SIMulation of new manufacturing PROcesses for Composite Structures (SIMPROCS)

Jonathan Belnoue, Adam Thompson, Xiaochuan (Ric) Sun, Iryna Tretiak, Kate Gongadze, Yi Wang, Anatoly Koptelov, Sarthak Mahapatra, Maria Onoufriou, Jordan Jones, Bassam El Saied, Byung Chul (Eric) Kim, James Kratz, Dmitry Ivanov and Stephen Hallett

Composites manufacturing simulation is a strong activity in the Bristol Composites Institute. Our activities range from material characterisation, to novel mathematical formulations, software development and industrial applications. Over the last 5 years, the main vehicle for these activities has been the EPSRC SIMPROCS platform grant.

Constitutive modelling of prepreg

Our Defect Generation Mechanisms in Thick and Variable Thickness Composite Parts: Understanding, Predicting and Mitigation - DefGen project started the development of numerical tools to predict the generation of consolidation-induced prepreg defects in 2014. Following further investments from the EPSRC (SIMPROCS), the National Composite Centre (Technology Pull-through project and DETI program) and Rolls-Royce (sponsorship of an EngD studentship), the technology has now matured to the point where we can simulate the autoclave moulding of industry-sized components with ply resolution in under an hour. The earlier ply-by-ply version of these tools are distributed for free from Bristol Composite Institute Github page.

Modelling of Textiles

Developing process modelling capability for textile composites is a core part of our research. Our focus has been on generating methods to predict the deformation of textiles at different length scales to inform both manufacturing and design. We have developed tools to predict deformations arising from forming and compaction, able to accurately predict the occurrence of defects. This capability is available via our BCI github. Alongside this we have developed advance modelling approaches to accurately predict the internal architecture of complex woven preforms. Our current focus is on developing a new solver, SimTex, which has been specifically formulated for process modelling, to produce highly accurate yet uniquely fast predictions.

Working with industry

Beyond the healthy pool for industrial partners who supported the project and attended quarterly review meetings to help steering the project direction, we have also supported industry one to one. For example, we worked with BAE systems in coupling in-situ sensing and real-time thickness predictions to gain greater control on part dimensional tolerance (see Figure 3). This piece of work was funded through an EPSRC Impact Acceleration (IAA). IAA funding was also used to raise the TRL level of our textile simulation tools (see Figure 2 - right).

International collaborations

The grant was also used to raise the group international profile. Our researchers have visited leading international centres such as the Ecole Centrale de Nantes and Technical University of Munich. We have welcomed visitors to come and work with us on process modelling, accessing our tools, techniques and software to create new capability, with many successful collaborations to date. A good example is the visit of PhD student Armin Rashidi from the University of British Columbia, Canada, who developed a user contact subroutine combining UBC’s friction model with our compliant contact approach and the 1D version of our compaction models, to simulate forming and consolidation induced defects in textile prepregs.

Figure 1: Prediction of consolidation-induced fibre path defect in severely tapered laminate.

Figure 2: Prediction of manufacturing-induced deformation of textiles: mesoscale modelling of fabric forming (left) and microscale modelling of complex woven T-section (right).

Figure 3: Together with BAE Systems we demonstrated the feasibility of using in-situ measurements with our 1D compaction models for tighter part dimensional tolerance control.

Figure 4: Experimental validation of consolidation-induced defects in woven prepreg laminates. This work was done in collaboration with the University of British Columbia.
Composites: Made Faster

Rapid, physics-based simulation tools for composite manufacture

Adam Thompson, Ekaterina Gongadze, Matthew Edwards, Laurence Kedward, Michael Pei, Yi Wang, Lachlan Williams, Siyuan Chen, Jonathan Belnoue, Tim Dodwell (University of Exeter), Stephen Hallett

Process simulation is a powerful tool to help mitigate part variability and reduce over-design of composite components. A major challenge in achieving good simulations is to consider the variability, inherent to both the material and the manufacturing processes, so that the statistical spread of possible outcomes is considered rather than a single deterministic result. This project aims to achieve this by developing a probabilistic modelling framework based on rapid numerical tools for modelling each step in the composite manufacturing process.

Focusing specifically on textile composites, this project will develop a new bespoke solver, with methods to simulate preform creation, preform deposition and finally, preform compaction, three key steps in composite manufacturing. Aided by new and developing processor architecture, this bespoke solver will deliver a uniquely fast, yet accurate simulation capability.

The methods developed for each process will be interrogated through systematic probabilistic sensitivity analyses to reduce their complexity while retaining predictive capability. This will ultimately provide a tool that is numerically efficient enough to run sufficient iterations to capture the significant stochastic variation present in textile composite manufacture processes, even at large scale. This will enable a step change in manufacturing engineer’s ability to reach an acceptable solution with significantly fewer trials, less waste and faster time to market, contributing to the digital revolution that is now taking place across the industry.

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Kinematically enhanced modelling for fast simulation of composites processing

Jonathan Belnoue and Stephen Hallett

Earlier work carried out at BCI has shown the possibility to accurately predict consolidation-driven defect formation in composite parts using a ply-by-ply approach (see Figure 1). However, using this method, a typical model for a lab-scale specimen can easily reach the hundreds of thousands of degrees of freedom, which makes it unsuitable for the modelling of full-scale components and limits its applicability for the modelling of real industrial cases. Recent efforts have allowed to overcome this difficulty using kinematically enhanced constitutive modelling for layered structures made of soft anisotropic material. The proposed framework is able to significantly reduce the computational cost of the simulation. The scheme allows the modelling of larger components.

