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Milani, A. S.; Nemes, J. A.; Lebrun, G.; Bureau, Martin

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Nom	Prénom	Centre financ.	Centre de coût	Externe	Signature	Date sign.	*
Milani	AS			UBC			*
Nemes	JA			Penn State U.			
Lebrun	G			UQTR			

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A Comparative Analysis of a Modified Picture Frame Test for Characterization of Woven Fabrics

A.S. Milani,[1] J.A. Nemes,[2] G. Lebrun,[3] M.N. Bureau[4]
[1]*School of Engineering, University of British Columbia Okanagan, Kelowna, British Columbia V1V 1V7, Canada*

[2]*Engineering Division, The Pennsylvania State University, Penn State Great Valley, Malvern, Pennsylvania 19355-1443*

[3]*Département de Génie Mécanique, Université du Québec à Trois-Rivières, C.P. 500 Trois-Rivières, Quebec G9A 5H7, Canada*

[4]*Industrial Materials Institute, National Research Council, Boucherville, Quebec J4B 6Y4, Canada*

An experimental, finite-element analysis framework is utilized to estimate the deformation state in a modified version of the picture frame test. During the analysis, the effect of fiber misalignment and the deformation heterogeneity in the tested fabric, a 2 × 2 PP/E-Glass twill, is accounted for and a force prediction model is presented. Using an equivalent stress–strain normalization scheme, the comparison of the modified test with the conventional (original) picture frame and bias-extension tests is also made, and results reveal similarities and differences that should receive attention in the identification of constitutive models of woven fabrics using these basic tests. Ideally, the trellising behavior should not change from one test to another but results show that in the presence of fiber misalignment, the modified picture frame test yields a behavior closer to that of the bias-extension test, while the general form of the test's repeatability, measured by a signal-to-noise metric, remains similar to the original picture frame test. POLYM. COMPOS., 00:000–000, 2009. © 2009 Society of Plastics Engineers

INTRODUCTION

Because of possibility of designing different weave architectures with different anisotropic directional behaviors, there has been a growing interest in the past decade in understanding the mechanics of woven fabrics. One of the early standard methods to characterize the trellising behavior of woven fabrics is the bias-extension test [1, 2]. In this test, a single layer of the fabric is stretched while two families of fiber yarns (warps and wefts) are ideally initially oriented at ±45° from the loading axis. Despite its simplicity, the test reveals a few difficulties [3, 4]. First, owing to the upper and lower edge clamping constraints and the fabric structure, the test specimen exhibits heterogeneous deformation zones. These can be divided into unreformed, half shear, and full shear zones, where the shear angle in the second zone is theoretically half of that in the third zone (see, e.g., [4] for more details). Additionally, the test often reveals undesired deformation modes such as inter- and intrayarn fiber slip and wrinkling. A similar but not identical test has been suggested in the study [5] in which the specimen can be subjected to a biaxial extension while the fibers are still oriented in the bias directions.

In parallel to the bias-extension testing method, the picture frame test has also been one of the widely used tools among researchers for the trellis characterization of woven fabrics (e.g., [6–10]). In this test, a square specimen is clamped between four bars and the test apparatus is loaded in the diagonal direction. Therefore, ideally, a pure trellis mode should be induced onto the material in which the initial angle between weft and warp yarns, ϕ, is reduced to ϕ' (Fig. 1a) with no additional deformation mechanism. However, experimental evidence in the literature (e.g., [4, 7]) has suggested that the attachment of specimens to the bars of the frame can be a critical factor in determining the true state of the deformation because

