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Title: *Predictive modelling of the automated fibre placement (AFP) processes:
perspectives and challenges*

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(FIRST PAGE OF ARTICLE)

ABSTRACT

The present contribution gives an overview of the recent efforts developed at Bristol Composite Institute (ACCIS) towards building a finite element modelling framework for AFP processes. Inputs include both fundamental understanding of the material behaviour and efficient numerical tools for implementation at large component scale modelling. The requirements for a numerical model for AFP are explored, limitations of the current state-of-art modelling techniques are assessed and a roadmap towards fully predictive and efficient simulation tools is proposed.

INTRODUCTION: STATE OF THE ART MODELLING OF AFP PROCESSES

Automated fibre placement (AFP) technology [1] allows the manufacture of composites parts with more complex geometry and more severe curvature than other automated methods. However, despite being widely used in the industry, the method still suffers from low deposition rates and manufacture of defect-free parts remains very challenging. Setting-up an AFP machine to reliably manufacture a composite part with a minimum number of defects is heavily dependent on engineering experience, and costly, wasteful and time-consuming trials. Being able to predict the as-manufactured geometry and fibre paths in parts made by AFP would significantly help reduce the empiricism inherent to current state-of-the-art AFP manufacturing. Looking forward, such models could also be very beneficial in the context of recent trends towards manufacturing 4.0 where the manufacturing process would be heavily instrumented with in-process sensing and the deposition parameters adapted on the fly to mitigate the formation of defects.

Over the last 10 years or so, a number of models for the prediction of AFP processes have been developed in the literature. Up until fairly recently, most of the work has concentrated on analytical derivation of increased complexity for the minimum steering

radius that can be reached without creating out-of-plane defects [2, 3, 4]. These models have been very useful in establishing which deposition and material parameters are crucial in the development of tape buckles. However, their use as fully predictive tools for the AFP process are somehow limited as their domain of applicability is restrained to simple geometries (i.e. flat surface of deposition) and the assumption made for the mechanical behaviour of the tape (i.e. elastic orthotropic tape) are not very representative of the real behaviour of a block of resin reinforced by carbon fibres. These models are unable, for example, to capture the effect of deformation rates and strong temperature gradients at play in a real AFP process.

Ideally, a proper model for AFP should be able to describe the deposition of a prepreg tape by a moving roller (which needs to be characterised [5]) onto a complex-shaped surface (e.g. doubly curved). The heat conduction problem for the heating of the tape through the lamp ahead of the deposition roller should be formulated properly. The change of the tape mechanical properties with temperature and pressure rate (i.e. viscoelasticity) should be taken into account. Such a complex process can only be simulated through numerical modelling such as the finite element method. Early work in the area has concentrated on getting the thermal behaviour of the process right [6]. These studies considered some coupling between thermal and mechanical behaviour of the materials. However, the constitutive description of the tape has mostly remained quite simplistic with the incoming tape often considered as an elastic material [7]. Measurement and modelling [7, 8] of the tack behaviour is probably the area which has seen the most effort being deployed in the last couple of years.

Apart from an overly simplistic description of the constitutive behaviour of prepreg, current numerical models for AFP processes also represent the incoming tape with shell elements. These are appropriate to capture the bending behaviour of the tape but do not account for the through thickness consolidation which is an important mechanism in the formation of gaps and overlaps defects [9]. Additionally, whilst analytical models have shown the importance of the compliance of the substrate in the mechanism of defect formation, most of the numerical models available only consider the deposition of the first prepreg tape onto the rigid tool as the computational cost of the simulation increases exponentially with the number of prepreg tapes being modelled. These gaps in the current state of the art of the modelling of AFP processes have been at the heart of the research at Bristol Composite Institute (ACCIS) over the last couple of years. The present paper presents new advancement in the modelling of the time-dependent constitutive behaviour of prepreg tapes (for both shear and consolidation) and in the computational efficiency of the overall scheme.

