EXPERIMENTAL AND THEORETICAL EVALUATIONS OF THE IOSIPESCU SHEAR TEST FOR HYBRID FIBER COMPOSITES

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ABSTRACT

The Iosipescu shear test with a modified Wyoming test fixture (ASTM D5379-93) was investigated experimentally and theoretically as a mean for determining the in-plane shear modulus and strength of unidirectional hybrid composites. Two types of hybrid systems having different fiber-tow volume fractions composed of carbon and glass fiber tows with epoxy matrix was used for the experimental study. An impregnated fiber-tow based finite element analysis was used to evaluate the effect of varied microstructures in hybrids on the shear stress-strain states. The good agreement found between experiments and analysis suggests that the v-notch shear test is a viable technique to determine the elastic shear modulus of unidirectional hybrid composites. On the other hand, the use of this specimen for shear strength determination is questionable as no failure in the test region occurred in the specimens. Therefore, at this stage, we conclude that the v-notch shear test is useful for the evaluation of the shear modulus, but not the shear strength, of the unidirectional hybrid composites. This study suggests that more detailed investigations on the shear strength measurements of hybrid composites are needed.

KEY WORDS: Iosipescu Shear Test, V-notch Specimen, Carbon/Glass Tow, Hybrid Composites, Shear Properties, Finite Element Analysis

1. INTRODUCTION

The Iosipescu shear test was originally designed for measuring shear properties of isotropic and homogenous materials such as metals [1]. Compared with other test methods, such as the thin-walled tube test and the solid rod torsion test [2,3], the Iosipescu shear test uses a flat specimen that is easier to fabricate while achieving a pure and uniform shear strain-stress state over the test region. Consequently, more reliable results can be obtained, and the test has become well accepted among researchers in the field. In the 1980's, Walrath and Adams [4-5] introduced the Iosipescu shear test to composite materials. Since then many investigations of the v-notch shear test, as applied to non-hybrid composite materials, have been conducted [6-10]. In all of these investigations, non-hybrid composites (only one type of fiber) were used, and they were treated as a homogeneous media. However, hybrid composites (different types of fibers mixed with one matrix material) might not have the relatively homogeneous system that non-hybrid composites possess due to the varied microstructures of hybrids. Therefore, through experimental and theoretical (numerical) evaluations, this study extends the current application of the Iosipescu shear test on non-hybrid composites to hybrid composites for determining the in-plane shear properties (stiffness and strength). This work is limited to a model composite material with unidirectional glass/carbon/epoxy hybrid systems.

2. EXPERIMENTS[*]

The modified Wyoming Iosipescu test fixture [11] with the double v-notch specimen shown in Fig.1 and MTS 810 loading cell were utilized for experimental study. 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. The fiber tow is defined as an impregnated tow in this study (in other words, the fiber tow is taken as a fiber/matrix system rather than a bundle of fibers). Two types of hybrid systems having different volume fractions of fiber tows were used for the Iosipescu specimens: the "low carbon" refers to a hybrid system with lower volume fraction of carbon/epoxy fiber tows (34 %, defined as the volume fraction of carbon/epoxy tows out of total fiber/epoxy tow volume in hybrid composites), and "high carbon" refers to a higher volume fraction of carbon/epoxy fiber tows (62 %). For both systems, the volume fraction of epoxy matrix of glass/epoxy and carbon/epoxy fiber tows is the same at 30 %. Note that this implies that the volume fraction of the epoxy matrix in the hybrid composites is also 30 %. The v-notch specimen geometry is displayed in Fig.3. The thickness of the specimen is 2.20 mm for high carbon samples, and 2.13 mm for low carbon samples (the standard uncertainty associated with the thickness is 0.01 mm). 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 indicated in Fig.3 (referred to as 0^o and 90^o specimens).

The stacked $\pm 45^o$ strain gauge rosettes (Micro-measurements CEA-06-120WR-350) are used with the approximate gauge size covering a square area of (4×4) mm^2 at the test region for the strain measurements. 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:

$$\overline{\gamma}^o = \varepsilon_{45^o} - \varepsilon_{-45^o} \tag{1}$$

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

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[*] Certain commercial materials, equipment and computer code are identified in this paper in order to specify adequately the experimental 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.

modulus, $\overline{G}$, of the hybrid composites can be calculated as:

