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Composites: Part B 33 (2002) 461–470

composites
Part B: engineering

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An analytical assessment of using the Iosipescu shear test for hybrid composites

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Received 18 April 2002; accepted 14 May 2002

Abstract

A theoretical evaluation of the applicability of the Iosipescu test (v-notch shear test) has been conducted for hybrid composites having unidirectional glass and carbon fiber tows that are intimately mixed, instead of being arranged in separate lamina. The v-notch specimen of hybrid composites was analyzed using the finite element method based on the fiber tow properties to evaluate the effect of varied microstructures in hybrids on the shear stress and strain states. The analyses were conducted to determine how closely the test would meet the requirement of an ideal shear test that there should be pure and uniform stress and strain distributions in the test region. The study shows that, theoretically, the v-notch 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 the hybrid composite.

Keywords: A. Hybrid; A. Carbon and glass fibers; B. Fracture; C. Finite element analysis; Iosipescu v-notch shear test

1. Introduction

The development of composites containing more than one type of fiber reinforcement (hybrid composites) has been motivated from industry because of the improved performance as well as reduced weight and cost that hybrid composites could provide. Consequently, the complete and accurate knowledge of mechanical properties of hybrid composites becomes important in approaching the design requirements or in developing new hybrid materials. For tensile and compressive properties, there are many well-documented testing techniques for non-hybrid composites that are widely accepted by many researchers, and it should be possible to apply them to hybrid composites without any significant problems. However, for shear properties, the situation is much more complex because one of the major problems in shear testing is the influence of stress components other than shear stress on the final measurements. In particular, the state of shear in hybrid composites is expected to be complicated since they possess varied microstructures. Among the existing shear test methods for non-hybrid composites, we selected the v-notch shear test (and is also known as the Iosipescu shear test, ASTM D5379-93 [1], Fig. 1) as a potential candidate for characterizing shear properties of hybrid composites, since the test has been well characterized and widely accepted. Therefore, the objective of this report is to assess the applicability of the v-notch test to hybrid composites through finite element analysis (FEA). The effects of different material parameters on test results will be discussed. The work is motivated by experimental observations [2] and, consequently, is limited to the investigation of unidirectional glass–carbon fiber hybrids.

The v-notch shear test was originally proposed by Iosipescu for determining shear properties of isotropic materials such as metals [3]. The test uses flat specimens that are easy to fabricate while achieving a pure and uniform shear stress–strain state over the sample region to be tested. In the 1980s, Walrath and Adams [4,5] applied the v-notch specimen with a modified test fixture to non-hybrid composites. Since then, many numerical and experimental investigations on the application of the v-notch shear test to different composite material systems have been carried out [e.g., 6–11]. Linear and non-linear numerical analyses (both material and geometry non-linearities) have been performed to promote the understanding and to improve the original v-notch shear test for application to composite systems. These studies have investigated the effects of composite material orthotropy, notch angle and tip radius, and fiber orientation on the stress distribution in the test region

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1359-8368/02/$ - see front matter
PII: S1359-8368(02)00022-7

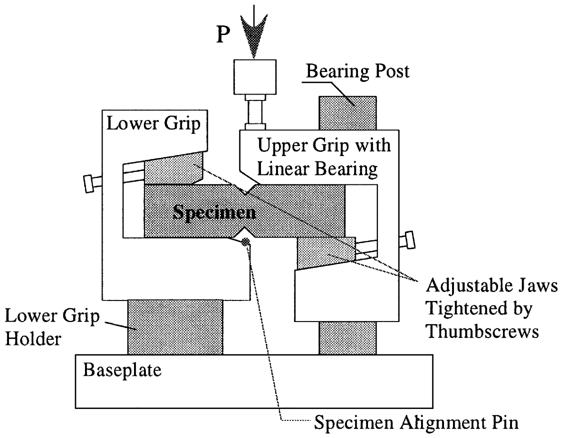


Fig. 1. Schematic of the modified Iosipescu shear test fixture with the v-notch specimen.

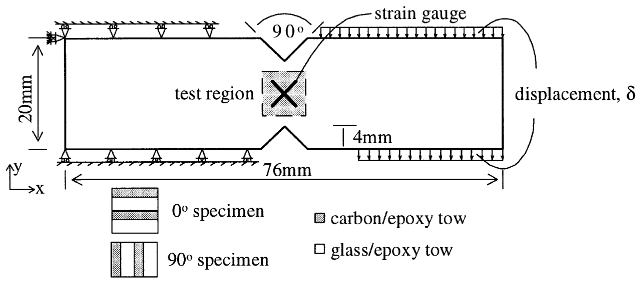


Fig. 2. The v-notch specimen configuration and loading/boundary conditions in FEA.

between the notches. All of these theoretical and/or experimental evaluations on the v-notch test are based on non-hybrid fiber/matrix composite systems.

The hybrid composite we used in this study contained different types of fiber tows that were intimately mixed throughout the resin matrix (microcombination). 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). This microcombination of reinforcement will affect the composite micromechanics, and the difference in mechanical behavior between such a hybrid and non-hybrid reinforcements may be appreciable. Therefore, in this study a theoretical evaluation for understanding the applicability of the v-notch shear test has been conducted for hybrid composites having unidirectional glass/epoxy and carbon/epoxy tows intimately mixed. To determine how closely the v-notch test would meet the requirement of ideal shear test for hybrid composite, the stress–strain distributions of v-notch test samples were determined using FEA with tow-based models. In this study, the tow-based model is defined such that the tow is treated as a minimal microstructure, and necessary material properties that are input for the analyses are based on tow properties. Detailed models for FEA and necessary material properties used in the analyses are described in Section 2. Numerical results and discussions are presented in Section 3. Conclusions and recommendations are given in Section 4.

