in the academic journals has been published to support this. In the present work the effect of varying the level of twist on the braid architecture for multilayer preforms has been investigated. Studies on prismatic circular section mandrels and converging and diverging conical sections are presented. Samples were braided using T700 12K fibres on a 48-carrier axial braider. Two twist levels of 0 twist per metre (tpm) and 5 tpm have been investigated. It was observed that more levels of twist led to damage to the fibres during the winding process. Key architecture parameters such as yarn width and thickness have been measured using photography, laser scanning and optical microscopy. Braid angle has been detected using photography and image analysis using OpenCV [1] to automatically detect the angle between the fibres at set points along the length of the mandrel.

For constant section mandrels no statistical difference in braid angle was observed for 0 tpm and 5 tpm fibres. Changes in the cross-sectional shape can be seen in figure 1(a) and (c) with dry preform measurements showed up to a 20 % reduction in tow width for 5 tpm yarns compared to 0 tpm with an increase of 23 % in the thickness for greater levels of twist.

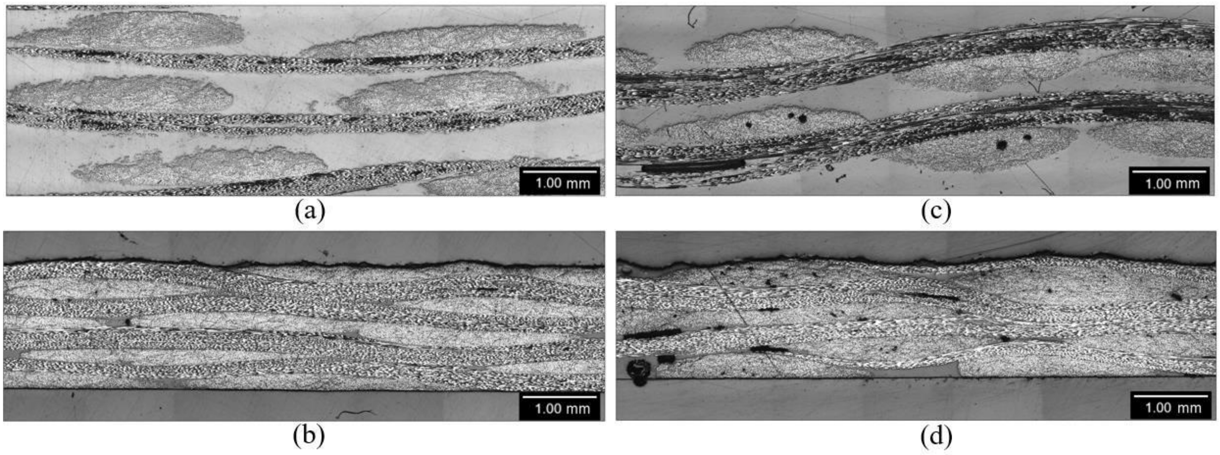


Figure 1: Optical microscopy of biaxial braided fabrics before and after vacuum infusion. (a) 0 tpm before infusion, (b) 0 tpm after infusion, (c) 5 tpm before infusion and (d) 5 tpm after infusion.

The effect of twist on infusion in liquid moulding manufacturing technologies was also considered, shown in figure 1(b) & (d). A 9.3 % difference in yarn width was observed between the two twist levels. An increase in resin rich areas and voids has been observed within the 5 tpm infused panels,

explained by the lower initial coverage of the fabric. Twist was seen to have little influence on the overall thickness of the infused panels due to an increase in the nesting between layers.

The influence of changing cross-sectional mandrels was investigated using diverging and converging conical sections. Similar results have been seen for width and thickness data, with lower levels of twist leading to wider and thinner yarns. However, a difference in braid architecture for converging and diverging conical sections was observed. For a converging section (large to smaller diameter) the braid formation was seen to be more consistent as seen in figure 2. For diverging sections braid angles were seen to vary by up to 19%, as seen in Figure 1. This is attributed to fibre slippage in contact with the mandrel. Both were braided with a constant target angle of 45 degrees, however instability in the braiding over the conical sections shows that this is difficulty in achieving this.