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

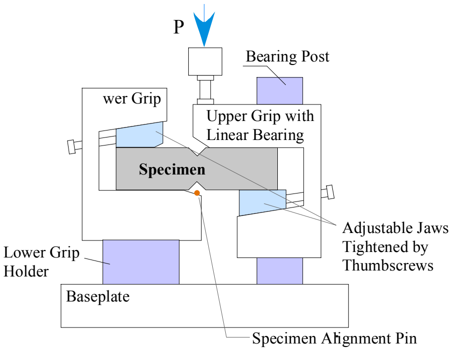
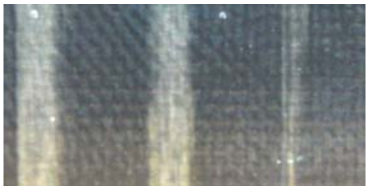


Fig.1 The modified Wyoming Iosipescu test fixture with v-notch specimen

(2a) cross section



(2b) surface

Fig.2 Photo images of hybrid composite flat samples

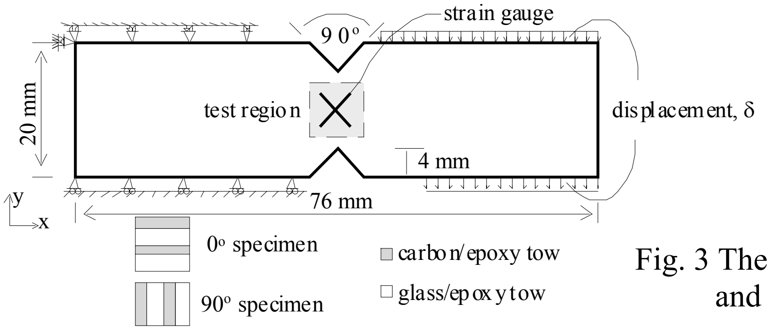


Fig. 3 The Iosipescu specimen configuration and loading/boundary conditions

3. THEORETICAL EVALUATION

To meet the requirements of uniform and pure shear strain-stress states for shear property measurements, a tow-based finite element analysis was used to simulate the v-notch specimen of hybrid composite made of carbon and glass fiber tows. A linear elastic approach was invoked by employing the commercial code ABAQUS [12] to analyze the stress-strain distributions of the specimen as shown in Fig.3. The loading and boundary conditions for the finite element analysis (FEA) is also displayed in Fig. 3. The tow-based microstructure was modeled based on the real image as shown in Fig.2. The whole specimen was modeled in FEA due to the asymmetric boundary and loading conditions. In the analyses, 8-node isoparametric continuum elements were used and the element dimensions continuously decreased towards the notch tips. Using more refined meshes allows the assessment of the convergence of the finite element solution on stress distributions around the notch tips. It was concluded from this study that good convergence of local stress is achieved.

The fiber content plays a major role on the stress distribution of composites, therefore, the hybrid composition, α, (defined as the volume fraction of carbon tows in the hybrid composites) was set as a variable in this study, ranging from 0 to 1.0 corresponding to non-hybrid glass/epoxy and carbon/epoxy composites, respectively. Both tows were treated as two-phase material systems with epoxy matrix and their corresponding fibers. For the stress analyses, we assumed that the volume fraction of epoxy matrix in glass and carbon fiber tows is the same as with the experiments at 30%, while the hybrid composition was varied. The material input requirements in FEA for each tow-based material properties were calculated from the rule-of-mixtures based on the mean value of each constituent properties reported in the literature (listed in Table 1). All the numerical calculations are based on these values. Once tow properties were determined with the pre-determined epoxy content, they were input into finite element models based on the hybrid composition for stress analyses.

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	3.00	51.79 ^{a}	165.33 ^{a}
E_{22}	72.70	13.80	3.00	10.05 ^{b}	7.49 ^{b}
ν_{12}	0.22	0.20	0.40	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

From eq. (1), one can see that the uniformity of the shear strain is governed by the uniformity of normal strain distributed in $\pm 45^{o}$ directions from the center of the specimen. The distributions of the normal strain for 0^{o} and 90^{o} specimens are shown in Fig. 4. From this figure, it is noted that, regardless of the hybrid composition, within the range studied the normal strain distributions in the gage directions are almost uniform for the specimens with tow orientations in 0^{o}. However, for the 90^{o} specimen, the uniformity in the normal strain of $\pm 45^{o}$ 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 both 0^{o} and 90^{o}

specimens, the test region should be limited up an area of (4x4) mm^2. The slight wavy patterns of shear train distributions seen in the figure implies the influence of the varied microstructure of hybrid composites on the stress/strain distributions.