Homogenisation scheme

The behaviour of each ply constituent of the structure follows BCI’s model for prepreg under processing conditions. The interactions between the plies are explicitly modelled as thin extra layers of pure fluid. As illustrated in figure 2, 2 layers inside the stack can be homogenized using a combination of: a volumetric averaging of the strains, the compatibility condition at the plane where the 2 volumes join and the Hill-Mandell condition. This allows linking the macroscale apparent behaviour of the stack to the responses of the materials it is made of. Once 2 plies have been homogenised, the homogenised block can be homogeneised with another layer and the whole laminate can be build by successive homogeneisation of 2 layers.

Speed Improvement

The number of degrees of freedom seen by the solver is drastically reduced. Additional reduction of the runtime is obtained through the fact that highly strained regions are smeared-out within the laminate homogeneous response thus easing the convergence of the FE scheme. In the case of a lab-scale L-bend specimen in Figure 1, the runtime has been taken down to 30 mins from 3 days for the ply-by-ply. Figure 3 shows a more complex specimen, where the time improvements are even more significant.

Model-based Optimisation of Automated Fibre Placement (AFP) Deposition

Jonathan Belnoue, Yi Wang, Sarthak Mahapatra, Dmitry Ivanov and Stephen Hallett

AFP is the most widespread automated deposition technique for composites in industry. Although the method has been around for over 40 years and works well for relatively simple geometries (i.e., low level of double curvature), setting up machine parameters in order to avoid defects remains challenging. Current industry practices rely largely on time-consuming, costly and wasteful physical trials. The SIMPROCS team has recently developed simulation tools that would allow to do most this work virtually on a computer.

Industrial challenge

A commercial AFP machine is built from a computer numerically controlled support robot (gantry in Figure 1) that controls the layup path and speed and a deposition head controlling feeding, cutting and compaction of the incoming material. As illustrated in Figure 2, one of the main obstacles to wider uptake of AFP is the difficulty to produce preforms of sufficient quality when tapes are deposited along curved paths or on complex doubly-curved surfaces.

Virtual AFP platform

An essential part of the virtual AFP platform developed in this project has been the development of bespoke material characterisation techniques and models able to capture how the mechanical behaviour of prepreg tapes evolves with temperature, pressure and deformation rate.

Virtual AFP platform validation

The virtual AFP platform was validated by comparing its predictions with real-life AFP data from the open literature [1]. The same material and deposition conditions were considered in the model and in the experiments.

Model-based process optimisation

The developed platform is the only AFP simulation capability worldwide that can account for the effect of process parameters and allow optimisation of the deposition conditions.

Current developments and Future activities

In another EPSRC-funded project (i.e., Composites: Made Faster - EP/V039210/1) on real-time simulations and optimisation of textile forming, the group is developing Bayesian optimisation methods. These could be directly used to find the optimum deposition conditions in the context described here. Ongoing work is looking at improving run times through adaptive re-meshing and homogenisation of the plies already deposited. Early results are very promising with runtimes for the deposition of one tape being as low as 20 minutes (see Figure 6).

Deep learning approach for predicting the architecture of 3D textile fabrics

Anatoly Koptelov, Bassam El Said, Adam Thompson, Stephen Hallett

The idea of the proposed system is to capture the features of fabric's deformation process by learning yarns' behaviour from a set of test simulations. The proposed tool for this task is a complex system of convolutional and long short-term memory neural networks. The network facilitates the extraction of relevant features from a deformed yarns' geometry and learns characteristic patterns in evolution of these features throughout the deformation process. The trained network is able to mimic fabric's behaviour and to predict further stages of compaction without employing time-consuming textile solvers.

Time-distributed solution
Weaving simulations are performed within a number of consecutive timesteps. It is important to be able to predict the mechanical properties of the woven fabric based on its initial geometry and architecture.

From kinematic to FE model
Kinematic geometry is converted into a voxel grid, where each voxel stores information about fibre volume fraction and fibre orientation. Voxel grid is then transferred into FE model.

Generating training set
4000 weaving architectures with different yarn paths were generated for further neural network training.

Learning deformation patterns
A combination of convolutional and recurrent neural networks was considered to extract relevant features and to learn their evolution throughout deformation process.

Predicted woven architecture for voxel models
The comparison between compacted textile structure (ground truth) and AI prediction is shown below. Colour represents fibre volume fraction.

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SimTex: a high-fidelity modelling tool for technical textiles

Adam Thompson, Jordan Jones, Matt Edwards, Ric Sun, Stephen Hallett

SimTex is a bespoke solver initially developed to generate virtual models of textiles, accurately predicting deformations to tow paths and cross sections. Through the use of efficient contact detection algorithms and unique boundary conditions, SimTex is able to model highly complex and non-periodic textiles, providing the ability to analyse their internal architecture at a whole new level of detail.

Using basic weave design information, SimTex constructs an initially simple representation of the weave architecture. The tows are represented by multiple chains of truss elements, each chain considered to be a virtual fibre. The virtual fibres within a single tow are interpenetrating in their initial configuration. Through the introduction of contact models, the virtual fibres are pushed out of contact, while under tension, until the structure equilibrates thus creating a hyper realistic virtual model of the textile.

Originally developed to create unit cell models of 3D woven textiles, it has evolved to construct complex near net shape preforms with bifurcations and tapering, as well to explicitly model textile processes, such as braiding, with the introduction of novel features such as the 'Virtual Bobbin'.
A fully automated framework for composites structure mould design optimisation
Yi Wang, Jonathan Belnoue, Stephen Hallett

The mould tool is a critical part in composite structure manufacturing, largely determining the structure’s quality, particularly for dimensional tolerance and consolidation-induced defects. Meanwhile, it is a very expensive single part, and too costly to modify once made and full-scale part production begun. In this work, a fully automated framework for the prediction of thickness and consolidation-induced defects in composite parts manufactured by autoclave moulding was delivered. A physical demonstrator with industrial complexity was used to assess the accuracy of framework and manufactured for validation. The comparison between the part quality predicted by the software tool and the quality of the manufactured demonstrator showed good agreement. Further, an automated tool allowing for optimization of the tooling for increased part quality was developed based on a Gaussian process and Genetic algorithm approach.