2. Finite element analyses and material properties[1]

In the tow-based FEA of the v-notch specimen, a linear elastic approach was invoked by employing the commercial code ABAQUS [12] to analyze the stress–strain distributions of the v-notch specimen shown in Fig. 2. In an experiment, stacked strain gages at ±45° 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 radius of the notch tips is 1.3 mm. The thickness of specimen was assumed to be 2.0 mm. The tow size varies depending on the fiber volume fraction, which will be discussed later. The specimen of the unidirectional hybrid composite was assumed to be made of carbon/epoxy and glass/epoxy tows. The tow-based microstructure model was based on images of unidirectional glass/carbon/epoxy hybrid composites [2]. Fig. 3 shows the photographs of a representative hybrid composite.

V-notch specimens with tow orientations in horizontal and vertical directions (referred to as 0° and 90° specimens) as shown in Fig. 2 were considered. Both 2D and 3D FEA were carried out for the specimens. The 2D and 3D models for 0° and 90° specimens, based on ASTM specifications on geometry and loading conditions, are shown in Fig. 4. The whole specimen was modeled in FEA due to the asymmetric boundary and loading conditions. In 2D analyses, 8-node isoparametric continuum elements were used, while in 3D analyses, 8-node isoparametric solid elements were used. For the best accuracy, the v-notched specimen should be analyzed using the 3D model, but after comparing the 2D analyses and 3D analyses, we found that the added cost and complexity of 3D analysis was not warranted, since the 2D approach provided the in-plane stress states accurately. Therefore, all the analyses reported here used the 2D approach.

The fiber content plays a major role in the stress distribution of composites, therefore, the hybrid com position, α, (defined as the volume fraction of carbon/epoxy tows out of the total fiber/epoxy tow volume in the hybrid composite) was set as a variable in this study. α ranges from 0 to 100% corresponding to non-hybrid glass/epoxy and carbon/epoxy composites, respectively. Both types of tows were treated as two-phase material systems with epoxy matrix and their corresponding fibers. In the 2D finite element model, glass/epoxy and carbon/epoxy tows were alternated and a fixed dimension (4 mm—based on the images of a representative glass/carbon hybrid composite

[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.

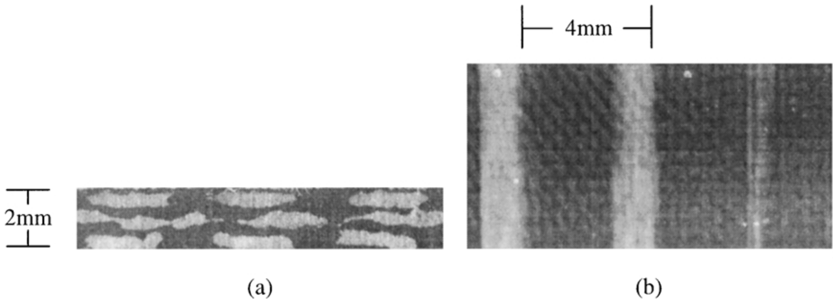


Fig. 3. Photo images of a representative glass/carbon hybrid composite sample: cross-section (a), surface (b). The bright regions represent the glass/epoxy fiber tows and the dark regions represent the carbon/epoxy fiber tows.

sample shown in Fig. 3(b)), was chosen to include one glass/epoxy tow and one carbon/epoxy tow. Within this 4 mm, α is changed for the parametric study and the tow sizes will vary accordingly. Typical 2D finite element meshes are shown in Fig. 5. The element dimensions continuously decrease towards the notch tips. We refined the mesh until good convergence of the local stress at the notch tips was achieved. The FEA results indicate that the stress states in the specimen are not sensitive to the ordering of tows with respect to the notch tip (Fig. 4(a)). Also, in 3D analyses, the arrangement of tows in the thickness direction does not affect the in-plane stress state. These results are early indications that there is a little effect of hybrid construction on the in-plane shear modulus of hybrid composites.

For most of the stress analyses, we assumed that the volume fraction of epoxy matrix in the glass/epoxy and carbon/epoxy tows is 30%, while the hybrid composition was varied. This implies that the total volume fraction of the epoxy matrix in the hybrid composites is also 30%. Some other values of epoxy volume fraction with high or low carbon fiber contents were also examined in FEA to assess the importance of this parameter. The material input requirements in FEA for each tow-based material property were calculated from the rule-of-mixtures 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. The longitudinal modulus, E_{11}, was predicted from a general rule-of-mixtures. A modified rule-of mixtures was used to calculate the transverse modulus, E_{22}, and shear modulus, G_{12}, because of the Poisson's effect between the fiber and matrix [13]. Once tow properties were determined with a given epoxy content, they were input into finite element models based on the hybrid composition for stress analyses.

