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EXPERIMENTAL CHARACTERIZATION OF FILAMENT WOUND GLASS/EPOXY AND CARBON/EPOXY COMPOSITE MATERIALS

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ABSTRACT

Composites have been used extensively in application such as pipes and pressure vessels. Therefore there is a need for further studies on the properties of these materials. This paper presents the results from a series of tensile tests on the mechanical properties of composite materials. Specimens cut from pipes made from composite materials were tested under internal pressure loadings have been tested by using a series of ASTM Standards test methods for mechanical properties. Based on the results obtained, the longitudinal E_{11}, transverse E_{22} and shear modulus G_{12} of 101.2 GPa, 5.718 GPa, 4.346 GPa and 36.6, 5.4 GPa, 4.085 GPa for carbon and glass fiber/ epoxy composites, respectively, while the ultimate longitudinal X^L, transverse X^T and shear tensile τ_0 strengths of 1475.4 MPa, 20 MPa, 36 MPa and 618.9 MPa, 14 MPa, 28 MPa for carbon and glass fiber/epoxy composites, respectively. The results from this series of tests have been presented and compared with results from analytical equations. Good agreement was achieved between the experimental results and analytical results.

Keywords: characterization, filament wound pipes**,** glass, carbon, epoxy, composite, mechanical properties, tensile test.

INTRODUCTION

In order to of estimate strength and stiffness, structural materials are subjected to mechanical testing. Tests aimed at evaluating the mechanical characteristics of fibrous polymeric composites are the very foundation of technical specification of materials and for design purposes [1]. Composite materials in the context of high performance materials for structural applications have been used increasingly since the early 1960s; although materials such as glass fiber reinforced polymers were already being studied 20 years earlier. Initially conventional test methods originally developed for determining the physical and mechanical properties of metals and other homogenous and isotropic construction materials were used. It was soon recognized however that these new materials which are non homogenous and anisotropic (orthotropic) require special consideration for determining physical and mechanical properties [2]. The uses of composite structures have proliferated recently to include a large number of new applications. Once only used for specialized parts or secondary members, composites are now considered to be competitive with other materials in many applications. The fact that composites in general can be custom tailored to suit individual requirements have desirable properties in corrosive environment; provide higher strength at a lower weight and have lower life-cycle costs has aided in their evolution. Also it provides a good combination in mechanical property, thermal and insulating protection. These qualities in addition to the ability to monitor the performance of the material in the field via embedded sensors give composites an edge over conventional materials. So to understand the behavior of the composite materials under different loading conditions and because composite materials are produced by different manufacturers, studying the mechanical and physical properties becomes vital [3]. The focus here is to expand the general understanding of these materials to illustrate the importance of knowing the mechanical properties and to show the ease with which this information can be gained through simple laboratory tests. Specifications given by manufacturers are often average values for an entire product line and not a specific item. This is a source of error when considering small test samples cut from product sample. Further much of the specific information is not published in manufacturers literature which requires the user to conduct the tests himself to determine the exact information. Accurate mechanical properties of the composite materials are essentially important because they provide the fundamental materials parameters in the design of composite structures under different loading modes.

In this work material characterization tests of the coupons for glass and carbon fiber composite used in the current research were carried out. The coupons were cut from laminated plate fabricated by wetted filament winding process using a rectangular mandrel. The objectives of this paper is to present processing techniques of specimen preparation, analysis of test methods, and test procedures to determine mechanical properties and strength data for composite materials. All the test methods presented are based on the American Society for Testing and Materials (ASTM). These tests are useful for engineers who desire to extend their expertise into experimental characterization of anisotropic materials.

MATERIALS SELECTED

The materials tested consisted of glass fiber reinforced composites with epoxy resin matrix and carbon fiber reinforced composites with epoxy matrix. The types of fiber used are E-glass fiber from PPG. Ind., Inc., USA and PAN-based carbon fiber from Zoltek Corporation,

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USA. Table 1 shows the mechanical properties of the fibers. The matrix used in this study is epoxy resin and hardener types of MW 215 TA and MW 215 TB respectively. The properties of the fibers were supplied by the manufacturers.