Key points:
- A ‘one-click’ automated workflow to give feedback for consolidated part quality and mould design optimisation;
- Virtual Layup ➔ Virtual Autoclave ➔ Virtual inspection ➔ Mould optimization;
- A robust, fast and high-fidelity approach;
- Homogeneous modelling approach - 1000 times faster - lays the base for optimization [1];
- High fidelity material model in consolidation/cure simulation [2].

Virtual Layup: from as-designed geometry to as-layup FE model

Experimental Validation

Comparison between the physical part and model prediction in defects generation.

Virtual Autoclave: Fast and robust consolidation process simulation

Virtual Autoclave workflow.

Machine Learning-based Optimisation

Tool thickness optimisation using Gaussian process emulator (uniform thickness).

Optimisation of multi-section tool thickness.
Autonomous and objective characterisation of composite precursors in manufacturing
Anatoly Koptelov, Jonathan Belnoue, Ioannis Georgilas, Stephen Hallett, Dmitry Ivanov.

The research was focused on the application of a novel adaptive consolidation sensor framework for the characterisation of composite precursors. The designed framework develops material driven test programmes in real-time and defines robust material models for the studied composite precursor. The proposed approach allows to remove any subjective judgement about the material behaviour and to reduce human involvement at the experimentation stage. The proposed framework along with the developed data transfer/acquisition hardware setup was put to the test within several characterisation exercises. The output of the proposed testing method—model and properties for the tested materials—is compared with the results of the conventional deterministic characterisation tests.

Autonomous real-time testing setup
The adaptive testing framework is located on the host (PC/laptop) and connected to the compaction rig throughout data acquisition hardware.

Detailed algorithm of the framework
The main purpose of the ATF is to build a testing programme in real time and in a responsive manner based on the continuously supplied data on thickness evolution of a tested sample. After the end of each load step, the framework challenges all models from the library (candidate models) to analyse the incoming compaction response from the testing machine.

Compaction rig setup
Resulting loading programmes and compaction curves for the real-time experimentation. Upon the completion of each test, the framework successfully identified the best performing material models and the corresponding set of material parameters. Overall, the autonomous testing demonstrated strong potential for objective assessment of complex material systems and clear direction for further development.

(A) IMA/M21 prepreg, (B) IM7/8552 prepreg.
HypoDrape: Continuum based textile model for simulating forming processes
Adam Thompson, Jonathan Belnoue, Stephen Hallett

HypoDrape is a user material subroutine for Abaqus Explicit that includes the kinematic behaviour of the fibrous tows in biaxial textiles to ensure the stresses are resolved correctly. This enables key behaviours of to be included within forming simulations of textiles, resulting in accurate predictions of deformations and defects.

The subroutine is distributed freely from the Bristol Composites Institute Github page: https://bristolcompositesinstitute.github.io/HypoDrape/

It is being actively used by both the National Composites Centre and Airbus and has led to international collaborations with the University of British Columbia and Aalborg University.

Effect of fibre orientation on bending deflection (stiffness) [0/90] (left) and [±45°] (right)

Comparison of multi-layer forming experiments with simulation for blank holder forming processes

Comparison of multi-layer forming experiments with simulation for Double Diaphragm forming processes

Gradient plot showing the variation of thickness after forming (left) and after consolidation (right) of 18 plies of a pre-preg textile

Recent developments Include:
- extension to pre-impregnated textiles, capturing the inter-ply interactions and through-thickness consolidation behaviour
- introduction of non-linear bending stiffness to improve the accuracy of wrinkle shape and size
- use for optimisation of forming processes through external constraints and local stiffening of the preform.
Model based optimisation of an induction coil for improved macro-scale temperature uniformity

James Uzzell, Laura Pickard, Ian Hamerton, Dmitry Ivanov

Electromagnetic (EM) induction has great potential in energy efficient manufacturing as it provides rapid, volumetric and localised heating. Heat is induced directly within electrically conductive carbon fibres reducing thermal losses to tooling and producing high heating rates.

Application of induction to composites is challenging due to (a) non-uniform magnetic field of conventional coil, (b) low electrical and thermal conductivity of CFRP. Sequentially coupled magnetic and transient thermal modelling has been used to optimise the heating process through (i) parametric design of induction coil, (ii) engineering material architecture.

Challenge:

Above: (Left) Photograph showing standard pancake coil design used for metallic processing. (Right) Thermal image showing the ring shaped heating pattern produced using the pancake coil.

Research Hypothesis:

To reduce characteristic heat propagation length, a cellular coil structure has been trialled. Each cell forms isolated EM vortices if the process parameters are properly tuned. Each EM vortices imprints a pattern of Eddy currents and Joule heating.

Coil manufactured approx. A4 size (350mm x 200mm).

Modeling Workflow:

EM Input parameters:
- Geometry
- Electrical conductivity
- Magnetic permeability

Thermal Input parameters:
- Thermal conductivity
- Heat capacity
- Density

Temperature distribution

Joule heating distribution

EM model and analysis

Transient heat transfer model

Comparison of temperature in carbon fibre laminate between experimental pancake coil and model.

Right: Comparison of cooling rate in lab verses using the applied surface convective film conduction in the model.