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Correspondence to: Abbas Milani; e-mail: abbas.milani@ubc.ca
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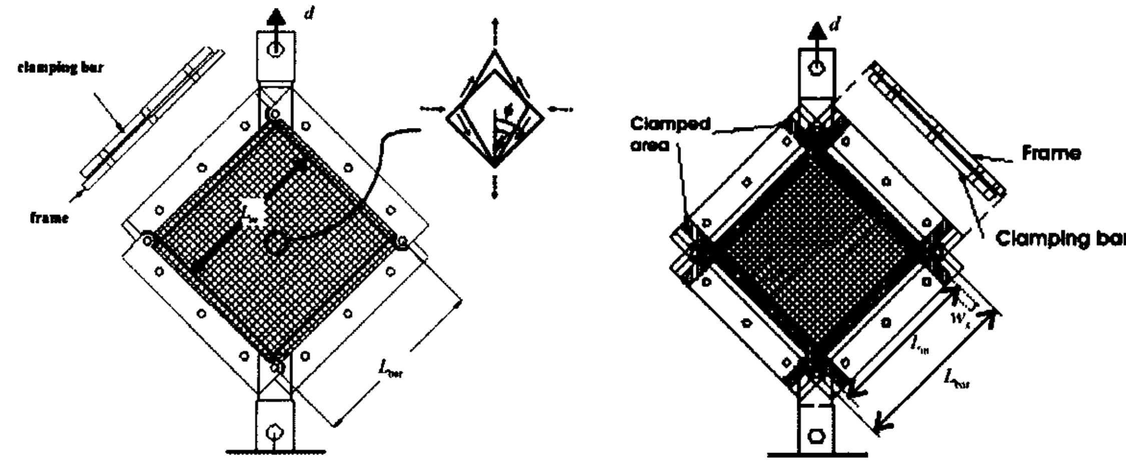

FIG. 1. Schematic of (a) the original and (b) modified picture frame test with an ideal trellis deformation.

of the presence of fiber misalignment. The latter often rises during the fabric fabrication processes [11] or forms because of the misplacement of the fabric into the test frame. If a specimen is loosely pinned, the frame may fail to induce the required kinematics. If clamped tightly, the misaligned tows may either be forced to bend severely at the point of clamping, slip out of the clamping device, or stretch the fibers [2, 3, 7]. The stretching of the fibers, in turn, can be coupled with an apparent increase in the material stiffness because it is opposing the global deformation of the fabric governed by the picture frame apparatus.

Despite the care taken by experimenters during the placement of specimens into the picture frame and/or using toggle clamps with no pinning, a misalignment in the range of 1°–5° has been reported to be present for plain weave and twill weave fabrics during the deformation and has revealed considerable nonrepeatabilities in material data [4, 8]. To reduce this effect to a lesser degree, a modified test layout was designed [4] at the Industrial Materials Institute of the National Research Council Canada where the clamping using a small contact-type condition is only applied to a small area in each corner of the specimen (Fig. 1b). Intuitively, in the modified layout, the shearing of the middle zone of the fabric, marked as A_1 in Fig. 2, can be analogous to the one in the bias-extension test given that in both cases the fiber ends are not fixed relative to the bars and the misalignment may not be a primary concern [7]. Nevertheless, the fiber misalignment in the four clamped strips of the modified test, marked as A_2 in Fig. 2, can still be expected to influence the response, but perhaps by a smaller amount than in the original layout. Accordingly, if this is true, the modified picture frame test is expected to produce (normalized) load magnitudes lower than the original picture frame test but higher than those in the bias-extension test. This will be verified experimentally in "experimental analysis" section.

The rest of this article is focused on the deformation state in the modified picture frame test. To date, the original picture frame and bias-extension tests have received considerable attention in the literature (e.g., [1–10]), but there has been little or no effort in understanding the woven materials behavior under the modified test introduced in [4]. The analysis done here is based on a comparative experimental ("experimental analysis" section) and a finite-element framework ("using finite-element simulation" section). During the experimental analysis, explicit metrics for a direct comparison of the modified picture frame test with the original picture frame and bias-extension tests are presented. In "model verification" section, to verify the applicability of the approach in modeling the fabric behavior under the modified picture frame test, a force prediction model is established and compared with the measured test data. In "discussion: a role in constitutive model identification" section, remarks regarding the

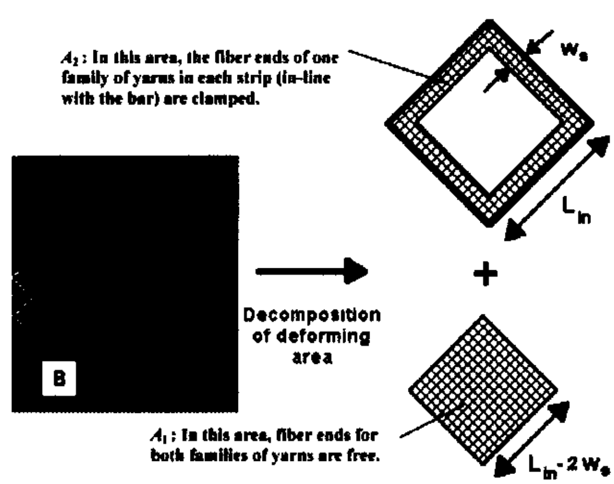

FIG. 2. Decomposition of the deforming area in the modified picture frame test specimen (B).