Table-1. Mechanical properties of composite fibers.

Types of fiber	E_f (GPa)	ν_f	G_f (GPa)	ρ (g/cc)
Carbon fiber	228.0	0.31	41.16	1.81
Glass fiber	72.52	0.33	29.721	2.0

TEST METHODS

Properties of Matrix

In order to find the mechanical properties of matrix, tensile specimens were prepared according to ASTM D 638-97 [4]. Figure-1 shows the dimensions and geometry of tensile specimen for the matrix. A mixture of epoxy and hardener was prepared and cast in mold as shown in Figure-2. After curing at room temperature for 24 hours, the specimen was peeled out from the mold and finally tensile test was performed using universal tensile machine (INSTRON 8500).

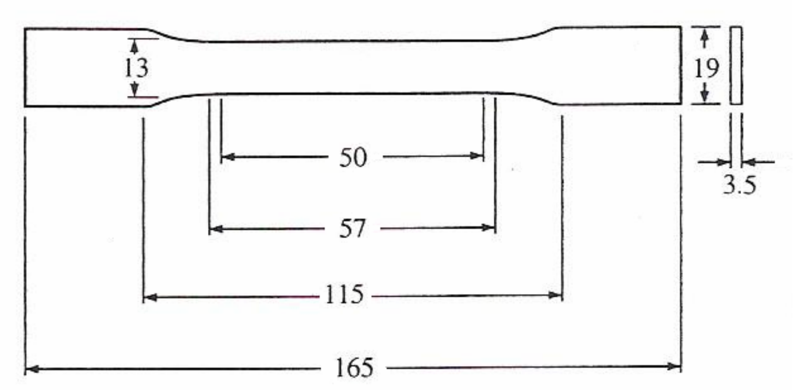

Figure-1. Epoxy tensile test specimen, (Dimensions are in mm).

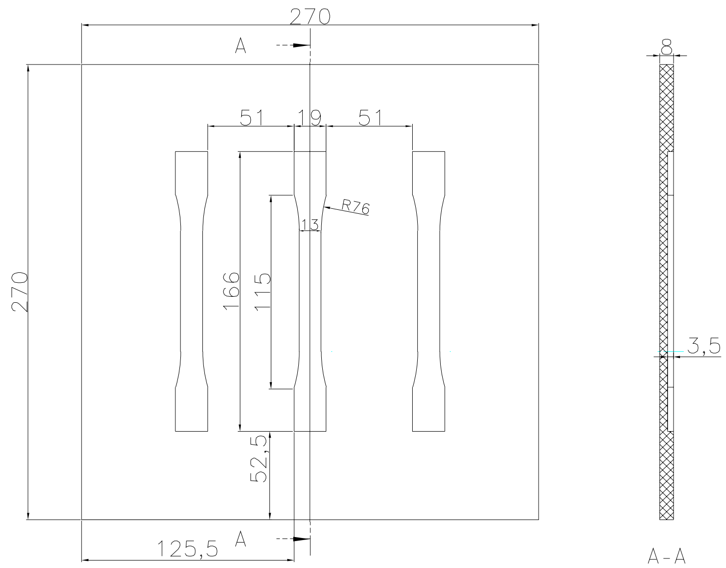

Figure-2. Geometry and dimensions of the mold for making epoxy specimens.
(All dimensions are in mm).

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The stress strain relation for epoxy resin/hardener specimen under tensile test is shown in Figure-3. It can be seen that the stress increases linearly with strain to the maximum value and then dropped suddenly as a brittle fracture. Figure-4 shows the photograph of matrix specimens after failure. It can be seen that the failure on the specimen is sudden and catastrophic. In addition the failure of specimen is in the gage zone and close to center. Table-2 shows the physical and mechanical properties of the matrix.

