World Academy of Science, Engineering and Technology
International Journal of Materials and Metallurgical Engineering
Vol:10, No:2, 2016

Out-of-Plane Bending Properties of Out-of-Autoclave Thermosetting Prepregs during Forming Processes

Hassan A. Alshahrani, Mehdi H. Hojjati

***Abstract*—**In order to predict and model wrinkling which is caused by out of plane deformation due to compressive loading in the plane of the material during composite prepregs forming, it is necessary to quantitatively understand the relative magnitude of the bending stiffness. This study aims to examine the bending properties of out-of-autoclave (OOA) thermosetting prepreg under vertical cantilever test condition. A direct method for characterizing the bending behavior of composite prepregs was developed. The results from direct measurement were compared with results derived from an image-processing procedure that analyses the captured image during the vertical bending test. A numerical simulation was performed using ABAQUS to confirm the bending stiffness value.

***Keywords*—**Bending stiffness, out of autoclave prepreg, forming process, numerical simulation.

I. Introduction

SEVERAL deformation mechanisms come into play during the forming of composite prepregs to a desired shape, including intra-ply shear, inter-ply friction, and out-of-plane bending. When deformation occurs through any of these mechanisms, defects in the material may arise, leading to failure rates among the resulting composite parts. In order to reduce the chance of failure, therefore, a thorough understanding of these mechanisms is necessary [1]. Among the possible defects that occur during composite forming, wrinkling is particularly common [2]. Some studies in this area have shown that locking angle cannot be the only factor involved in the onset of wrinkling [3]–[5]. According to [6], an increase in bending stiffness leads to wrinkle reduction. While all three deformation mechanisms are important for an accurate prediction of wrinkling, only intra-ply shear and inter-ply friction have received significant attention in the literature; by contrast, out-of-plane bending of prepreg composites has been largely ignored.

Wrinkling occurs when compressive loading in the plane of the material causes out-of-plane deformation. An important factor in this process is the relative magnitude of the bending stiffness. In order to obtain appropriate forming simulation results, it is essential that the bending stiffness magnitudes be represented correctly in the finite element model. Several test methods have been developed to measure the out-of-plane bending properties of dry reinforcement and prepreg composites; the main methods applied to prepreg composites are listed in Table I. However, none of the current bending test methods manage to maintain affordability while also allowing for sufficient control of the testing parameters and the applied load.

Soteropoulos et al. [12] and Dangora et al. [13] introduced a new test design in which samples are hung vertically in order to avoid twists (which may otherwise arise due to non-linear loading effects in the cantilever setup). In their setup, masses were attached to a string tied to the tip of the sample. A digital camera was then used to capture the relative displacement of the sample under each load. Next, the digital image was graphically processed to generate data points along the sample length. To date, this method has not been applied under processing temperature conditions and has not been tested with prepreg materials.

TABLE I
Test Methods Developed to Determine Out of Plane Bending Properties of Prepreg Composites

Ref.	Method	Temperature (°C)	Rate control	Material
Liang et al. [7]	Cantilever test + thermal chamber	Up to 600	No	5HS satin thermoplastic prepreg
Martin et al. [8]	V-bending test + thermal chamber	Up to 170	Yes	UD thermoplastic prepreg
Wang et al. [9]	Buckling test	Up to 150	Yes	UD thermosetting prepreg
Ten Hove [10]	Rheometer + thermal chamber	Up to 450	Yes	UD thermoplastic prepreg
Margossian et al. [11]	DMA system	Up to 260	Yes	UD thermoplastic prepreg

The present study proposes a direct method, based on the vertical cantilever test, to measure the bending behavior of composite prepregs. In particular, the bending stiffness of woven fabric thermosetting prepreg was measured at room temperatures. Obtained results from direct measurement were then compared with image-processing results generated along the sample length.

II. Test Method

The material tested in this study was the 5-harness (5HS) satin carbon/epoxy woven-fiber prepreg, toughened with epoxy resin (Cycom 5320) designed for out-of-autoclave manufacturing applications. The fabric’s areal weight is 380

H. Alshahrani is with the Concordia Center for Composites, Concordia University, 1455 De Maisonneuve Blvd. W., Montreal, Quebec, H3G1M8, Canada (phone: +1514-660-8871; e-mail: eng0880@hotmail.com).

