FOUNDATION PARAMETERS CHARACTERIZATION FOR PREDICTION OF CRITICAL STEERING RADIUS IN AUTOMATED FIBER PLACEMENT

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Keywords: AFP, Steering, Buckling, Elastic foundation

Abstract

Thermoset automated fiber placement (AFP) improves the efficiency of composite structures by steering where properties such as stiffness can vary within the same part. However, steering of tapes often produces some manufacturing defects, including out-of-plane wrinkling. These defects occur at the inner and outer radii of the tow due to the excessive compression generated from the difference in length between the tow and the steering path. In the theoretical modeling of out-of-plane wrinkle formation during steering, the prepreg is considered as an orthotropic plate resting on two-parameter elastic foundations. In this paper, these two parameters include elastic springs (normal stiffness) attached to a shear layer (shear stiffness) are experimentally characterized. The effect of processing temperature on the elastic foundation parameters and critical steering radius is investigated. The probe test is used for normal stiffness characterization, while the bias extension test is used for shear stiffness. Both tests are performed at different temperatures; therefore, the results are compared for each test. These results are also used to study the influence of temperature variation on critical steering radius. The results show that processing temperature significantly influence the normal and shear stiffness of the foundation, and, hence, the critical steering radius. The presented results in this paper help to increase the design flexibility for successfully producing complex shapes with small curvatures.

1. Introduction

AFP technology has been used in the aerospace industry to produce large curved composite parts of Boeing 787 and Airbus A350 Airplanes [1]. By using fiber placement technology, the fibers in each ply can be steered in curved paths that allow the mechanical properties to vary from one point to another over the structure, which is defined as “Variable Stiffness Panels” [2]. These laminates remarkably increases the design flexibility leading to higher structural performance compared to its classical counterpart [3]–[5].

However, steering of tapes produces some manufacturing defects. The main defect of this process is out-of-plane wrinkling. This defect occurs at the inner radii of the tow due to the excessive compression or tensile forces generated from the difference of length between the tow and the steering path [6]. Minimum steering radius has been introduced as a steering limit to avoid such defect.

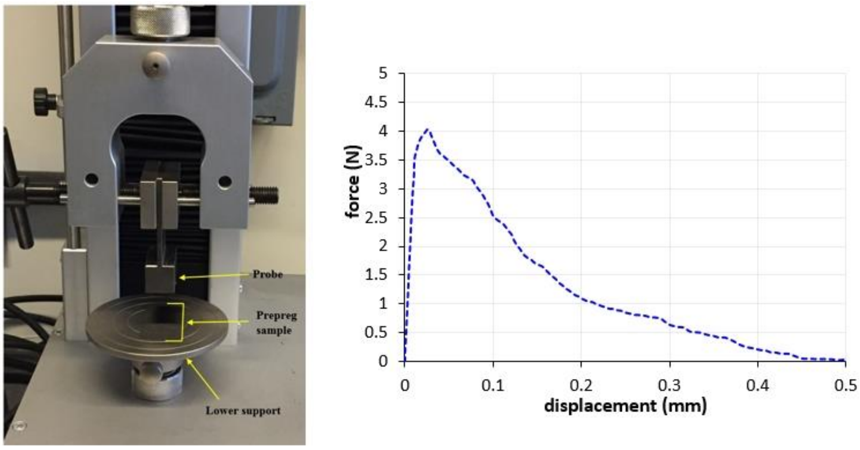
In the modeling of out-of-plane wrinkles developed during steering [7]. The steered tape was considered as an orthotropic plate resting on a two parameter elastic foundation with an elastic spring layer represents the normal stiffness (Tackiness) of the prepreg, and a shear layer acting for the normal stiffness of the material.

This study focuses on the experimental characterization of these two parameters. First, the two tests used for this purpose and the effect of processing temperature on them are presented. Then, the impact of processing temperature on critical steering radius is discussed. Finally, some results and conclusions are reported.

2. Foundation parameters characterization

2.1. Normal stiffness of foundation (*k*)

The material used for this experiment was a ¼ in unidirectional prepreg (CYCOM 977-2/ HTS-145). A simple probe tack test was used to measure the normal stiffness using a tensile machine as shown in Fig. 1(a). When the test started, the probe came into contact with the sample for 60 sec before it was debonded at a cross-head rate of 50 mm/min. The force required for debonding was recorded as a function of displacement as shown in Fig. 1(b). Then it was converted to stress vs. displacement curve by applying the section area of the probe. In this curve, only the section up to the maximum debonding force was linearly fitted and the material normal stiffness was considered as the slope of this fitted curve.



(a) (b)

Figure 1. (a) Probe test setup; (b) force vs. displacement curve.