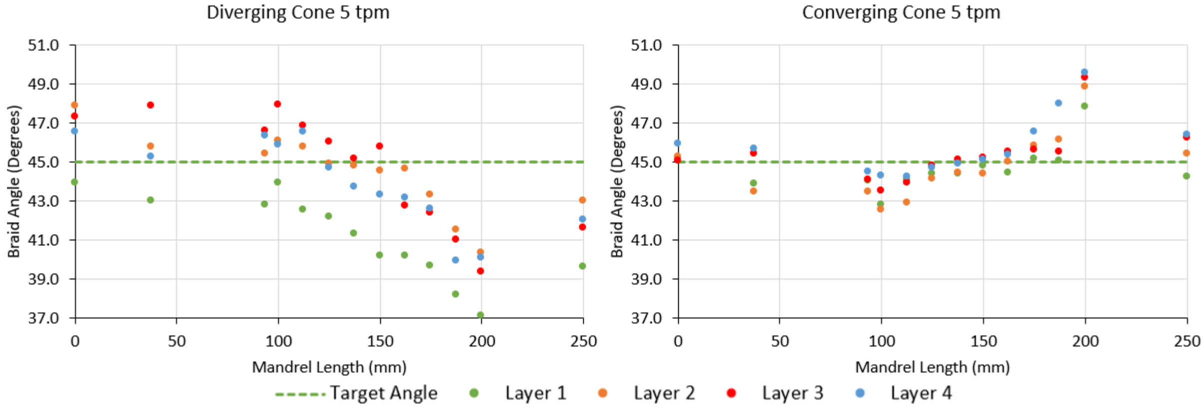
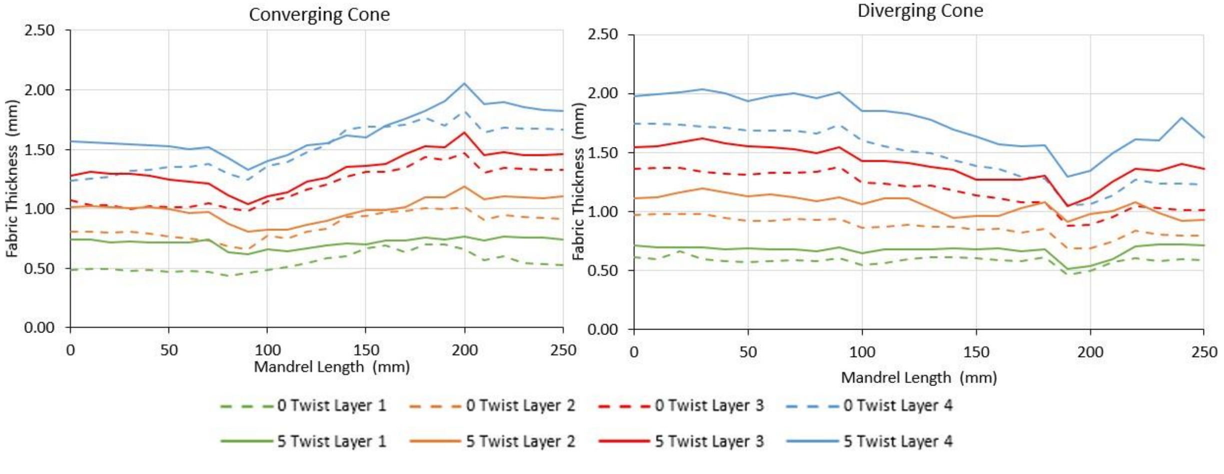


Figure 2: Measured braid angle on diverging and converging conical sections

Alongside angle data, layer thickness data was collected using a hexagon RS6 laser scanner to capture the topology of the surface. This method allows the thickness to be captured along the length of the mandrel without requiring contact on the surface. As seen in figure 3 both twist levels follow similar trends with a peak of thickness seen at 200 mm on the converging cone, corresponding to the base of the conical section. This is suspected to be due to bridging of the fibres within this area. The work presented shows a good agreement with a previous study by Du et al. [2] investigating braiding on conical sections.

Figure 3: Measured fabric thickness for converging and diverging conical sections



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FIBRE-WAVINESS CHARACTERISTICS OF FIBRE-STEERED LAMINATES PRODUCED BY CONTINUOUS TOW SHEARING PROCESS

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Keywords: Fibre orientation analysis, Continuous Tow Shearing, Image analysis, Process-induced defects, Non-destructive testing

ABSTRACT

Fibre-steering is essential for manufacturing complex or fibre-steered composite structures using Automated Fibre Placement (AFP) process. However, its steering process utilising in-plane bending of the tape (or tow) always generates defects such as fibre buckling and gaps. Continuous Tow Shearing (CTS), developed in response to the shortcomings of the AFP process, utilises the in-plane shear deformation of composite tapes to produce high-quality, fibre-steered laminates without such bending-induced defects [1-3]. However, due to the inherent fibre misalignments within the tape material, not all fibres can be perfectly aligned and thus some in-plane fibre-waviness is generated during the CTS process [3]. Although various fibre-waviness detection and analysis techniques have been developed in the past, most of them are not practical to inspect small features within large composite laminates.