3. Results and discussions

Determination of shear modulus. The shear modulus can be obtained with the shear stress and corresponding shear strain as long as the stress and strain are uniformly distributed in the test region where they are measured. Therefore, the uniformity of shear stress and corresponding strain in the test region need to be examined to assess the accuracy of the shear modulus determination. Based on the ASTM D5379-93 standards [1], the stacked $\pm 45°$ strain gages should be placed at the center between the notches of the specimen as shown in Fig. 2. The apparent in-plane shear strain, $\bar{\gamma}$, in the cross-section along two notch tips can be calculated from the measurement of normal (longitudinal) strain of the gages, $\varepsilon^{\pm 45}$, as follows:

$$\bar{\gamma} = \varepsilon^{45} - \varepsilon^{-45} \tag{1}$$

With the experimentally obtained $\bar{\gamma}$ and the average applied shear stress, $\bar{\tau}$ ($\equiv P/A$, where P is the resultant loading forces and A is the cross-sectional area between the notch tips), the apparent in-plane shear modulus, $\bar{G}$, of the hybrid composites can be calculated as:

$$\bar{G} = \frac{\bar{\tau}}{\bar{\gamma}} \tag{2}$$

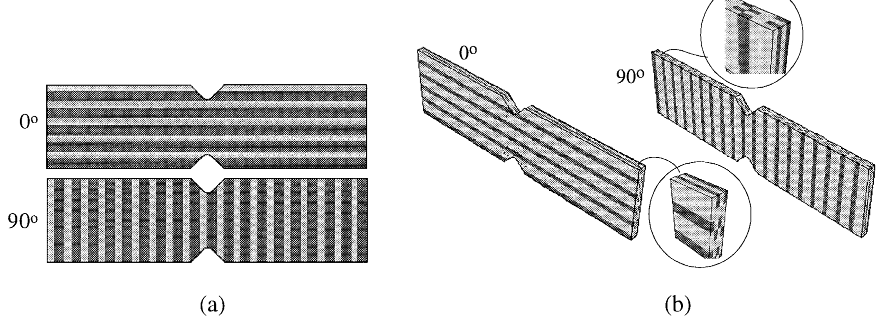


Fig. 4. Tow-based finite element model of hybrid composite: 2D model (a), 3D model (b).

Table 1
The constituent properties and calculated tow properties

Elastic modulus	E-glass fiber (GPa)	Carbon fiber (GPa)	Epoxy resin (GPa)	E-glass/epoxy tow[a] (GPa)	Carbon/epoxy tow[a] (GPa)
E_{11}	72.7	234.9	3.0	51.8[a]	165.3[a]
E_{22}	72.7	13.8	3.0	10.1[b]	7.5[b]
ν_{12}	0.22	0.20	0.40	0.27[a]	0.26[a]
G_{12}	30.0	28.8	1.1	5.1[b]	5.0[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.

One can see from Eq. (1) that the uniformity of the shear strain is governed by the uniformity of normal strain distributed in $\pm 45°$ direction from the center of the specimen. The distributions of the normal strains for 0° and 90° specimens are shown in Fig. 6. 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 of 0°. However, for the 90° specimen, the uniformity in the normal strain at $\pm 45°$ can be only approximately achieved in the region from -3 to 3 mm in the 45° direction shown in Fig. 6(b). This suggests that, in order to have a test region with uniform shear strain for both 0° and 90° specimens, the test region should be limited to an area of 4×4 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. 7 shows the shear stress distributions along the cross-section between two notch tips of 0° and 90° specimens with different hybrid compositions. From the figure, one can see in general for the hybrid system studied that the distribution of shear stress becomes singular near the notch tips and has a fairly uniform value in the central region of the cross-section. The results indicate that, for all the specimens considered, a normalized cross-sectional length ranging from -0.5 to 0.5 (corresponding to 6 mm) could be considered as a region having fairly uniform shear stress. Combined with the previous discussion on shear strain for the hybrid systems studied, one should be able to obtain a region with uniform shear stress and corresponding uniform shear strain if using strain gages to cover a test region limited within 4×4 mm^2. Consequently, an apparent shear modulus for unidirectional hybrid composites could be determined. The suggested test region has to be large enough to include different types of tow as a representative of the hybrid system.

From Fig. 7 one can also notice that the average applied shear stress, $\bar{\tau}$, does not represent the uniform shear stress at the test region covered by strain gauge in the v-notch specimen. Therefore, the shear modulus of the hybrid

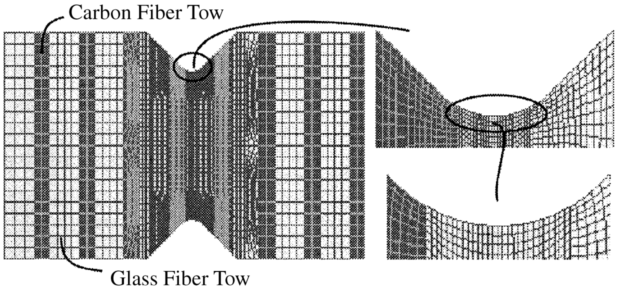


Fig. 5. Finite element mesh of Iosipescu specimen for the hybrid composites.

