THE EFFECTS OF LOCAL INHOMOGENEITY ON SHEAR PROPERTY MEASUREMENTS OF HYBRID COMPOSITES

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ABSTRACT

The effects of local inhomogeneity of the Iosipescu specimen on the shear property measurements have been investigated for unidirectional hybrid composites. The study shows that, theoretically, the Iosipescu test can be used to determine the shear modulus of the hybrid composites studied when it is correctly used. However, practically, premature failures caused by the stress concentrations near the notch roots can make the test undesirable for determining the shear strength of hybrid composites.

KEY WORDS: Iosipescu Shear Test, Hybrid Composites, Inhomogeneity, Finite Element Analysis

1. INTRODUCTION

This study is to extend the Iosipescu shear test as applied to unidirectional hybrid composites that contain different types of fiber tows that were intimately mixed throughout the resin matrix (small-scale combination). Such a small-scale combination, not like non-hybrid composites (only one type of fiber), can affect the mechanics of the composites and interfere with the test results, particularly in shear. In early 1980's, Walrath and Adams et al. [1,2] introduced the Iosipescu shear test [3] to non-hybrid composites materials. Since then many investigations of the Iosipescu shear test, as applied to non-hybrid composite materials, have been conducted [e.g., 4-6], and they were treated as homogeneous media. The issue that arises here is the influence of the local inhomogeneity inherent in the hybrid composite on the experimental measurements. Therefore, through experimental evaluation and finite element analysis (FEA), we extend the current application of Iosipescu shear test from non-hybrid composites to hybrid composites for determining the in-plane shear properties (stiffness and strength). Also, in this study, the effects of the local inhomogeneity on the measurement of shear properties were investigated. Two types of hybrid systems having different fiber-tow volume fractions composed of carbon and glass fiber tows with epoxy matrix were used for the study.

2. EXPERIMENTS

The doubly v-notched Iosipescu specimen shown in Fig. 1 was utilized based on ASTM standard [7]. The radius of the notch tips is 1.3 mm. The aforementioned two hybrid systems were named as low carbon and high carbon systems in this study. The "low carbon" refers to a hybrid system with lower volume fraction of carbon/epoxy fiber tows (33.8%), and "high carbon" refers to a higher volume fraction of carbon/epoxy fiber tows (61.8%). The fiber tow is defined as an impregnated tow in this study. In other words, the tow is taken as a fiber/matrix system rather than a bundle of fibers. Typical micrographs of sections of a hybrid composite sample are shown in Fig. 2, with the bright regions representing the glass/epoxy fiber tows and the dark regions representing the carbon/epoxy fiber tows. For both systems, the volume fraction of epoxy matrix of glass and carbon fiber tows is the same at 30%. Note this implies that the volume fraction of the epoxy matrix in the hybrid composites is also 30%. The thickness of specimen is 2.20mm for high carbon samples, and 2.13mm for low carbon samples (the standard uncertainty associated with these thickness is 0.01mm). For each hybrid system, the specimens were cut from the hybrid composite sheets in two different fiber-tow orientations: parallel and perpendicular to the longitudinal direction of the specimen as also indicated in Fig. 1 (referred to as 0^o and 90^o specimens).