M. Hojjati is with the Concordia Center for Composites, Concordia University, 1455 De Maisonneuve Blvd. W., Montreal, Quebec, H3G1M8, Canada (e-mail: mehdi_hojjati@concordia.ca).

g/m^2 and the resin content is 36% by weight. The measured thickness of uncured one-ply is approximately 0.55 mm. Fig. 1 shows the vertical cantilever setup and the test principles.

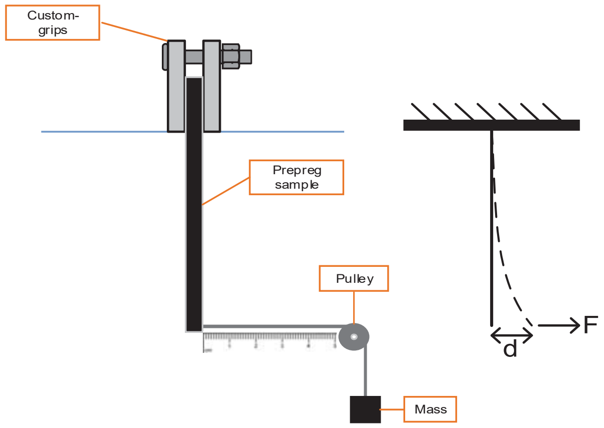


Fig. 1 Vertical cantilever bending test setup

First, the sample was clamped vertically and masses were attached; the resulting application of horizontal force on the sample produced tip displacement. Images of the bent shape, captured by a digital camera, were processed in ImageJ software to determine the deflection profile, which was subsequently fitted by proper polynomial functions. From the obtained polynomial fit, the curvature of the profile was calculated using (1). The value of the recorded load was used to calculate the moment at each selected point. Once calculated, these data points were used to describe the bending stiffness: this stiffness, corresponding to the slope of the linear trend, is derived by plotting the moment at each point against the corresponding curvature values.

$$\kappa = \frac{x''}{(1+x'^2)^{3/2}} \tag{1}$$

A direct measurement was made by assessing the measured load during the vertical cantilever test and the maximum tip deflection that occurred. The bending stiffness (B_S) was then calculated by using the maximum deflection equation for the cantilever beam with a concentrated load at the free end. Assuming that the load remains horizontal and the sample length does not change, bending stiffness can be calculated as:

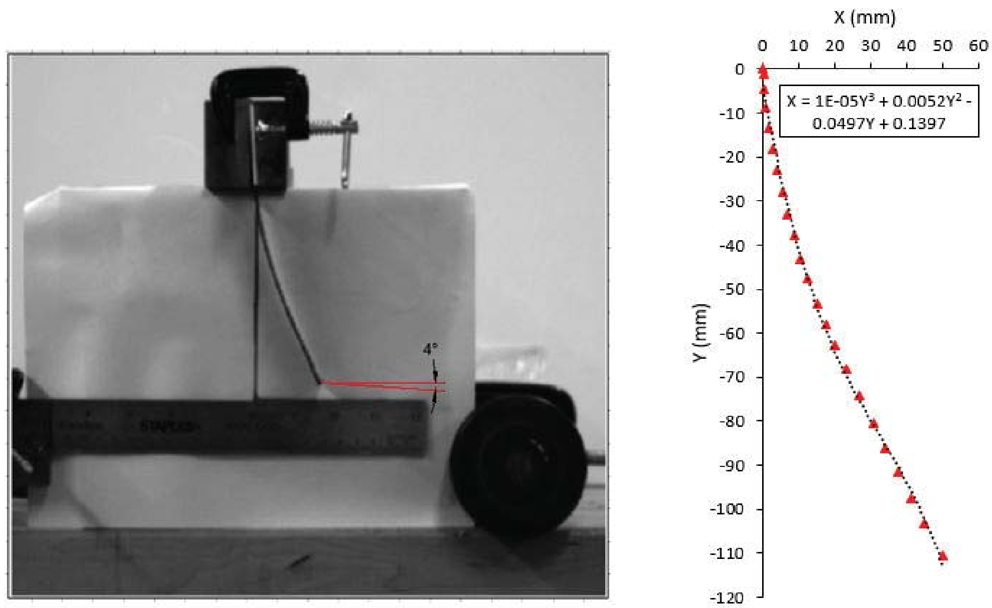
$$B_s = \frac{FL^3}{3d} \tag{2}$$

where F is the measured load during vertical cantilever test, L is the sample length, and d is the tip displacement.