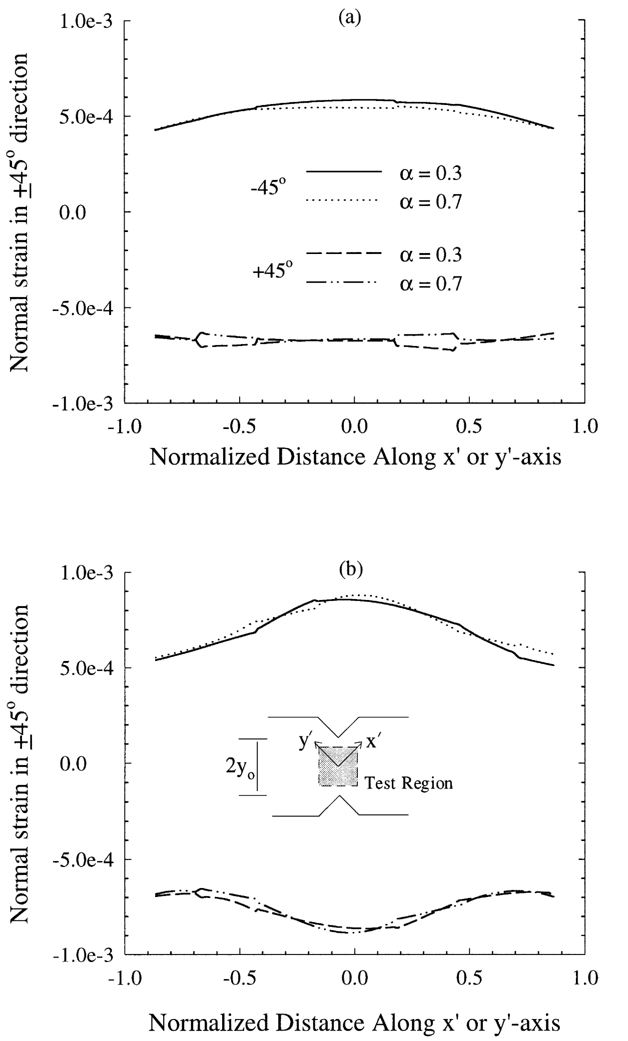


Fig. 6. The normal strain components along the strain gauge directions ($\pm 45°$) at the test region: 0° specimen (a), 90° specimen (b). The distance is normalized with y_0 (6 mm).

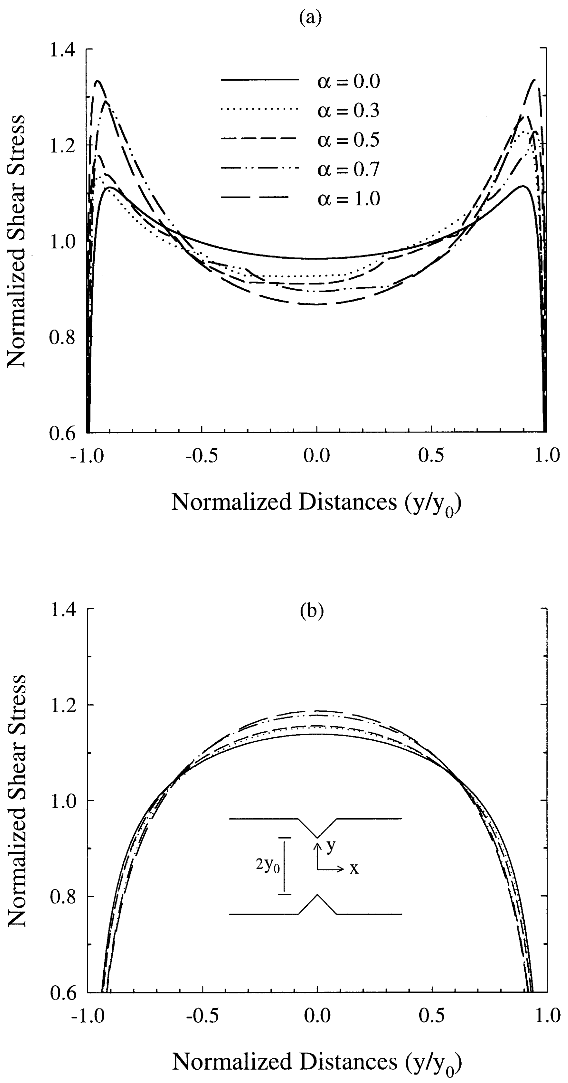


Fig. 7. Shear stresses, normalized by the average applied shear stress ($\bar{\tau}$), along the central line between the notch tips: 0° model (a), 90° model (b).

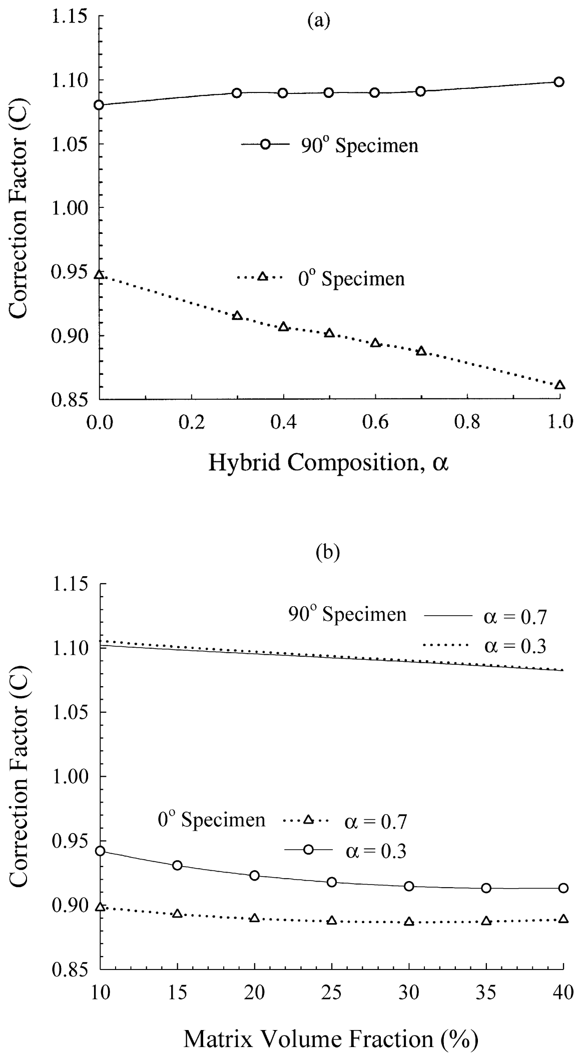


Fig. 8. Correction factors for both 0° and 90° specimens with respect to: hybrid compositions at 30% matrix volume fraction (a), matrix volume fractions (b).

composites, G, should be obtained by modifying $\bar{G}$ with a correction factor (C) as follows

$$G = C\bar{G} \tag{3}$$

with

$$C = \tau^0/\bar{\tau} \text{ and } \tau^0 \equiv \frac{1}{A_0}\int \tau \, dA \tag{4}$$

where $\int \tau \, dA$ represents the integration of the shear stress distribution over the test region, and A_0 represents the total area covered by the strain gauge. One can see that the local shear stress at the test region covered by the strain gauge is larger than the global average shear stress $\bar{\tau}$ in the 90° specimen, while in the 0° specimen the shear stress is smaller than $\bar{\tau}$. Therefore, different correction factors for 0° and 90° specimens are needed in the determination of the shear modulus.