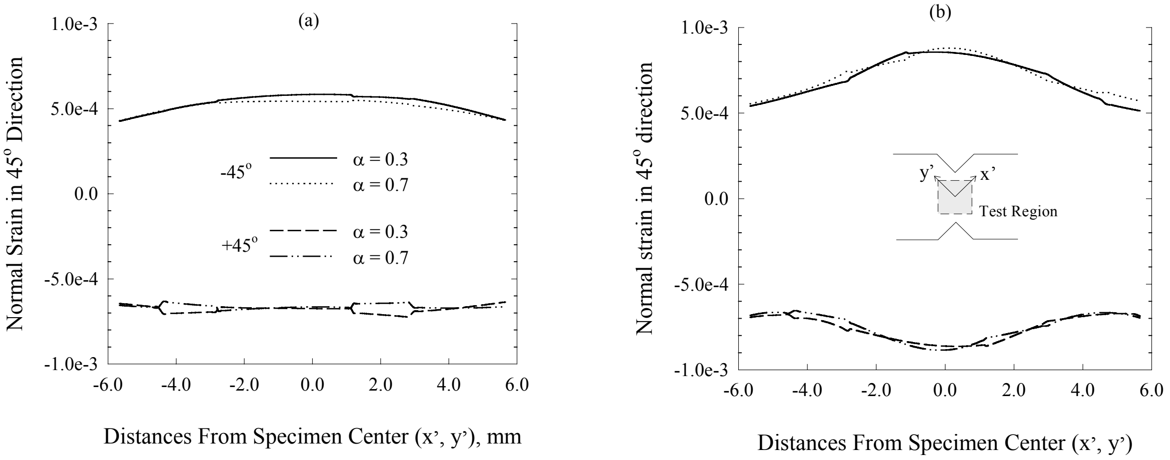


Fig.4 The $\pm 45^o$ normal shear strain components along the strain gauge directions at the test region: 0^o specimen (a), 90^o specimen (b)

One can also notice that the average shear strain at the test region ($\overline{\gamma}^o$) does not represent the global average shear strain ($\overline{\gamma}$) at the region between the two notch tips. Therefore, the shear modulus G of hybrid composites should be obtained by modifying the $\overline{G}$ with a correction factor (C) as following:

$$G = C\,\overline{G} \tag{3}$$

with $C = \overline{\gamma}^o / \overline{\gamma}$ and $\overline{\gamma} \equiv \frac{1}{A}\int \gamma \, dA$ (4)

where $\int \gamma \, dA$ represents the integration of the shear strain distribution over the cross sectional area between the notch tips.

Fig.5a shows the variation of correction factors for the measurements of shear modulus with different tow orientations as a function of hybrid compositions for a matrix volume fraction of 30 %. The effects of matrix volume fraction on the correction factor were also examined for hybrid compositions of 0.3 and 0.7 to represent the hybrid systems having low and high carbon content, respectively, and the results are shown in Fig.5b. For 90 ^{o} specimen, the correction factor practically is independent of hybrid composition for a fixed matrix volume fraction. Also, for a fixed hybrid composition, it is independent of matrix volume fraction at the extent numerically studied. This is because the shear deformation of the v-notch specimen is proportional to the ratio of E_x to G (E_x/G). E_x is the elastic modulus of the specimen in x-direction (shown in Fig.3), and G is the shear modulus of the specimen. For 90^o specimen, E_x is the transverse modulus of the specimen and varies insubstantially due to the change of hybrid composition or matrix volume fraction studied, since it is governed by the modulus of matrix. For 0 ° specimens, the E_x is the longitudinal modulus of the specimen that would be significantly affected by the hybrid composition but not the matrix volume fraction. Therefore, the correction factor for the 0 ° specimen only varies substantially when the hybrid composition changes.

