Int J Mater Form (2008) Suppl 1:895–898
DOI 10.1007/s12289-008-0240-8

Bias-extension of woven composite fabrics

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ABSTRACT: Woven-fabric reinforced composites have gained a significant attention from both industrial and academic fields, due to their high specific strength and stiffness as well as their supreme formability characteristics. In this work, the challenges in woven composites forming, from material variations, experimental material characterization methods to numerical modeling is reviewed and results on material shear behavior from bias-extension tests are presented. Three different types of fabrics (plain, balanced twill, and unbalanced twill weaves) were tested using various aspect ratios. From force-displacement curves, shear angles and normalized shear forces were theoretically determined and test data from different aspect ratios were compared with each other. Additionally, real-time shear angles were measured using the IcaSoft image correlation software developed at INSA-Lyon and compared with manually measured shear angles.

Key words: Woven fabric composites, material characterization, bias-extension tests, image correlation

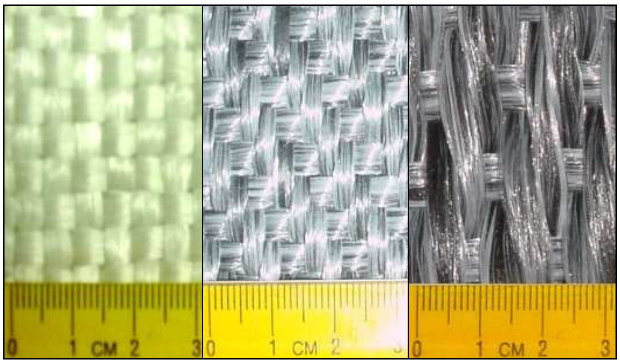
1 INTRODUCTION

Woven-fabric reinforced composites (hereafter referred to as woven composites) have attracted a significant amount of attention from both industry and academia, due to their high specific strength and stiffness as well as their supreme formability characteristics. These materials have been utilized in the aerospace industry and showed the potential in automotive industry through a thermo-stamping process.

The objective of this work was to gain a better understanding of the material properties of woven glass fabrics and how to best determine and predict their shear angle properties when subjected to tensile bias testing. The commingled fiber glass-polypropylene woven composite materials were considered in this work and the materials were donated by Vetrotex Saint-Gobain.

As shown in figure 1, three different types of fabrics - plain weave, balanced twill, and unbalanced twill - were tested and various aspect ratios were considered. During the bias-extension tests, force, displacement, and image data were collected. Shear angles at various points in the test procedure were determined theoretically. In addition, when the optical images were taken, shear angles were determined through the image correlation software, IcaSoft, and by manual measurements.

The work was a joint effort among researchers of various institutions. Through the international collaborative work, experimental material characterization methods were analyzed to better understand and predict the behavior of formed mechanical parts.



Plain weave Balanced twill Unbalanced twill

Fig. 1. Woven fabrics

2 EXPERIMENTAL CHARACTERIZATION

The research involved the testing of three woven composites and how they were sheared during bias extension testing. The bias extension test is used to determine the nonlinear shear stiffness of woven composites in pure shear. Samples of each of the three fabrics were tested in tension using a tensile machine. In order to measure the samples in pure shear, both the balanced and unbalanced weaves were prepared in such a condition that the yarns ran at ±45° with respect to the fixed ends.

The sample sizes also varied but in order to obtain a large area of pure shear the ratio of length (along the tensile direction) to width should be equal to or greater than 2:1. The longer samples included a larger area of material tested in pure shear, while the wider samples had more material that was not along the edges of the samples. Table 1 lists the sample sizes used in this work. All tests were performed at room temperature and the speed was 10mm/min. The prepared sample is placed in a tensile machine with a load cell for measuring the deformation force attached to the bottom clamp as shown in figure 2.

Table1. Sample size and process condition used in the bias extension tests

Materials	Length (in mm)	Width (in mm)
Plain weave	230	115
	300	150
	450	150
Balanced twill weave	300	150
	300	100
	450	150
Unbalanced twill weave	400	200

Fig. 2. Bias-extension test setup with image processing tools at INSA-Lyon

During the bias test the machine moves at a constant displacement while recording the force and displacement. Also included in the testing setup is a camera for image capture. The images recorded during testing can be either global or local. For recording local images the camera can be placed on an apparatus which moves vertically in sync with the tensile machine. Synchronized force, displacement and images of the fabric sample were recorded for post-processing.

3 METHODS OF SHEAR ANGLE MEASUREMENTS

Once the test is complete there are three main ways to determine the shear angle of the material during the test. The first method calculates the shear angle using the theoretical equation based on the kinematic analysis of the bias-extension test.

The bias extension test involves clamping a rectangular piece of woven material such that the warp and weft directions of the tows are orientated initially at ±45° to the direction of the applied tensile direction [1]. When the initial length of the sample (L_0) is more than twice the width of the sample (w_0), there exists a perfect pure shear zone in the center of a sample (zone C in figure 3). It has been shown [2] that the shear angle in region C can be assumed to be twice that in region B, while region A remains un-deformed assuming yarns being inextensible and no slip occurs in the sample. Therefore, the bias extension test is considered to study the material shear behavior of fabrics.

