INVESTIGATION OF SHEAR-BENDING COUPLED PROPERTIES IN COMPOSITE PREPREG FORMING

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ABSTRACT

The success or failure of composite formation is determined by the balance between deformation mechanisms that occurred during the forming process. Several deformation mechanisms, of which the most common are intra-ply shearing, out-of-plane bending, and inter-ply sliding, are involved in forming of the laminate to the desired shape. However, these deformation mechanisms during the actual forming process are coupled. This implies that the prepreg ply is subjected to shear and bending deformation at the same time as well as shear and tension. Consequently, this paper aims at studying the coupling effect of shear on bending properties at prepreg forming conditions. The out-of-autoclave (OOA) prepreg chosen for this study consist of a 5-harness (5HS) satin weave impregnated with an epoxy resin (Cycom 5320). To investigate such coupling properties, a three-step experiment is undertaken. First, the prepreg samples are pre-consolidated under conditions relevant to double diaphragm forming; next, these samples are tested using bias extension test at different shear angle values. Finally, the bending experiments are performed on the sheared-samples by a new test methodology in which the sample is clamped vertically while deflection shape and applied load are controlled by a linear actuator and a miniature-load cell, respectively. The experimental results show that the bending behavior of pre-deformed samples varies with the degree of shear angles.

1. INTRODUCTION

During the complex shapes forming process of the continuous fiber-reinforced composites, various mechanisms must occur to produce a high quality product. The understanding of these mechanisms is essential in reducing the failure rates of the composite parts and predicting the potential processing problems. There are three main key mechanisms: intra-ply shearing, out-of-plane bending, and inter-ply sliding [1] . Intra-ply shear is a mechanism that occurs when the material is subjected to in-plane shear. For UD fiber-reinforced composites, the shear mechanism entails parallel movement along the length of adjacent fibers. Whilst, the deformation is characterized by a change of fiber orientation, due to rotation of the yarns at their crossovers for woven reinforcements [1]. However, for thick layers, through the thickness becomes a significant deformation mode. The intra-ply shear of woven reinforcements under conditions of bias extension or picture frame test has been investigated experimentally and numerically by many researchers [2]–[6]. In a bias extension test, the material is extended along the bias direction initially at ±45^o to the direction of applied tensile force. The advantage of this test is that it needs no special equipment and can be performed on any tensile machine.

In order to accurately predict defects, such as wrinkling, that may arise during composite material forming processes, the bending properties of the prepreg, including their temperature and rate dependencies, must be known and properly represented in the finite element model to achieve useful simulation results [7]–[10]. However, the bending characterization and modeling of composite prepreg have received little attention in the literature compared to intra-ply shear and inter-ply friction. Some test methods have developed to measure the out-of-plane bending properties of prepreg composites [10]–[15]. For a comprehensive review of proposed bending tests towards prepreg composites, the reader is referred to [15].

These deformation mechanisms during the actual forming process are coupled. This implies that the prepreg ply is subjected to shear and bending deformation at the same time as well as shear and tension. Consequently, it is an important consideration to study the combined shear-bending properties. To date, there is no available test can accommodate the characterization of these combined properties. However, this paper presents a procedure in which the coupling effect of shear on bending properties at prepreg forming conditions can be investigated. The relationship between the shear angle and bending stiffness is also considered.

2. EXPERIMENTAL METHODOLOGY

2.1 Materials

The out-of-autoclave prepreg selected for this study was the 5-harness satin woven carbon/epoxy from Cytec Engineered Materials. The resin code is (Cycom 5320) toughened epoxy and the fabric has 6K fibers per tow. The fabric areal weight is 380 g/m^2 and the resin content is 36% by weight. The measured thickness of pre-consolidated one-ply is approximately 0.49 mm. From these properties, the fiber volume fraction can be calculated as

$$V_f = \frac{N M_f}{\rho_f h} \tag{1}$$

where M_f is the areal density of the fabric (kg/m^2), N is the number of plies, h is the ply thickness (m), and ρ_f is the density of carbon fiber (kg/m^3). Hence, fiber volume fraction is about 48.5%.