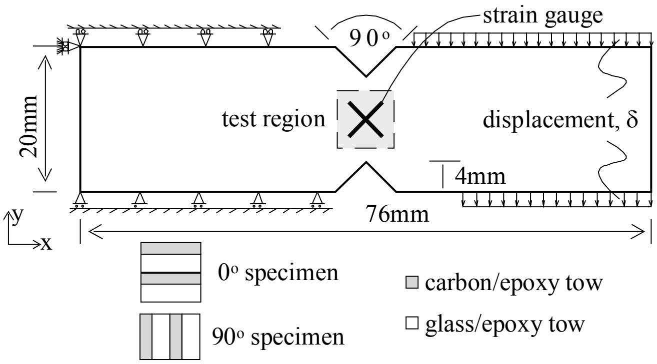

Fig. 1 Schematic of Iosipescu Specimen

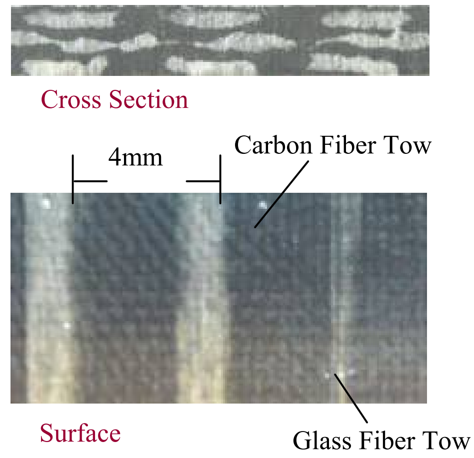

Fig. 2 Photo Image of Hybrid Samples

The stacked $\pm 45^o$ strain gauge rosettes are placed at the center between two notch tips. The square area covered by the gages is referred to as the test region in this study. The optimal test region that would achieve a pure and uniform shear stress-strain state shall be determined from the FEA. The average engineering shear strain of the specimen, $\overline{\gamma}^o$, at the test region can be calculated from the experimentally measured strains at $\pm 45^o$ directions (ε_{45^o} and ε_{-45^o}) as follows:

$$\overline{\gamma}^o = \varepsilon_{45^o} - \varepsilon_{-45^o} \quad (1)$$

Then the apparent in-plane shear modulus, $\overline{G}$, of the hybrid composites can be calculated as:

$$\overline{G} = \overline{\tau}/\overline{\gamma}^o \quad (2)$$

with $\overline{\gamma}^o$ and the average applied shear stress $\overline{\tau}$ ($\equiv P/A$, where P is the resultant loading forces and A is the cross-sectional area between the notch tips).

3. FINITE ELEMENT ANALYSES[1]

A tow-based linear-elastic approach was invoked by employing the commercial finite element code ABAQUS [8] to analyze the stress-strain distributions of the Iosipescu specimen and to determine how closely the test would meet the requirement of ideal shear test for hybrid composite. In this study, the tow-based finite element model is defined that the tow is treated as a minimal microstructure, and necessary material properties input for the analyses are based on the tow properties. The finite element model was based on images of unidirectional glass/carbon/epoxy hybrid composites. The Iosipescu specimens with tow orientations in

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1 Certain commercial computer code is identified in this paper in order to specify adequately the analysis procedure. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology (NIST) nor does it imply that they are necessarily the best available for the purpose.

horizontal and vertical directions (referred to as 0^o and 90^o specimens) shown in Fig. 3 were considered. The whole specimen was modeled in FEA due to the asymmetric boundary and loading conditions. 8-node isoparametric solid elements were used. The material input requirements in FEA for each tow-based material property were calculated from the rule-of-mixtures [9] based on the constituent properties (reported mean values from the literature) listed in Table 1. The calculated tow properties are also listed in the table.

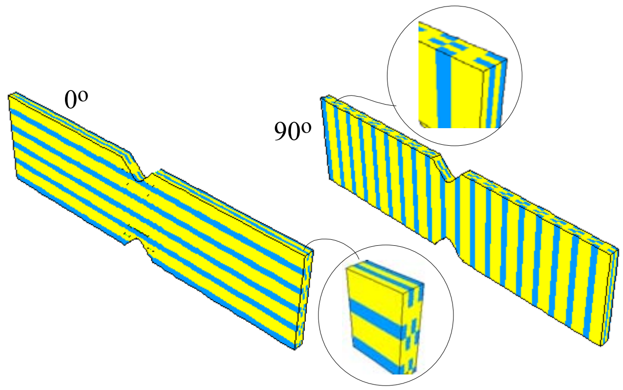

Fig. 3 Tow-based finite element model of hybrid composite

Table 1 Fibers and fiber tow's elastic properties

Elastic Modulus	Glass Fiber (GPa)	Carbon Fiber (GPa)	Resin Epoxy (GPa)	Glass Fiber Tow (GPa)	Carbon Fiber Tow (GPa)
E_{11}	72.70	234.90	3.0	51.79 [a]	165.33 [a]
E_{22}	72.70	13.80	3.0	10.05 [b]	7.49 [b]
ν_{12}	0.22	0.20	0.4	0.27 [a]	0.26 [a]
G_{12}	29.98	28.80	1.07	5.08 [b]	5.03 [b]

