Determination of Shear Properties for RP Pultruded Composites

S. S. SONTI AND E. J. BARBERO*
Constructed Facilities Center (CFC) West Virginia University (WVU), Morgantown, WV 26505

T. WINEGARDNER
Creative Pultrusions, Inc., Alum Bank, PA

ABSTRACT: A complete understanding of the behavior of a structural system comprising RP components necessitates the determination of material properties for these components. Properties of interest include tensile, compressive, shear and bending stiffness and strength. This study focuses on the identification of a reliable test method for the determination of in-plane shear modulus and strength. Iosipescu shear tests and torsion tests were conducted on coupon samples. Results indicate that the torsion test is an easier and reliable method for the determination of shear modulus whereas the Iosipescu test should be used for the determination of shear strength.

INTRODUCTION

SHEAR PROPERTIES ARE needed in the design of RP structures when considering local buckling, web crippling and connections in thin-walled structural members. Manufacturer's literature generally tend to overlook the shear properties and concentrate on in-plane moduli and strength, flexural moduli and strength, full-section moduli etc. The in-plane shear modulus G_{12} and shear strength S need to be established since these properties can control the behavior of the system. At times, a high longitudinal modulus can be obtained at the expense of a low in-plane shear modulus. The objective of this study was to identify an easy and reliable test method while producing material property data needed for design purposes.

In this study, two test methods were used for the determination of shear properties: 1) Iosipescu shear test method; and 2) Torsion test. The growing use of the Iosipescu shear test method for composite materials motivated us to use this test method for our experiments and thereby establish its reliability for pultruded materials. A redesigned Wyoming fixture was built for this test. Manufacture of

This paper was presented at the *49th Annual Conference, Composites Institute, The Society of the Plastics Industry, Inc.*, February 7–9, 1994
*Author to whom correspondence should be addressed.

0731-6844/95/04 0390-12 $10.00/0

the test samples was cumbersome and laborious. Also, a large scatter was observed in the test results. To overcome the problems encountered during the Iosipescu test a torsion test setup was used for the determination of shear modulus. Manufacture of the samples was easier and this test allowed us to use a larger sample thereby providing us with an average value of shear modulus for the composite laminate. For the prediction of shear modulus, an elasticity solution with contiguity was used. The predicted values did not correlate well with the experimental data. Therefore, a stress partition parameter 'η_s' was used. The stress partition parameter was obtained using experimental data for currently produced pultruded materials and assuming that it remained constant while varying the fiber volume and resin properties during material optimization studies.

IOSIPESCU SHEAR TEST METHOD

There has been an increasing trend in the composite materials community to use the Iosipescu shear test method for the determination of shear properties. The Iosipescu shear test method, originally developed by Nicolae Iosipescu for metals and isotropic materials [4] is being widely used in the composites community for the characterization of shear properties. Many researchers in recent years have used this test method and presented their results [1,2,6]. The growing use of the Iosipescu test method for composite materials motivated us to use this method for our experiments and thereby establish its reliability for pultruded materials.

Specimen Geometry and Preparation

Specimens were obtained from the web and flanges of an 8 × 8 × 3/8 in. I-beam (Vinylester 1625, CP stock WFI-beam [3].) The specimen is 3 in. long, 0.75 in. wide, 0.375 in. thick. Initially, the specimen had a planar rectangular shape before notches were cut on the longitudinal sides of the specimen at a depth equal to 20 percent of the specimen width, i.e., to a depth of 0.15 in. and a notch radius of 0.05 in. This was done by drilling a hole using a 0.1 in. diameter drill bit to a depth of 0.15 in. at the midsection of the specimen. The notch was ground using a 60 grit abrasive wheel while the specimen was fixed at a 45 degree angle. The depth of the cut was increased gradually in small steps in order to obtain a notch with an angle of 90 degrees merging smoothly into the notch radius of 0.05 in.