Fig. 8(a) shows the variation of shear correction factors 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 α equal 30 and 70%, and results are shown in Fig. 8(b). For 90° specimens, the correction factor is practically independent of hybrid composition or matrix volume fraction. 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 (Fig. 2), and G is the shear modulus of the specimen. For 90° specimens, 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, which would be significantly affected by the hybrid composition but not the matrix volume fraction. Therefore, the correction factor for the 0° specimen varies when the hybrid composition changes. Nevertheless, it should be acceptable for one to use 0.9 and 1.1 as correction

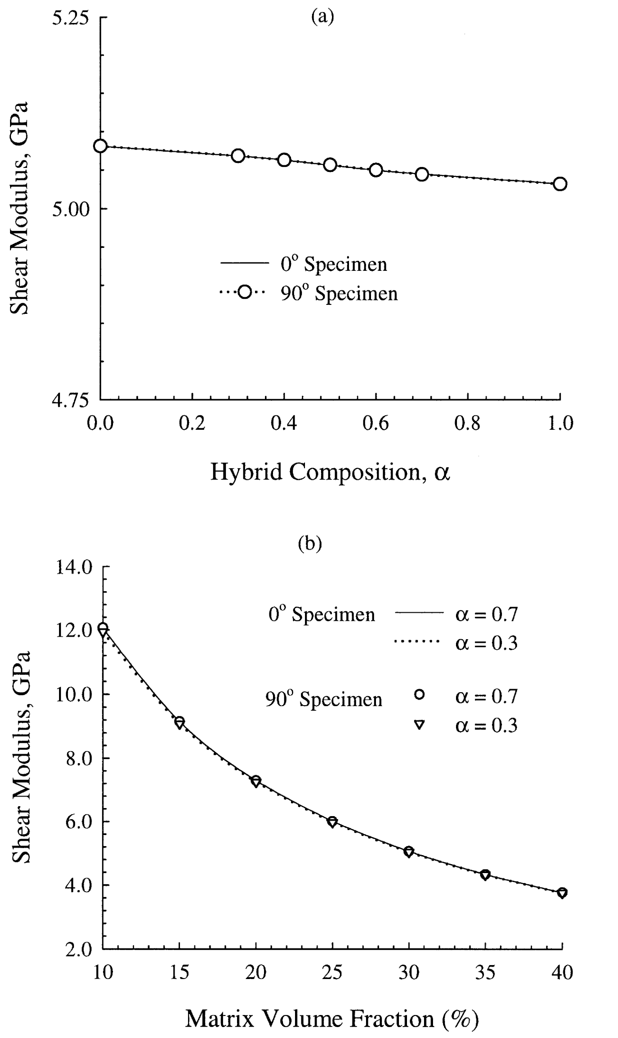


Fig. 9. Shear modulus obtained from both 0° and 90° specimens with respect to: hybrid compositions at 30% matrix volume fraction (a), matrix volume fractions (b).

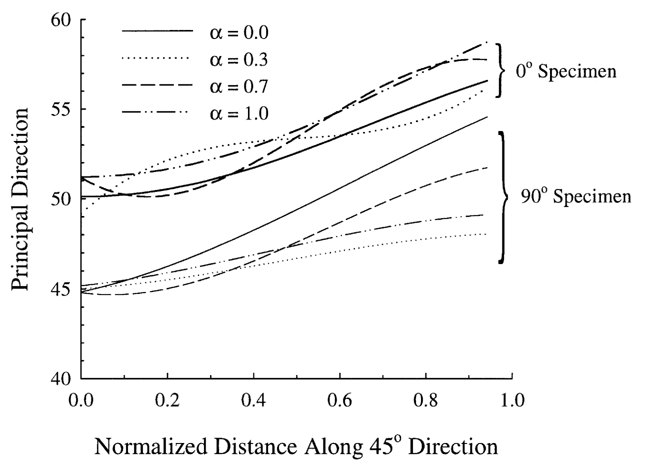


Fig. 10. The principal stress directions along the strain gauge direction (45°) from the specimen center. The distance is normalized with y_0 as shown in Fig. 5(b).