*a: the rule-of-mixtures predictions with 30% of the matrix volume fraction in fiber tow
*b: the modified rule-of-mixtures predictions with 30% of the matrix volume fraction in fiber tow

4. RESULTS AND DISCUSSIONS

One can see from eq. (1) that the uniformity of the shear strain is governed by the uniformity of normal strain distributed in $\pm 45^o$ direction from the center of the specimen. The distributions of the normal strains for 0^o and 90^o specimens are shown in Fig. 4. From this figure, it is noted that, regardless of the hybrid systems, within the range studied the normal strain distributions in the gage directions are almost uniform for the specimens with 0^o tow orientations. However, for the 90^o specimen, the uniformity in the normal strain at $\pm 45^o$ can be only approximately achieved in the region from -3 mm to 3 mm in the 45^o direction shown in Fig. 4b. This suggests that, in order to have a test region with uniform shear strain for 0^o and 90^o specimens, the test region should be limited to an area of (4x4) mm^2. The slight wavy patterns of shear strain distributions seen in the figure indicate the influence of the varied microstructure of hybrid composites on the stress/strain distributions.

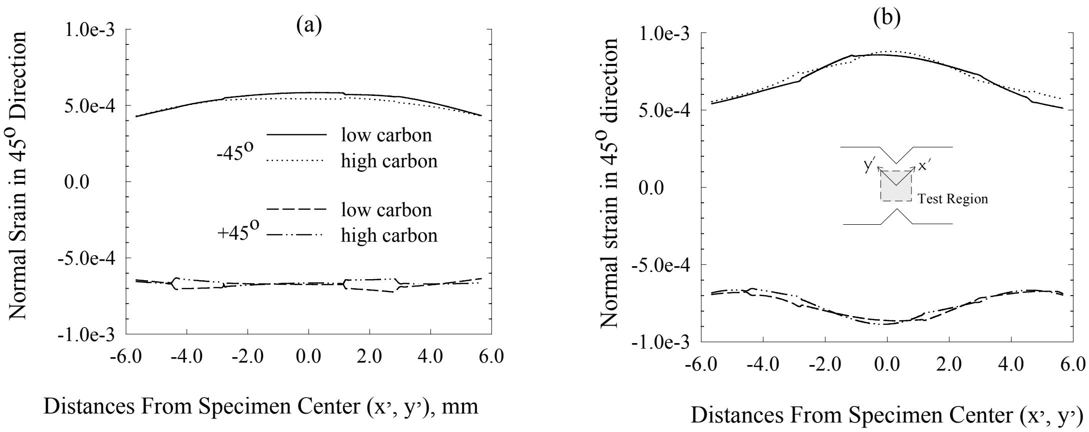

Fig. 4 The $\pm 45^{o}$ normal shear strain components along the strain gauge directions at the test region: 0^{o} specimen (a), 90^{o} specimen (b)

Unlike the measurement of the shear modulus, the measurement of shear strength ideally needs not only a uniform but also pure shear stress state in the test region of the Iosipescu specimen. In order to satisfy the condition of pure shear, the directions and magnitudes of principal stress in the test region were examined for 0^{o} and 90^{o} specimens possessing different hybrid systems. If we consider the test region as a representative cell, then in order to meet the requirement of pure shear in the test region, the directions of maximum and minimum principal stresses (σ_1 and σ_2) should coincide with the gage directions, $\pm 45^{o}$. Also, the values of σ_1 and σ_2 should be the same, but one in tension and the other in compression.

Fig. 5 gives the variation of the principal direction with the location along 45^{o} from the center of test region for different hybrid systems and tow orientations. Fig. 6 presents the ratio of σ_1 and σ_2 as a function of the location along 45^{o} from the center of the test region. From the deviation of principal directions from 45^{o} shown in Fig. 5 and the ratio of σ_1 and σ_2 shown in Fig. 6, we believe that the hybrid systems studied have an acceptable pure shear status near the central area of the test region. These results, coupled with the analyses on the measurements of shear modulus suggest that experiments with 0^{o} and 90^{o} specimens using a strain gage to cover (4x4) mm^2 should be acceptable for determining both the shear modulus and strength.