Test Procedure

The test fixture (Figure 1) was fabricated at West Virginia University on the lines of the redesigned Wyoming fixture. The shear test fixture was used in a testing machine set up in a compression mode to test specimens 0.75 in. wide allowing a variation of 0.04 inch on that width. The fixture comprises two identical halves of which the left half is fixed to the base and the right half moves up and down on four posts and a recirculating ball bushing. The right half of the fixture is so designed to be easily attached to the crosshead of a testing machine. The crosshead holds and positions the fixture and the specimen can be easily in-

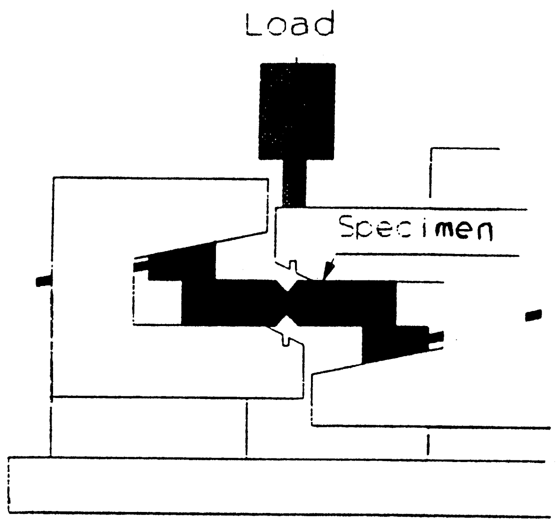

Figure 1. Iosipescu shear test fixture with the specimen.

stalled. The advantage of using this fixture is that the front face of the specimen remains visible during the test and failure progression can be monitored visually. This test induces a state of uniform shear stress at the midsection of the specimen by creating two counteracting moments which are produced by the applied loads. As suggested by many researchers, the loading points were located away from the notch edge. Adams et al. [1] indicated that loading points too close to the notches caused the influence of concentrated loadings to spread into the gage section region. Also Spigel et al. [6] found that for the determination of shear modulus, where the strains are measured near the center of the specimen, moving the load away from the notch edge resulted in a more uniform state of shear and therefore a more accurate shear modulus value.

For the tests conducted, loads were recorded in a computerized data acquisition system and the shear strains measured by using a ± 45 degree two-element strain gauge bonded at the centerline of the coupon between the notches. The gages were connected in a quarter bridge configuration. After balancing and calibrating the compression load cell of the Instron machine, the coupon is placed into the fixture and fastened with the trapezoidal blocks by tightening the screws. After the coupon is set and the entire fixture is aligned with the loading axis, the fixture is fastened on the load cell and the bonded strain gages are balanced with the strain conditioner. The test was performed at a loading rate of 0.02 in./min. The differential voltage output, transferred into the strain conditioner and through quarter bridge configuration and signal amplification, is recorded by a data acquisition system. As the load produces pure shear applied shear stress is given by

$$\tau_{xy} = \frac{P}{A_{no}} \tag{1}$$

where

τ_{xy} = shear stress
P = applied load
A_{no} = area of cross-section between the notches

For a plane strain problem, with an orientation of 45 degrees, the expression for shear strain is obtained as

$$\gamma_{xy} = \epsilon_{45} - \epsilon_{-45} \tag{2}$$

From Equations (1) and (2) the shear modulus G_{xy} can be given as

$$G_{xy} = \frac{\tau_{xy}}{\gamma_{xy}} \tag{3}$$

The shear strength can be obtained as

$$S = \frac{P}{A_{no}} \tag{4}$$

Test Results

Iosipescu shear tests are performed and the results shown in Table 1. The in-plane shear modulus and strength are computed as explained in the above section. The shear modulus is computed from the values obtained in the linear range of the recorded data. The shear strength is computed using the value of ultimate failure loads. Figures 2 and 3 show the load-strain curves for flange and web specimens respectively from the Iosipescu shear test. Figure 4 shows a stress-strain curve for a typical Iosipescu shear test.

