BENDING BEHAVIOR OF WOVEN FABRIC OUT-OF-AUTOCLVE PREPREG IN FORMING

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1 INTRODUCTION

1.1 Background

Forming of the laminate to the desired shape is associated with several deformation mechanisms, of which the most common are intra-ply shearing, out-of-plane bending, and inter-ply sliding [1]. Haanappel et al. [2] showed that the formability of a composite laminate is determined by a delicate balance between these basic deformation mechanisms. In order to ensure successful composite forming, therefore, it is necessary that the mechanisms that cause defects be thoroughly understood [3]. Among numerous possible negative outcomes during forming, wrinkling is the most prevalent defect [1]. The ability to accurately predict wrinkles and ultimately prevent them during forming process is highly desirable. Some studies attributed the occurrence of wrinkles to the material's locking angle [4, 5]. This implies that there are wrinkles in the zone with shear angle larger than the locking angle. However, Boisse et al. [6] showed that the appearance of out-of-plane wrinkles is a global phenomenon which depends primarily on boundary conditions, as well as material strains and stiffness. On the other hand, Haanappel et al. [2] report that wrinkle reduction can be achieved by increasing bending stiffness in forming simulation. Recently, Liang et al [7] have shown that, in forming simulations, the bending stiffness of the prepreg at the processing temperature is an important predictor of the size and quantity of wrinkles.

The bending properties of ply prepreg materials are significantly lower than what would be derived from the in-plane material properties using beam or plate theory [6]. This presents a significant difficulty during forming simulations, since finite element implementations assume that bending stiffness is derived from in-plane material response using a conventional shell element. Thus, in order for the forces associated with out-of-plane bending to be scaled correctly, it is necessary to obtain a firm understanding of the relative magnitude of the bending stiffness [1]. Furthermore, the bending stiffness must be represented separately in the finite element model. Despite the importance of all three deformation mechanisms to achieving an accurate prediction of wrinkling, the out-of-plane bending of prepreg composites has received little attention in the literature as compared to intra-ply shearing and inter-ply sliding.

1.2 Objectives

This paper aims to investigate the bending properties of 5-harness woven fabric-based out-of-autoclve prepregs. Both warp- and weft-direction samples were considered in the bending experiment tests. The tests were performed for both sample faces in the satin fabric due to asymmetrical nature about its middle plane. A comparison between the prepreg sample and the dry sample was carried out indicating the contribution of uncured resin to the bending results.

2 METHODOLOGY

2.1 Experimental setup and procedure

The bending behavior of woven fabric out-od-autoclave prepregs is carried out using a special bending test setup developed in a previous study [8]. In this proposed test, the sample is clamped vertically (vertical cantilever), while deflection shape and applied load are controlled by a linear actuator and a miniature-load cell, respectively, see Figure 1. Direct commands and change settings (such as required travel displacements, speeds, or current position) can be sent via the controller connected to the actuator, while the force required to achieve tip displacement is subsequently recorded by the load cell software. The rate-dependent effect can be measured by adjusting the testing speed using the actuator's controller.

The analysis of the bending behavior during composite forming process requires high curvature (higher displacement) to accurately simulate the process. Therefore, tip displacement of 50 mm was used. Images of the bent shape are captured by a digital camera and processed in ImageJ software to extract the data points. Data points on the deflection profile are subsequently fitted using a proper polynomial function. The curvature of the profile is then calculated from the obtained polynomial fit according to Euler-Bernoulli's law for large deformation produced by bending. The value of the recorded load can be used to calculate the moment at each selected point. Finally, the moments at each point can be plotted against the corresponding curvature values. The slope of moment-curvature curve gives a convenient assessment of bending stiffness