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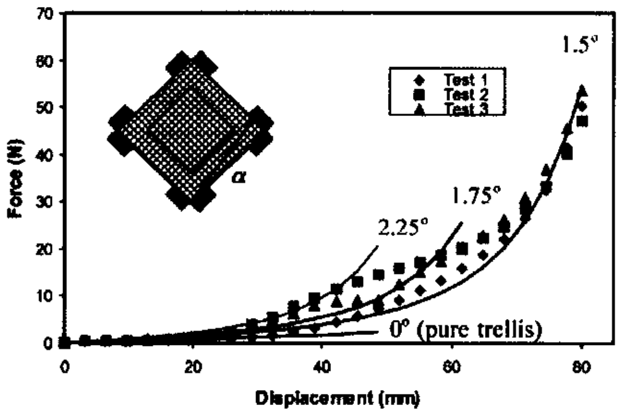

FIG. 3. Test data obtained from three repeats of the modified picture frame test (total inner area of each specimen: 100 × 100 mm^2) and model prediction for different misalignment angles.

potential role of the modified picture frame test for constitutive model identification purposes are outlined. Conclusions are given in the last section.

Experimental Analysis

Test data from three replicates of a modified picture frame experiment on the TWINTEX^{TM} 2 × 2 twill weave fabric are selected from [4]. The length of each bar in the four-linkage apparatus is $L_{bar} = 152.4$ mm. The temperature and the crosshead speed are set to be 170°C and 162 mm/s, respectively. All the replicates have been performed with a specimen size of $L_{in} = 100$ mm and $W_s = 14.7$ mm. The fabric thickness is 1 mm. The obtained load values were corrected for the weight of the unloaded frame. Figure 3 shows the measured load, F, vs. axial displacement, d, data considered as the response of the deforming material (the rest of information in this Figure will be refereed to in a later section).

Next, to evaluate the response in the modified test, test data from [4] on the original picture frame test and the bias-extension tests are taken at the same temperature and crosshead speed. For the bias-extension test, the initial length, L, and width of the specimens, W, were set to be 306 and 88.9 mm, respectively. For the original picture frame test, the bar length is the same as the modified picture frame test, and the specimen inner area is 100 × 100 mm^2. Note that ideally the three tests should result in a similar trellising response. In the following, test data from the three tests are compared with the main purpose of gaining some information regarding the state of deformation in the modified test.

According to the study [3], to account for a correct correlation between a bias-extension test and a picture frame test, measured force and displacement data in each test can be normalized following the corresponding test configuration. By taking into account the deformation heterogeneity in the bias-extension test, a conventional stress–strain characterization of this test is provided as follows.

$$\begin{cases} \varepsilon_N = \dfrac{d}{L-W} \\ S_N = \dfrac{F(L-W)}{WTL_{eff_0}} \end{cases} \tag{1}$$

where T is the initial fabric thickness, L is the specimen length, and W is the specimen width (see also Fig. 4a). ε_N and S_N are normalized displacement (here in the form of strain) and normalized force (in the form of stress); L_{eff_0} is an effective length of the test specimen to adjust for the effect of a heterogeneous deformation field and can be approximated as $L_{eff_0} = L - (1.5 - X)W$ for $L \geq 2W$ [12]. The use of L_{eff_0} is to consider an equivalent specimen throughout which the deformation is uniform with a full shear as shown in Fig. 4b (the rest of this Figure will be referred to later). X is a value that depends on the ma-