Process design:

Above: (Top) Experimental temperature variation with different QI carbon fibre panel sizes. (Bottom) Modelling results for same sized panels.

Parametric design optimisation:

Above: Graph showing parametric design varying size and spacing of each cell. Focusing on reducing standard deviation to improve inplane temperature uniformity and maximising average temperature for heating efficiency. Light blue bar indicates current experimentally tested geometry.

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Tensile Characterisation of HiPerDiF PLA/Short Carbon Fibre Tape
Under Processing Conditions with Micromechanical Model

Burak Ogun Yavuz, Ian Hamerton, Marco Longana and Jonathan Belnoue

Aim: Material characterisation for forming simulations of aligned discontinuous fibre thermoplastic (HiPerDiF) prepreg by using micromechanical model

Manufacturing Method

Impregnation

- Vacuum Bagging
- Breather
- Peel Ply
- PLA Tape
- Mould
- PLA
- PLA
- PLA
- PLA
- PLA

One batch of production

Under Vacuum Pressure For 4 Hours

Tensile Characterisation

under Processing Conditions

@ 195 °C
Under Vacuum Pressure

Specimen

- Fibre Volume fraction ≈ 35%

Cross section

Testing setup

- @ 20 °C, 80 °C, 100 °C, 120 °C, and 140 °C
- @ 1mm/min, 10mm/min, 100mm/min crosshead speeds
- Shimadzu electromechanical test machine
- Thermal Chamber
- 10 kN load-cell
- 5MP Stereo DIC
- Strong LED light source

Tensile behaviour temperature and speed dependency

- Temperature => Load transfer
- Speed => Load transfer

Rheology and DSC of PLA

Rheology test setup

- Oscillations
  - From 1 rad/s to 628 rad/s
  - @ 80 °C, 100 °C, 120 °C
- 0.5mm thickness

Temperature history

Viscosities with two different temperature history

➢ Corresponding viscosity of high crystallinity PLA has less temperature dependence

Differential scanning calorimetry (DSC)

- 1°C/min ramp rate
- 20°C>190°C>20°C>190°C>20°C>110°C>20°C>190°C
- PLA and PLA/Carbon fibre

Shear rate dependent storage modulus (\(G'(\dot{\varepsilon})\)) and corresponding viscosity (\(\eta(\dot{\varepsilon})\)) data taken from rheology experiment with high crystallinity

- Fibre length (L)=3mm, Diameter (D)=7µm, Fibre volume fraction (\(f\))=0.35, Overlap length (\(\delta\))=1.5mm, Fiber volume fraction parameter (\(K\))=2.64

Maxwell viscoelastic model

- \(\sigma = \frac{2G(\dot{\varepsilon})} {D} [L - \delta] / [K - 1 + \frac{\delta}{D}]\)
- \(\dot{\varepsilon} = \frac{G(\dot{\varepsilon})} {\eta(\dot{\varepsilon})}\)

Micromechanical Model

- \(\sigma = 2\tau \frac{L - \delta} {D} [K - 1 + \frac{\delta}{D}]\)
- \(\varepsilon = \frac{\dot{\varepsilon}} {\eta(\dot{\varepsilon})}\)

Future work: Implementing material behaviour into forming simulations ➔ Forming defect free parts experimentally

This study is supported by the EPSRC through the CoSEM CDT and a scholarship from the Republic of Türkiye Ministry of National Education
Laminate Thickness Control

Kate Gongadze, Chris Dighton, Martin Moss, Brett Hemingway, Jonathan Belnoue, Stephen Hallett

When manufacturing composite laminates, the cured ply thickness can vary by as much as 5%. In order to achieve the required laminate thickness, compensation plies are co-cured or co-bonded onto the laminate and machined back. This procedure is lengthy and therefore costly to include in the manufacturing phase. Consequently, this manufacturing procedure could be further optimised by modelling and simulating the process, taking into account the material and process variabilities.

The Challenge

Material Variability

Uncured material with variability in thickness, volume fraction, resin content

Process Variability

The laminate goes through several stages of cure making it difficult to account for the process variability

Validation

State-of-the-art laser line scanner provide accurate measurements of the thickness variability

Process Modelling

Predicted cured ply thickness

Conclusions

Cured ply thickness (CPT) remains a challenge, especially when tight tolerances are required. Combining process modelling with material and process variability could prove to be an invaluable tool.

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Virtual Un-manufacturing of Fibre-steered Preforms for Complex Geometry Composites

Xiaochuan(Ric) Sun, Wei-Ting Wang, Jonathan Belnoue, ByungChul(Eric) Kim, Stephen Hallett

Automated Fibre Placement (AFP) technology is ideally suited to manufacture structures with simple geometry due to its robustness, speed and repeatability. However, AFP is not well-adapted for directly laying up complex 3D shapes as the geometry and need for defect-free manufacture constrain the head speed, making manufacture time consuming and thus costly. In most cases, complex geometry composites components are designed based on ideal or theoretical fibre angles, with little or no consideration of the manufacturing processes or constraints involved in delivering them. This study took a novel virtual approach to "un-manufacture" these ideal designs for the case of formed composites, so that flat tailored preforms can be created via the continuous tow shearing (CTS) technique, which results in the required ideal fibre architectures after forming (see Fig. 1). The primary manufacturing process envisaged to deliver this is the diaphragm forming of thermoset prepregs deposited using automated deposition. However, it is anticipated that the concept developed will be applicable to textile preforms (including non-crimp fabrics) and thermoplastic prepregs. The objectives of this project is to demonstrate the proof of concept and feasibility of the proposed manufacture processes and to develop numerical tools needed, along with experimental validation.