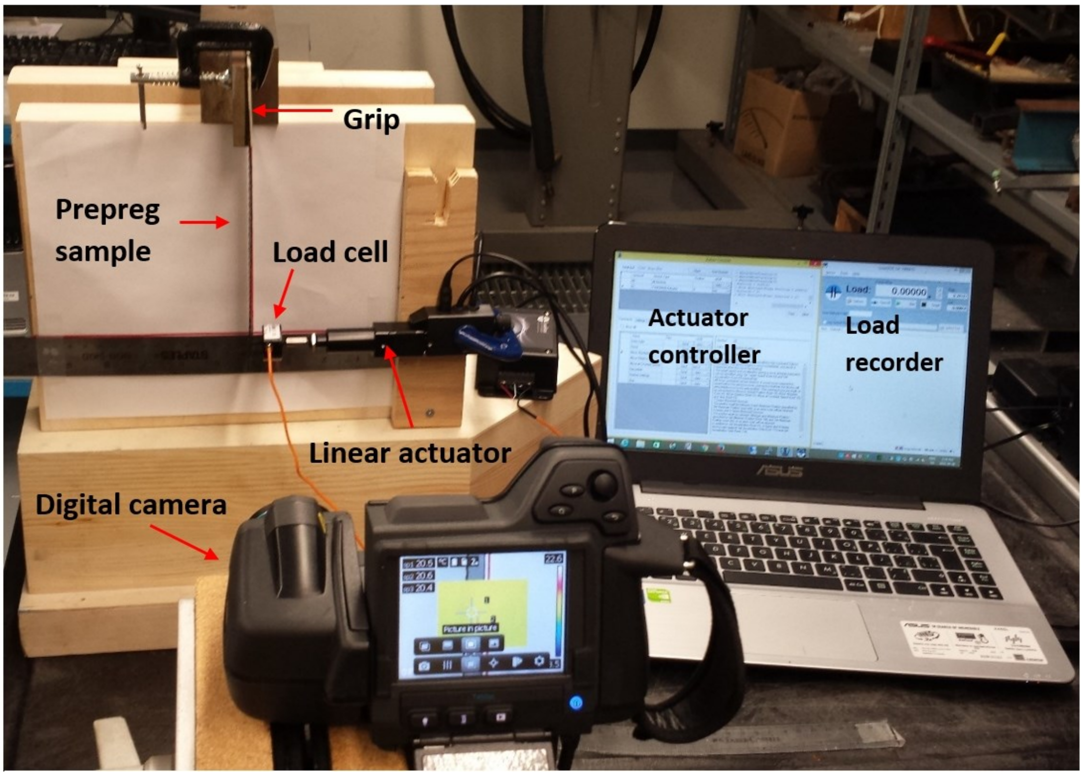

Figure 1. Bending test setup for prepreg characterization purposes.

2.2 Materials and samples preparation

The out-of-autoclave (OOA) prepreg chosen for this study consist of a 5-harness (5HS) satin weave (6 K carbon fiber tows) impregnated with an epoxy resin (Cycom 5320). The fabric's areal weight is 380 g/m^2 and the resin content is 36% by weight. The measured thickness of uncured one-ply is approximately 0.55 mm.

The samples selected for the bending experiments were 150 mm long by 50 mm wide, with an un-gripped length of 120 mm. The samples were cut so that their warp and weft directions were perpendicular to the applied load as shown in Figure 2. The satin fabric is an asymmetrical style about its middle plane; therefore, both face 1 and 2, shown in Figure 2, are tested.