In this work, the feasibility of characterising shear-induced fibre-waviness due to the CTS process was investigated via the use of optical scanning and image analysis. The previously developed fibre- waviness detection and analysis techniques require high-resolution micrographs, which are not practical for inspecting large laminates without destroying the sample. The image analysis technique used in this research is the Structure Tensor Method (STM) [4, 5], often used to analyse fibrous structures within a biological system. Via STM, it is possible to analyse virtually any laminate provided that the laminate's surface is imageable and the fibres are discernible. The main advantage of STM over other methods is that it can detect local fibre directions reasonably well with low resolution images, as it processes image intensity gradients via calculating the structure tensor, which means that fibres do not need to be clearly distinguished and the image does not need to be binarised.

In this work, STM was applied to a high-resolution scan of a CTS produced, fibre-steered, cured laminate to check the layup accuracy and the variation in local fibre alignment due to shear-induced fibre-waviness. The panel dimensions are 300 mm x 100 mm, as shown in Figure 1, and it was produced by shearing a 100 mm wide prepreg tape. The minimum steering radius and maximum shear angle were 6 mm and 40°, respectively. Prior to applying STM, the scanned image was contrast enhanced to make the fibres stand out via Contrast Limited Adaptive Histogram Equalisation (CLAHE). The following STM parameters were inputted: processing window size of 100 pixels and a gaussian window of 2 pixels. The resulting hue, saturation, and brightness (HSB) image was overlaid on the greyscale image as shown in Figure 1, corresponding to the orientation and coherency of alignments. The standard deviation in fibre alignments for a given shear angle and at a given x location are shown in Figure 2. As indicated by the increase in standard deviation with respect to shear angle, variation in fibre alignments increases due to the in-plane fibre-waviness present with highly sheared regions having the greatest amount of fibre-waviness present. Furthermore, the STM analysis shows good agreement between the measured shear angle and the intended shear angle, thus verifying the layup accuracy.

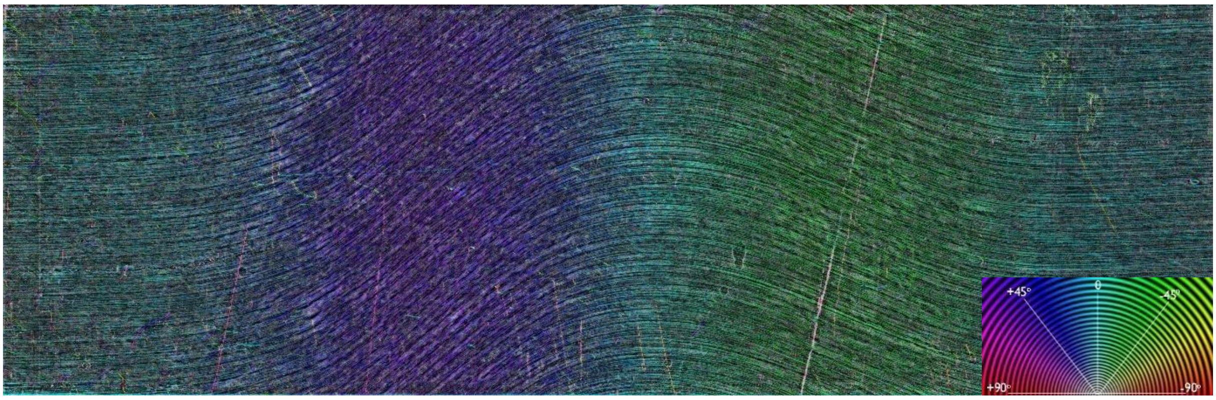

Figure 1: HSB overlay of the fibre-steered panel. The panel is 300 mm × 100 mm.

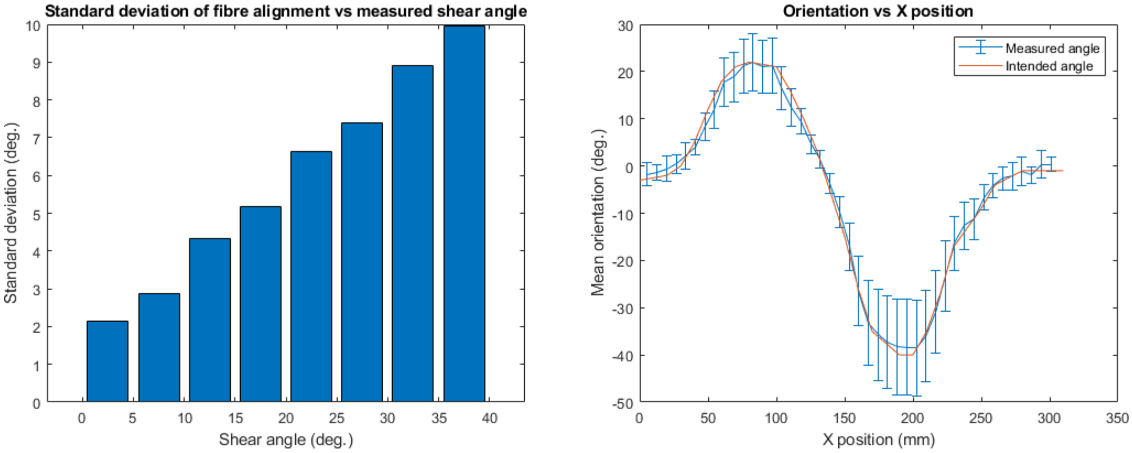

Figure 2: Standard deviation in fibre alignment for a given shear angle (left); measured orientation versus intended orientation with error bars corresponding to 1 standard deviation (right).