PREPREG TAPE SHEAR BEHAVIOUR

Earlier researches have indicated that defects formation during composite manufacturing is influenced by the in-plane and out of plane behaviour of the prepreg material, e.g. bending, friction, shear, tackiness [4]. Amongst these properties, the shearing behaviour of the tape is of particular importance for the derivation of the critical steering radius. The in-plane shear behaviour of uncured thermoset prepreg was studied using 10° off-axis characterization method inspired by Potter [10]. To make the testing method relevant to the AFP process, the possible maximum shear rates during the deposition was estimated [11]. A test campaign was then designed to study the influence

of temperature and deformation rate on the shear behaviour of uncured prepreg. These tests were then used as a basis for the formulation of a new model for prepreg tape.

Experimental Set-Up

The material used was unidirectional carbon/epoxy prepreg IM7-8552 manufactured by Hexcel®. The dimension of the specimen was 320mm*40mm, which is decided by the width of grips on test machine, the off-axis angle and the tow width of shear band, as shown in Figure 1a. To average out possible local weakness of the tow interface, the specimen was designed with more than one layer. All the samples were laid-up by hand and vacuum consolidated.

Unlike cured laminate, uncured prepreg is very compliant and can easily undergo wrinkling when loaded. After wrinkling happens, the sample is not subjected to pure shear anymore and the data collected become irrelevant. The onset of wrinkling and the measurement of strain in the shear band were performed using a DIC (Digital Image Correlation). The specimens were speckled with fine black-on-white pattern using acrylic paint for DIC measurement. A 5 Mega Pixel LaVision DIC system with two LaVision cameras was used. This allows to capture the surface strain distribution as well as the out of plane deformation of the specimen. The specimen surface was illuminated by normal lights. The capture results were analysed by LaVision Davis software (a typical result shown in Figure 1a). An analogue-Digital Converter was set to the synchronise the load from test machine. The setup of the test facilities is shown in Figure 1b.

The tests were conducted using a Shimadzu test machine with thermal chamber (for elevated temperature tests). Different test strain rates (i.e. 0.1%/s, 1%/s, 5%/s) with temperatures (25°C, 50°C and 75°C) were studied. 5 repeats of each combination of test rate and specimen thickness were performed.

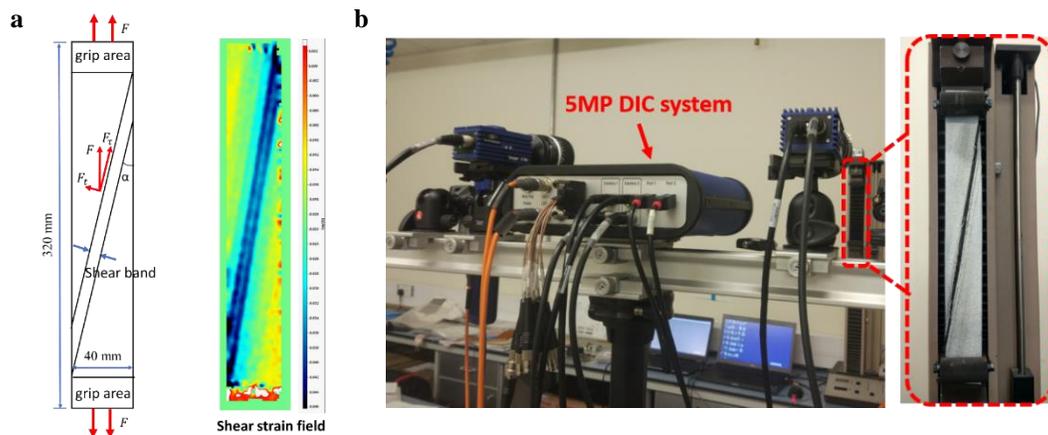


Figure 1. Schematic of the test: (a) Sample Dimensions and typical DIC results (b) Test set up.