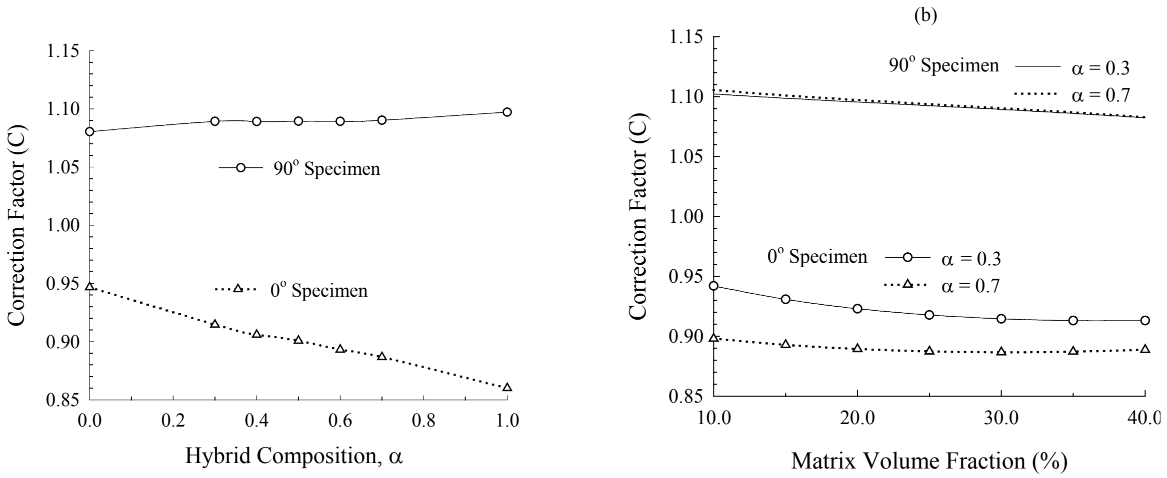


Fig.5 Correction factors for both 0° and 90° specimens with respect to: hybrid compositions at 30% matrix volume fraction (5a), matrix volume fractions (5b)

Unlike the measurement of 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 v-notch 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° and 90° specimens possessing different hybrid compositions. If we consider the test region as a representative cell, then in order to meet the requirement of the pure shear status in the test region, the directions of maximum and minimum principal stresses (σ_1 and σ_2) should coincide with the gage directions, ± 45°. Also, the values of σ_1 and σ_2 should be the same, but one in tension and the other in compression.

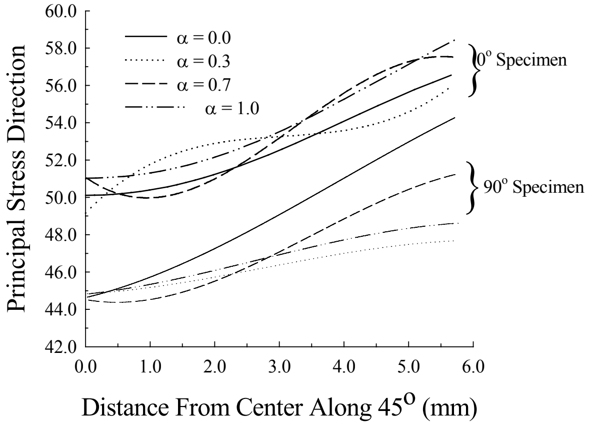


Fig.6 Principal stress directions along the strain gauge direction (45°) from the specimen center obtained from FEA

Fig.6 gives the variation of the principal direction with the location along 45° from the center of test regions for specimens possessing different hybrid compositions and tow orientations. From the deviation of the principal direction from 45° shown in Fig.6, one can consider that the 90° specimen of hybrid systems studied have an acceptable pure shear status near the central area of the test region. By recalling the analyses on the measurements of shear modulus, one may conclude that in experiment using a strain gage with a length to cover of (4x4) mm^2

should be good enough for determining both the shear modulus and strength.

In the 0^o specimen, the severe deviation of the principal direction from 45^o implies that the strain measured in the test region would have the influence of stresses other than the shear component, which in general may not be acceptable for the measurement of shear strength. However, in a study of using the v-notch specimen to determine shear properties for unidirectional monolithic composite, Pierron and Vautrin [10] suggested use a quadratic failure criterion [13] that takes the influence of stress other than shear into account, then the 0^o specimen can become acceptable for the shear strength measurement.

Based on the above analysis, theoretically both 0^o and 90^o specimens can be used to determine the shear strength of hybrid composites, while the interpretation of the shear strength from 0^o specimen would need extra effort. However, one may practically not be able to acquire a desired failure in shear mode that would happen in the test region. Instead, due to stress concentrations (singularity) caused by the existence of geometry and material discontinuities [14] at the free edges of the notches, a premature failure may occur in the notch tip area. This failure would affect the measurement of shear strength. Fig.7 displays the contour lines of stress distribution for all the stress components (longitudinal, σ_x; transverse, σ_y; and shear stresses, τ_{xy}) in the area near upper notch root of 0^o and 90^o specimens with hybrid composition of 0.7. In both specimens, stress concentrations are observed near the intersection of the notch root and notch flank on the opposite to the inner loading point. From these results we can see that the crack initiation (if it exists) may be caused by transverse tensile stress concentration rather than shear because the composite has much lower transverse tensile strength than other components including shear.