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ADVANCED CONTINUOUS TOW SHEARING

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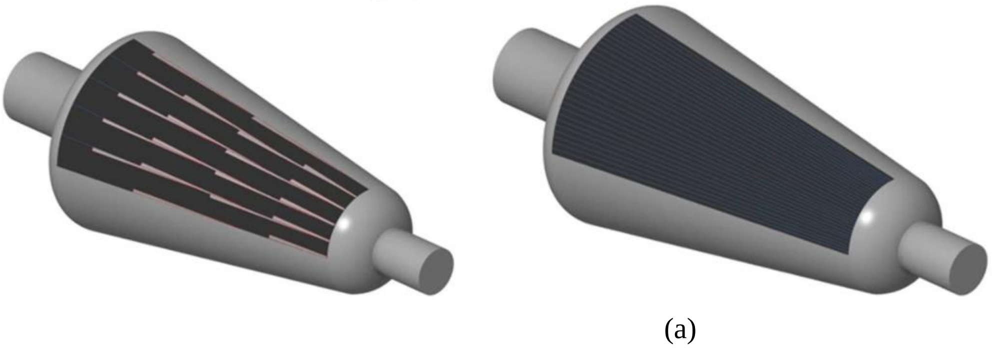
Keywords: Continuous tow shearing, CTS, Automated fibre placement, AFP, Fibre Steering, Tow width control

ABSTRACT

Although the automated fibre placement (AFP) is one of the most advanced composite manufacturing technologies in aerospace industry, it has a critical limitation in fibre steering due to its principle of utilising in-plane bending deformation of the tow. Particularly when producing lay-ups over complex geometries, the AFP process generates process-induced defects, which result in considerable reduction of the structural performance of the composite. A recently developed promising approach to eliminate such defects is the Continuous Tow Shearing (CTS) technology, which enables defect-free fibre steering for 1D fibre angle variation layups by utilising in-plane shear deformation of the tow. By shearing instead of bending the tows, common lay-up defects, such as fibre buckling or stretching, and tow drops or overlaps can be eliminated [1,2]. Moreover, the CTS approach features no coupling between the minimum radius of curvature and the tow width, which highly improves the design flexibility [3].

Even though such defect-free fibre-steering capability of the CTS was proven on a flat surfaces, laying up on a complex 3D surface is still challenging. For the surfaces that cannot be tessellated using finite width tapes, tow drops are still inevitable to avoid tow overlaps, and the tow-drop-induced triangular gaps with fibre discontinuities is unavoidable. As shown in Figure **1** (a), even for a simple developable (i.e. a singly-curved) surface, which is much easier to lay up than non-developable (i.e. doubly-curved) surfaces, such triangular gaps are generated. Such gaps with fibre discontinuities and resin rich areas present a significant strength reduction of about 22.1% for 0% gap-covered test specimens. The strength reduction could be mitigated by increasing the gap coverage ratio and ply staggering; it has been reported that 100% gap coverage and staggering resulted in lower strength reductions of 10.8% and 8.6%, respectively [4]. However, they still lead to strength reductions and to unevenness of the layup surface.



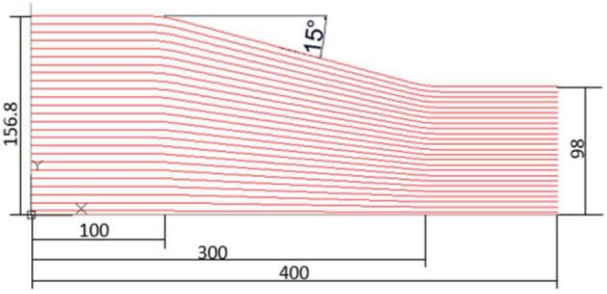
(a) (b)

Figure 1: Schematics of layups over a conical surface: (a) AFP layup with tow drops, (b) 'defect-free' Advanced CTS layup.