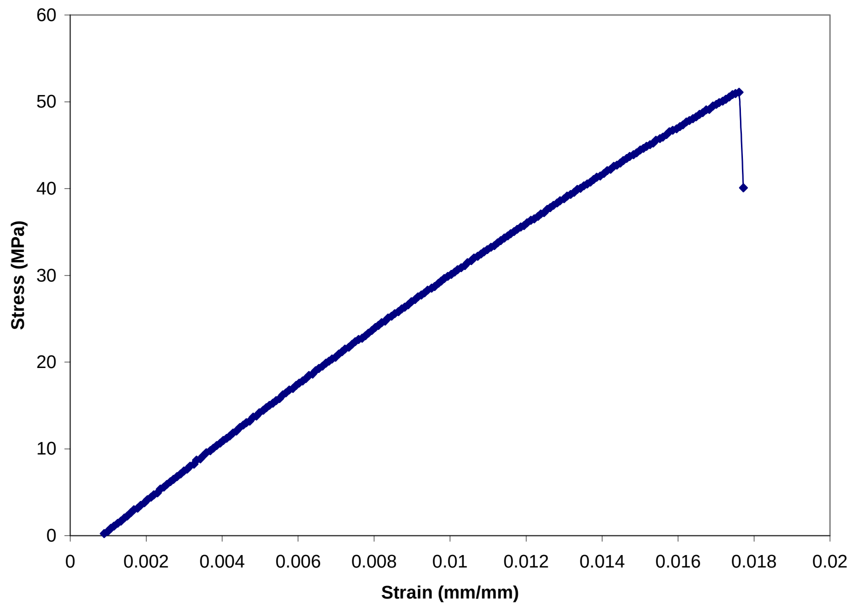

Figure-3. Stress strain relations for the Matrix.

Figure-4. Photographs of the failed tensile test specimen for Matrix.

Table-2. Physical and mechanical properties of the Matrix.

Item	**Unit**	**Epoxy WM-215TA**	**Hardener WM-215TB**	
Appearance	-	White viscous liquid	Colorless liquid	
Viscosity	Cps@ 30°C	5500 ±1000	30 ± 20	
Mixing ratio by volume	-	100	25	
Mechanical properties of Matrix				
E_m (GPa)	ν_m	**G_m** (GPa)	ρ_m **(g/cc)**	**Ultimate tensile stress** (MPa)
3.2	0.28	1.25	1.1	51

Properties of reinforced composite

Static tension test

The laminates were experimentally tested under tensile load to determine material properties in the longitudinal and transverse direction as well as the shear properties for the composite materials. Sheets of carbon and glass fibers epoxy composite were fabricated using filament winding machine [5], the mandrel is made of wood with dimensions 400mm x 200 mm x 20mm. Hoop winding was used to prepare the sheet of composite for both carbon and glass fibers. After curing at room temperature for 24 hours, the specimens were cut according to ASTM D3039, (1995) [6] for angle 0^o, 90^o and 45^o. Figure-5 shows the geometry of tensile specimen for reinforced composite. Table-3 shows the dimensions of tensile specimens for glass and carbon fiber/epoxy composite tested. In the determination of elastic constants and of strength, the requirements for a uniform state of stress are different. For anisotropic materials, Saint Venant's principle is satisfied more poorly than for isotropic materials so, to obtain reliable data on stiffness for composite materials it is necessary to increase the specimen length. This, in turn, causes a possibility of a transition from one type of failure to another. The equation for the calculation of tensile strength as the maximum load per unit cross-sectional area of the gage section assumes one failure mode that is breaking of the specimen perpendicular to its longitudinal axis. However, in practice, the specimen often fails by longitudinal delaminating (that is peeling of a number of layers), shearing, fiber pull out or breaking outside the gage section in the test machine grips. These errors, often encountered in tension, should be eliminated by a proper selection of a specimen size and by proper clamping.

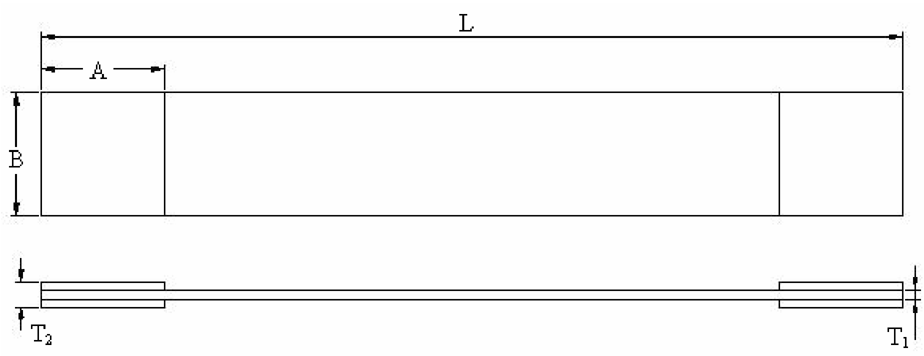

Figure-5. Tensile specimen for reinforced composite.