2.2 Pre-consolidation process

The shear and bending properties would 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 was carried out to measure the combined shear-bending properties 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, as shown in Fig. 1. The vacuum bag-only (VBO) consolidation process of OOA prepreg includes air evacuation, fiber bed compaction, and resin flow. Once vacuum is applied, trapped air is evacuated through the dry tows, the void content decreases, and the fiber bed is compacted. The pre-consolidated sample was then cut to the bias extension specimen dimensions, which is 150 mm long by 50 mm wide with an un-gripped length of 100 mm.

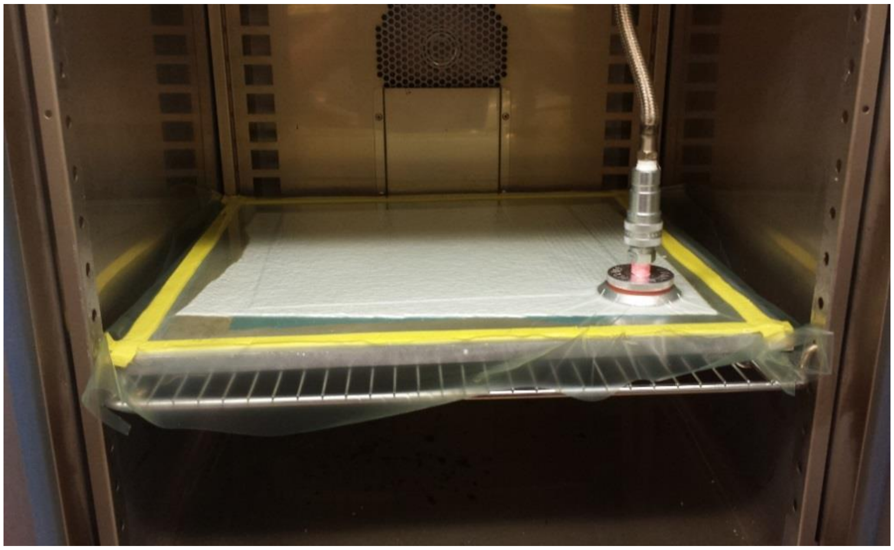

Figure 1: Pre-consolidation process at conditions relevant to double diaphragm forming

2.3 Bias extension test

Bias extension test is implemented to characterize the shear behavior of fabric. The specimen for the bias extension test divided into three zones, as depicted in Fig. 2. In order to obtain a uniform deformation in zone A, the specimen's length *L* must be equal to or greater than twice its width *W*. The specimens were cut where their fiber direction (warp and weft) set at ±45º to the direction of applied tensile force. The initial angle θo is 45º, while the final angle θ can be deduced from the specimen geometry as shown in (Eq. 2).

$$\theta = \arccos\left(\frac{D+d}{\sqrt{2}D}\right) \tag{2}$$

The shear angle γ in the bias sample can be calculated as

$$\gamma = 90 - 2\theta \tag{3}$$

To deform the sample to a desired shear angle, different axial displacements, such as 5, 10, 15 mm and so forth, were set during the bias extension test. Note that the sample was kept for 10 minutes at selected displacement to minimize the recovery effect. However, the shear angle on the deformed sample needs to be measured again before the bending experiment to confirm the shear angle value as shown in Fig. 3. Tests were carried out at cross-head rate of 20 mm/min and at room temperature. For each angle, at least two samples were tested to explore repeatability.