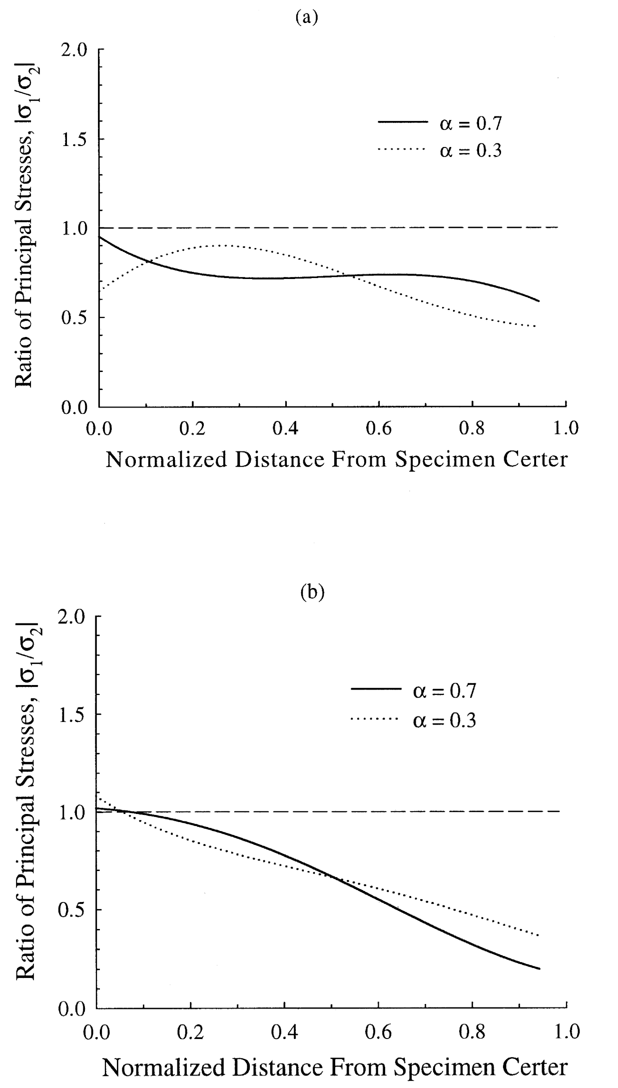


Fig. 11. Principle stresses, $|\sigma_1/\sigma_2|$, along the strain gauge direction from specimen center at test region: 0° specimen (a), 90° specimen (b). The distance is normalized with y_0 as shown in Fig. 5(b).

factors for 0° and 90° specimens, respectively, regardless of the hybrid composition and the matrix volume fraction.

Fig. 9 shows the prediction of the corrected shear modulus as a function of hybrid composition and matrix volume fraction. For all the cases, the predicted shear modulus is independent of tow orientations as expected. For a fixed matrix volume fraction, the effect of hybrid composition on the shear modulus is negligible (Fig. 9(a)), but the shear modulus decreases as matrix volume fraction increases. These results reflect the fact that the shear modulus is dominated by the matrix. In a separate report on the experimental evaluation of the shear modulus for hybrid composites [2], it has been demonstrated that there is good agreement between the experimental measurements and finite element predictions for the hybrid composite systems studied here.

Determination of in-plane shear strength. Unlike the measurement of the shear modulus, the measurement of

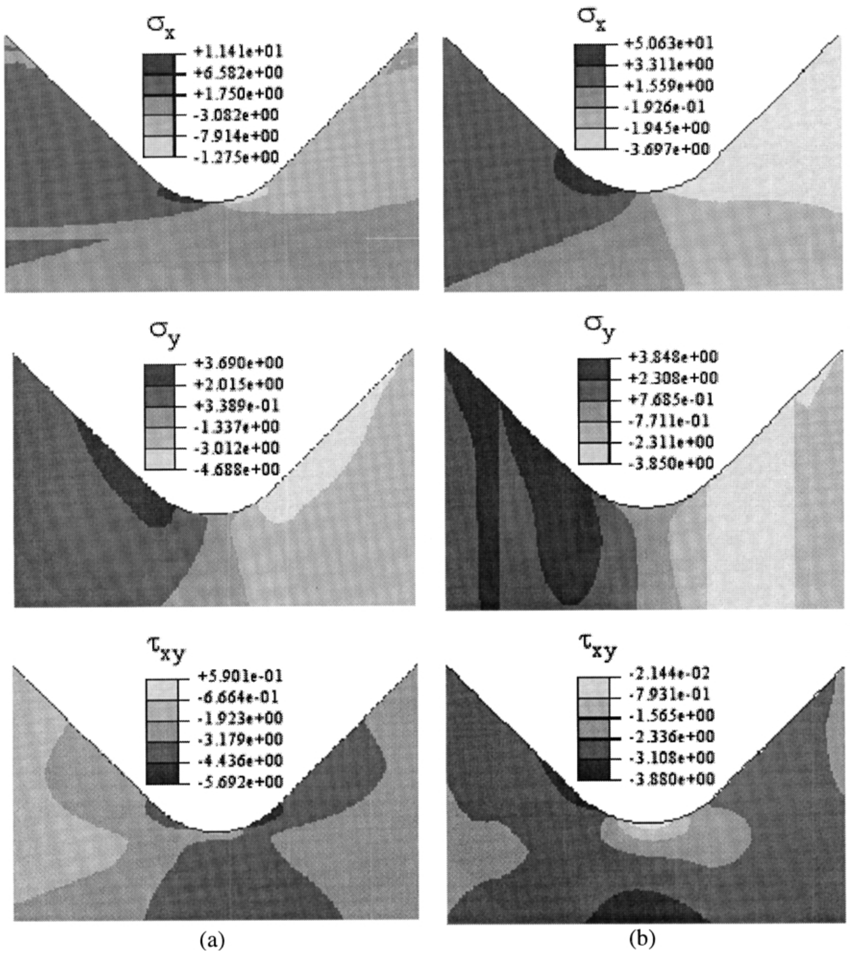


Fig. 12. Contours of stress distributions around the notch root: 0° specimen with average shear stress, 3.2, in the test region (a), 90° specimen with average shear stress, 4.1, in the test region (b).

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 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, $\pm 45°$. Also, the values of σ_1 and σ_2 should be the same, but one in tension and the other in compression.