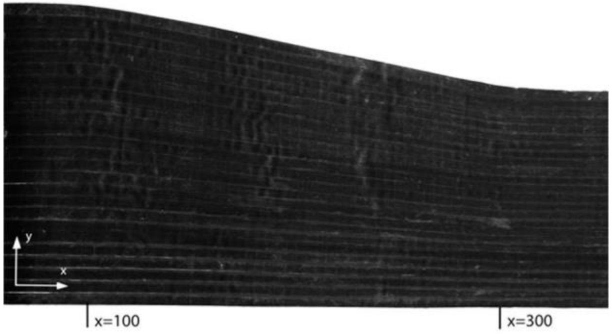
In this work, to solve the aforementioned defect issues in the 3D CTS process, a novel concept of controlling the tow width was developed and implemented in a CTS prototype head, and its feasibility was experimentally demonstrated. Tow Width Control (TWiC) mechanism developed in this work enables the adjustment of the tow width on the fly, which allows for eliminating tow drops and resin pocket defects whilst maintaining a constant fibre volume fraction, as shown in Figure 1 (b). Eliminating these defects allows achievement of ultrahigh structural efficiency and significantly simplifies the

composite design process. To demonstrate the advantage of this innovative mechanism, a single-ply fibre-steered laminate was produced on a flat surface using the CTS prototype head with the TWiC module, and its lay-up quality and accuracy were assessed using an image analysis technique.

Figure **2** (a) illustrates the target tow paths used for the lay-up, comprising of 25 tows places next to each other, narrowing their tow widths from 6.4 mm to 4 mm across the x-direction. The substrate with the laid tows was scanned using a high-resolution image scanner (Figure **2** (b)) and a bespoke image analysis software code was used to detect the tow edges to evaluate the accuracy of the tow width control.



(a)



(b) (b)

Figure 2: CTS layup with tow width variation: (a) tow path design, (b) a scanned image of the laid tows.

ACKNOWLEDGEMENT

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CHARACTERISATION OF INTER-PLY FRICTION OF A DRY BI-AXIAL NON-CRIMP FABRIC DURING AUTOMATED PREFORMING

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Keywords: Fabrics/Textiles, NCF, Friction, Defects, Preforming

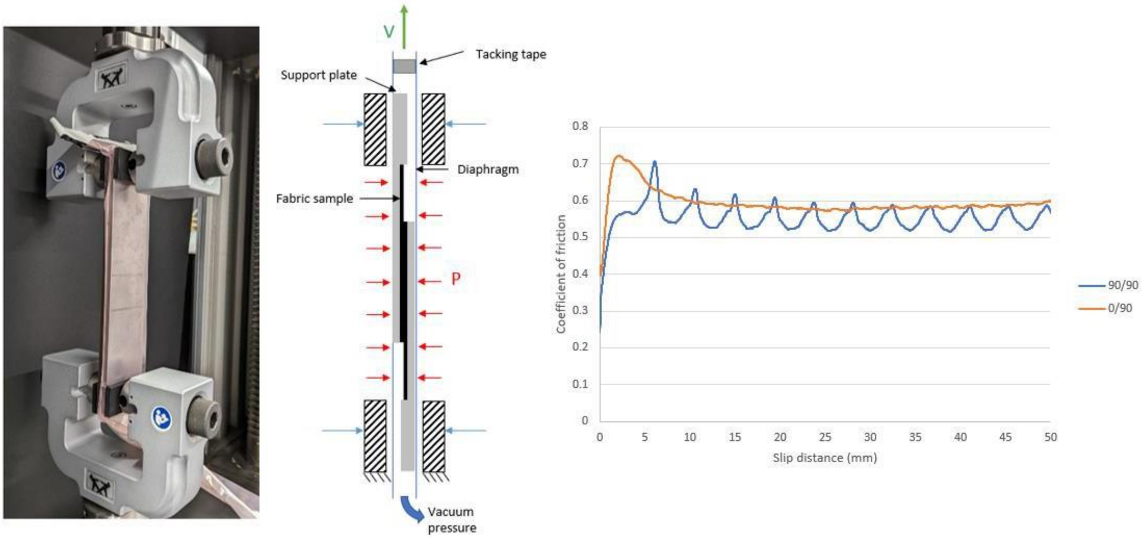
ABSTRACT

Preforming of complex parts is difficult to automate to ensure defect-free architectures, as multiple plies are often formed at the same time according to predefined forming loads and constraints. Out-of-plane wrinkles, in-plane fibre buckling, and fabric bridging can remain within the preform, resulting in a reduction in mechanical properties of the final composite part. Inter-ply friction plays an important role in the formation of defects during the forming of multiple fabric plies, when stacked at different orientations. Dissimilar shear deformation between adjacent plies can cause relative sliding at the contact interface, which can lead to compressive stresses in the fibres and consequently out-of-plane wrinkling. Likewise, additional constraints to inter-ply sliding caused by areas of high inter-ply friction can also produce local compressive stresses within the fabric, depending on the geometry being formed.

