EXPERIMENTAL CHARACTERISATION OF IN-PLANE SHEAR BEHAVIOUR OF UNCURED THERMOSET PREPREGS

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Abstract

The generation of defects (such as wrinkles and tow pull off) in the course of the steering process of automated fibre placement (AFP) is one of the critical limitations of this technique for the manufacturing of composite laminates. The in- and out-of-plane properties of the prepreg materials used have a strong influence on the final quality. In this paper, the in-plane shear behaviour of uncured thermoset prepreg was characterised to analyse the limits of steering and derive material parameters for the model predicting defects. An off-axis tensile test was applied to unidirectional uncured prepregs subjected to different testing rates consistent with the AFP processes. Innitial tests on the influence of temperature were also performed. Test parameters were optimized to minimise earlier buckling of thin samples, non-uniformity of strain distribution. The results show expected strain-rate and less-expected strain dependency of apparent viscosity, as well as common trends in material response at range of temperaures as determinded previously for compaction behaviour of the same material. The data presented in this paper opens the way towards a new material model for predicting the quality of the steering of prepreg tapes in automated deposition processes.

1. Introduction

Automated Fibre Placement (AFP) is one of the mainstream automated prepreg lay-up techniques employed in the aerospace industry. It provides much higher efficiency, better quality and a feasible way to manufacture variable angle tow (VAT) composites [1,2]. The process lays down the uncured unidirectional prepreg tapes on a mould surface by a robot-controlled head which feeds, heats, compacts and cuts off the deposited material. The layup speed, temperature and compaction force can be tuned to materials response to ensure better steering and adhesion [3].

The process, however, suffers from several limitations. In particular, defect-free automated deposition over complex doubly-curved surfaces is always challenging. In the industry, the optimization of deposition parameters for a reduced number of defects is achieved through costly and time-consuming trial-and-error methods which could be greatly reduced if validated and accurate process simulation tools were available.

Previous research has indicated that defects formation during composite manufacturing is influenced by the in-plane and out of plane behaviour of the prepreg material [4], e.g. bending, friction, shear, tackiness. Amongst these properties, the shearing behaviour of the uncured tape is the least well understood, but of particular importance for the derivation of the minimum steering radius. In this paper, the in-plane shear behaviour of uncured thermoset prepreg is studied using a 10° off-axis characterization method inspired by Potter [5] and Schirmaier et al. [6]. To make the testing method relevant to the AFP process, the possible maximum shear rates during the deposition is first estimated. Then, the test preparation and set up are described and the influence of temperature is investigated. Finally, the test results are discussed and future improvements to the method are proposed.

2. Background

2.1. Off-axis tensile test of prepreg

The off-axis tensile test is one of the commonly used methods for the characterization of shear properties of cured laminate [7]. Following a method originally proposed by Potter [5], this has been adapted for the characterization of the shear behaviour of uncured prepreg strips. The schematic of the proposed test and the stress state applied on the tape are shown in Figure 1. In the Figure, θ is the off-axis angle and the x-y and 1-2 axes are the testing and material coordinate systems, respectively. The force is applied in the x direction, and 1 is the fibre direction of the prepreg. σ_{11} is the local normal Cauchy stress in fibre direction, σ_{22} is the local normal stress in transverse direction, τ_{12} is the local shear stress. Following this notations, it can be easily calculated that the local stress state on the tape, follows Eq. 1.

$$\sigma_{11} = \frac{F \cdot cos^2\theta}{A}, \quad \sigma_{22} = \frac{F \cdot sin^2\theta}{A}, \quad \tau_{12} = \frac{F \cdot sin2\theta}{2A} \tag{1}$$

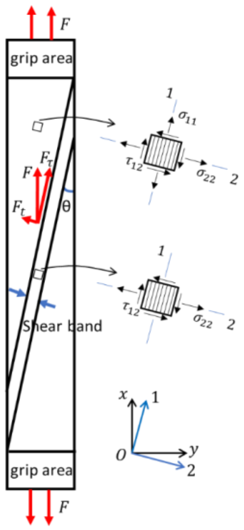


Figure 1. Schematic of off-axis tensile test for uncured prepreg.

The inclined band displayed in Figure 1 is not clamped by the grips and thus corresponds to the effective gauge area of the sample (i.e. the area where shear localises). A 10° fibre angle is selected in order to measure a load of sufficient magnitude for the load cell employed. The width of the shear band is adjusted to match the width of a real AFP tape (i.e. ~6 mm) by adjusting the sample dimensions.

2.2. Estimation of test rates

In previous shear charaterisation studies of thermoset prepregs, the shear rates were varied between 0.0008 rad.s^{-1} and 0.004 rad.s^{-1} [4]. This is well below the rates reached in the course of a real industrial process. Therefore, an attempt was made to estimate the shear rates seen by a prepreg tape deposited by an AFP machine. The test rates were then adjusted to similar levels of magnitude.