**Work Flow**

1. **Un-manufacture process from 3D to flat preform**
2. **2D flat preform with tailored fibre path after numerical processing**
3. **Re-manufacture process from 3D to required shape**
4. **Final 3D preform with as-designed manufacturable fibre path**

**Methodology**

**Work packages:**

- **WP1.** Numerical modelling of forming and un-forming of steered fibres prepreg stacks on representative complex 3D shape
- **WP2.** Experimental characterisation of prepreg in-plane properties
- **WP3.** Manufacture of technology demonstrator and quality inspection

**Experimental Results**

- **Figure 6.** Double diaphragm forming test on tailored CTS prepreg where fibre path was derived from un-forming simulation
- **Figure 7.** Comparison between Formed tailored CTS prepreg and Reformed preform with tailored fibre path

- Steered fibre tape was made using CTS technique with fibre trajectory derived numerically
- Reformed steered prepreg was found to be similar to modelling results.

- Validated numerical and experimental results demonstrated the feasibility of the proposed manufacture processes which can have lower cost and greater efficiency compared to direct AFP on complex shape
- Steered fibre paths on demonstrator was found to have less wastage and more continuous fibre across the whole part
Springback During Cyclic Compressive Loading of Carbon/Epoxy Prepregs

Iryna Tretiak, Anatoly Koptelov, Jonathan Belnoue, Dmitry Ivanov, Stephen Hallett

During AFP processing, the deposited material undergoes cyclic mechanical loading and unloading induced by sequential passes of the compaction roller. The behaviour of the material under cyclic compaction becomes much more complex for material systems where hysteresis and permanent strain are an issue. Previous studies have also documented a springback effect in dry fibres, 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. 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.

Materials and Methods

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Experimental Results

Stress – strain curves show highly non-linear and visco-plastic behaviour. The area of the hysteresis loop initially decreases and then reaches the equilibrium.

- Springback tends to decrease with each successive cycle
- Higher springback value is different based on material type, loading schedule and dwell time (all these parameters influence compaction level)

Modelling Approach

Material model

\[ \frac{dh(t)}{dt} = Q(t) \cdot P(t) \]

Gutowski Model

\[ P_{\text{Gutowski}}(t) = \sigma_y \left( \frac{\sqrt{T_\text{eq}}}{T_\text{eq} - 1} \right) \]

Split the compaction response for loading and unloading sequences

\[ \frac{dh(t)}{dt} = Q(t) \cdot P(t) \]

\[ \frac{dh(t)}{dt} = Q(t) \cdot (-P_{\text{Gutowski}}) \]

Pros:

- Easy to use
- Can isolate parameters
- Original model is intact

Cons:

- Springback response is not active during loading

Load, N

<table>
<thead>
<tr>
<th>Loading case</th>
<th>Loading dwell time, s</th>
<th>Unloading dwell time, s</th>
<th>Compaction temperature, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 – simulates debulking process</td>
<td>240; 360; 480</td>
<td>120; 240; 360</td>
<td>30, 60, 90</td>
</tr>
<tr>
<td>2 – simulates AFP process</td>
<td>6; 360; 480</td>
<td>120; 240; 360</td>
<td>30; 60, 90 for IM7/8552; 45, 60 for IMA/M21</td>
</tr>
</tbody>
</table>

Loading/unloading rate - 45 N/s
Shear occurs when a 2D textile is formed over a 3D geometry with double curvature. During shear, the warp and weft tows rotate away from their orthogonal axes, changing the anisotropy of the material. This is carried through the consolidation process and is locked into the cured composite component. An experimental campaign was carried out to validate the response from the multi-scale modelling framework. The material used is a 2x2 twill woven prepreg. Composite plates are manufactured, coupons are cut and are subject to tensile tests with DIC.

**Shear individual plies using picture frame and debulking**

- Cure the composite using a hot press
- Coupons are drawn on the cured plate and then sent to the workshop for cutting
- Failure patterns for 15° shear in +45° tensile test configuration compared with DIC
- DIC response matches well with linear homogenisation (in RVE modelling)
- Meso-scale damage model is able to capture the initial stiffness but not well in damage initiation
Multi-scale modelling of woven composites accounting for shear
Meng yi Song, Adam Thompson, Bassam El-Said and Stephen Hallett

Shear occurs when a 2D textile is formed over a 3D geometry with double curvature. During shear, the warp and weft tows rotate away from their orthogonal axes, changing the anisotropy of the material. This is carried through the consolidation process and is locked into the cured composite component. This workflow focuses on finding the mechanical properties of the sheared woven composite materials; and the application of these properties into macro-scale simulations.

Perform a forming simulation to obtain shear angle distribution and RVE rotation

Create a series of RVE models for a range of shear angles informed by the forming simulation.

Homogenise the solution for each RVE model to obtain engineering constants such as Young’s modulus. Or to plot a stress-strain graph.

The macro-scale shell model has their element assigned with their respective material and orientation based on the shear angle, RVE rotation and the homogenised RVE properties.
Prepreg tack is a critical material property that plays a key role in Automated Fibre Placement (AFP) manufacture-induced defect generation. However, there is a gap in current state-of-the-art manufacturing process modelling that includes tack phenomena and experimental data that shows the influence of multiple factors. A modified probe test method, which is capable of inter-ply and ply-tool tack measurement, is proposed. The influence of multiple factors, consistent with the AFP deposition process (i.e. pull-off rate, contact time, pressure and temperature) on tack is studied. Further, a comprehensive modelling framework accounting for all the factors is developed and implemented as a user subroutine for a commercial finite element (FE) package. The work highlights the complexity of tack behaviour at play and shows promise for filling the gap between the tack data/model scarcity and simulation of manufacturing processes such as AFP and forming.