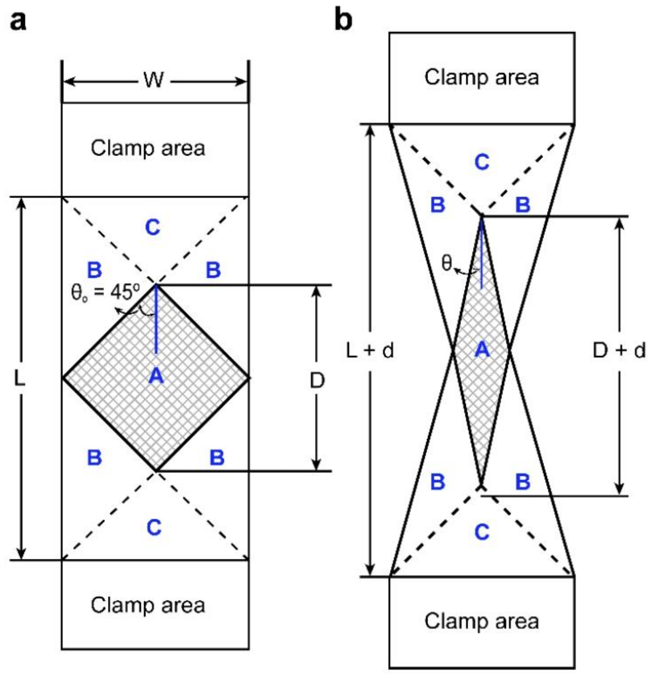

Figure 2: Bias extension test: (a) initial specimen, (b) deformed specimen [6]

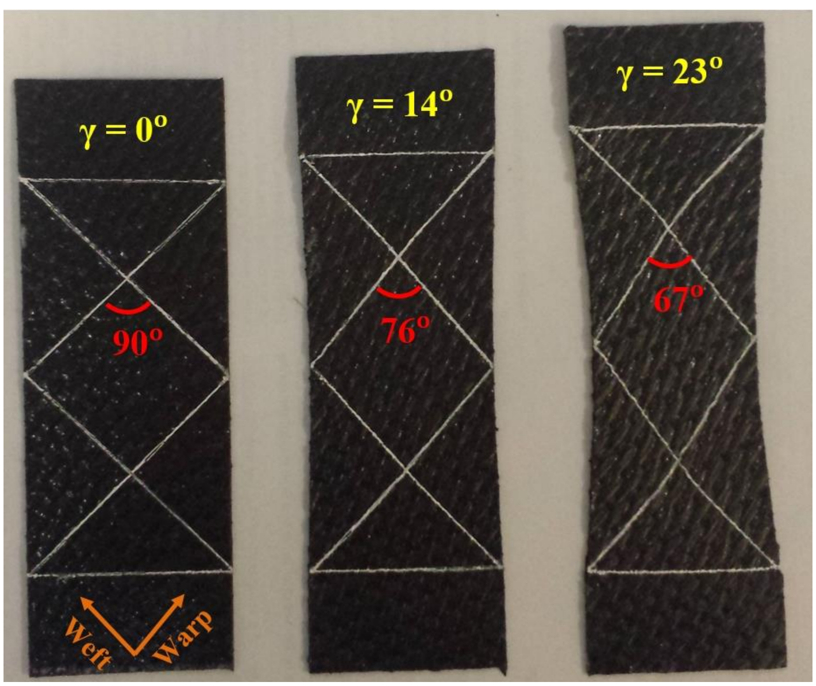

Figure 3: Measured shear angle on selected samples before bending test

2.4 Bending test

The bending behavior of woven fabric out-of-autoclave prepregs is carried out using a special bending test setup developed in a previous study [15]. 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 4. 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 30 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. This bending experiments were performed on all the sheared-samples obtained from bias extension test as described above.