Since both shear and bending deformation are involved in the steering process, an upper bond analysis is performed. The magnitude of the shear rate is obtained by assuming that the prepreg is subjected to pure shear deformation during steering. In Figure 2, the path of the tape is described by the neutral axis. Assuming inextensibility of the reinforcing fibres gives a shear angle denoted by θ. l and w are the length and width of the tape, respectively. r is the radius of the inner curvature and α is the corresponding rotation angle. Simple trigonometric relationships and the definition of the shear rate give rise to Eq. 2 and 3, respectively.

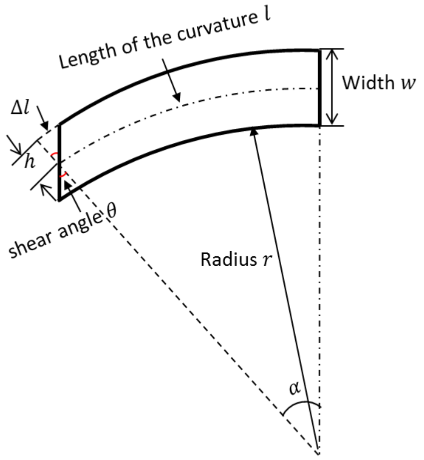


Figure 2. Pure shear deformation of the prepreg in steering process.

$$\theta \approx tan\theta = \frac{\Delta l}{h} = \frac{(r+w)\cdot\alpha - (r+w/2)\cdot\alpha}{w/2} = \alpha. \quad (2)$$

$$\dot{\theta} = \frac{\theta}{t} = \frac{\alpha}{t} = \frac{l}{r\times t} = \frac{v}{r} \quad (3)$$

In practice, the layup speed of commercial AFP machines can reach 1 m/s and the minimum radius for defect free layup is 500 mm ideally [3]. Following Eq. 3, this corresponds to a maximum shear rate of around 2 rad.s^{-1}. A lower bound estimation can be obtained by assuming that the prepreg tape is subjected to pure bending. This corresponds to shear rate of 0 rad.s^{-1}. In consequence, the range of the shear rates is 0-2 rad.s^{-1}.

To achieve better deposition quality, AFP machines are often programmed to be slower at curved paths. Meanwhile, the speed will decrease significantly on a non-flat geometry due to the constrains imposed by the robotic movements. For radius ≥900 mm, the layup speed is around 200-500 mm/s. Using Eq.3, this corresponds to shear rates between 0.22 and 0.56 rad.s^{-1}.

3. Experiment

3.1. Material and sample preparation

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 3a. To average out possible local weakness of the individual plies, 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 measure of strain in the shear band were performed using a Digital Image Correlation (DIC). The specimens were speckled with fine black-on-white pattern using acrylic paint for DIC measurement.

3.2. Experimental setup and test

A Hounsfield single column universal test machine with 500N load cell was used for tests under room temperature. Displacement control was applied. The prepreg was gripped through roller jigs. The test rate of the machine can vary from 0.1 mm/min to 1 m/min. The test results were recorded and analysed using a custom-made Labview routine.

A 5 Mega Pixel LaVision DIC system with two high-resolution video cameras was used. This allowed for capturing 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 3a). An analogue-Digital Converter was set to synchronise the load from test machine with the image capture. The test setup is shown in Figure 3b.

Different tensile strain rates (i.e. 0.1%/s, 1%/s, 5%/s) with different thickness (3/4/5 layers) were studied. 5 repeats of each combination of test rate and specimen thickness were performed.