**Conclusions:**
- The modified probe tack test provides a feasible approach to measure the prepreg tack between adjacent layers of prepreg.
- The experimental study reveals the strong and non-monotonic dependence of the tack properties on temperature, pressure level and contact time.
- A full modelling framework was proposed and is capable to show the tack role in AFP process.
- The test approach and modeling framework can be extended to other manufacture processes that use uncured prepreg, such as forming.

New experiments for in-plane shear characterisation of uncured prepreg

Yi Wang, Dmitry Ivanov, Jonathan Belnoue, James Kratz, Stephen Hallett

Automated Fibre Placement (AFP) is becoming one of the mainstream composites manufacturing techniques in commercial aerospace. However, one of the limitations is the occurrence of the defects generated in the tow steering process, e.g. wrinkles and tow pull off. Defect formation is closely related to the in- and out of plane properties of uncured prepreg. This work focuses on the in-plane shear behaviour characterization of thermoset prepreg by a unidirectional off-axis tensile test, taking into account the layup speed and tow width, to better understand and further simulate the AFP process.

In-plane shear characterisation
- Method: 10˚ off-axis tensile test
- Hexcel IM7-8552 carbon/epoxy prepreg
- Shear strain extraction by DIC analysis results
- Resolving local stress state for shear stress

Conclusions:
- This test allows extraction of the non-linear in-plane shear stress/strain relationship of uncured prepreg;
- The shear behaviour of uncured prepreg does not vary much with different thickness specimens;
- The stiffness of the material is heavily dependent on the test rates and temperatures.

Fast Optimisation of the Formability of Dry Fabric Preforms: a Bayesian Approach

Siyuan Chen, Adam Thompson, Tim Dodwell (Exeter University), Stephen Hallett and Jonathan Belnoue

Composites are becoming increasingly important for light-weight solutions in the transport and energy sectors. In the field of composites manufacture, resin transform moulding (RTM) is a cheaper alternative to traditional manufacturing methods. Before resin infusion, the fabric is to be formed into shape, however, the quality of forming is highly sensitive to wrinkles. These defects could induce considerable reduction to the quality of final parts. Simulation is a good way to understand the process and help to investigate the effect of the forming parameters (such as pressure and tensile forces) to wrinkle generation. Current BCI’s forming process simulation tool can make high quality predictions but have long run times. On the other hand, we need large batches of simulations to find the forming conditions that minimise defects.

The project aims at exploring a new framework for the efficient optimisation of the processing conditions in the dry fibre forming process. This is achieved by building a Gaussian Process (GP) emulator that is trained from finite element (FE) simulation data. The work opens the door for digital twin. Longer term, a fully autonomous forming rig that allows defect mitigation by automatic adaptation of the process based on in-situ measurements and predictions from the GP will be built.

Validation of the 4D GP emulator
- A machine learning method, mathematically tractable.
- Only needs a few data points to make accurate predictions and uncertainty quantification.
- Input: position of four risers  Output: SSWI
- Each data point represents a simulation.

Sequential Design
- Iterative addition of supplementary data points, to improve model predictive capabilities.

FE simulations
- Double-diaphragm forming.
- Single layer of dry NCF, hemisphere mould geometry.
- Risers used to provide tensions to eliminate wrinkles.
- UoB Hypodrape subroutine, mutually constrained membrane and shell elements, 2mm mesh.

Wrinkle index (WI)
- A metric that measures the level of wrinkling near an element.
- Sum of squared wrinkle index (SSWI) A value that reflects the overall wrinkling level of a formed fabric.

Optimisation of forming process by GP: wrinkle index significantly reduced

Validation of the 2D GP emulator
- A 2D GP (two parameters) and a 4D GP trained
- For most validation batches, predictive deviations reduced during sequential design. Batch 5 and 7 are good initially.
- Final predictive error is lower than 10%.

Optimisation of forming process by GP: wrinkle level significantly reduced

Development of Forming Simulation Capabilities for use in Large-Scale Next-Generation Composite Aerospace Structures

Lachlan Williams, Jonathan Belnoue, Adam Thompson, Christian Knipprath (Airbus), Stephen Hallett

How to Simulate an NCF
This research is focused on enabling competent simulation of Non-Crimp Fabric (NCF) during forming. NCF is a developing class of fibrous textiles which could be a key enabler for high rate production of composite parts in future aircraft designs. Airbus is currently evaluating NCFs in the Wing of Tomorrow programme.

Academia has gotten quite good at modelling woven textiles, but NCFs need to be modelled differently. Instead of being held together by a weave, NCFs are stitched. This stitch can behave very differently to a weave. How to accurately model the effect of the stitch on forming, without introducing excessive computational cost, is the fundamental question of this research (fig. 2).

This past year work has focused on material model development, data handling, visualization, Finite Element (FE) fundamentals (fig. 1), software robustness and understanding the industrial digital environment.

A Case Study in the Challenges of Digitalisation
Forming simulation is an excellent example of the challenges of adopting digital processes in an industry historically dominated by physical trials:
• Simulation does not completely remove the need for physical trials
• Availability of compatible and adaptable computational resource
• Engineering firms are more often customers than developers of software
• Who can communicate in both aerospace engineering and computer science?

Composite aerospace parts are getting bigger and more complicated. Cost pressure is driving increased part integration, which reduces overall manufacturing costs at the expense of increased forming process complexity.

High fidelity insight into forming, the process which conforms composite materials to the required geometry, and therefore dictates the all important local fibre orientation in the final part, is only increasing in importance.