III. Results and Discussion

A. Experimental Work

The samples selected for this test were 50 mm wide with an un-gripped length of 120 mm. Fig. 2 (a) shows the test setup and bent shape of the sample up to a tip displacement of 50 mm. The captured image was processed to generate data points along the sample length. Fig. 2 (b) shows the profile of the bent sample and the polynomial fit used to calculate the curvature per (1). The bending moment of 5HS (warp) along the sample length was calculated and plotted in Fig. 3. The moment at each selected point and the corresponding curvature values were plotted and fitted by a linear trend, as shown in Fig. 4. The slope of this linear trend represents the bending stiffness value.



(a) (b)

Fig. 2 Bending profile with tip displacement of 50 mm, (a) test setup and bent shape, and (b) data points along the sample length

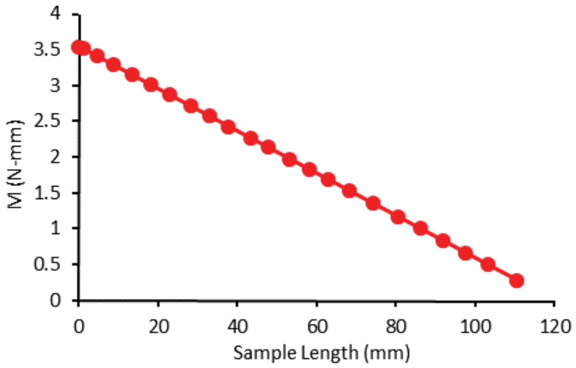


Fig. 3 Calculated moment along the sample length

Two different trials were made at each condition, and the average among these values was calculated. All results that extracted from image-processing procedure and calculated using (2) are summarized in Table II. The bending stiffness of 5HS (warp), based on image-processing (slope), at room temperature with tip displacement of 50 mm is 348.97 N-mm^2 (see Fig. 4), versus 340.3008 N-mm^2 using the proposed direct measurement. A good agreement between image-processing and direct measurement was observed for all obtained results. Note, however, that care must be taken when extracting data points during the image-processing procedure. The results show that the bending stiffness in the warp direction is higher than in the weft direction. This distinction is attributed to the fact that the warp is straighter than the weft (lower number of crimps) and is subjected to more stress during weaving. Therefore, it is hypothesized that alignment of the warp direction to the tool during the diaphragm-forming process is facilitated wrinkle reduction, especially for L-shapes. However, this observation requires further investigation for other tool geometries.