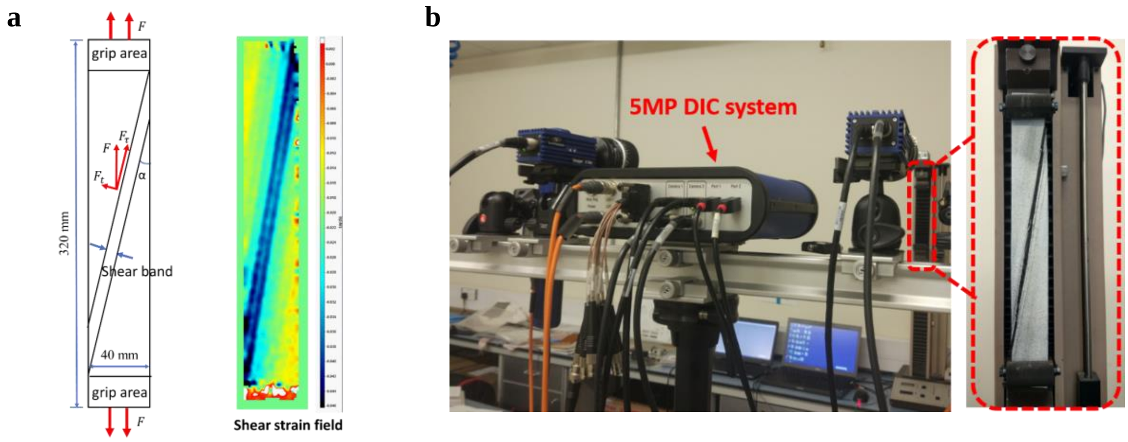


Figure 3. Schematic of the test: (a) Sample Dimensions and typical DIC results (b) Test set up.

4. Results and discussion

4.1. Load-displacement curves and buckling assessment

A typical load-displacement curve of material is shown in Figure 4a. The observed behaviour is almost linear at the start of the test. At advanced deformation, the curve starts diverging from linearity. The nonlinearity onset point is postulated to be related to wrinkle occurrence which may come from the compression in the transverse direction during the test (i.e. Poisson’s effect). The corresponding transverse compressive force increases with applied load. This leads to the buckling of the specimen once the load magnitude reaches the critical level.

This assumption was validated by further analysis of the DIC data. As shown in Figure 4b, the out of plane deformation in the centre line of the specimen was plotted for different load magnitudes. The figure shows that there is a critical load (between 150N and 220N) after which the out of plane deformation of the specimen becomes significant (i.e. the sample buckles). This point corresponds well to the point where the load-displacement curve starts diverging from the linearity.

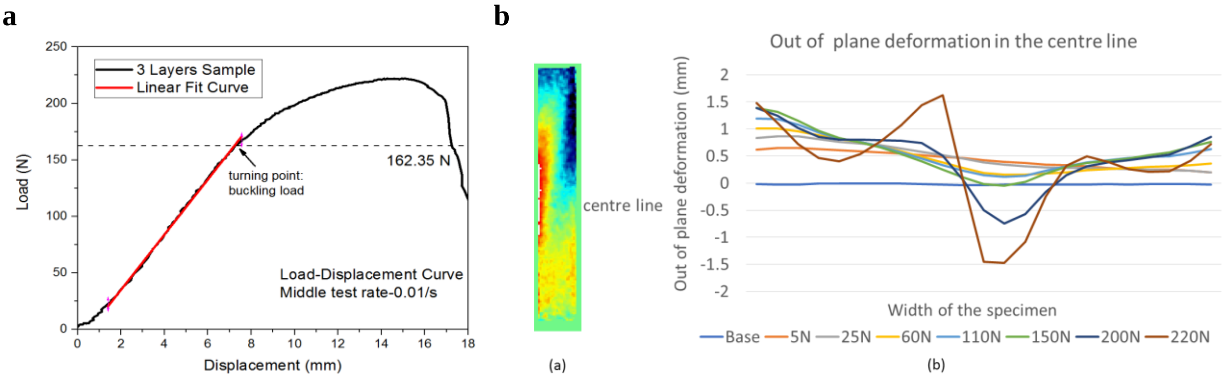


Figure 4. Buckling assessment of the specimen: (a) Load displacement curves of the specimen (b) Out of plane deformation in the central line.

4.2. The influence of test rates and effective width

4.2.1. The influence of thickness

The test specimens were designed with more than one layer to deal with the possible local weakness in a single layer of uncured prepreg. In addition, this allows increasing the load at which the samples start buckling and thus collection of more useful data for the study of the prepreg's shear behaviour. Samples with a range of thickness (i.e. 3/4/5 layers) were manufactured and tested under different test rates. Since the different test rates lead to the same conclusion, here only the curve corresponding to a strain rate (1%/s) is shown here (Figure 5a). The figure shows that the shear stress/strain curves do not change much with different thickness, which means that unlike its compaction behaviour [8], the in-plane shear property of the uncured thermoset prepreg is not dependent on the material thickness.