Creating a Generic Aerospace Surface Generator
Model creation is often a slow, manual process. To examine the robustness of a simulation material model, ideally the model should be subjected to many representative surface geometries which capture the intended design space. Preliminary work has been done to create a forming surface generator which would facilitate this (fig. 3). This tool could be used to generate training and validation data for surrogate modelling approaches to forming simulation.

Capturing the Stitch Effect
With current and near-future computational resource available to engineers, simulating at the macro scale is here to stay. The question becomes how can we preserve some micro and meso scale physics in a computationally efficient way. Future work will explore candidate methods to realize stitch effects at the interface between constituent plies of an NCF.

Figure 1: The progression of a simple simulation in an explicit finite element code written during the EngD to support general understanding, verification of subroutine logic and de-risking of future efforts.

Figure 2: Visualisation of the local fibre orientations in two constituent unidirectional plies within a Non-Crimp Fabric (NCF). Stitch response to relative sliding of the two plies is highly dependant on the local fibre orientation of each ply.

Figure 3: Three example outputs of randomly generated generic aerospace surfaces showing variable double curvatures and ramps.
Closed loop control for thermal management in manufacture

Anagnostis Samanis, Janice M. Dulieu-Barton, Jason Zheng Jiang, Dmitry S. Ivanov

This work focuses on local processes of composites manufacture under heating load aiming at optimizing the process through thermal management of temperature evolution in a controlled way of minimizing process time while avoiding any potential risk of damaging the material. The methodology finds perfect application on thermal management of thermosetting resins during infusion for local processes of repairing/bonding. The idea is the development of a heat transfer model based closed loop system which depending on temperature sensor readings is able to update the model with true values of material thermal properties and process parameters and this knowledge is exploited in a further stage by a control algorithm in a way to predict material behaviour and taking control decisions on-line to steer the temperature evolution and optimize the process.

Could conventional technology offer a solution?

Conventional technology known for many years (Autoclave, Oven) ensures temperature uniformity during heating, but it applies heating to the whole structure and not locally and even to the tool making the process slow and inefficient.

Promising heating techniques

There are some promising heating techniques offering local heating effect with fast heat supply. Though, they appear to have issues of heat sink to material/environment and non uniformity making their control quite complicated.

Induction heating

This work applies induction heating as a thermal source because of its ability to provide volumetric heat supply to the composite material having effect on its close surface and through thickness. Combination of induction heating with fast resin systems is a significant challenge of this study. Fast curing resin systems exhibit thermic reactions raising the risk of burning the composite. Knowing the temperature evolution everywhere in the material could eliminate that risk.

Closed loop

Closed loop system developed in the lab based on thermo-camera & thermocouples

Simulation of temperature evolution

Temperature is higher through thickness. How to know in advance where to put thermo-couples to capture maximum temperature ?

Couple thermo-conduction cure kinetics & induction model

Identification

Identification algorithm to capture unknown thermal properties & process parameters

Numerical validation of black-box identification using 1D through thickness model

Identification results in different scenarios

The model can achieve some physical resemblance but accuracy is not sufficient. A 2D heat transfer model is under deployment to improve accuracy.
Cure-Compaction Model for use in Fast Simulation Tools to Predict Consolidation-induced Defects

Raul Gomez Quinones, Attilio Chiappini (Airbus Atlantic), Stephen Hallett and Jonathan Belnoue

Automated Fibre Placement (AFP) is one of the most prevalent methods used in the aerospace industry for the manufacture of large-scale composite parts, consisting of a fibre placement head that is usually attached to either a robotic arm or placed onto a gantry system. Whilst its use has been well established, preventing defects in complex geometries has been a persistent challenge, and usually dealt with by costly and time consuming trial-and-error methods. The aim of this project is to create a framework of tools that can be used to predict consolidation-induced defects in large, autoclave-cured AFP parts using the IMA/M21 material system, building up on work done by the DEFGEN project, starting with a coupled cure-compaction model before moving on to considering residual stresses.

1. Background

1. Model Layout.

All simulations performed on a crucifix shaped laminate:
- Comprising of 16plies 25x50 mm in a block-pty lay-up with overhangs as shown in Figure 1 and 2.
- Laminate is placed between two aluminium plates, the lower plate being fixed in place and the upper plate under ramp dwell loading as shown in Figure 3.

2. Experimental Parameters of Interest

The Cure Hardening Instantaneously Linear Elastic (CHILE) model is a widely-used approach for the computation of residual stresses. Moretti et al, from IMT Mines Albi Carmaux, proposed a modified version that more accurately describes the behaviour of IMA/M21, as shown in Figure 4. This model could potentially be incorporated into the framework of tools being developed in order to predict residual stresses in composite parts made of IMA/M21.

To be confident that the derived modified-CHILE parameters can be used, their cure kinetics model needs to be compared and validated with UoB's cure kinetics model².

2. Cure Modelling

Both models used are autocatalytic cure kinetics models:
- A diffusion rate limitation term is added directly into the cure kinetics’ rate constants in UoB's model.
- Moretti et al’s model uses the maximum DoC (degree of cure, \(\chi_{\text{max}}\)) at a given temperature to stop reaction as DoC approaches 1.
- The values for \(\chi_{\text{max}}\) used are linearly interpolated from experimentally-derived values at various temperatures.

As both cure kinetics models are different, like-for-like comparison of their respective cure kinetics parameters is not possible.