Table-3. Dimensions of tensile specimens for glass and carbon fiber/epoxy composite.

Angle (Degree)	**Width B** (mm)	**Thickness T_1** (mm)	**Thickness T_2** (mm)	**Overall length L** (mm)	**Depth A** (mm)
$[0]^o$	15	2.0	5.0	200	40
$[90]^o$	25	2.0	5.0	175	30
$[45]^o$	25	2.0	5.0	175	30

Tensile tests for unidirectional specimens (0^o) are conducted following the ASTM D3039, (1995) [6] on three samples cut from laminated plate of composite for both glass and carbon fiber composites. All tests were conducted in displacement control at a rate of 1 mm/min., using universal tensile test machine (INSTRON 8500). The specimens are 2.0 mm thick, 15 mm wide and 200 mm long. They have 40 mm long composite tabs bonded at each end, giving a 120 mm gage length. One extensometer is attached to the specimen. A 40 mm extensometer (INSTRON) was located at the center of the specimen for strain measurement as shown in Figure-6. The average stress strain relationship for $[0^o]$ unidirectional carbon/epoxy and glass/epoxy composite are shown in Figure-7. The stress is defined as the force applied to the specimen divided by the test cross-sectional area. The modulus, E_{11}, was obtained using a least-squares linear fit [2] to the linear initial portion of the stress versus strain curve. The modulus, E_{11} is 101.2 MPa and 36.6 MPa for carbon fiber epoxy composite and glass fiber/epoxy composite respectively. The volume fraction was calculated for glass fiber/epoxy composite and carbon fiber/epoxy composite in different paper as 0.476 and 0.545, respectively [7]. The failure mechanism is found to be complex, i.e. the failure surface was very rough with fiber splitting, fiber pull out, matrix cracking and shear crack.

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Figure-6. Extensometer installation.

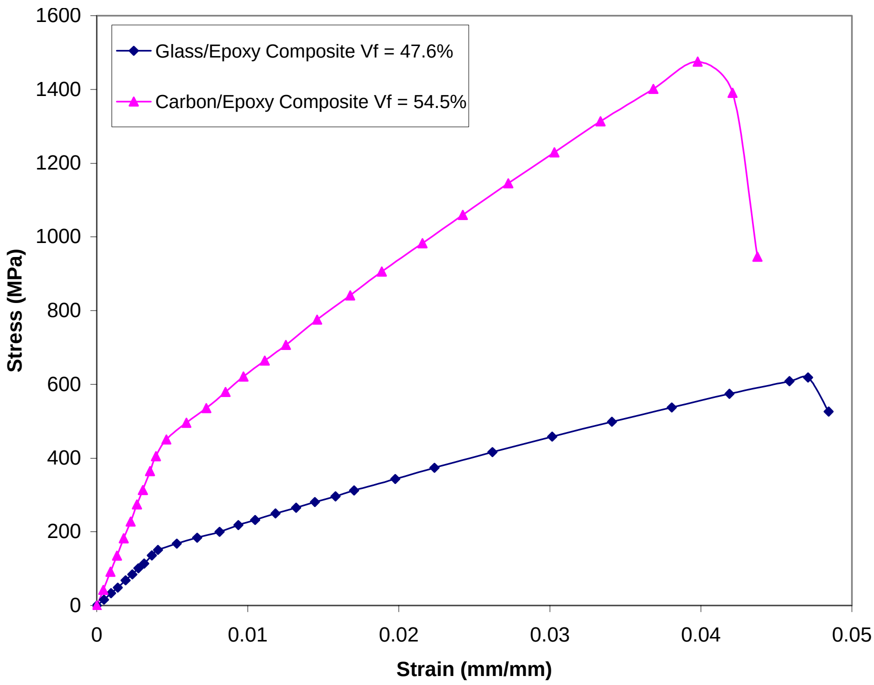

Figure-7. Tensile Stress-Strain response of a $[0^o]_4$ carbon/epoxy composite. (v_f = 54.5%) and $[0^o]_4$ Glass/Epoxy Composite (v_f = 47.6%)