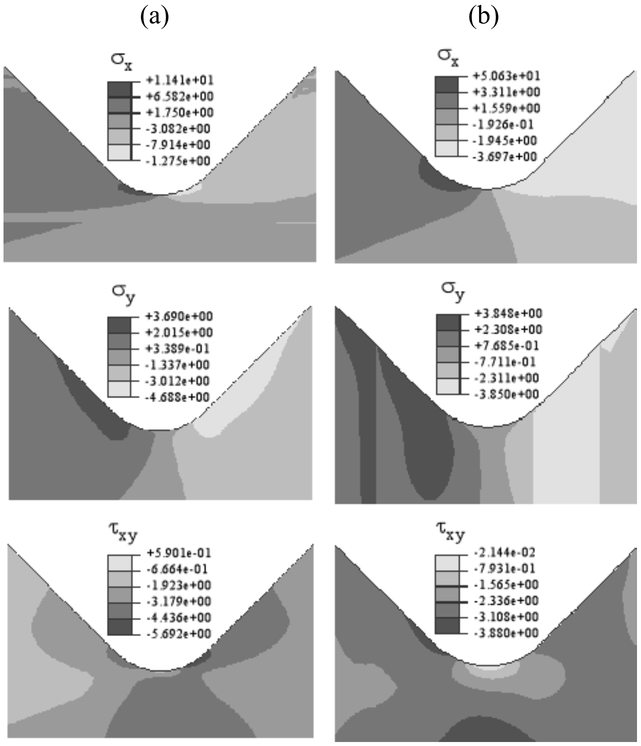


Fig.7 Contours of stress distributions around the notch root: 0^o specimen with average shear stress, 3.2 MPa, in the test region (a), 90^o specimen with average shear stress, 4.1 MPa, in the test region (b)

4. EXPERIMENTAL EVALUATION

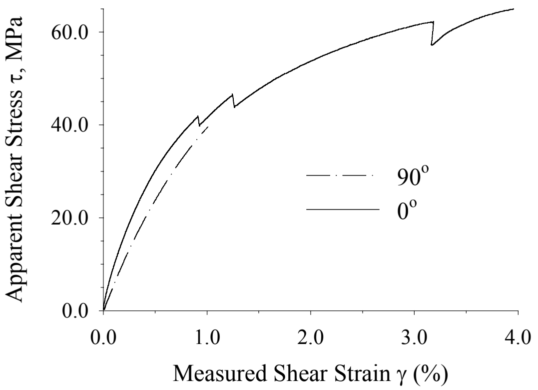


Fig.8 The typical shear stress/strain curves of 0° and 90° specimens

Typical shear stress-strain curves obtained from the Iosipescu shear tests for both 0° and 90° 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° 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 crushing at the inner loading points. For the 90° 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, the slope of the stress-strain curve in this case is less steep than the 0° specimen. For all specimens, the 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 0.3 %, 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 eq. (3) with $\overline{G}$ and the correction factors calculated from FEA. Within experimental uncertainties, there is generally an acceptably good agreement between the experimental measurements and FEA predictions for all of 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 0° specimens are worse than the results for the modulus of 90° 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 results of principal stress directions calculated from FEA shown in Fig.6.

A slight non-linearity is observed in the shear stress-strain curves for both the 0° and the 90° specimens presented in Fig.8, especially in the 0° specimens. One may argue that this apparent non-linearity is due to plastic deformation in the resin. However, we speculate that this is due to the micro cracks or micro damages, or local fiber instability before the major rupture events that will be discussed later. The apparent nonlinear behavior starts from the lower level of the shear strain (around 0.5 %) of the hybrid composite. The corresponding shear strain level in the epoxy matrix is estimated to be less than 2.5 %, since the shear modulus of the hybrid composites (≈ 5.0 GPa, Table 2) is about five times higher than the epoxy resin (≈1.0 GPa, Table.1). However, the shear yield strain for epoxies is generally around 6% [15]. Therefore, we believe that the epoxy resin does not exhibit plasticity at the shear strain range of the measurements.