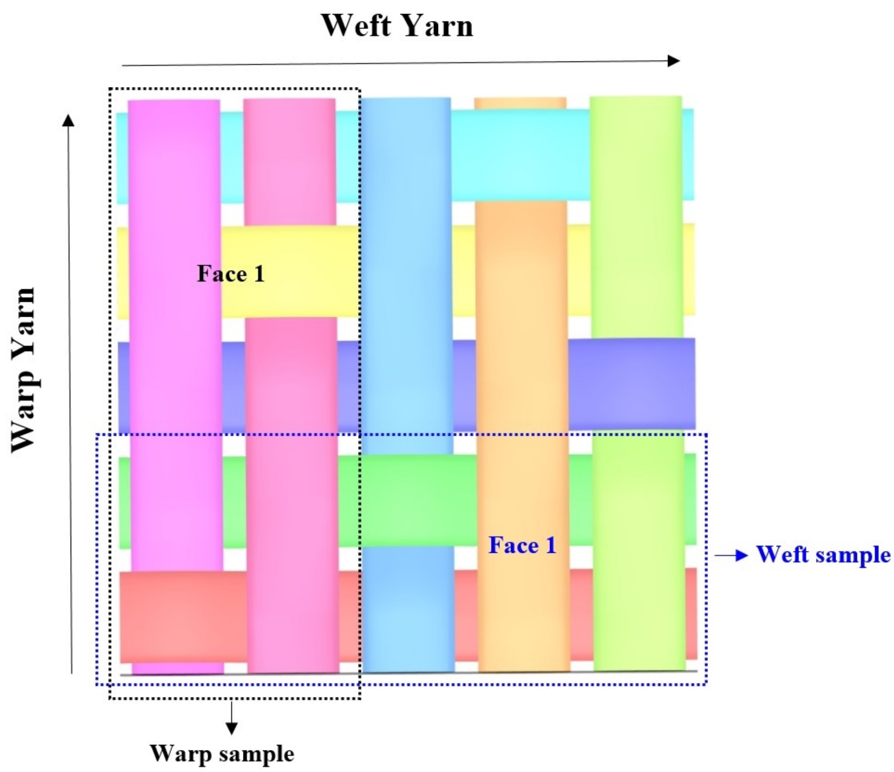

Figure 2. 5HS prepreg samples and yarn direction to the applied load.

3 RESULTS & DISCUSSION

3.1 Warp vs. weft samples

As previously mentioned, both the warp- and weft-direction samples are considered in the analysis. Figure 3 shows the difference between the two faces (warp direction) tested at room temperature with a speed of 3 mm/s. The maximum bending moment in the warp direction (face 1) is 4.816 N-mm, versus 4.175 N-mm in warp direction (face 2). The variation between weft (face 1) and weft (face 2) is depicted in Figure 4. The face 1/face 2 difference is likely to have as much impact on the outcome as the difference between warp and weft alignments. However, the results do show that the bending moment in the warp direction is approximately 20% higher than the bending moment in the weft direction. This distinction is attributed to the fact that the warp is straighter than the weft (lower number of crimps) and the number of warp threads per unit area is also higher than weft (more fabric density).

It should be noted that the difference between warp and weft directions in dry 5HS is greater than the one observed in 5HS prepreg. Results for dry 5HS in both directions are shown in Figure 5. The moments plotted for the warp direction differ by up to 29% from those obtained in the weft direction, whereas the equivalent warp/weft moments only differ by18% in prepreg samples. This contrast is likely due to the prepreg manufacturing technique, which pulls the weft rovings out of alignment by slightly bending them. However, it is also possible that the presence of resin in the OOA prepreg plays a role in this difference

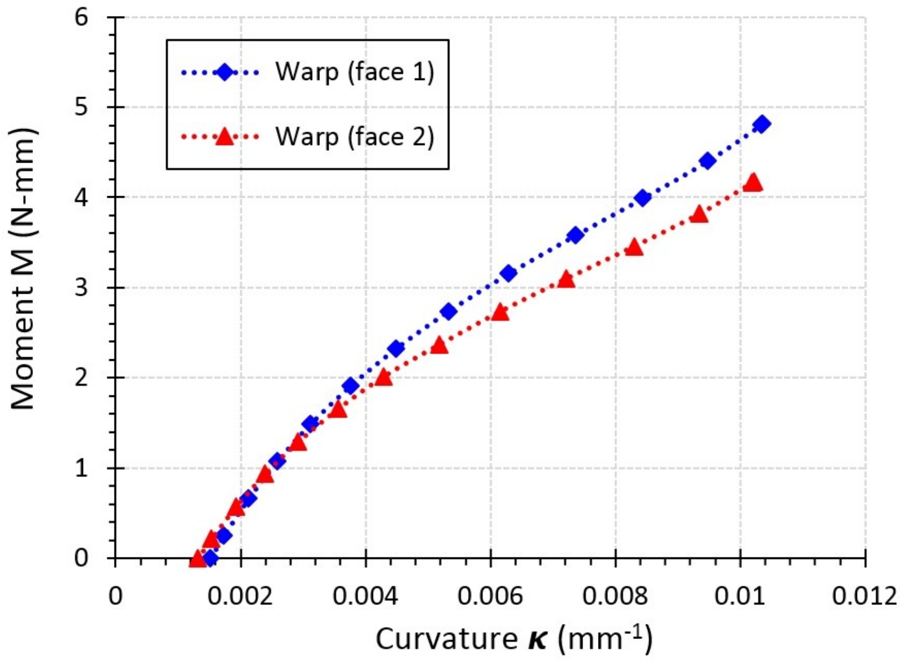

Figure 3. Bending moment versus curvature of 5HS prepreg sample in warp direction at room temperature.