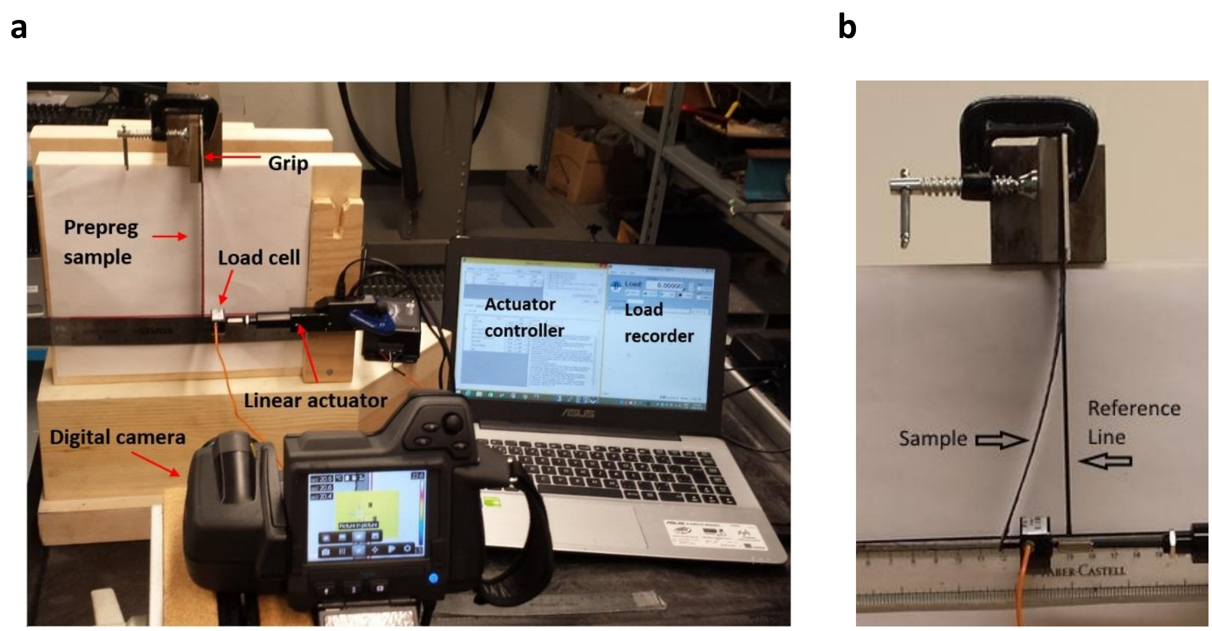

Figure 4: Bending test for prepreg characterization purposes: (a) test setup, (b) bent sample

3. RESULTS AND DISCUSSION

3.1 Sample orientation effect on bending properties

First, the [45°] sample (un-sheared bias extension sample) was compared with the [0°] sample respect to warp direction. The warp direction is perpendicular to the applied load during the bending experiments. Fig. 5 shows the moment-curvature curves for both samples. The results showed that a major difference in terms of bending resistance responses was observed when the sample is tested with [0°] and [45°] orientations. The bending stiffness of [0°] sample is about 498 N.mm^2, while the [45°] sample 322 N.mm^2 in [45°] sample; a reduction of 35.34 %. This is turned out that the formed part quality is also dependent on start angle orientation with respect to the applied forming loads during forming operation. Note that the selected materials are also sensitive to which face is in tension and which is in compression during bending experiment. This is due to that in a 5HS woven fabric, 80% of the fibers on one face are in the strip-long direction, whereas 80% of the fibers on the other face are perpendicular to that direction. In this study, only one face was tested for all selected samples; see Ref. [15] for more details.