The tensile test for unidirectional specimens $[90^o]$ was to find the transverse modulus of elasticity and the transverse tensile strength for both glass and carbon epoxy composites. The glass/epoxy composite layers were used as reinforcement for tab of the specimens with 2.0 mm thick. The stress strain relationship for $[90^o]$ unidirectional carbon/epoxy and glass/epoxy composites are shown in Figure-8. It can be seen that the load increases linearly to the maximum value and then dropped suddenly as a brittle fracture. The transverse modulus E_{22} is 5.718 MPa and 5.4 MPa for carbon fiber/epoxy composite and glass fiber/epoxy composite, respectively.

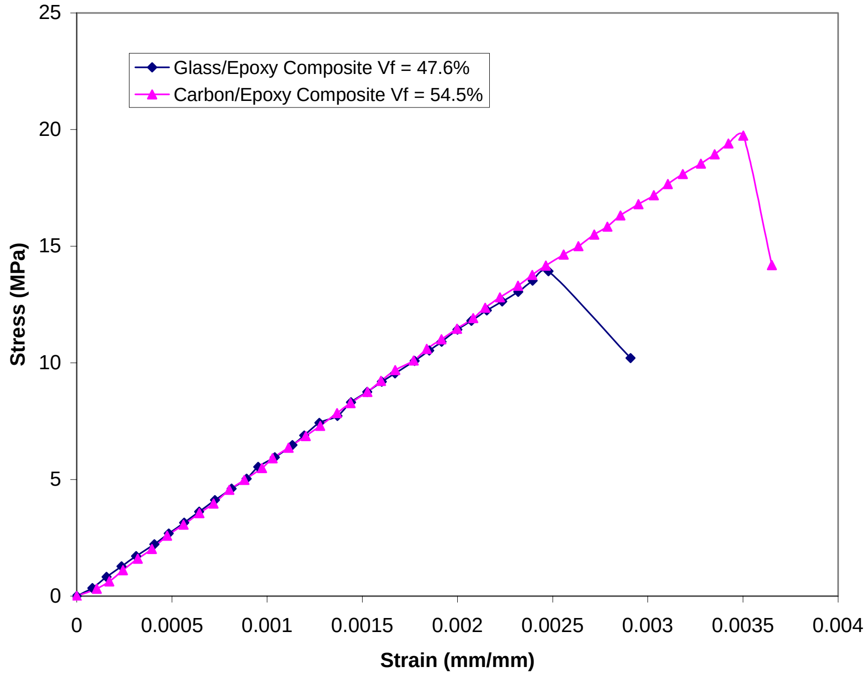

Figure-8. Tensile Stress-Strain response of a $[90^o]_4$ carbon/epoxy composite. (v_f = 54.5%) and $[90^o]_4$ Glass/Epoxy Composite (v_f = 47.6%).

The $[45^o]_4$ tensile coupons were prepared to determine the shear properties of composite materials used in this research according to the ASTM D3518, (1994) [8]. These include the in-plane shear modulus, G_{12}, and the ultimate shear stress. The $[45^o]_4$ laminate tension test provides an indirect measure of the in-plane shear stress-strain response in material coordinate system. The tensile specimen was instrumented with a $0^o/90^o$ biaxial strain gages and the in-plane shear stress shear strain and shear modulus were measured as explained in Appendix-I. The shear stress versus shear strain relationship for $[45^o]_4$ unidirectional carbon/epoxy and glass/epoxy composite are shown in Figure-9 for carbon fiber/epoxy composite and glass fiber epoxy composite. It should be noted that the in-plane shear response was linear up to some point then becomes nonlinear up to fracture. This behavior is due to matrix yielding, causing by the scissoring acting of the fiber. However, to find the in-plane shear modulus the slop of the initial portion of shear stress-shear strain curve was obtained. The in-plane shear modulus is 4.346 MPa and 4.085 MPa for carbon fiber/epoxy composite and glass fiber/epoxy composite, respectively.