A Time-Dependent Phenomenological Model for the Deformation of Prepreg Tape Under Pure Shear Loading

As expected, the experimental results revealed a significant dependency of prepreg tapes shear behaviour with both the loading rate and the temperature. Perhaps more

surprisingly, none of the existing physically based models for the apparent behaviour of fibre reinforced fluid [12] allowed to match the observed response which seemed to be divided into 2 parts:

- A viscous (i.e. rate dependent) term which decreases with the applied rate (i.e. shear thinning).
- A (pseudo) elastic term which depends on both the temperature and the loading rate. This term was subsequently additively decomposed into an elastic term (which changes with temperature) and a viscous term (constant with temperature). It is hypothesised that this is related to the fibres' contribution. The viscous term could originate from the lubricated friction between 2 fibres. The resistance created by this frictional term could, in turn, result in a load transfer to the fibres which would explain the observed elastic term.

The proposed phenomenological model was used to extract material parameters from the experimental tests described in section 1.1 and implemented as an adaption of [13] as a VUMAT subroutine for the commercial FE package Abaqus/Explicit. As illustrated in Figure 2, the model was used to simulate the series of tests performed in section 1.1. Good agreement between model prediction and experimental result was obtained for all the tested conditions. More work aiming at a better understanding of the micro-mechanical phenomenon at play is currently under way.

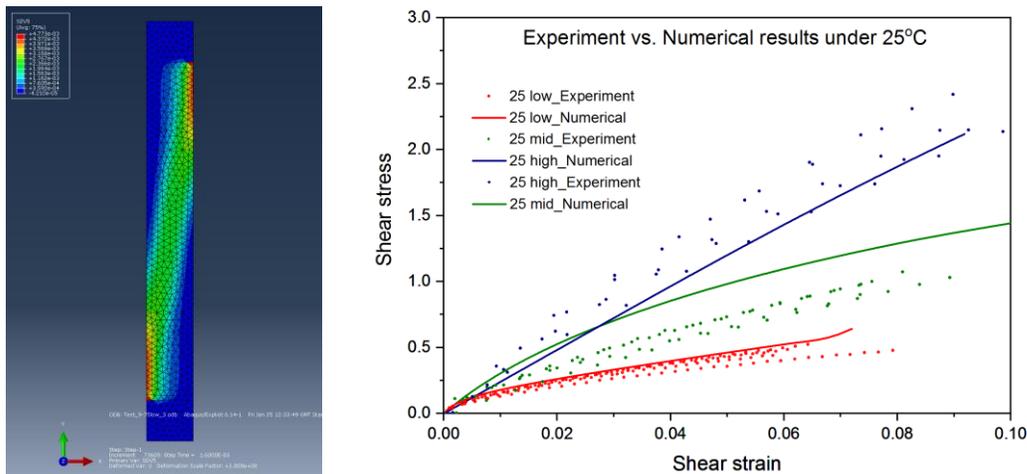


Figure 2. Numerical modelling of the test: (a) The FE model (b) Comparison between the model predictions and the experimental results for the tests performed at 25°C.

CONSOLIDATION BEHAVIOUR

Size Effect in the Consolidation Process

As mentioned, in the introduction, the consolidation behaviour of prepreg is important in the context of the prediction of gaps and overlaps defects in AFP manufactured laminates. An experimental study designed to understand the compaction behaviour of

uncured preregs under processing conditions within a wide enough range of temperature, pressure and pressure rate (to be consistent with AFP as well as hot debulking) was performed [14]. The prepreg system IM7/8552 was investigated. Three layups of 16 plies were investigated (see Figure 3): Cross-ply (CP), $[90/0]_8$; Blocked-ply (BP), $[90_4/0_4/90_4/0_4]_2$; and Semi-blocked (SB), $[90_2/0_2/90_2/0_2]_2$ with two in-plane sizes in each case giving effective areas of 15mm x 15mm and 30mm x 30mm. Isothermal experiments with temperatures varying from 30 to 90°C were performed. At each of the temperature tested, the samples were subjected to a ramp-dwell regime consisting of five steps in which a fast application of load is followed by longer constant pressure intervals.