From Table 1 it can be observed that the value of the shear stiffness varies from 0.3×10^6 psi to 0.7×10^6 psi. There is a variability in the material due to the pultrusion process. During the Iosipescu test we are concentrating on a very small area for the material property and the stiffness will vary depending on whether it is a fiber rich or a resin rich area. Table 2 shows the results for the shear stiffness from the torsion tests and a greater consistency can be observed. The consistency of the results in the torsion test vs. the Iosipescu test can be clearly appreciated in Figure 7, that shows the normal probability density for G_{xy}.

TORSION TEST METHOD

The Iosipescu shear test results show a large scatter which can be attributed to the fact that the samples are obtained from various locations of the beam under

Table 1. Iosipescu shear test results.

Location	Shear stiffness $G_{xy} \times 10^6$ psi	Shear strength (S) psi
Flange 1	0.719	14285.71
Flange 2	0.627	19714.28
Flange 3	0.414	11011.90
Flange 4	0.362	9821.42
Flange 5	0.341	10085.35
Flange 6	0.570	10463.15
Flange 7	0.746	10201.60
Flange 8	0.744	9969.04
Flange 9	0.568	9066.66
Flange 10	0.604	8811.01
Web 1	0.670	13095.23
Web 2	0.639	11607.14
Web 3	0.504	9736.54
Web 4	0.487	7992.67
Web 5	0.354	9184.34
Web 6	0.855	10782.85
Web 7	0.812	10056.25
Web 8	0.888	9108.80

Table 2. Shear modulus results from torsion tests.

Location	Twisting	Loading G_{xy} (psi $\times 10^6$)	Unloading G_{xy} (psi $\times 10^6$)
Flange 1	Clockwise	0.532	0.526
Flange 1	Counterclockwise	0.554	0.557
Flange 2	Clockwise	0.545	0.565
Flange 2	Counterclockwise	0.576	0.590
Flange 3	Clockwise	0.560	0.560
Flange 3	Counterclockwise	0.575	0.595
Flange 4	Clockwise	0.511	0.511
Flange 4	Counterclockwise	0.539	0.543
Web 1	Clockwise	0.554	0.556
Web 1	Counterclockwise	0.573	0.584