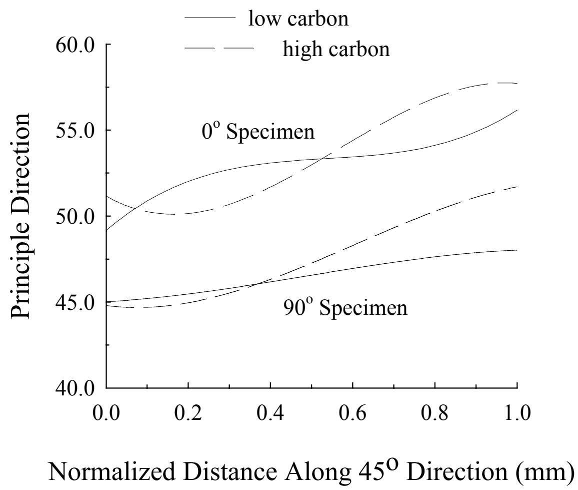

Fig. 5 Principal stress distributions along the strain gauge direction (45°) from specimen center, the distance is normalized by 6mm

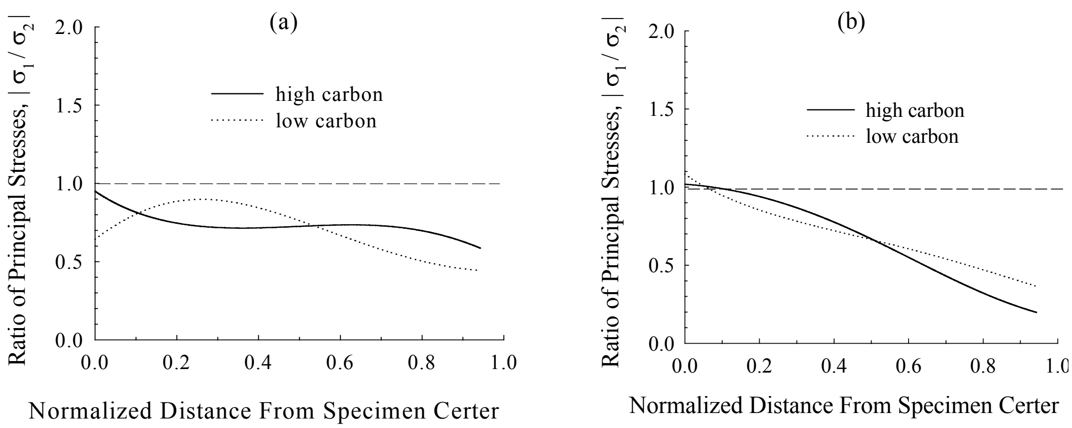

Fig. 6 Principle stresses, $|\sigma_1/\sigma_2|$, along the strain gauge direction from specimen center at test region: 0° specimen (a), 90° specimen (b). The distance is normalized by 6mm.

Fig. 7 presents the experimental shear stress-strain curves of a typical 90° specimen at the strain range from 0.1 % to 0.2 % for different gage lengths. It can be noted, from the slope of the curves, that using gage size covering an area larger than that of (4×4) mm^2 gives higher value of the apparent shear modulus. The results in Fig. 7 imply that the Iosipescu specimens exhibit a limited region where the influence of local inhomogeneity inherent in the hybrid composites on the measurements can be neglected.

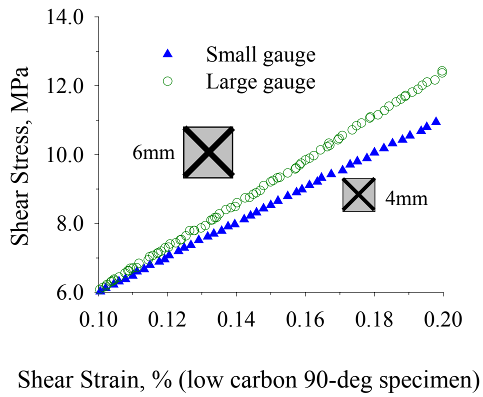

Fig. 7 Typical stress-strain curves at the strain ranging from 0.1 % to 0.2 % for different gage lengths (90^o specimen)