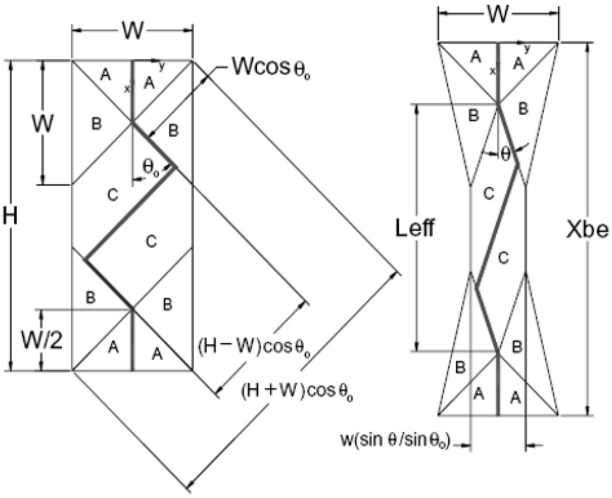


Fig. 3. Illustration of a fabric specimen under the bias-extension test [2]

A simple kinematic analysis of a bias extension sample in figure 3 gives us the shear angle in zone C, γ, as a function of fabric size and the end displacement, δ, as

$$\gamma = 90^\circ - 2\theta = 90^\circ - 2\cos^{-1}\left(\frac{L_o + \delta}{\sqrt{2}L_o}\right) \tag{1}$$

where $L_0 = H - W$ and H and W are the original height and width of the specimen, respectively.

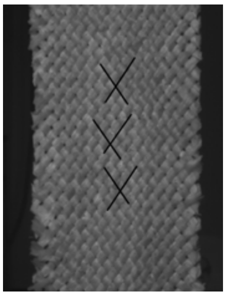


Fig. 4. Manual shear angle measurement

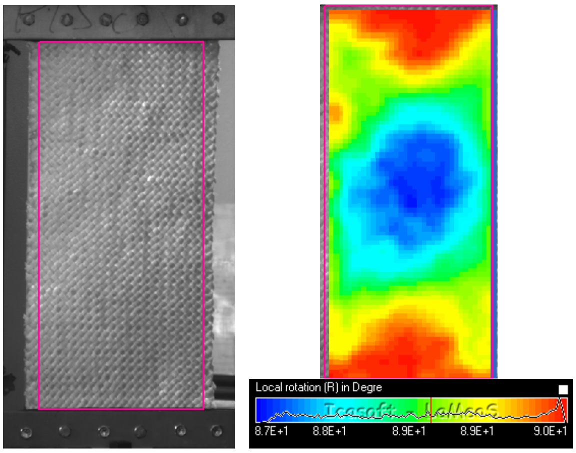


Fig. 5. A sample at the beginning of a bias test

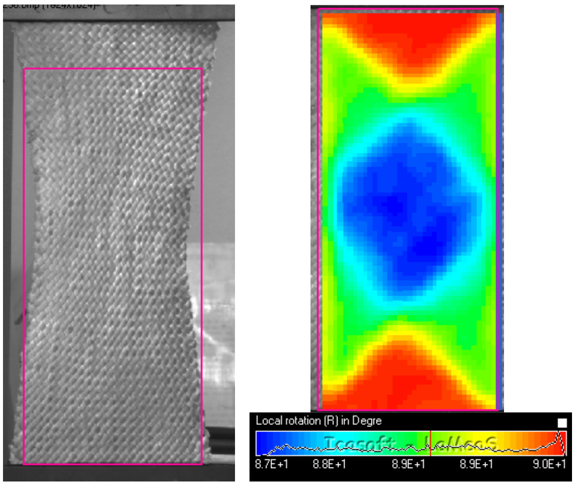


Fig. 6. A sample at the end of a bias test

The second method to measure the shear angle is the most basic one, which simply involves drawing straight lines along the yarns for various images from a bias test. As shown in figure 4, the angle between the warp and weft directions is equal to the shear angle of the fabric at that moment.

As shown in figures 5 and 6, the third method is to use a series of images obtained from the test along with the IcaSoft image correlation software developed at INSA-Lyon [3,4]. This software was originally developed for measuring strains in sheet metal parts and has been enhanced for automatically determine the shear strain in woven fabrics. To achieve this, small dots of black acrylic paint were speckled on so that IcaSoft can follow the movement of the otherwise uniformly white fabric. The twill, which was of a darker color, was often speckled with white paint for the same purpose.

4 DETERMINATION OF SHEAR FORCE

The normalized shear force from a bias extension test can be obtained following the four basic assumptions, i.e., a) shear angles in each zone are considered uniform; b) the shear angle in zone C is twice that in zone B; c) there is no shear deformation in zone A; and d) the initial fabric has a perfect orthogonal configuration, i.e., $\theta_0 = 45^\circ$.