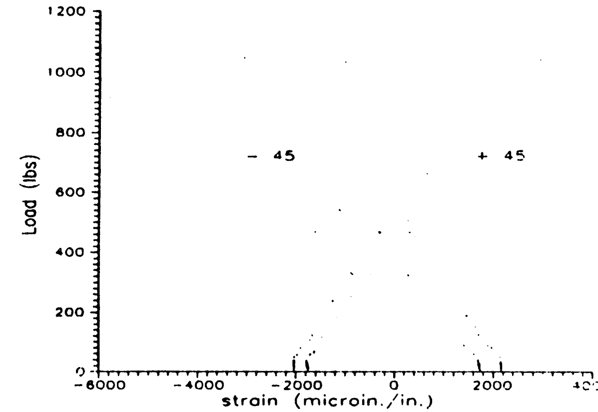

Figure 2. *Iosipescu shear test on a flange specimen.*

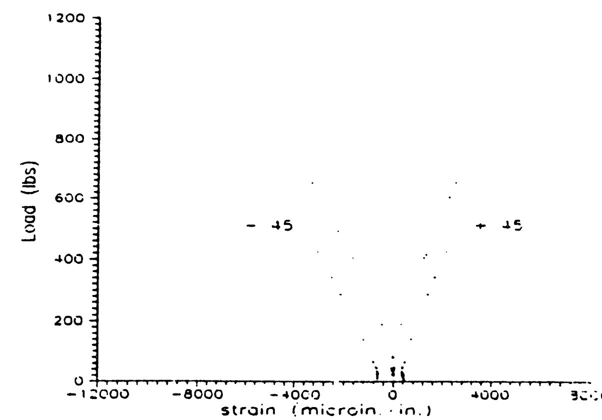

Figure 3. *Iosipescu shear test on a web specimen.*

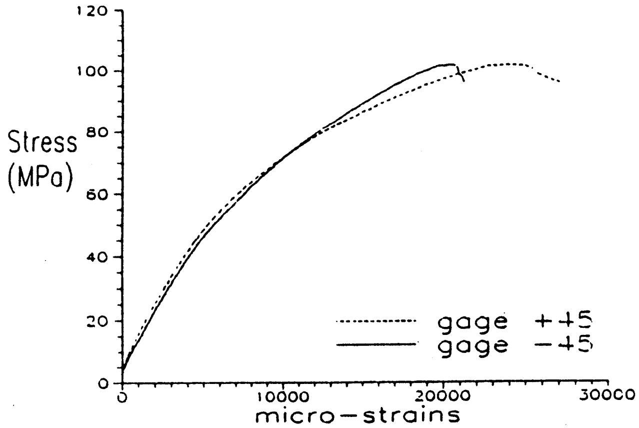

Figure 4. *Stress-strain curve for an Iosipescu specimen.*

investigation. Also a very small cross-sectional area (pure shear zone) is being considered for the evaluation of the shear property. Properties vary from point to point because of the irregularities of the pultruded materials. There is a need for a test method which would give consistent shear test results. A torsion test setup was used that allowed the use of larger test samples. On a large sample, irregularities compensate each other and the resulting properties are more representative of the structural behavior of the material. For this test, transverse isotropy was assumed [8].

Test Procedure

Five 7″ × 1″ samples were used that were obtained from the flanges and web of the 8 × 8 × 3/8 in. I-beam (Vinyl ester 1625, CP stock WF I-beam, [3].) Torque was applied on the samples at a loading rate of less than 3 degrees per minute both in loading and unloading. To assess the effect of possible misalignment we applied both clockwise and anticlockwise twisting. Figure 5 shows the schematic of applicaiton of torque to the specimen. The moment was computed from the displacement of the reacting arm on a torsion machine, displacement that was measured by a LVDT hooked to a computerized data acquisition system. The twisting angle was measured on a gage length of 11.17 in. as the difference between two LVDT's hooked to the data acquisition system. The shear modulus was computed using the Lekhnitskii torsion solution for orthotropic rectangular plates. The formula used is

$$K = \frac{T}{\theta^t} = \frac{G_{12} d t^3}{L} \frac{1}{\beta^t} \quad (5)$$

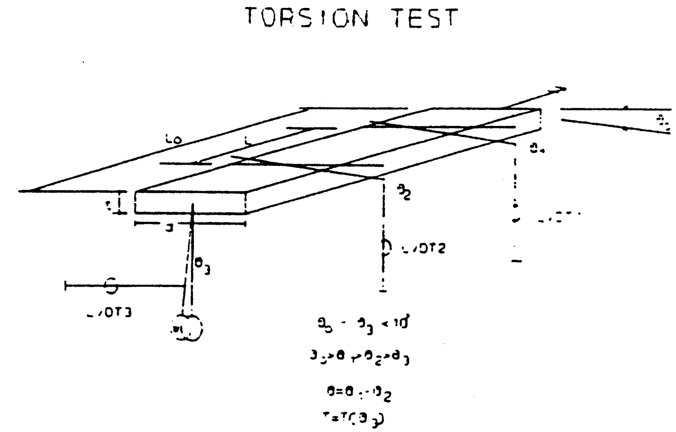

Figure 5. *Schematics of a torsion test.*

where (Figure 5)

dt = cross-sectional area
L = gage length ($L < L_o$)
T = Torque
Θ^t = twist angle
$\beta^t = \beta^t (G_{12}, G_{13})$

Test Results

Figure 6 shows a typical torque vs. angle of twist curve. The apparent hysteretic effect is not due to the material but due to the static friction of the hubs

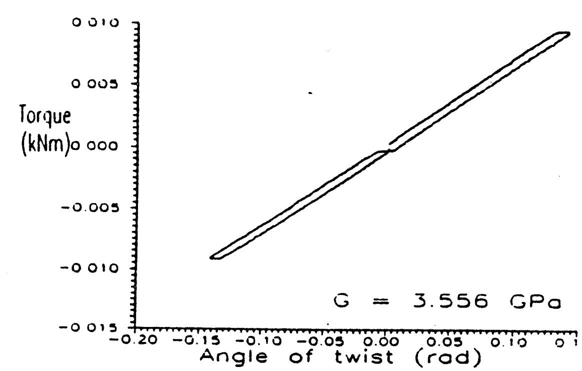

Figure 6. *Torque vs. angle of twist curve for a torsion test.*

on the torsion machine. The curves are linear due to the low strain level experienced in the material during test. Table 2 shows the test results for the torsion test.