Reducing the coefficient of friction at the inter-ply interface has been shown to decrease wrinkling and influence shear behaviour [1], but a better understanding of this phenomenon is required to facilitate the development of a high-fidelity finite element process model. This work presents a novel characterisation method for measuring the inter-ply coefficient of friction, holding plies under vacuum pressure to represent the behaviour during double diaphragm forming. The test employs a universal testing frame to apply a displacement between two vertical plates, to which fabric samples are fixed (
Figure 1(a) and 1(b)). The vacuum pressure applied to the fabric-fabric surface interaction can be varied via the use of a valve to examine the effect of normal load on the measured coefficient of friction.

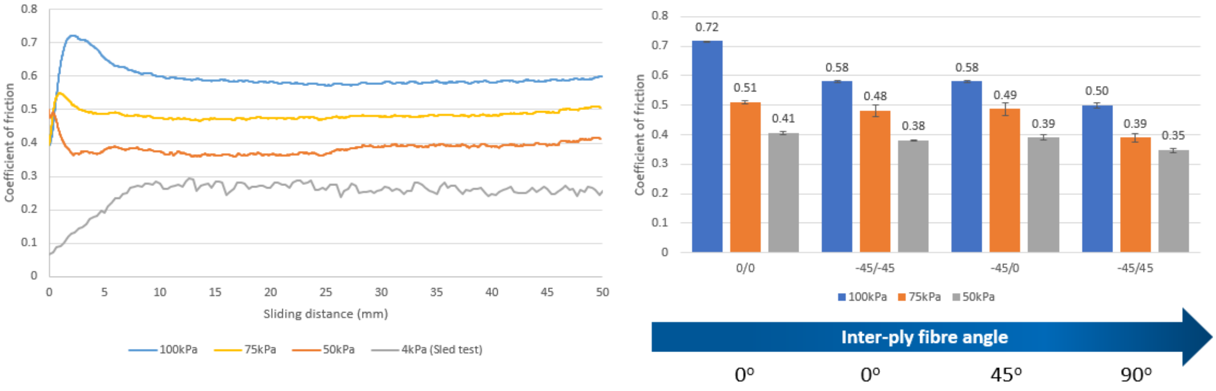
Results for a pillar stitched biaxial NCF show significant pressure dependency and anisotropy of the coefficient of friction, which is dominated by the relative fibre angles at each surface interaction.
Figure 2(a) describes the variations in coefficient of friction for a range of applied pressures, showing that deformation of the fabric under a full vacuum load produces coefficients over 60% higher than previously considered in forming simulations [2]. This pressure dependency was found to reduce as the inter-ply fibre angle increased (
Figure 2(b)): parallel fibre angles (i.e., 0^{o}) produced the highest coefficients as yarns were flattened and nesting increased, enlarging the real contact area at the interface. Additionally, sliding interference caused by stitch-to-stitch interactions was shown to create significant oscillatory frictional forces (Figure 1(c)), which was not previously seen during sled tests (ASTM D1894) with a lower normal force (0.1×10^{5} Pa), further indicating the pressure dependency of the frictional behaviour.

The data gathered from this new test will be used to develop an accurate surface interaction model in Abaqus Explicit, using a VFRICTION subroutine. This will be used to assess the significance of the anisotropic and pressure dependent inter-ply frictional behaviour on double-diaphragm (DDF) and match tool forming processes, with a long-term aim of exploring ways to efficiently reduce the inter-ply friction and mitigate wrinkling defects.



(a) (b) (c)

Figure 1(a): Overlap friction test set-up in universal testing frame. (b): Schematic of overlap friction test. (c): Variation in coefficient of friction for a fabric-fabric interaction at two different orientations



(a) (b)

Figure 2(a): Coefficient of friction as a function of sliding length, for a range of contact pressures. Interactions are for a fabric-fabric scenario with parallel fibres. (b): Effect of varying pressure and increasing relative fibre angle on dynamic coefficient of friction

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TESTING SETUP FOR COMPONENT OPTIMISATION OF MEMBRANE-SHAPED MR-BASED DRAPING TOOLS

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Keywords: Automation, Draping, Magnetorheological, Membrane-shaped, Preforming

ABSTRACT

This paper describes the development of an optimisation and characterisation setup for automated membrane-shaped magnetorheological (MR) based draping tools, first presented in Schouterden et al. [1]. This novel approach for composite textile draping provides a potential solution for industrial applications characterised by cost-intensive manual tasks within SME's to high-end aerospace OEMs. The difficult handling properties of the fabric material combined with a high variety and complexity of the product contours are today in automation often addressed by cost-increasing multi-robotic systems, using multiple degrees of freedom in combination with a large range of feature-specific tools. More extensive analyses of other automation approaches are described in Schouterden et al. [1]. A broader overview of automated textile handling is presented by Björnsson et al. [2].