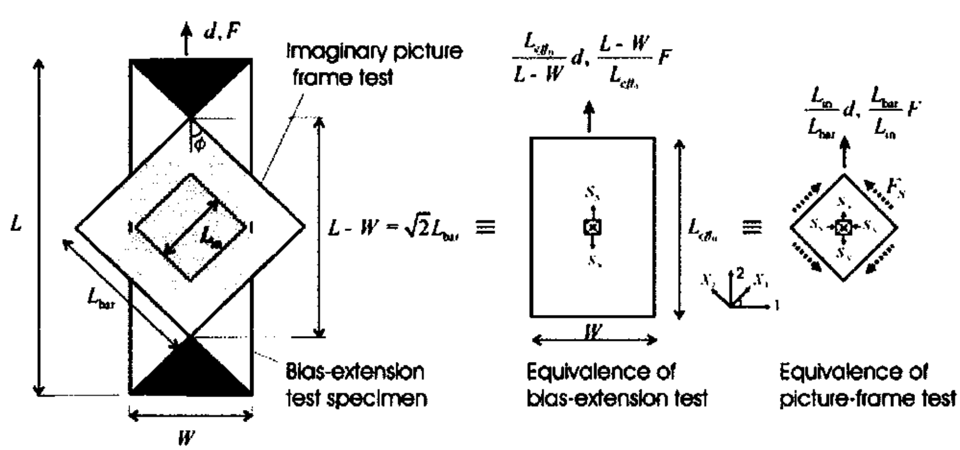

FIG. 4. Schematic of a bias-extension test specimen and its relation to an imaginary picture frame test in the reference configuration with $\phi = 45°$. The trellis deformation is assumed uniform in the two equivalent tests and they result in the same deformation power, Fd, given a shear level and its rate.

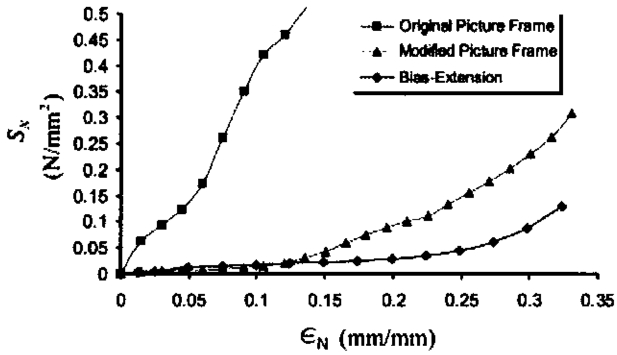

FIG. 5. Experimental comparison of three different shear tests in a normalized space (values shown are average of three repeats in each test).

terial constitutive model, shear strain, and its rate [3], and it can be approximated between 0 and 0.25 in the absence of an exact material model [12].

To correlate the bias-extension test to the picture frame test, an imaginary picture frame set-up can be assumed with the bias-extension set-up as illustrated in Fig. 4a. Accordingly, an equivalent picture frame test can be idealized where the deformation power remains unchanged. From the force equilibrium on the loading point of the equivalent picture frame test in Fig. 4c, the induced shear force on each edge of the fabric in the reference configuration is written as $F_s = \frac{F L_{bar}}{2\mathrm{Cos}\phi L_{in}}$. The shear stress in this configuration is $S_s = \frac{F_s}{L_{in}T}$ and for an idealized alignment condition of $\phi = 45°$ with no tow axial forces it becomes $S_s = \frac{F L_{bar}}{\sqrt{2}L_{in}^2 T}$. A 45° stress transformation of the material coordinate system $X_1 - X_2$ to the 1–2 coordinate system in Fig. 4 renders $S_N = S_s$ (see [5, 13] for details of such transformations; also note that if the fiber angle in the current configuration is used, the true stress values should be considered). Finally, a nominal stress–strain relation with respect to the axis of loading is characterized as:

$$\begin{cases} \varepsilon_N = \dfrac{d}{\sqrt{2}L_{bar}} \\ S_N = \dfrac{F L_{bar}}{\sqrt{2}L_{in}^2 T} \end{cases} \tag{2}$$

Equation 2 can also be used for the modified picture frame test set-up provided that the corresponding bar length and inner specimen dimensions are employed. Previously, for a general test set-up where $L_{bar} \geq L_{in}$, the study [9] revealed that the force data in different sets of picture frame tests should be normalized using a factor of L_{bar}/L_{in}^2. Also, the study [3] for a special case where $L_{bar} = L_{in}$ provided a correlation between the bias-extension and picture frame test measurements. *Equations 1* and *2* confirm and generalize both of these studies. In all cases, however, the bending contribution of fiber yarns compared to the trellising is neglected and it is assumed that the specimens follow idealized kinematics.

For the performed trellising tests on the TWINTEX fabric, the dimensions of the tested specimens are chosen such that

$$L - W \simeq \sqrt{2}L_{bar} \tag{3}$$

and, therefore, for the same crosshead speed (162 mm/min), the induced shear rate is comparable given a shear strain. For a more general case, however, the specimen sizes and crosshead speeds can be selected arbitrarily such that

$$\frac{\dot{d}_{be}}{L - W} - \frac{\dot{d}_{pf}}{\sqrt{2}L_{bar}}. \tag{4}$$

For two sets of picture frame and bias-extension test with different set-ups and specimen sizes, the calculated stress–strain values at a common strain, strain rate, and temperature should be identical. A deviation from such identity can be indicative of additional deformation mechanism in the corresponding test(s).