To study the effect of processing temperature, the test was performed at three different temperatures. The sample and the probe were heated to the required temperature using an infrared lamp. The temperature for this test was selected based on the real AFP process. Fig. 2 shows the results at three different temperatures.

The curve shows that the normal stiffness is highly influenced by the processing temperature. The normal stiffness decreases from 6.78×10^8 N/m^3 to 2.65×10^8 N/m^3 when the temperature increases from 25 °C to 45 °C. The normal stiffness decrease is due to the deponding force drop, which attributed to the resin content variation through the thickness with less resin at the probe-prepreg contact area [8]. Therefore, the critical steering radius is affected by this decrease of the normal stiffness [7], which increases by 0.4m. These results prove the inconsistent reaction of different prepreg materials to temperature increase [9].

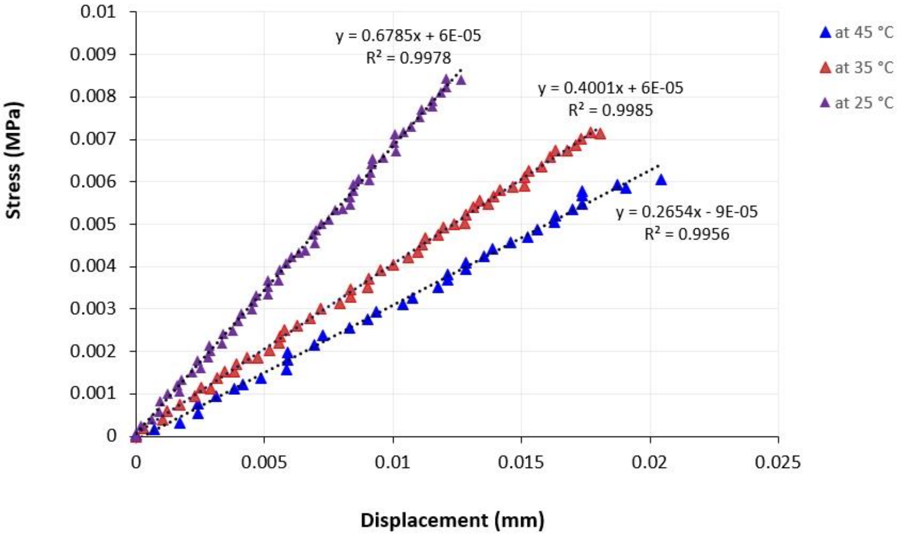
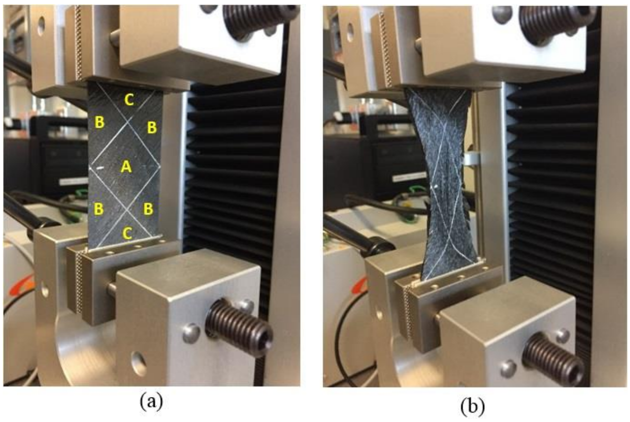


Figure 2. Stress-probe displacement curve of removal phase at different temperatures.

2.2. Shear stiffness (*G*)

A bias extension test was used to determine the shear stiffness of the uncured prepreg. In the bias extension test, the material is extended along the bias beginning at ±45º to the direction of the applied tensile force. The specimens selected for the bias extension test were 120 mm long by 40 mm wide, with an ungripped length of 80 mm. Each sample was made out of two ±45° layers that were pre-consolidated at 70 °C with 0.1 MPa (vacuum pressure) for 30 minutes. The tests were performed using a tensile testing machine and non-contacted infrared lamps.[7]. The processing temperature chosen for this test was 25,35, and 45 °C with a cross-head rate of 50 mm/min. The specimen for the test can be divided into three zones, as depicted in Fig. 3.



(a) (b)

Figure 3. Bias extension test showing (a) undeformed sample; (b) deformed sample.

The force and displacement were recorded as shown in Fig. 4. The force was converted to the normalized shear stress using the equation reported in Ref. [10]. The shear angle throughout the test was captured by a digital camera, and the images were inserted into software to measure the corresponding angles. The shear stiffness was calculated based on the normalized shear stress and the resulting shear angle (radian).