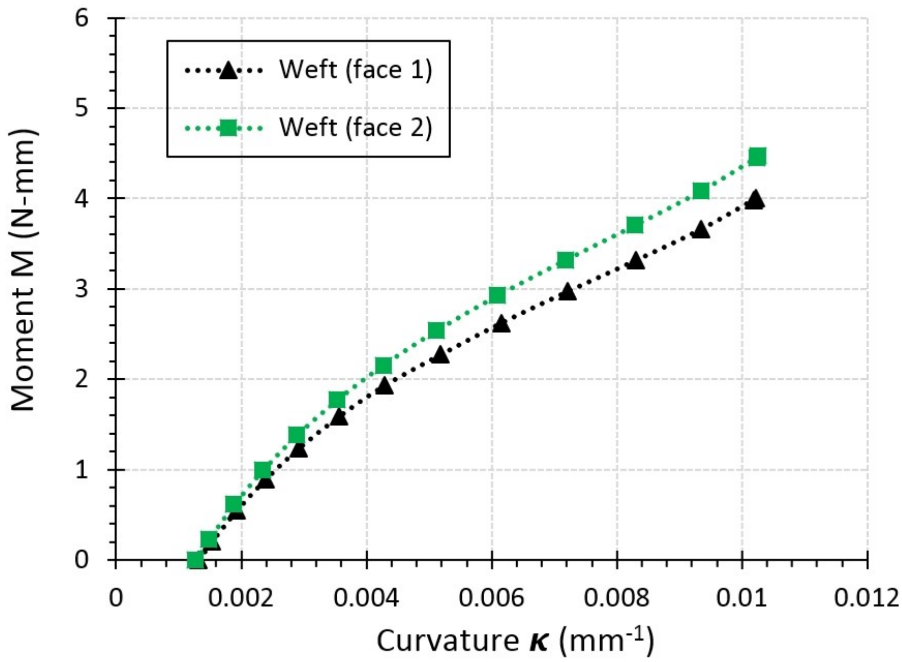

Figure 4. Bending moment versus curvature of 5HS prepreg sample in weft direction at room temperature.

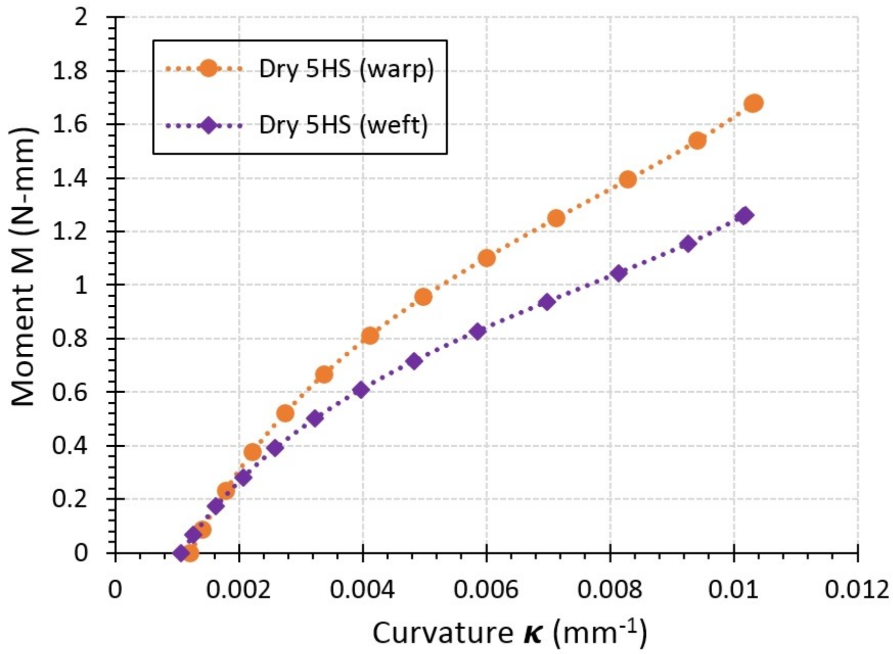

Figure 5. The difference between warp and weft directions in dry 5HS.

3.2 Prepreg vs. dry samples

A room-temperature comparison between the prepreg sample and the dry sample can indicate the contribution of resin to the bending results. The results of this comparison, shown in Figure 6, reveal a significant difference between the obtained bending moments in prepreg and dry samples: the maximum bending moment in the prepreg sample was 4.816 N-mm, versus 1.681 N-mm in the dry sample. It was expected that the difference between the maximum bending moment of the prepreg sample and the dry one is related to the resin content, which is 36% of the prepreg sample's weight. However, the observed difference in maximum bending moment between the two materials is much larger than that: about a factor of 3. Thus, the uncured resin has a significant impact in the outcomes more than the fabric and its style.