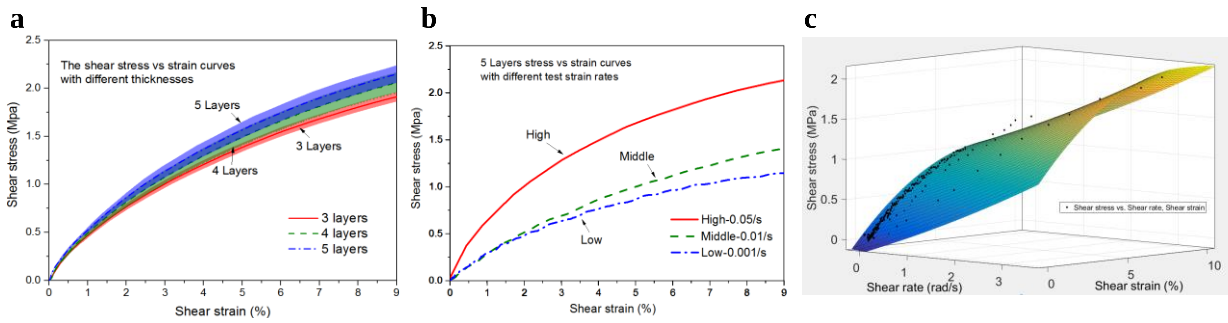


Figure 5. Shear behaviour vs different specimen thickness: (a) Shear behaviour vs thickness (b) Shear behaviour vs test rate (c) 3D plot of the test data.

4.2.2. The influence of test rates

Layup speed of the robotic head is a key parameter in AFP process affecting the final deposition quality of the material. As explained in section 2.2, different test rates (which is analogous to different layup speeds) are adopted in order to investigate the influence the strain rate on the materials' in-plane shear behaviour. The tests rates tested were 0.1%/s, 1%/s, 5%/s. The average shear stress/strain behaviour of the 5 layers thick are shown in Figure 5b.

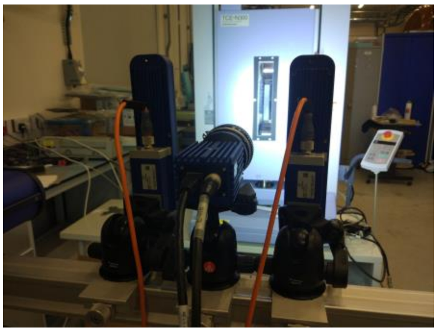
A nonlinear behaviour and a strong dependence on the test rates (which corresponds to the viscoelastic nature of uncured prepreg) are observed that the stress vs strain curve vary much with different test rates. The shear strain rate in the specimens are obtained by differenciating the shear strains with time. It can be seen the value of shear rate reaches the range of commercial AFP processes, as calculated in section 2.2. A 3D plot (of the evolution of the shear stress with the shear strain and shear strain rate) for the 5 layers thick samples is shown in Figure 5c. Considering the actual shear rate in each test is variable, a 3D surface fit was conducted in MATLAB in order to investigate the material behavior at a constant shear rate. This graph provides some useful information for the formulation of a predictive model of the prepreg shear behaviour.

4.2.3. The influence of temperature

The mechanical properties of uncured prepreg are highly resin-dominated. They should therefore be greatly affected by the temperature. In the AFP deposition process, one key setting is the heated temperature of the substrate. As a consequence, the temperature influence on the prepreg in-plane shear behaviour was investigated. The tests were conducted using a Shimadzu test machine with thermal chamber. The set up of the test is shown in Figure 6a. 2D DIC was used to measure the amount of strain in the samples. The onset of large out-of-plane deformation was judged using the deviation from linearity of the load-displacement curves. The test temperature was varied between 25°C and 85°C at 10°C increments.

Only initial results with one data point per temperature are presented here and the test matrix needs to be extended. The test results are presented in Figure 6b. As expected, temperature is shown to influence greatly the mechanical behaviour of uncured prepreg.

a



b

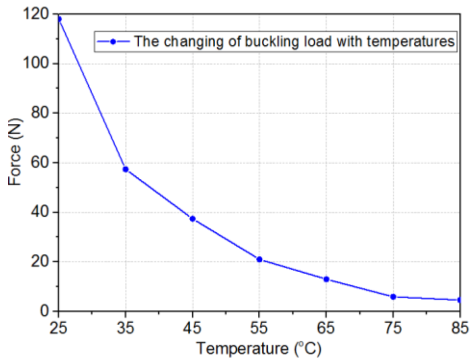


Figure 6. Temperature influence investigation: (a) High temperature test setup (b) The changing of buckling load with temperatures.s

5. Conclusion

In this paper, the in-plane shear behaviour of the uncured thermoset prepreg was investigated by 10° off-axis tensile tests. The effect of strain rate and specimen dimensions (i.e. specimen thickness) were investigated. Test rates of the same order of magnitude as the layup speed of a real AFP process were reached. Varied temperature conditions were also studied. The point at which the specimen started to buckle in shear, making the measured data become unusable was determined by measuring out-of-plane displacement through a Digital Image Correlation (DIC) system. The test results prove the feasibility of the test method and show that test rates and temperatures have a considerable influence on the shear properties of thermoset prepreg, while the effect of specimen dimensions was not obvious. The new insight into the material behaviour gained will lead to the ability to build predictive modelling capabilities.

Acknowledgments

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