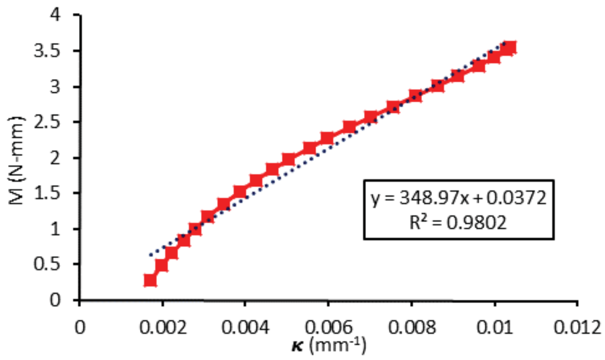


Fig. 4 The moment versus curvature with linear fit

In the present experiment, the bending stiffness value was confirmed by repetition of the method under various tip displacements (50 and 20 mm). The difference in image-processing bending stiffness values between a tip displacement of 50 mm and a tip displacement of 20 mm was found to be small — approximately 2.5% and 6.3% for the 5HS (warp) and 5HS (weft), respectively. This indicates that the vertical bending test offers acceptable repeatability of results. However, error percentage can be further decreased by replacing manual measurement with a more accurate load-measuring method. Thus, in future work, it is planned to integrate the proposed setup with a micro-load cell to improve result accuracy. Moreover, it should be noted that the variation between image-processing and direct measurement values decreases as the tip displacement descends from 50 to 20 mm. For example, in the 5HS (weft) sample with tip displacement of 50 mm at room temperature, the difference was nearby 2.35%, compared to a 1.36% difference under 20 mm displacement. This discrepancy is attributed to the fact that the equation used to calculate maximum deflection of the cantilever beam assumes a small deformation. As noted above, the load in this case was assumed to be horizontal during the test; the greater the tip displacement in the sample, the less accurate this assumption is. For the sample with 50 mm tip displacement, an inclined angle of 4° from horizontal was observed, thus increasing the discrepancy between the image-processing and direct measurement values.

B. Numerical Simulation

The bending test was simulated as part of a finite element analysis using shell elements (S4 in ABAQUS). Experimental loads were applied progressively to the model in order to achieve an accurate replication of the experimental profile shape of the sample. The correct bending stiffness value (defined as the moment required for imparting a unit curvature M/κ) was confirmed by an iterative process in which the bending stiffness in the finite element model is varied until the tip displacement matched the experimental value (50 mm) as shown in Fig. 5. Bending stiffness was given in N-mm^2 in ABAQUS. It was found that value of 416.66 for 5 HS prepreg warp and 321.875 for 5 HS prepreg weft gave good agreement between the model and the experiment.

While this approach offers a quick method for determining bending stiffness, note that it does depend on numerical curve fitting. Therefore, in order to successfully integrate bending stiffness into the FEM forming simulation model, the bending stiffness must be decoupled from the in-plane properties in standard elements.

TABLE II
RESULTS FROM IMAGE-PROCESSING AND PROPOSED DIRECT MEASUREMENT AT SELECTED CONDITIONS

Sample	Tip displacement (mm)	Testing temperature (°C)	Measured Load (N)	Bending stiffness (N-mm^2)	
				Image-processing (slope)	Direct measurement (2)
5HS (warp)	50	RT	0.02954	348.97	340.3008
5HS (weft)	50	RT	0.02228	262.72	256.6656
5HS (warp)	20	RT	0.01162	339.74	334.6561
5HS (weft)	20	RT	0.00846	246.95	243.648

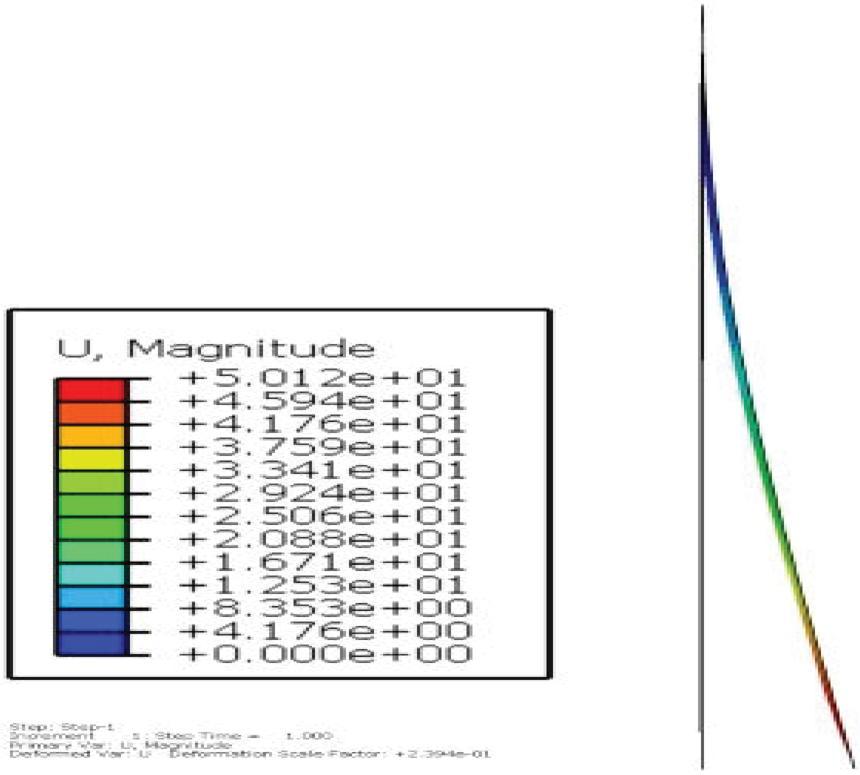


Fig. 5 The FEA results using shell element (S4 in ABAQUS)