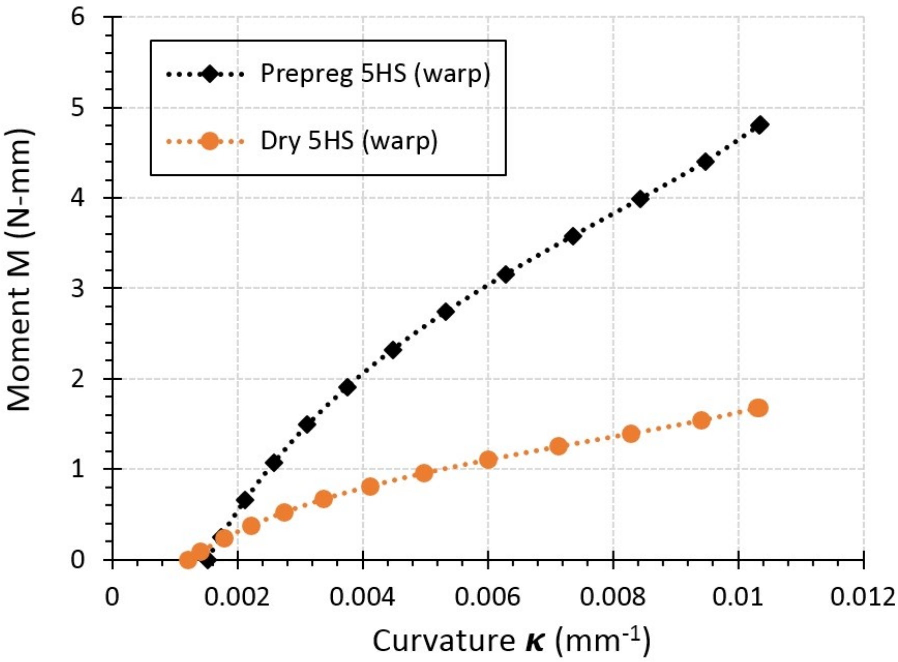

Figure 6. The difference between prepreg and dry samples in warp direction.

3.3 Consolidated vs. unconsolidated samples

The bending properties would also be expected to depend in part on the state of consolidation of the prepreg, especially during the double-diaphragm forming; pre-heating within a vacuum necessarily causes some degree of consolidation. The experimental approach described above was carried out to measure the bending behavior of the consolidated sample under conditions relevant to double-diaphragm forming. One ply of OOA prepreg was consolidated at 70 °C with a pressure of 0.1 MPa using vacuum bagging for 30 minutes. The consolidated sample was then cut to the same dimensions as the unconsolidated samples with respect to warp direction. The evacuation of entrapped air caused by the applied pressure reduced the measured average thickness of the consolidated sample to 0.49 mm. The bending moments and the corresponding curvatures for consolidated and unconsolidated samples, tested at room temperature and 3 mm/sec, are given in Figure 7. A notable increase in the bending stiffness of the consolidated sample was observed (almost 17%). In this context, the increase in the bending stiffness is attributed to the change in the degree of curing, as well as the increase in fiber volume fraction. Based in our measurements, the fiber volume fraction prior to consolidation was about 43.53%, versus 48.44% in the consolidated sample. Note also that the OOA prepreg microstructures underwent impregnation during consolidation; see Centea and Hubert [9] for further details.