The power made through the clamping force, F, is dissipated in two zones, B and C.

$$F \cdot \dot{\delta} = \left(C_S(\gamma) \cdot A_\gamma \cdot \dot{\gamma}\right) + \left(C_S\left(\frac{\gamma}{2}\right) \cdot A_{\gamma/2} \cdot \frac{\dot{\gamma}}{2}\right) \tag{2}$$

where A_γ is the original area of zone C, $A_{\gamma/2}$ is the original area of zone B, and $C_S(\gamma)$ is the torque per original unit area that is needed to deform the fabric in shear. Also the upper dot represents the time derivative. Using the relationship between the unit torque C_S and the shear force F_{sh}, $C_S(\gamma) = F_{sh}(\gamma) \cdot \cos\gamma$, the normalized shear force finally becomes

$$F_{sh}(\gamma) = \frac{1}{(2H - 3W)\cos\gamma}\left\{\left(\frac{H}{W} - 1\right) \cdot F \cdot \left(\cos\frac{\gamma}{2} - \sin\frac{\gamma}{2}\right) - W \cdot F_{sh}\left(\frac{\gamma}{2}\right)\cos\frac{\gamma}{2}\right\} \tag{3}$$

The above derivation can also be found in [5]. Note that here F_{sh} is the normalized shear force per unit length.

5 EXPERIMENTAL RESULTS

The history of shear angle in zone C as a function of clamp displacement obtained from the three above mentioned methods were compared for the plain weave fabric in figure 7. The shear angle from the IcaSoft software showed a good agreement with the physically measured shear angles. Furthermore, it was concluded that the theoretical shear angle calculated by equation 1, represented by the solid black line, can accurately reflect the true shear angle in the fabric until the shear angle reaching a value of 30^o. Note that the differences between the theoretical shear angle and the true shear angle were below 5^o until a 30^o shear angle and became large afterwards. In figure 8, normalized shear forces per unit length were plotted for all three fabrics. As shown in the figure, the balanced twill weave showed the largest normalized shear force curves while the unbalanced twill weave showed the smallest value. Note that the normalized shear force curves for the plain weave were almost similar regardless of the different sample aspect ratio. However, for the balanced twill weave, even two curves showed similar behavior, they still showed a large deviation between each other.

6 CONCLUSIONS

In order to better understand the mechanical property of woven composites, bias-extension tests were performed for three different woven fabrics. The optical methods showed that determining the shear angle mathematically from the crosshead displacement was a reasonable method before the plain-weave fabric reaches 30^o in the bias extension tests. For the plain weave, test data showed similar behaviors, even though aspect ratios were different. Therefore, it can be concluded that the suggested normalization methods by equations 1 and 2 for bias extension tests give consistent the shear force behavior for isotropic and homogeneous fabrics. As for the unbalanced twill weave in which the anisotropy and directionality are quite large, the normalization methods did not give as consistent results as that for the balanced fabric and further research is needed.

ACKNOWLEDGEMENTS

Support from the NSF grant CMMI-0300168 and its IREE supplement 0637072 is deeply appreciated.

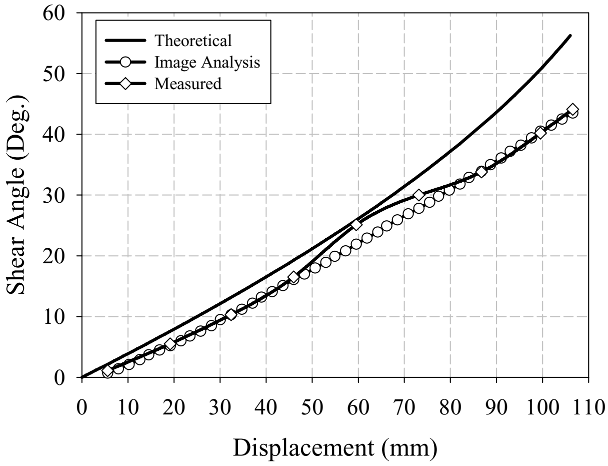


Fig. 7. Plot of shear angle in zone C vs displacement of the plain weave fabric with a sample size of 150mm x 450mm

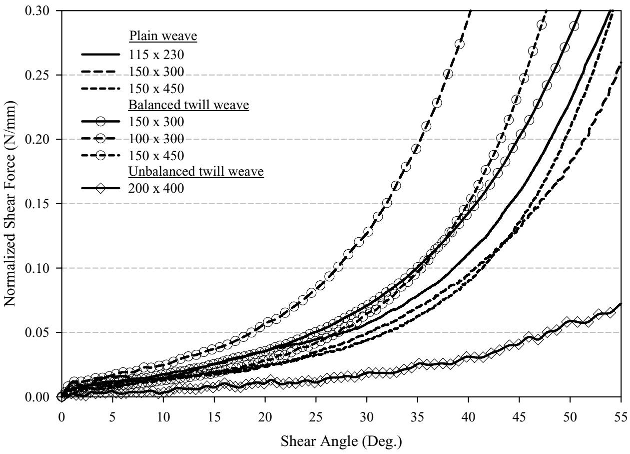


Fig. 8. Normalized shear force curves of bias-extension tests

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