IV. Conclusion

The present study reports on the development of a direct method for measuring the bending stiffness of composite prepregs based on a vertical cantilever test. The results derived from this direct method were compared with results from an image-processing procedure. A good agreement between image-processing and direct measurement was observed for all obtained results. The value of bending stiffness was confirmed by repetition of the method under various tip displacements. The vertical bending test is a promising method to characterize the bending properties of prepreg composites due to that sufficient control of the testing parameters and the applied load to avoid twisting can be achieved.

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. Supporting provided by Najran University is also gratefully acknowledged.

References

[1] J. S. Lightfoot, M. R. Wisnom, and K. Potter, “Defects in woven preforms: Formation mechanisms and the effects of laminate design and layup protocol,” *Compos. Part A: Appl. Sci. Manuf.,* vol. 51, pp. 99–107, Aug. 2013.

[2] A. C. Long, Ed., *Composites Forming Technologies*. Richmond: Taylor & Francis, 2007, pp. 1–328.

[3] P. Boisse, N. Hamila, E. Vidal-Sallé, and F. Dumont, “Simulation of wrinkling during textile composite reinforcement forming. Influence of tensile, in-plane shear and bending stiffnesses,” *Compos. Sci.,* vol. 71, pp. 683–692, Mar. 2011.

[4] H. Alshahrani and M. Hojjati, “Optimum processing parameters for hot drape forming of out-of-autoclave prepreg over complex shape using a double diaphragm technique,” in *Proc. 20th ICCM Conf.*, Copenhagen, Denmark, 2015.

[5] H. Alshahrani, R. Mohan, and M. Hojjati, “Experimental investigation of in-plane shear deformation of out-of-autoclave prepreg,” *Int. J. Compos. Mater.* vol. 5, pp. 81–87, May 2015.

[6] S. P. Haanappel, R. H. W. ten Thije, U. Sachs, B. Rietman, and R. Akkerman, “Formability analyses of uni-directional and textile reinforced thermoplastics,” *Compos. Part A: Appl. Sci. Manuf.,* vol. 56, pp. 80–92, Jan. 2014.

[7] B. Liang, N. Hamila, M. Peillon, and P. Boisse, “Analysis of thermoplastic prepreg bending stiffness during manufacturing and of its influence on wrinkling simulations,” *Compos. Part A: Appl. Sci. Manuf.,* vol. 67, pp. 111–122, Dec. 2014.

[8] T. A. Martin, D. Bhattacharyya, and I. F. Collins, “Bending of fibre-reinforced thermoplastic sheets,” *Compos. Manuf.,* vol. 6, pp. 177–187, 1995.

[9] J. Wang, A. Long, and M. Clifford, “Experimental measurement and predictive modelling of bending behaviour for viscous unidirectional composite materials,” *Int. J. Mater. Form.,* vol. 3, pp. 1253–1266, Sept. 2010.

[10] C. H. Ten Hove, “Bending of CF/PEEK prepregs,” Master’s Thesis, University of Twente, 2012.

[11] A. Margossian, S. Bel, and R. Hinterhoelzl, “Bending characterisation of a molten unidirectional carbon fibre reinforced thermoplastic composite using a Dynamic Mechanical Analysis system,” *Compos. Part A: Appl. Sci. Manuf.,* vol. 77, pp. 154–163, Oct. 2015.

[12] D. Soteropoulos, K. Fetfatsidis, J. A. Sherwood, and J. Langworthy, “Digital method of analyzing the bending stiffness of non-crimp fabrics,” in *AIP Conf. Proc.*, Belfast, 2011, pp. 913–917.

[13] L. M. Dangora, C. J. Mitchell, and J. A. Sherwood, “Predictive model for the detection of out-of-plane defects formed during textile-composite manufacture,” *Compos. Part A: Appl. Sci. Manuf.,* vol. 78, pp. 102–112, Nov. 2015.