From Table 2 it can be observed that there is less scatter in the results than those obtained from Iosipescu tests listed in Table 1. Figure 7, showing the normal probability density curve for G_{xy}, clearly establishes the difference in scatter between the two test methods. In the torsion tests the property is the average over a certain length of the specimen. Better consistency of the results makes it an economic alternative over Iosipescu tests for the determination of shear stiffness.

THEORETICAL PREDICTION

The shear modulus based on elasticity solutions with contiguity is determined by [5].

$$G_{12} = (1 - C)\, G_m 2G_f - (G_f - G_m)V_m/2G_m$$
$$+ (G_f - G_m)V_m + CG_f(G_f + G_m) \quad (6)$$
$$- (G_f - G_m)V_m/(G_f + G_m) + (G_f - G_m)V_m$$

This equation underpredicts the shear modulus. Therefore, the mechanics of materials approach equation modified by the stress partitioning parameters is used in this work. The in-plane shear modulus of the lamina G_{12}, is determined by the mechanics of materials approach by assuming that the shearing stresses on the fiber and the matrix are the same. The expression for the shear modulus is given by

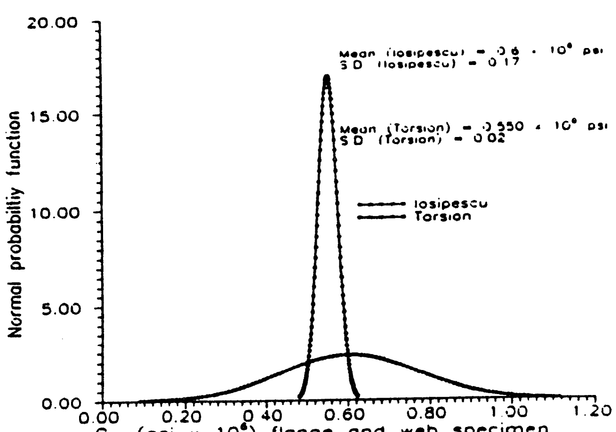

Figure 7. Statistical distribution curves for G_{xy} from Iosipescu and torsion tests.

$$G_{12} = G_m G_f / V_m G_f + V_f G_m \quad (7)$$

The above equation for the shear modulus is a series-connected model unlike the models for longitudinal and transverse modulus which are parallel models. Parallel models give upper bound predictions and series models give lower bound predictions. In this study, it was observed that Equation (7) gives values lower than the measured data. This can be corrected by adding an empirical constant to this equation as shown next.

Hahn [7] suggested a stress partitioning parameter to be used to correct the prediction of the shear modulus

$$\eta_s = \langle \sigma_m \rangle / \langle \sigma_f \rangle \quad (8)$$

where

σ_m = average matrix stress
σ_f = average fiber stress
η_s = stress partitioning parameter

Equation (7) can be modified to include the stress partition parameters as

$$(1 + \eta_s V_m/V_f)/G_{12} = 1/G_f + (\eta_s V_m/V_f)/G_m \quad (9)$$

Individual layers of pultruded materials cannot be isolated for testing of G_{12}. So, from a sample of a typical pultruded composite, we back-calculate η_s from the experimenetal data for G_{xy}, using the following equation.

$$(1 + \eta_s V_m/V_f)/G_{xy} = 1/G_f + (\eta_s V_m/V_f)/G_m \quad (10)$$

In Equation (10) the average of the experimental values is used for G_{xy} and the shear moduli for the fibers and the matrix are computed from their longitudinal moduli assuming both the fibers and the matrix to be isotropic. The stress partition parameter thus obtained is used in Equation (9) to obtain G_{12} for each individual lamina. With the inclusion of the stress partitioning parameter, the micromechanics Equation (9) is reliable for performing a sensitivity study of micromechanics variables such as constituent properties and volume fraction as long as the manufacturing process is not altered. After the computation of G_{12} for individual layers, classical lamination theory is used for the determination of G_{xy} for the laminate.