For all the experimental specimens, apparent shear modulus ($\overline{G}$) were conclusively calculated based on the slope of the shear stress-strain curve at the strain ranging from 0.1 % to 0.2 %, and the results are listed in Table 2. Also listed in this table are the corrected shear modulus (G) and FEA predictions. The shear modulus (G) is obtained from $\overline{G}$ using a correction factor [10]. Within the experimental uncertainties, there is generally an acceptably good agreement between the experimental measurements and FEA predictions for the hybrid composite systems studied here. As expected, the experimental results and the predictions are independent of the tow orientations used. It is also noted from the table that the FEA predictions for the shear modulus are independent of carbon contents. This is simply because the shear modulus of the composites is dominated by the epoxy resin, which is the same at 30 % for both low and high carbon hybrid systems. Interestingly, the experimental results for modulus of 90^o specimens are better than the results for the modulus of 0^o specimens. This discrepancy can be attributed to the influence of other strain components besides the shear on the strain measurements, which is consistent with the analytical results shown in Fig. 5.

Table 2 Elastic shear modulus of hybrid composites

Hybrid Composite Systems		$\overline{G}$ (GPa)	G (GPa)	FEA Results (GPa)
Low Carbon	0^o Specimen	6.78 ± 0.32	6.03 ± 0.28	5.07
	90^o Specimen	4.87 ± 0.17	5.34 ± 0.19	5.07
High Carbon	0^o Specimen	6.48 ± 0.41	5.90 ± 0.37	5.05
	90^o Specimen	5.09 ± 0.18	5.48 ± 0.19	5.05

Typical complete shear stress-strain curves obtained from the Iosipescu tests for shear strength of both 0^o and 90^o specimens are shown in Fig. 8. Although the figure is obtained for a high carbon hybrid system, the stress-strain curve for a low carbon hybrid system is nearly identical. For 0^o specimens, the shear stress-strain relationship is moderately linear up to about 1 % of shear strain, where the first load drop was observed. By increasing the loading, sequential load drops were observed until specimen rupture, which is caused by severe crush at the inner loading points. For the 90^o specimens, there is also a nearly linear relationship between shear stress and strain up to the approximately 1 % of shear strain, where the specimens completely ruptured and no further stress-stain information could be recorded. Moreover, it was observed that the slope of the stress-strain curve in this case is less steep than the 0^o specimen. Furthermore, we used the tabbed specimens as suggested in the ASTM D-5379 [7], and still experienced similar observations since the tabs eventually would come off (debonding) before the specimen reached a desired failure. We attribute these premature failures, at about 1 % of shear strain in both 0^o and 90^o specimens, to stress concentrations caused by the existence of both geometry and material discontinuities at the free edges of the notches (not like non-hybrid composites where only the geometry discontinuity presents). This premature failure affects the measurement of shear strength. Therefore, at this stage, it is unlikely for us to interpret the shear strength based on the information given by the premature failure.

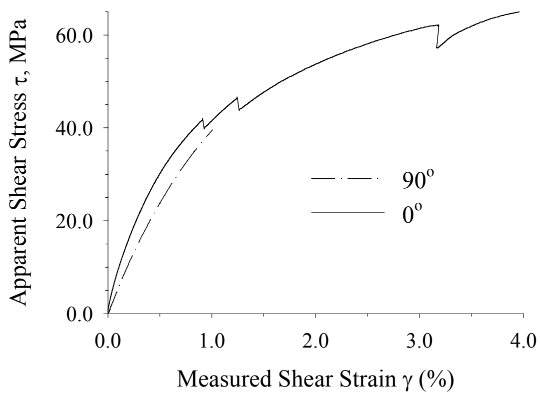

Fig. 8 Typical shear stress/strain curves of 0^o and 90^o specimens

5. CONCLUSIONS

The applicability of Iosipescu shear test as applied to unidirectional hybrid composites was investigated analytically and experimentally. The tow-based finite element analysis shows that although the small-scale reinforcement affects the composite micromechanics in the Iosipescu specimen, the test still exhibits a region possessing the uniformity and purity of stress-strain state between the notches to meet the requirement for determining the in-plane shear modulus and strength. Using different gage lengths in Iosipescu specimens, the effects of local inhomogeneity inherent in the hybrid composites on the shear property measurements are demonstrated. The study indicates that the Iosipescu test can be used for the measurement of shear modulus of the hybrid composites when it is correctly used. However, due to the premature failure, which is sensitive to the stress concentration in the notch area, can make the test undesirable for determining the shear strength of the hybrid composite.

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