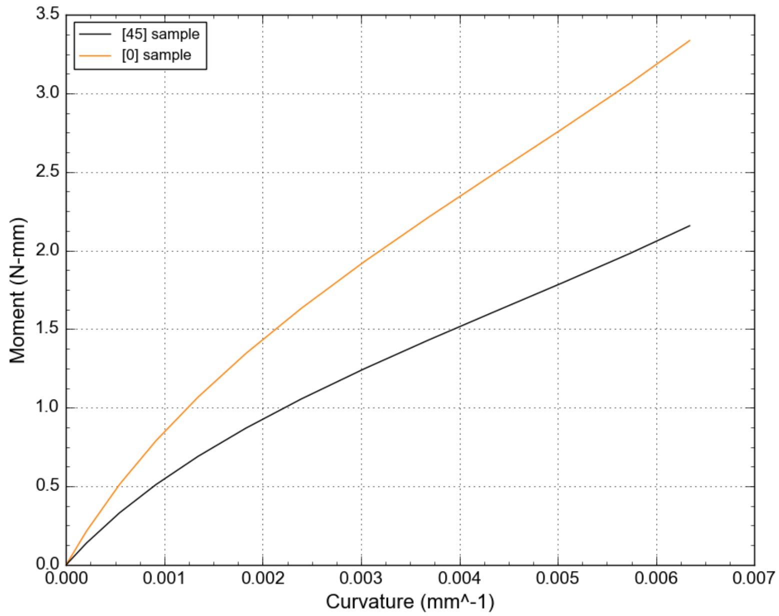

Figure 5: Moment-curvature curves for [45] and [0] samples respect to the applied bending load

3.2 Un-sheared vs. sheared samples

Fig. 6 shows the moment-curvature curves for un-sheared bias extension sample (shear angle = 0°) and sheared sample (shear angle = 51°). The results showed that the bending stiffness increases significantly as the shear angle increases. The bending stiffness is 322 N.mm^2 for un-sheared sample, versus 386 N.mm^2 in the sheared sample (γ= 51°). It should be noted that the length of sheared sample is larger than the length of un-sheared sample due to deformation. However, the width is also decreased and the thickness tends to increase as shown by [6]. The variation in thickness is an important consideration during textile forming process that must be included in the forming prediction analysis. Moreover, the deflection shape will change as the sample's length changes, which is affecting the curvature values. Therefore, the original length of the sample was used to calculate the bending moment under the constant volume assumption. This implies that only the load required to achieve the specified displacement is considered to calculate the bending moment.

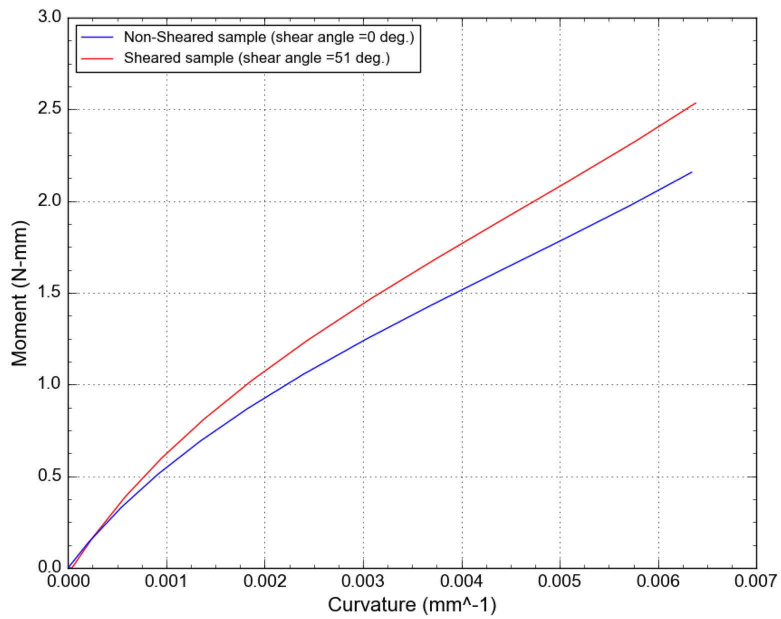

Figure 6: Moment-curvature curves for un-sheared and sheared samples

3.3 Effect of shear angle on bending stiffness

Following the procedure mentioned above, the bending stiffness was obtained for different shear angle samples as shown in Fig. 7. It can be seen that a relatively small change was noticed in bending stiffness at a smaller shear angle (up to about 15º). However, the bending stiffness values were increased rapidly along with the shear angles after this stage. This is attributed in fact to that the adjacent yarns after the shear angle of 15º become in contact with each other during the shear deformation. The deformation continues until the shear angle between weft and warp becomes locked. At this stage, the shear stiffness increases as the adjacent yarns start to compress each other. Thus, the bending stiffness tends to significantly increase. To calculate the bending stiffness as a function of shear angle, shown in Fig. 7, a fifth degree polynomial approximation was used as

$$Bs(\gamma) = a_0 + a_1\gamma + a_2\gamma^2 + a_3\gamma^3 + a_4\gamma^4 + a_5\gamma^5 \tag{4}$$