Results of the data normalization are shown in Fig. 5. From a comparison of these experimental data, it can be noticed that the material under the modified picture frame test shows on average a behavior closer to that of the bias-extension test, yet it seems that the fiber stretch is not fully omitted in the modified picture frame test and high load values are recorded toward the end of the test. The modified test has resulted in normalized force values ~80% less than the original picture frame test and ~20% larger than the bias-extension test on average. The observation supports the earlier indication that the condition of majority of fiber ends in the middle region of the specimen in the bias-extension and modified picture frame tests are similar in the sense that they can rotate with no restriction from the test configuration. The effect will be further verified in the next section using a finite-element model. As the previous study of [5] had revealed, any further constraint on the edge of a trellis specimen (e.g., to perform a biaxial extension instead of uniaxial extension) can result in more complex deformations in each yarn direction and cause larger axial tow forces.

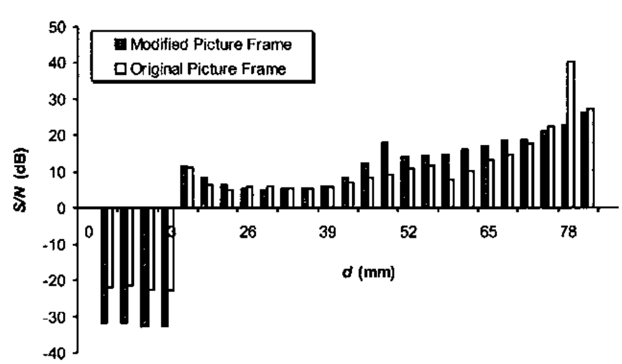

FIG. 6. S/N ratio distributions obtained in the original and modified picture frame tests (in both tests: L_{in} = 100 mm).

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Next, it is assessed whether or not the reduction of clamping area (precisely by 19.2%) in the modified picture frame test has helped improve the test repeatability relative to the magnitude of average response. To this end, a Type I-nominal-the-better signal-to-noise (S/N) measure from the study [14] is used and compared for both picture frame tests. The S/N ration can be written as

$$S/N_i = 10\,\mathrm{Log}\left(\frac{Y_i^{\mathrm{Ave}}}{\sigma_i}\right)^2 \tag{5}$$

where Y_i^{Ave} and σ_i are the mean response and standard deviation of the sample at the ith measurement point, respectively. Results are shown in Fig. 6. The general form of the S/N distributions remains comparable in the two tests. More closely, during the initial stage of deformation (up to ~16%), where straightening of initially curvy yarns takes place, the magnitude of noise (standard deviation) has been larger than the average response (force), and thus S/N values have become negative (i.e., inadmissible region for model identification purposes). Toward the end of deformation, when the majority of fibers are straightened and fibers take most effect in the material response, the S/N values are positive and increase monotonically. In the modified test, some improvements are noticed in the magnitude of the S/N values (the larger the S/N, the better the repeatability). For an ideal condition, provided a sufficient number of repeats are available, an experimenter would expect a high and uniform distribution throughout the test.

Using Finite-Element Simulation

Previously, the study [9] employed a finite-element model and revealed that the deformation in the original picture frame test is uniform. For the modified version of the test, it is also necessary to check whether or not the same condition holds. To this end, a finite-element model of the modified test is built in Abaqus/Standard with plane stress quadrilateral continuum elements. The dimensions, loading, and boundary conditions are modeled similar to the test layout in Fig. 1b. Each bar of the picture frame is considered as a rigid body. The constitutive model was chosen to be linear orthotropic in the reference configuration, which can be valid for the early stage of fabric deformation. Consequently, the stress (S_{ij})–strain (E_{ij}) relation in the material coordinate system reads

$$\begin{Bmatrix} S_{11} \\ S_{22} \\ S_{12} \end{Bmatrix} = \begin{bmatrix} D_{1111} & D_{1122} & 0 \\ D_{2211} & D_{2222} & 0 \\ 0 & 0 & D_{1122} \end{bmatrix} \begin{Bmatrix} E_{11} \\ E_{22} \\ E_{12} \end{Bmatrix} \tag{6}$$