Fig. 10 shows the variation of the principal direction with the location along 45° from the center of test region for specimens possessing different hybrid compositions and tow orientations. Fig. 11 shows the ratio of σ_1 and σ_2 as a function of the location along 45° from the center of the test region. From the deviation of principal directions from 45° shown in Fig. 10 and the ratio of σ_1 and σ_2 shown in Fig. 11, we believe that the 90° specimen of 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 an experiment with a 90° specimen using a strain gage to cover 4×4 mm^2 should be acceptable for determining both the shear modulus and strength.

In the 0° specimen, the severe deviation of the principal direction from 45° implies that 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 using v-notch specimens to determine shear properties for non-hybrid unidirectional composites, Pierron and Vautrin [11] suggested using a quadratic failure criterion (proposed by Tsai [13]) that takes the influence of stress other than shear into account. If one accepts such a failure criterion, and one can evaluate the unwanted stresses, then the 0° specimen could be acceptable for the shear strength measurement.

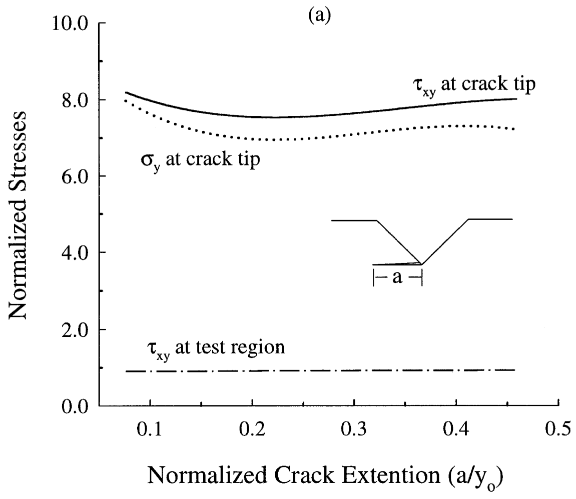
Based on the above analysis, theoretically both 0 and 90° specimens can be used to determine the shear strength of hybrid composites, while the interpretation of the shear strength from 0° specimen would need extra effort. However, in practice, one may not be able to achieve the desired failure mode in the test region. Instead, due to stress concentrations caused by the existence of geometry and material discontinuities at the free edges of the notches, a premature failure may occur in the notch tip area [14,15].

This failure would affect the measurement of shear strength. Fig. 12 shows the contour lines of the stress distribution for all the stress components (longitudinal, transverse and shear stresses) in the area near upper notch root of 0° and 90° 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.

In the case of 0° specimen, from Fig. 12(a), one can notice that near the notch root there is a significant stress concentration in the longitudinal component of the stress (σ_x) compared with other stress components, σ_y and τ_{xy}. Since the strength of the composite along the fiber direction is much higher than that in other directions, it is not likely that this large stress concentration would cause any premature failure of the specimen. What could be possible is that σ_y and τ_{xy} in the notch root region may initiate a crack parallel to the tow orientation before a shear failure in the test region. We speculate that this crack, if it occurs, would be located in the epoxy resin phase between tows along the fiber–matrix interface (indeed, cracks were observed in an experimental study [2]). Also, the crack initiation could be due to a mixed-mode fracture, where more than one loading mode is present (opening and shearing modes). A comparison of the stress concentrations of σ_y with τ_{xy} shown in Fig. 12(a) would suggest that the crack initiation would be highly dominated by the opening mode (tensile transverse stress, σ_y, normal to the tow orientation), since the tensile strength of the resin is much lower than the shear strength. In the case of 90° specimens, from Fig. 12(b) it can be seen that the σ_x (the stress transverse to the fiber orientation) is tensile near the notch root, and it has larger magnitude than the shear stress at the same place or at the test region. Again, this tensile stress could initiate a crack.

Based on the above discussion on possible crack formations, we placed a crack in the finite element model at the notch root to mimic the failure due to the stress concentration. The crack is located at the stress concentration region observed in Fig. 12 for 0° and 90° specimens. The crack orientations are along the tow direction. The length of initial crack is taken as a variable in FEA. The shear and normal stresses at the crack tip and the average shear stress in the test region (τ^0) are monitored.

A comparison of shear and normal stress at the crack tip and τ^0 with respect to the different initial crack extensions are shown in Fig. 13. It is noticed that the length of the initial crack extension does not affect the magnitude of shear stress at the test region for either the 0° or the 90° specimens. This is because the shear deformation of the specimen is affected by the stress transfer due to the longitudinal stiffness of the specimen, and that stiffness is not affected by the existence of the crack along the interface of tows or fibers. Fig. 13(a) shows the results of stress analysis for 0° specimens with a crack at the location of the stress concentration indicated in the inset of the figure. The results in the figure show that the magnitudes of normal and shear stress at crack tip are much