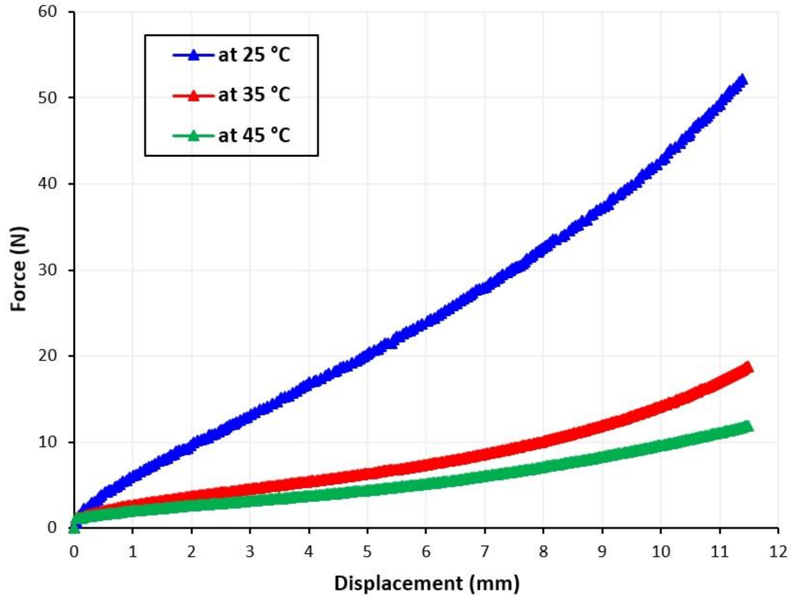


Figure 4. Force vs. displacement curve recorded during bias extension test at different temperatures.

The normalized shear stress was plotted against the corresponding shear angle at three different temperature as illustrated in Fig. 5. The results reveals that temperature has a significant influence on shear stiffness. Increasing the temperature reduces the critical steering radius, as the temperature increased from 25 °C to 45 °C, the shear stiffness decreased from 1600 to 400 N/m. This drop of the shear stiffness is related to the reduced viscosity of the resin at higher temperatures. On the other hand, decreasing the shear stiffness leads to a higher critical steering radius.

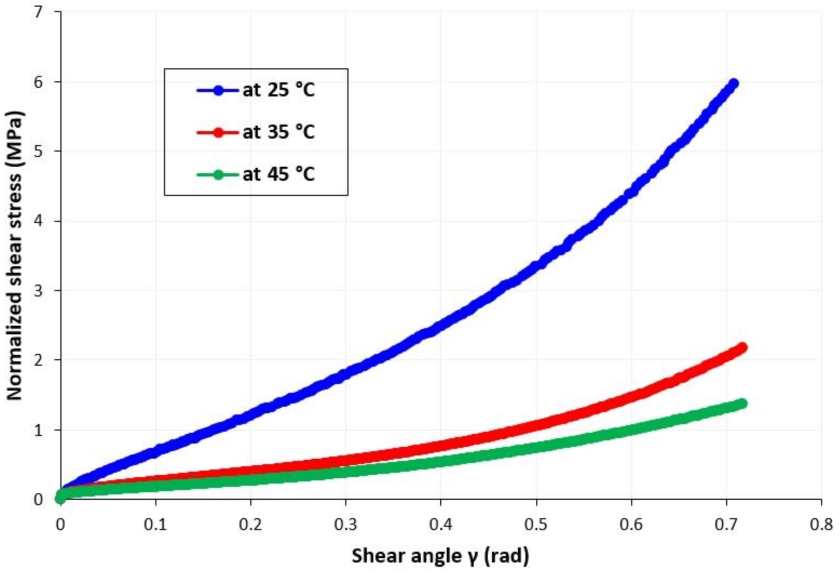


Figure 4. Normalized shear stress vs. shear angle curve generated from bias extension test at different temperatures

3. Conclusions

The current study presented the experimental characterization of foundation parameters during steering in automated fiber placement. These parameters include normal stiffness and shear stiffness of a thermoset prepreg. The effect of the processing temperature on both parameters was also investigated. In addition, the influence of processing temperature on critical steering radius through its impact on foundation parameters was discussed. First, the normal and shear stiffness of the prepreg were successfully characterized by performing a probe and bias extension tests respectively. However, developing a new tests that simulate the real AFP process could provide more accurate results. Second, in terms of processing temperature, the results show that foundation parameters were significantly affected by increasing the temperature. Consequently, the critical steering radius was also influenced. On a broader level, the results reveal that selecting an appropriate temperature within the range of thermosetting resin helps to increase the degree of formability by steering prepreg at lower radii, and thus expanding the design window for more complex parts can be produced without major defects.

Acknowledgments

The authors of this paper would like to acknowledge the financial support of NSERC (Natural Sciences and Engineering Research Council of Canada). Thanks to Bombardier Aerospace for supplying the materials.

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