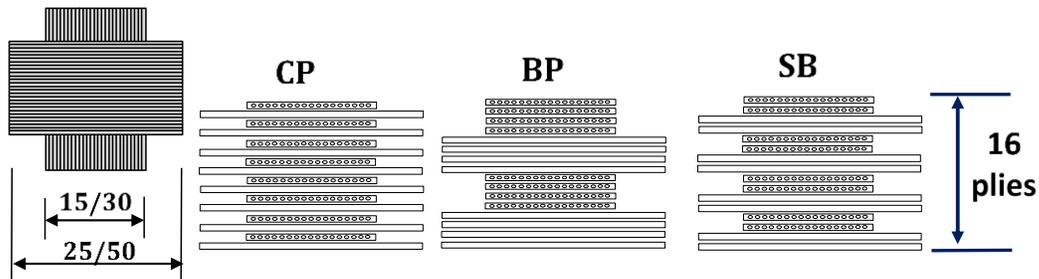


Figure 3. Plan view of baseline and scale-up specimens with cross section view of lay-up.

For all BP configurations, a compaction limit is reached at 70°C. BP specimens showed a greater ability to deform (both through thickness and in terms of transverse expansion) than their CP counter-parts subjected to the same temperature and pressure program. The SB configuration show intermediate behaviour between BP and CP specimens. Doubling the in-plane dimensions of the specimens gave rise to quite significant size effects in which lower transverse spreading and slightly greater final thicknesses were obtained. This can be explained by the comparably lower transverse strains arising with greater in-plane dimensions.

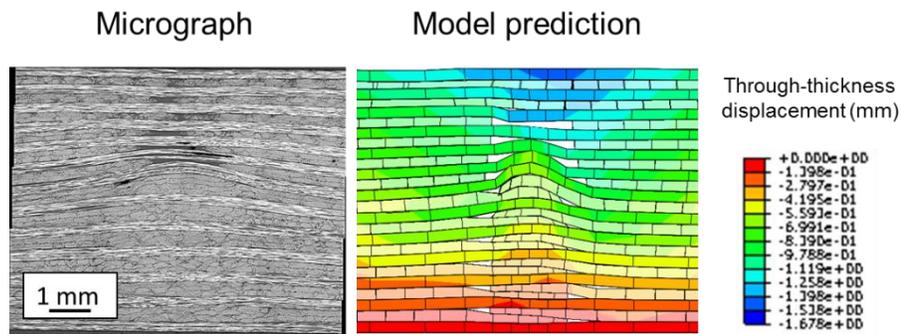


Figure 4. Model prediction comparison with sample micrographs for the internal ply geometry around a central wrinkle [17].

These tests clearly highlighted the coexistence of bleeding (e.g. existence of a compaction limit) and squeezing flow (as shown by the existence of large size effects and great ply distortion of the specimens tested at the higher temperatures). To model the macroscopic response of toughened prepreg under processing, Belnoue et al. [15] proposed a phenomenological model whereby the existence of a transition mechanism between

squeezing (at low temperature, low pressure) and bleeding flow (at high temperature, high pressure) was hypothesised. The model was subsequently applied [16] to subcomponents-sized specimen and gave good prediction for the specimens' final thickness and internal ply geometry at the meso-scale. From an AFP perspective, Belnoue et al. [17] have shown how considerations on bleeding/squeezing flow transitions and size effects, affects how gaps and overlaps originally present in a layup give rise or not to porosity and fibre path defects (see Figure 4) depending on the consolidation pressure and the plies' ability to squeeze.