As shown in Figure 1, the proposed testing setup consists out of three main parts: the membrane tool and its handling unit, the draping area with mould and magnetic actuation, and the control and steering area.
The tool's handling unit is a centrally placed linear actuator that is able to accommodate multiple membrane tool designs and sizes. The actuator has the function of lifting the membrane tool in a perfect vertical fashion. The need for controlled lifting was determined in proof-of-concept testing. Lateral movements during the lifting could result in local disturbances or even complete displacement of the fabric material. The linear actuator itself in mounted on a rotational actuator that moves the tool between the draping area on the mould to a waiting station above a leakage tray for emergencies. Design of these components allows to test the influence of both the membrane tool (e.g. membrane material and thickness) and the type of the magnetic medium. The influence of the magnetic medium includes both the optimisation of the consistency of the MR-fluid with regards to sedimentation and attraction force as well as the exploration of other magnetic media such as, for example, ferro-fluids or magnetic membranes.
The draping area is located next to the handling unit and can accommodate multiple mould shapes and types of construction. Underneath the mould arrays of electromagnets are placed. The magnets can selectively be moved under the desired areas of the mould through sloths in the bottom mounting plate. To adapt to features in the mould, the magnet can be adjusted in height by sliders and in angle through ball joints. The design of the draping area allows testing the influence of the magnetic field generation (e.g. control and placement). Furthermore, the ability to quickly interchange moulds allows to explore the influence of mould and product related features.

The control and steering area accommodates all the electronics for the control of the magnet arrays and handling unit. The communication is EtherCAT-based and can be controlled through Simple Open Source EtherCAT Master (SOEM) [3] using a standard laptop or pc.

Furthermore, the test setup will allow to investigate the influence of other product related features, such as for example, fabric material, reinforcement types, or the presence of gelcoats.

Evaluation of the resulting draping quality is performed via visual inspection and computer vision- based surface comparison similar to the proof-of-concept testing [1]. Additionally, in-mould force measurements will be performed to evaluate the draping force magnitude as well as the force

distribution through the magnetic medium from the discrete magnets. Based on the system's characteristics with optimised components and insights in the influence of product and other related characteristics, system specific draping strategies and usage guidelines can be developed to be used in combination with an intuitive programming interface. In future developments this information lso be used for automated draping sequence generation.

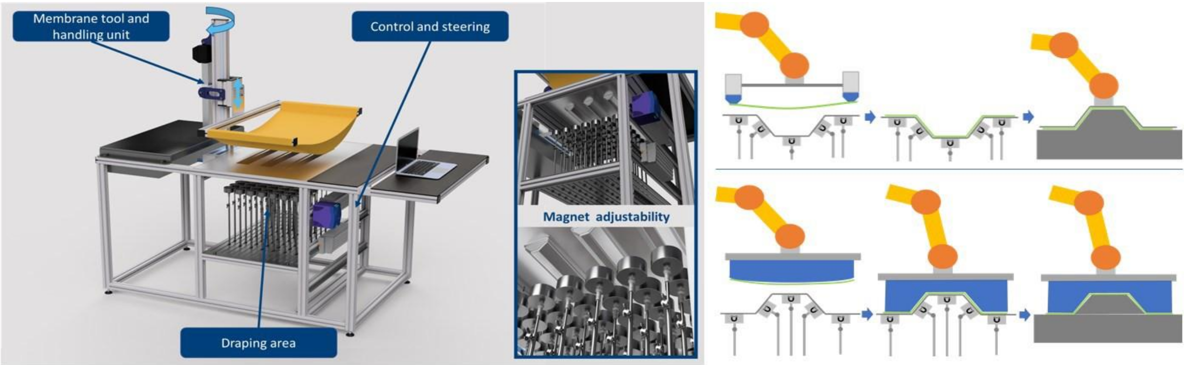

Figure 1: Overview of the testing setup for membrane-shaped MR-based draping tools (left). Handling of fabric material before and after the draping process by the means of rigid gripping frames and on-mold fixation respectively (top right). Handling of fabric material by the means of a combined FORMHAND and magnetic draping tool approach (bottom right).