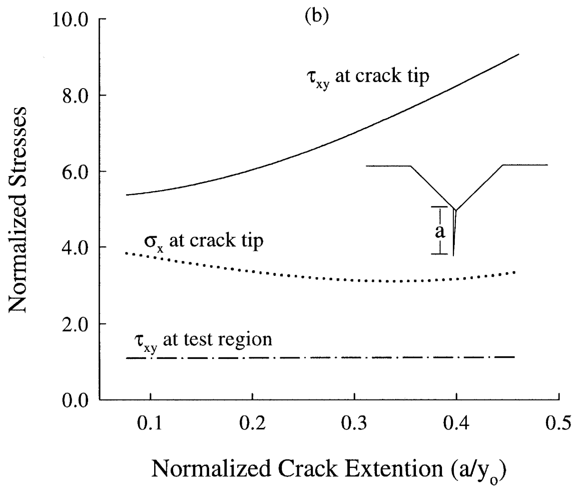
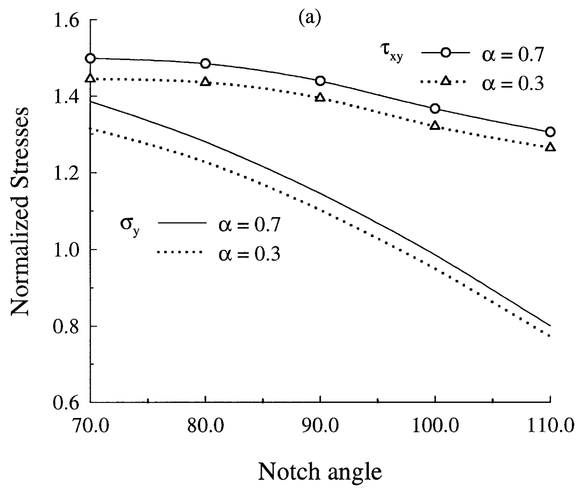


Fig. 13. Stresses, normalized by the average applied shear stress ($\bar{\tau}$), with respect to the initial length of crack extension: 0° specimen (a), 90° specimen (b).

higher than the shear stress in the test region, and they are nearly independent of the crack extension. This suggests that the crack would not propagate without increasing the load. The propagation event should be arrested when the crack extension reaches the compression region under the loading point. During the stage of crack extension in the 0° specimen, it might be difficult to get the desired failure in the test region, and difficult to interpret the shear strength from the crack initiation (as mentioned in Ref. [11]), due to a highly mixed-mode failure.

Fig. 13(b) shows the results of stress analysis for 90° specimens with a crack at the location of the stress concentration indicated in the inset of the figure. The figure presents the variation of normal and shear stress at crack tip with the length of the initial crack extension. One can notice from the figure that the shear stress at the crack tip increases with crack extension, while the normal stress at the crack tip and shear stress at the test region remain unchanged. This predicts that, once the crack is initiated, the crack would



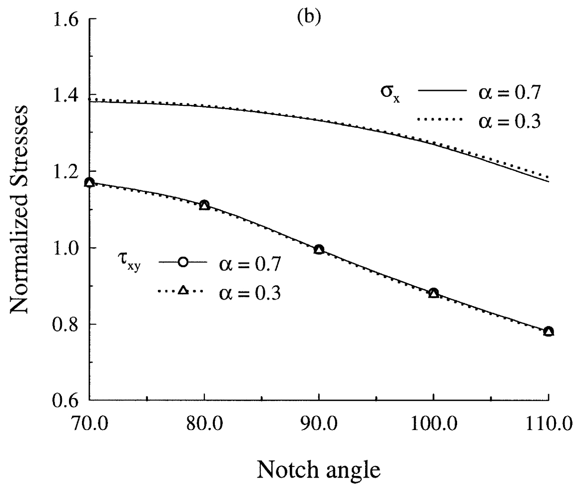


Fig. 14. Stresses, normalized by the average applied shear stress ($\bar{\tau}$), around the notch root with respect to different notch angles: 0° specimen (a), 90° specimen (b).

become unstable and propagate through the cross-section and finally cause the rupture of the specimen. Therefore, for the 90° specimen, it is impossible to get the desired failure in the test region, or to interpret the shear strength based on the information given by the crack initiation. The increase of the shear stress at the crack tip is due to the decrease of the cross-sectional area. Since the bending moment at the mid span of the specimen is nearly zero, the normal stress (σ_x shown in Fig. 13(b)) induced is due to the existence of the interfacial crack.

One way to reduce the stress concentration around the notch roots is to change the notch angles [15]. The stress concentrations in the notch root area have been evaluated for different notch angles in the finite element model, while keeping the sizes of the mesh unchanged. The comparisons of the maximum shear and normal stresses around the notch roots and the average shear stress at the center region with respect to different notch angles are shown in Fig. 14. Both 0° and 90° specimens with two hybrid compositions (0.3 and 0.7) were considered. For 0° specimens, stress concentration of σ_y and τ_{xy} components were assessed. For 90° specimens, σ_x with τ_{xy} were evaluated. One can notice from the results that all the stress concentrations decrease with the increase of notch angles for the hybrid systems studied. In the 0° specimen, σ_y decreases much faster than τ_{xy} when the notch angle increases. Therefore, it is possible that the increase of the notch angle might change the initial failure occurring at the notch roots in 0° specimens from an opening or mixed-mode to a shear mode. In 90° specimens, one can see that σ_x and τ_{xy} decreases with a similar pace, from which we may speculate that the change of notch angle will not influence the initial failure mode near the notch roots.

4. Conclusions

The applicability of v-notch shear test as applied to unidirectional hybrid composites was investigated analytically. The tow-based FEA shows that although the microcombination of reinforcement affects the composite micromechanics in the v-notch 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. Thus, the analytical study indicates that the v-notch test can be used for the shear testing of the hybrid composites studied when it is correctly used. However, due to stress concentrations caused by the existence of geometry and material discontinuities at the free edges of the notches, a possible premature failure of the specimen can occur in the notch tip area. This 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. By changing the notch angle to reduce (or eliminate) the stress concentration, one may achieve a stress equal to the ultimate shear strength in the test region. Therefore, for determining the optimal notch angle, a more rigorous analysis of the stress distribution near the notch area for composites with different degrees of anisotropy is necessary. Finally, the study indicates that there is no hybrid effect on the in-plane shear modulus of hybrid composites.

Acknowledgments

The authors gratefully acknowledge Dr Carl Schultheisz for valuable comments and suggestions as a reviewer during the internal review of this manuscript.

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