Therefore, each simulation was performed up to a shear strain of 0.3 before the lock up point. Note that the main objective of the approach here is to verify the state of deformation imposed by the modified test configuration, not to introduce the geometric or material nonlinearities. The model parameters were determined to be $D_{1111} = 62.66$ MPa, $D_{1122} = D_{2211} = 18.73$ MPa, and $D_{1212} = D_{2121} = 0.048$ MPa using sets of the uniaxial and bias-extension tests following the study [14]. To understand the effect of possible fiber misalignment in the response, two separate sets of simulations are proposed. One is with the perfectly aligned fiber assumption, and the other is with an assumption of 2° misalignment. For the latter, the material orientation in fabric elements is rotated in the counter clockwise direction with respect to the frame axes. As the constitutive model is defined and identified in the reference configuration, the material directions are not updated with the deformation. It was observed that in the absence of misalignment, the imposed deformation in the modified test similar to the (ideal) original test is a uniform trellis. On the other hand, for the misaligned simulation (see Fig. 7), it was noticed that in the middle region marked as A_1, the shear strains are dominant and the majority of the elements (85%) acquire an E_{12} value between 0.275 and 0.29 similar to the nonmisaligned case. The theoretical value using *Eqs. 7* [15] and *8* [6] is found to be 0.29.

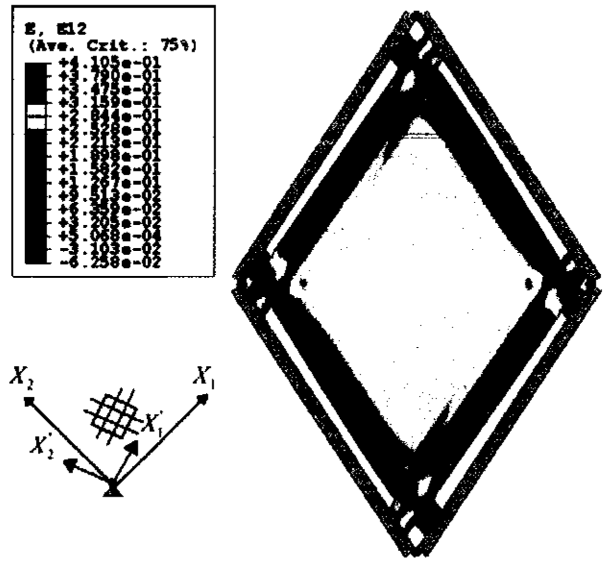

FIG. 7. Contours of shear strain in the modified picture frame test with 2° of misalignment with respect to the rotated material coordinate system $X_1' - X_2'$. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

$$E_{12} = \mathrm{Sin}(\gamma) \tag{7}$$

$$\gamma = \frac{\pi}{2} - 2\mathrm{Cos}^{-1}\left(\frac{d + \sqrt{2}\,L_{\mathrm{bar}}}{2L_{\mathrm{bar}}}\right) \tag{8}$$

Finally, from Fig. 8, it is inferred that the misalignment has caused an apparent tensile strain, E_{11}, in the two corresponding strip regions in the misaligned simulation. Across the length of the other pair of strips perpendicular to the first pair, the misaligned fibers induce compression (see [10] for theoretical considerations from a continuum

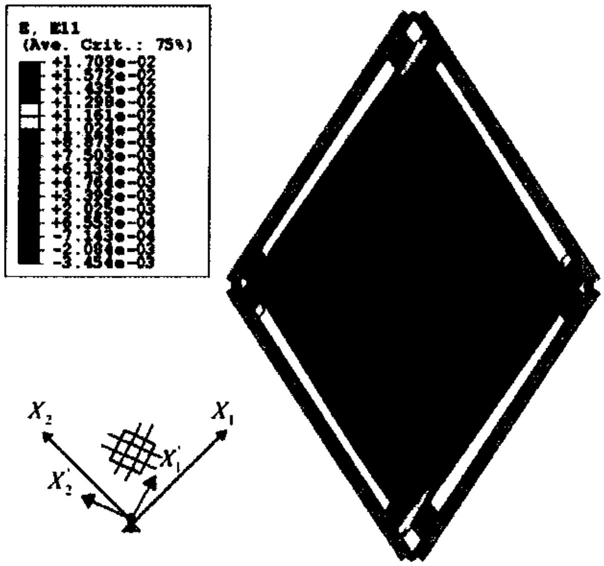

FIG. 8. Contours of tensile strain in the modified picture frame test with 2° of misalignment with respect to the rotated material coordinate system $X_1' - X_2'$. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