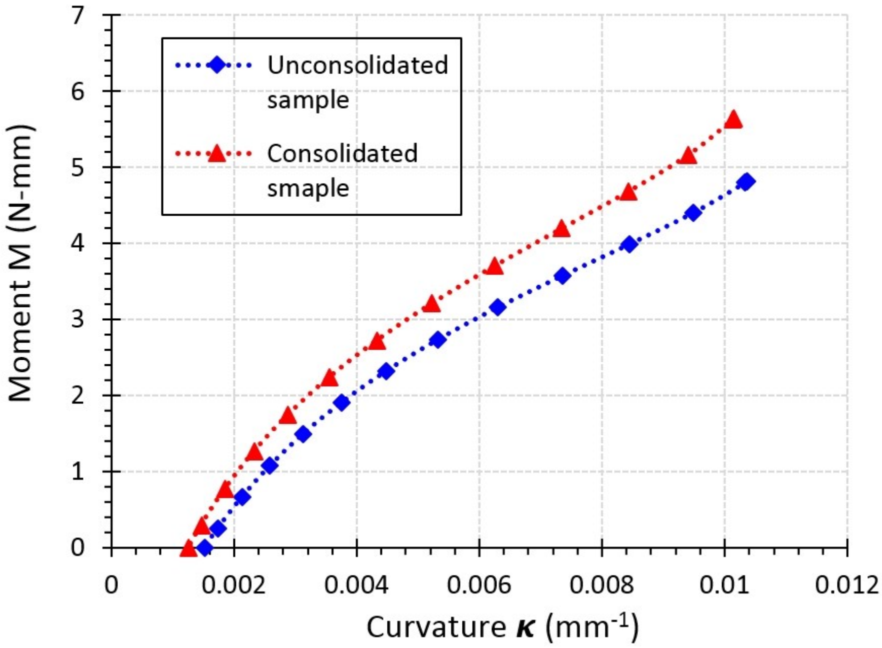

Figure 7. Bending moment versus curvature for consolidated and unconsolidated samples (warp-face 1).

3.4 Viscoelastic behavior

The viscoelastic behavior of 5HS prepregs during bending was investigated by measuring the stress-relaxation response of the cantilever. In the proposed test, the sample can be loaded to a specific tip displacement and then held in that position. Stress-relaxation tests were performed for a tip displacement of 50 mm and held in position for 5 minutes. Figure 8 shows the bending moment as a function of time for warp prepreg samples, tested at room temperature with a load rate of 3 mm/sec. The load value decreased from 0.042 to 0.031 N in the first 50 seconds but had only decreased to 0.025 N after 200 sec. Upon load removal, all samples showed a decrease in displacement, but none returned fully to their original position. Thus, stress relaxation yielded a non-reversible displacement and a slight curved shape for all samples. Multiple tip displacements and temperatures should also be tested to further understand the relaxation behavior of selected materials.

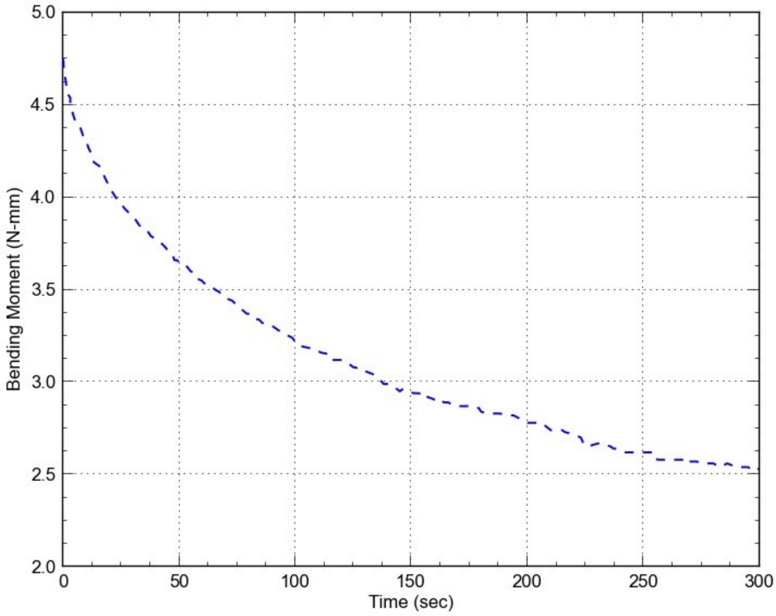

Figure 8. Relaxation of 5HS prepreg sample (warp) recorded at room temperature.

4 CONCLUSION

Investigations of out-of-plane bending behavior of satin woven carbon/epoxy prepregs were assessed across different sample configurations and conditions. The results revealed that bending stiffness is approximately 20% higher in the warp direction than in the weft direction. This distinction should be considered during future forming simulation inputs. The uncured resin has a significant impact in the outcomes more than the fabric and its style. Therefore, it is essential to assess temperature and rate effect during the bending experiments. To determine the correct parameter values to set during the simulation process, the bending stiffness as a function of consolidation state, relevant to the applied forming process, must be known. Investigation of viscoelastic behavior may help in the selection of an appropriate mathematical model to predict the behaviors of viscoelastic materials in future work.

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