The coefficients in Equation 4 were obtained by the polynomial regression fitting procedure. Hence, Equation 4 becomes as follows:

$$Bs(\gamma) = 322.17 + 0.904\,\gamma - 0.109\,\gamma^2 + 5.95e^{-3}\,\gamma^3 - 9.44e^{-5}\,\gamma^4 + 4.45e^{-7}\,\gamma^5 \tag{5}$$

The change in bending stiffness followed a fifth degree polynomial approximation with the shear angle in the selected samples (see Fig. 7). This fit was sufficient for estimating the bending stiffness as a function of shear angles investigated in this study. However, future work should be conducted on different woven fabrics using a wide range of sheared samples. This would be an interesting direction to develop a predictive bending model as a function of the degree of shear, as these appear in the real forming process. It should be noted that the complex boundary conditions and other deformation modes occurred during the forming process may contribute to the bending stiffness values differently, especially when the friction comes to play for multilayered parts. Moreover, the tests should be performed for both sample faces in the satin fabric due to asymmetrical nature about its middle plane. Accordingly, a numerical study using the combined shear-bending properties can be compared with those obtained from each separate test to justify its effect on the forming simulation outcomes. Additionally, the contribution of transverse intra-ply shear to the bending behavior needs to be determined and explored through the finite element implementation for thick samples.

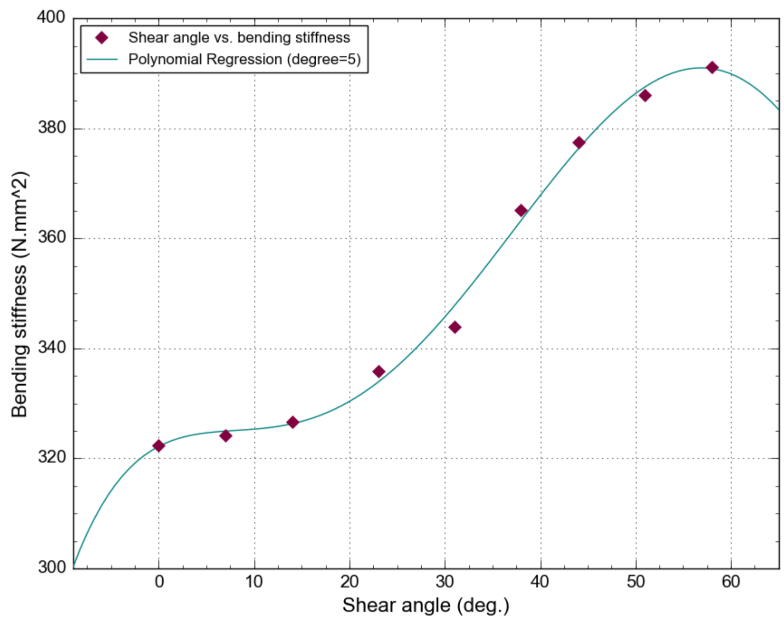

Figure 7: Bending stiffness values at different shear angles

4. CONCLUSION

The current study explored the coupling effect of shear on bending properties during prepreg forming process. The relationship between the shear angle and bending stiffness was also investigated. First, this study demonstrated that the bending properties of selected materials depend strongly on the sample orientations, as the different results between [0°] and [45°] samples reveal. The results also showed that the bending stiffness increases significantly as the shear angle increases. However, a relatively small change was observed in bending stiffness at a smaller shear angle (up to about 15º). The change in bending stiffness followed a fifth degree polynomial approximation with the shear angle investigated in this study. Future work should be conducted on different woven fabrics using a wide range of sheared samples. Moreover, the tests should be performed for both sample faces in the satin fabric due to asymmetrical nature about its middle plane.

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