Efficient Modelling of the Substrate

Lastly, even though analytical models have shown the importance of the mechanical response of the substrate in AFP defect formation mechanisms, there is only very little work on the numerical modelling of AFP processes which take this into account. This is, in large part, due to the computational cost involved with the modelling of every single ply of a lay-up. Recent efforts have allowed to overcome this difficulty (see Figure 5) using kinematically enhanced constitutive modelling [18].

The behaviour of each ply constituent of a structure follows the model for prepreg under processing conditions mentioned in section 2.1. The interactions between the plies are explicitly modelled as thin extra layers of pure fluid. Two layers inside the stack are homogenised using a combination of: a volumetric averaging of the strains, the compatibility condition at the plane where the two 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 homogenised with another layer and the whole laminate can be built by successive homogenisation of two layers at a time. The computational efficiency of the proposed scheme comes from the reduction of the degrees of freedom used and the easing of the convergence of the FE scheme through the reduction of the number of contacts and the smearing of highly strained region into a homogenised apparent response of the laminate.

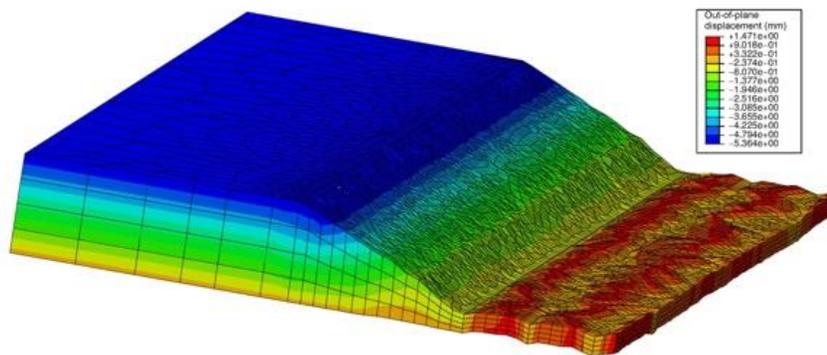


Figure 5. Homogenised model of a tapered component showing wrinkle formation.

GOING FORWARD...

The basis for efficient modelling of AFP processes have been set-out. New constitutive models for a prepreg tape under consolidation and pure shear have been developed and could be used within a traditional framework for the numerical analysis of AFP processes as illustrated in Figure 6. Recent effort at Bristol Composite Institute (ACCIS) have also set the foundation for very efficient modelling of prepreg stack which should allow to take account of the effect of the substrate mechanical behaviour on the development of defects in AFP processes. The platform thus created opens the way towards the exciting prospect of being able to use process modelling to help reduce the need for machine trials. In this context, process modelling could be deployed to guide part design and programming. In the longer term, it will be possible to use data collected on the fly during AFP deposition, in conjunction with process modelling and modify the deposition parameters on the go to minimise defect appearance and help reduce scrap and wastage.

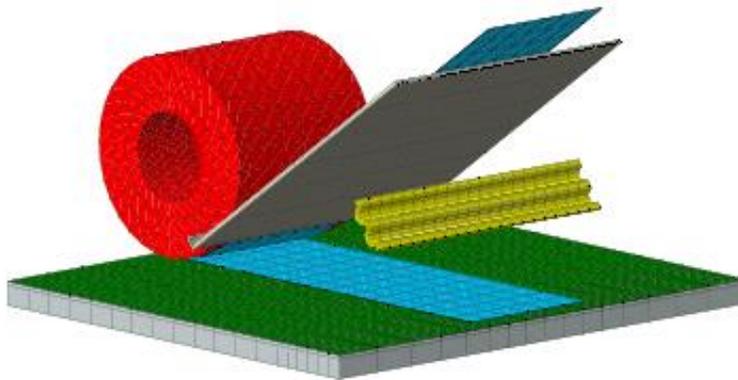


Figure 6. A typical FE model of the AFP process as described in [5]. This involve a roller (in red), the infra-red lamp (in yellow), the substrate (in green) and the prepreg tape being deposited (in blue).

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