mechanics point of view). The normal strains in the nonmisaligned simulation and the middle zone of the misaligned simulation are found to be essentially zero. The identification of deformation state using the finite-element analysis is consistent with the earlier hypothesis in "experimental analysis" section using the experimental data. It is worth adding that the recent study [16] shows that the misalignment effect in the fabric level is statistically more significant than that in a unit cell level, thus the constitutive models in macrolevels should account for the effect of nonuniform reinforcements more closely as they are to be used in simulation of forming processes.

Model Verification

In this section to further verify the applicability of the proposed partitioning in Fig. 2 for modeling of the material behavior under the modified picture frame mode, a force prediction equation is constructed and compared to the experimental data in "experimental analysis" section.

In a previous study [10], a closed form solution for the force prediction in the original picture frame test was presented. Based on this solution, given α and β as arbitrary weft and warp fiber misalignment angles, the force at a shear angle of γ, can be written as

$$F = \left(\frac{L_{\text{in}}^2 T \sin 2\gamma}{2\,L_{\text{bar}} \sin(\frac{\pi}{4} - \frac{\gamma}{2})}\right) \{c_1 \sec^4\gamma + c_2\,(2\sec^4\gamma - 1) + \frac{m}{2}\sin\gamma \sec^2\gamma\,(2\sec^2\gamma + 1)(\sin 2\alpha + \sin 2\beta) + k_1 [e^{k_2 \sin^2\gamma \sin^2 2\alpha} \sin^2 2\alpha + e^{k_2 \sin^2\gamma \sin^2 2\beta} \sin^2 2\beta]\} \tag{9}$$

where γ is related to the frame tip displacement, d, via *Eq. 8*; $c_1 = 0.045$ MPa and $c_2 = 0.012$ MPa are resin material parameters; $k_1 = 14.39$ MPa and $k_2 = 1456.87$ are fiber material parameters; $m = 0.067$ MPa is a fiber–resin interaction parameter. To accommodate the above solution for the modified picture frame test, recalling Fig. 2 for the subarea of A_1 with free fiber ends, one can employ *Eq. 9* without including the fiber stretch contribution. It follows,

$$F_1 = \left(\frac{A_1 T \text{ Sin } 2\gamma}{2\,L_{\text{bar}} \text{ Sin }(\frac{\pi}{4} - \frac{\gamma}{2})}\right) \left[c_1 \text{ Sec}^4\gamma + c_2\,(2\text{Sec}^4\gamma - 1)\right]. \tag{10}$$

For the subarea of A_2 with clamped fiber ends, considering a misalignment mode as shown in Fig. 7, one can employ *Eq. 9* with a contribution of stretching misaligned fibers (the other family of fibers is subject to compression and has negligible contribution to the global fabric stiffness). It follows,

$$F_2 = \left(\frac{A_2 T \text{ Sin}2\gamma}{2\,L_{\text{bar}} \text{Sin}\,(\frac{\pi}{4} - \frac{\gamma}{2})}\right) [c_1 \text{ Sec}^4\gamma + c_2\,(2\text{Sec}^4\gamma - 1) + \frac{m}{2} \text{ Sin }\gamma \text{ Sec}^2\gamma\,(2\text{Sec}^2\gamma + 1) \text{ Sin } 2\alpha + k_1\, e^{k_2 \text{Sin}^2\gamma \text{ Sin}^2 2\alpha} \text{Sin}^2 2\alpha], \tag{11}$$

Subsequently, the total force applied to the fabric is written as $F = F_1 + F_2$. A comparison of the measured data versus the total force prediction within the misalignment range reported for the TWINTEX twill fabric [4] is shown in Fig. 3. It is seen that the model without accounting for the misalignment effect (i.e., $\alpha = 0°$) is not capable of capturing test data, while a good agreement between the predictions and data points from the repeats of the test is feasible by using arbitrary misalignment angles in the range of 1.5°–2.25°. It is worth adding that one may also account for possible nonuniformity of misalignment distribution across the fabric by using an effective (mean) value of α as a function of the shear angle γ. This can improve the performance of prediction models of woven fabrics, specially in the earlier stages of deformation where fiber yarns are not straightened and test nonrepeatabilities are more pronounced (see [10] for more details).