1. University of Bristol [3]:

\[
\frac{d\chi_p}{d\tau} = k_1 (1 - \chi_p)^n + 2k_2 (1 - \chi_p) \exp \left( -\frac{E_D}{RT} \right)
\]

where

\[
k_1 = A_1 \exp \left( -\frac{E_R}{RT} \right)
\]

\[
k_2 = A_2 \exp \left( -\frac{E_R}{RT} \right)
\]

\[
R = \text{Rate of reaction}
\]

1. IMA/M21 (Temperature):

\[
\frac{d\chi_{\text{max}}}{d\tau} = k_1 (1 - \chi_{\text{max}})^n + 2k_2 (1 - \chi_{\text{max}}) \exp \left( -\frac{E_D}{RT} \right)
\]

where

\[
k_1 = A_1 \exp \left( -\frac{E_R}{RT} \right)
\]

\[
k_2 = A_2 \exp \left( -\frac{E_R}{RT} \right)
\]

\[
R = \text{Rate of reaction}
\]

3. Results

1. Isothermal Conditions:

Both cure cycles compared in MATLAB under the recommended temperature cycle for 15-48 mm thick laminates of IMA/M21 [4].
- 1. Isothermal Conditions:.
  - Temp. ramp up of 1°C min\(^{-1}\) up to 180°C.
  - Temp. dwell for 180 mins
  - Temperature ramp up to 25°C at 5°C min\(^{-1}\).

No heat transfer or heat generation taken into account initial comparison.

2. Non-Isothermal Conditions:

- Two aluminium plates at 50°C, with adjacent ply surfaces also at 90°C.
- Initial laminate temperature of 25°C.

Conductivities and heat capacities of IMA/M21 are known to vary with temperature and calculated in the UMATHT subroutine. UMATHT currently able to deal with heat transfer under non-isothermal conditions.

4. Conclusions & Future Work

5. References
A numerical study on process-induced defects and variability in thick tapered laminates
Maria Onoufriou, Jonathan Belnoue and Stephen Hallett

A modelling framework for predicting material deformation during autoclave moulding of industrial scale composite laminates was developed. The aim of the framework is to fully automate the modelling process in an efficient way, to remove the barriers to its utilisation in an industrial setting and enable a process simulation based iterative design methodology.

Ply-by-Ply Reconstruction
A reconstruction tool, which uses the strains extracted during the homogenised simulation to calculate the deformation of individual plies was developed, enabling an accurate depiction of the consolidated geometry on a ply-by-ply level, in a computationally efficient way (under an hour).

Validation
In order to validate the simulation results, the initial and +10% laminate designs were manufactured. The final thicknesses were accurately captured, and defect formation was correctly captured in the ply-by-ply reconstruction. There was a clear improvement between the initial and +10% design, as predicted by the simulations. Highlighting the crucial role process simulations can play in removing the need for costly manufacturing trials and capturing issues that would not have otherwise been intuitive.

Iterative Design Methodology
A laminate ply-book was initially designed for a specified geometry. However, the process simulations showed underfilling of the mould; to combat the issue, the plies ending in the transition region were extended by +5% and then +10%. The design iterations resulted in a more robust and dimensionally compliant part.

Effect of material variability
Manufacturing of composite structures involves sources of variability which can lead to stochastic defect formation. It is therefore important that the effects of variability are understood and accounted for in process simulations. The results for dimensional compliance for the three designs with added thickness and length variability are shown below.

<table>
<thead>
<tr>
<th>Thickness (mm)</th>
<th>Initial Design</th>
<th>+5% Design</th>
<th>+10% Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
<td>40.75</td>
<td>41.14</td>
<td>41.11</td>
</tr>
<tr>
<td>Modeled</td>
<td>40.14</td>
<td>41.14</td>
<td>41.11</td>
</tr>
<tr>
<td>Targeted</td>
<td>40.11</td>
<td>41.11</td>
<td>41.11</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Thickness (mm)</th>
<th>Initial Design</th>
<th>+5% Design</th>
<th>+10% Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
<td>12.35</td>
<td>11.70</td>
<td>11.78</td>
</tr>
<tr>
<td>Modeled</td>
<td>11.70</td>
<td>11.70</td>
<td>11.78</td>
</tr>
<tr>
<td>Targeted</td>
<td>11.78</td>
<td>11.78</td>
<td>11.78</td>
</tr>
</tbody>
</table>

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Phenomenological Mechanical Damage for Ceramic Matrix Composite Yarn

Peter Foster, Adam Thompson, Stephen Hallett, Giuliano Allegri, Luiz Kawashita

Constituent Representation in Material Model

- Fibre
- Interphase
- Chemically Vapour Infiltrated (CVI) Matrix
- Voids
- Silicon Melt Infiltrate (SMI) Matrix

Mori-Tanaka (MT) Homogenisation

\[ \begin{align*}
C &= \text{stiffness tensor} \\
E &= \text{eshelby tensor} \\
v &= \text{volume fraction}
\end{align*} \]

\[ f \left\{ \begin{array}{l}
C_{\text{inclusion}} \\
C_{\text{matrix}} \end{array} \right\} E v_{\text{inclusion}} \]

\[ \begin{align*}
\varepsilon_{\text{inclusion}} &\rightarrow \varepsilon_{\text{global}} \\
\varepsilon_{\text{matrix}} &\rightarrow \varepsilon_{\text{global}}
\end{align*} \]

Damage in MT Homogenisation

Local fibre failure -> global yarn failure

Fibre aligned MT damage global load curve and local constituent load curves

MT Damage Model in CMC Textile

Textile is either matrix or yarn element

Fibre volume fraction in yarn elements for homogenisation scheme

Unit cell textile under axial tension

Open hole textile under axial tension

Damage in yarn

Fibre - CVI + voids + SMI

Matrix - CVI + voids + SMI

Local matrix stiffness degradation

Local fibre failure -> global yarn failure

3D damage - Off-axis loading of single elements from 0° to 90°

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