The handling of the fabric material before and after forming has not yet been integrated into the current testing setup. However, two potential approaches have already been devised that can be integrated by the attachment of an identical frame to the side of the current setup. In both approaches the draping setup uses a low-cost preforming mould. This is done to both reduce the time needed with the significantly more expensive production mould (e.g. infusion or RTM), and to be able to optimise the preforming mould for the draping process. An illustration of both approaches is shown in figure 1.
The first approach keeps the handling of the fabric material and the draping as a separate operation as suggested by Björnson et al. [2]. The draping step would be kept identical to the presented design. The transport of unformed 2D fabric to the draping station can already be performed by numerous industrial needle or pneumatic based gripping frames, and is thus not anymore viewed as a challenge. Transport of the preformed fabric could be done by using binders in the fabric and a similar gripping frame or by using the preform mould itself as a fixation frame to transport the fabric to the production mould. In this case all the fabric needs to be preformed in a negative shape of the production mould.
The second approach would be a combination between the MR-based tool and another membrane-shaped draping tool presented by Löchte et al. [4], called FORMHAND. By changing the granulate in the FORMHAND tool to a ferro-magnetic material, the selective force application of the presented approach could be combined with the textile handling properties of the FORMHAND tool. Thus, also eliminating the need for separate membrane tool handling and reducing the potential problems related with MR-fluid and process contamination.

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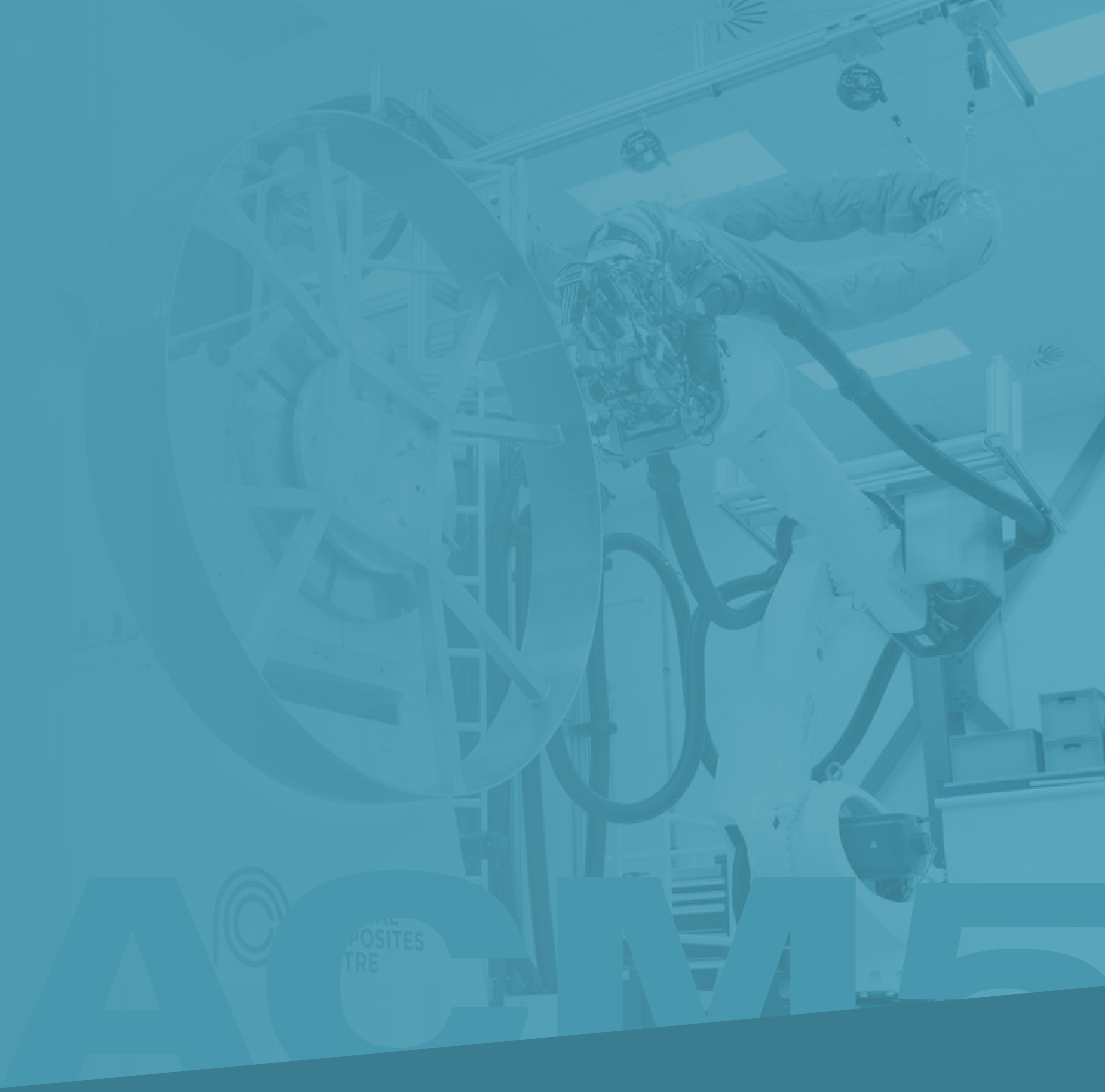
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