Discussion: A Role in Constitutive Model Identification

For woven fabrics, nonlinear constitutive models are employed to predict the material response in large deformation ranges (e.g., [13, 14]), and therefore the number of unknown model parameters often becomes large. These parameters are identified using data from basic mechanical tests and an inverse method, normally followed by a validation test. Different identification/validation strategies

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can be seen in the literature. The study [13] employs the uniaxial extension test and picture frame test with zero off-angles to determine the normal and shear parameters, respectively. Next, a set of misaligned picture frame tests are used to validate the model. The study [10], when the range of degree of misalignment is unknown, suggests identifying the normal parameters from the uniaxial test and the shear parameters from the bias-extension test and then validating the model in the picture frame test by using a range of possible misalignments, etc. Other validation tests seen in the woven composites literature include three points bending tests under different deformation rates [17].

The modified picture frame test may be used in different ways during an identification process. Some possibilities are outlined as follows and further research can be worthwhile to assess the most promising strategies. One can use the modified test as a more complex validation tool given that in this test the imposed deformation in the presence of misalignment appears to be heterogeneous; namely, more like the trellising in A_1 and the trellising-fiber stretch in A_2. In the same relation, the contribution of the predicted force for the A_1 region can be compared to that of a separate bias-extension test using a normalization scheme similar to that of "experimental analysis" section. Such a comparison using the original picture frame test is not straightforward because the misalignment can affect the entire deforming area. Another way of using the modified picture frame test would be in the identification process itself as follows. After determining the normal parameters from a uniaxial or biaxial extension test, they can be fixed and the shear parameters then obtained from a modified picture frame test. An advantage of the picture frame tests over the bias-extension may be the absence of excessive fiber slippage. Finally, it is important to note that in reality the initial state of misalignment in the fabric may rely on a random distribution, rather than a uniform distribution. The inclusion of a nonconstant misalignment formulation similar to the one suggested in the study [10] can improve the predictability of a material model in both picture frame tests.

CONCLUSIONS

In the original picture frame test configuration, misalignment can produce a response that is distant from the pure trellis mode. To reduce this effect (or in other words to improve the likelihood of the pure trellis mode), the modification of the clamp condition of fiber ends is useful. In the modified picture frame test, perhaps because of the smaller clamped area, large misalignments are less likely to dominate the global response. For the same reason, the imposed deformation mode in the deforming area of the specimen seems to be practically different from the original test. In particular, deformation heterogeneity in the modified specimens is likely in the presence of fiber misalignment. Under this condition, the four clamped strips can still behave similar to the original test, whereas the inner region with free fiber ends can behave more similar to the bias-extension test. This implies that the modified picture frame test next to other basic tests may be employed in different ways during material model identifications.

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NOMENCLATURE

A_1	forming area in the middle region of the modified picture frame test
A_2	forming area consisting of four clamped strips in the modified picture frame test
D_{ijkl}	orthotropic material parameters
E_{12}	shear strain
Eii	tensile strain in the material coordinate
F	measured crosshead force
F_1	force corresponding to the forming area A_1
F_2	force corresponding to the forming area A_2
F_s	induced shear force
L	initial length of the bias-extension test specimen
L_{bar}	bar length in the picture frame
L_{eff_0}	effective length of the bias-extension test specimen
L_{in}	effective specimen length inside the picture frame
S/N	signal-to-noise weighting factor
S_N	normalized crosshead force
S_s	nominal shear stress
T	initial fabric thickness
W	specimen width in the bias-extension test
$X_1 - X_2$	original material coordinate system
$X'_1 - X'_2$	rotated material coordinate system
Y^{Ave}	mean response
c_1 and c_2	resin model parameters
d	crosshead displacement
$\dot{d}_{be}$	crosshead speed in the bias-extension test
$\dot{d}_{pf}$	crosshead speed in the picture frame test
k_1 and k_2	fiber model parameters
m	fiber-resin interaction model parameter
w_s	the width of each clamped strip in the modified test
α	weft fiber misalignment angle
β	warp fiber misalignment angle
γ	shear angle
ϕ	angle between weft and warp yarns before deformation

ϕ'	angle between weft and warp yarns during deformation
σ	sample standard deviation
ε_N	normalized crosshead displacement

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