EXPERIMENTAL AND THEORETICAL CORRELATION

In this section, a comparison is made between the average of the experimental values and the theoretical predictions. Table 3 shows the correltion for the flange specimen and Table 4 shows the correlation for the web specimen. Also, a statistical study was done where normal probability density distribution was shown for

Table 3. *Correlation for flange samples.*

Property	Predicted Value	Experimental Average (Iosipescu)	Experimental Average (Torsion)
G_{xy}	0.435×10^6 psi	0.484×10^6 psi	0.552×10^6 psi
S	8533 psi	10819.05 psi	#

Table 4. *Correlation for web samples.*

Property	Predicted Value	Experimental Average (Iosipescu)	Experimental Average (Torsion)
G_{xy}	0.444×10^6 psi	0.651×10^6 psi	0.566×10^6 psi
S	8720 psi	10195.47 psi	#

each of the experimentally measured quantities. Figure 7 shows the probability distribution of shear modulus from Iosipescu and torsion tests.

From Tables 3 and 4 it can be observed that experimental average for the torsion tests is consistent regardless of it being a flange or web specimen. The Iosipescu test shows a significant amount of difference between the flange and the web specimen which is due to fiber concentration over a small area. The values for the shear stiffness and strength correlate well with the theoretical values obtained for stiffnesses and strengths except the shear stiffness for web from the Iosipescu test where the experimental average is higher. This can be due to more samples tested with fiber dominated areas around the notch. The statistical distribution curve (Figure 7) is indicative of the consistency of the torsion test over the Iosipescu test for shear stiffness. The statistical curve for the shear strength from Iosipescu tests also shows a poor consistency indicating that these results are also highly affected by the variability in the composition of the material. This variability is caused by the pultrusion process; it is random, and difficult to predict.

CONCLUSIONS

The Iosipescu test is being widely used for the evaluation of shear modulus of composite materials. It was found that the torsion test provided more consistent results for the in-plane shear modulus. There was a considerable amount of scatter in the Iosipescu tests which can be attributed to the fact that the test area is very small and the material is not uniform. The torsion test results obtained are approximately the average of the Iosipescu shear test results. The use of the torsion test is recommended for the evaluation of in-plane shear modulus. The Iosipescu test (or similar) is the only test available for the determination of shear strength. An extension of the torsion test to determine strength is desirable. A torsion failure criterion is being developed which would allow us to use the torsion test method for the determination of shear modulus and strength.

REFERENCES

1. Adams, D. F. and D. E. Walrath. 1987. "Further Development of the Iosipescu Shear Test Method," *Experimental Mechancis*, 27(2):113–199.
2. Bank, L. C. 1989. "Shear Properties of Pultruded Glass FRP Materials," *ASCE Structures Congress*, San Francisco: CA.
3. Creative Pultrusions. 1988. *Design Guide*. Creative Pultrusions Inc., Pleasantville: PA
4. Iosipescu, N. 1967. "New Accurate Procedure for Single Shear Testing of Metals," *Journal of Materials 2(3):537–566*
5. Jones, R. M. 1975. *Mechanics of Composite Materials*. Hemisphere Publishing Co., USA
6. Spigel, B. S., R. Prabhakaran, and J. W. Sawyer. 1987. "An investigation of the Iosipescu and Asymmetical Four-point bend tests," *Experimental Mechanics*, 27(1):57–63.
7. Tsai, S. W. 1987. "Composite Design," *Think Composites*, Dayton, OH.
8. Davalos, J. F., J. R. Loferski, Holzer, S. M. and Lawada, V. 1991. "Transverse Isotropy Modeling of 3-D Glolaw Timber Beams," *J. Mater. in Civil Eng.*, 3(2):125–139.