Table.2 The elastic shear moduli of hybrid composites*

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

*The values after the (±) in all the tables refers the standard uncertainty of the measurement

As mentioned previously in Fig.8, we observed a catastrophic failure in 90^{o} specimens once the shear strain reached about 1 %. Crack initiation was observed at the point opposite to the inner loading points (see Fig. 3), near the intersections of the upper notch root and straight flank, not at the notch tips, and the crack aligned to the tow direction as shown in Fig.9a. Once the crack initiated, it propagated through the specimen and caused complete failure, see Fig.9b. Based on the analytical study, the 90^{o} specimen exhibited purer and more uniform shear strain distribution over the test region covered by the strain gages. Therefore, one may expect the 90^{o} specimen to produce better shear strength data. However, the early failure around the notch root area in the 90^{o} specimen makes it impossible to measure the shear strength.

For the 0^{o} specimens, when the shear strain reaches about 1 %, crack initiation occurs. The crack was also located opposite to the inner loading points near to the intersection of the upper notch root and straight flank, and the crack was parallel to the tow direction as shown in Fig. 10. Once the crack initiated, it would propagate. However, the propagation of the crack eventually would be arrested. When the load was increased, a second crack initiation was observed in a very similar location as the first crack but in another notch root. The locations of the first and second cracks are basically asymmetric. Similar to the behavior observed in the first crack, the second crack was also arrested after some propagation. These two crack initiations correspond to the first and second load drops in the stress-strain curve shown in Fig.8. Under further loading, these two cracks propagated along the fiber tow direction and stopped near to the high compressive zone caused by the loading fixture. By continuously increasing the loading, crush of material occurred at the inner loading points due to the stress concentration. So the latter loading drops could possibly correspond to the material crush at inner loading points or more cracks occurred around the notch roots instead of the center region between the notches. Therefore, although there is a theoretical modification in the shear strength determination to compensate for the poor purity and uniformity of the shear stress state in 0^{o} specimen, one still cannot get a desired failure in test region.

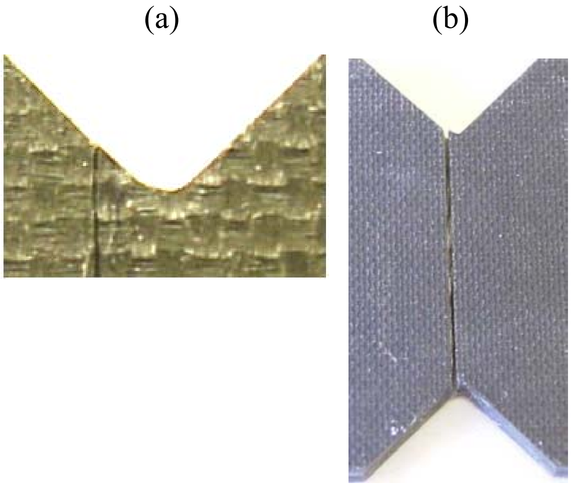


Fig.9 The crack and rupture images of 90^o specimen: initial location (a); rupture (b)

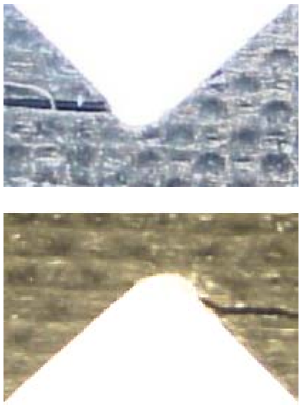


Fig.10 Photo images of first and second cracks occurred at notch roots in 0^o specimen

5. CONCLUSIONS

Using the Iosipescu shear test with the modified Wyoming test fixture, the in-plane shear properties of unidirectional hybrid composite were evaluated theoretically and experimentally. The v-notch specimen of hybrid composite contains carbon/epoxy and glass/epoxy tows in 0^o and 90^o directions. The good agreement between analytical approaches and experiments demonstrates that the Iosipescu shear test is a viable means for determining the elastic shear modulus of unidirectional hybrid composites, while the 90^o specimens give a better evaluation of the elastic modulus. The study also demonstrates that the matrix content dominated the shear modulus of unidirectional hybrid composite, as it does for non-hybrid composites.

Based on experimental observations and the finite element analysis, it seems impossible to use 90^o specimens for characterizing the shear strength of the hybrid composite, although they have better purity and uniformity than 0^o specimens in shear stress distribution over test region. On the other hand, no desired shear failure in the test region can be observed for the 0^o specimen. Therefore, at this stage, we conclude that Iosipescu shear test is effective for the evaluation of the shear modulus, but not for the shear strength, of the unidirectional hybrid composites.

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