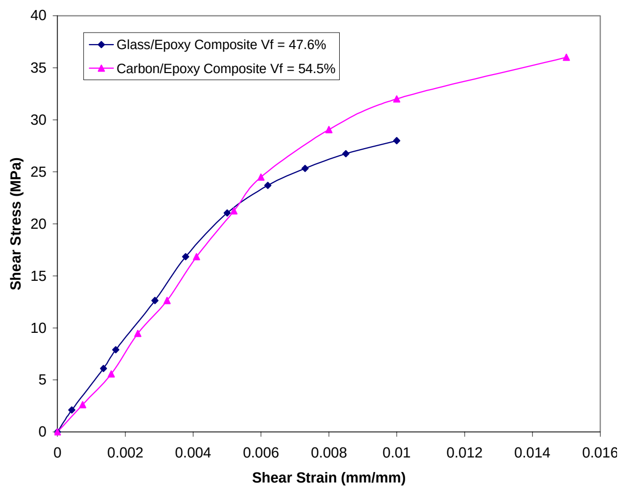

Figure-9. Shear Stress-Strain curve obtained from a tensile test of a $[45]_4$ carbons. Fiber Test Specimen, (v_f = 54.5%) and $[45]_4$ Glass Fiber Test Specimen, (v_f = 47.6%).

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The experimental results as well as the theoretical results (see Appendix-II) of the mechanical properties for a glass epoxy and carbon epoxy composites are summarized in Table-4. The failure modes of the composite materials under tension loading are affected by the type of reinforcement lay-ups but mechanical characteristics of the composite material and their interaction, fabrication defects such as voids, fiber waviness etc and specimen dimensions like edge and end effects are also considered essential effects.

A photograph of the tension Glass/Epoxy specimens after failure is shown in Figure-10 while a photograph of the tension Carbon/Epoxy specimens after failure is shown in Figure-11.

Table-4. Summary of the mechanical properties for composite materials.

Properties	Glass/Epoxy composite (v_f = 47.6%)			Carbon/Epoxy composite (v_f = 54.5%)		
	Experimental	**Theoretical**	**% Diff.**	**Experimental**	**Theoretical**	**% Diff.**
Longitudinal modulus E_{11} GPa)	36.60	36.196	1.10	101.2	125.716	19.50
Transverse modulus E_{22} (GPa)	5.40	5.872	8.04	5.718	6.917	17.33
Shear modulus G_{12} GPa)	4.085	3.521	13.81	4.346	4.245	2.32
Poisson's ratio ν_{12}	0.30	0.304	1.32	0.31	0.296	4.52
Volume fraction v_f	0.476	-		0.545	-	
Longitudinal strength X^L (MPa)	618.90	-		1475.40	-	
Transverse strength X^T (MPa)	14.00	-		20.00	-	
Shear strength τ_o (MPa)	28.00	-		36.00	-	

a) b) c)

Figure-10. Photographs of the failed tensile test glass/epoxy specimens for orientation angles a) 0°, b) 90° and c) 45°.

a) b) c)

Figure-11. Photographs of the failed tensile test carbon/epoxy specimens for orientation angles a) 0^o, b) 90^o and c) 45^o.

To describe and identify the failure mode and location, the standard three-part failure mode code presented in the ASTM D3039, (1995) [6] was used, the first character of this code denotes the failure type, the second the failure area, and the third denotes the failure location. The failure mode and locations vary slightly from specimen to specimen. Some specimen failed as a LAT (Lateral - At grip/tab -Top). The failure type is lateral meaning that the fracture goes from one side to the other across the width of the specimen. It is suggested in the ASTM D3039, (1995) [6] that when a significant fraction of failures in a sample population occurs within one specimen width from the tab the means of load introduction into the material, like the tab alignment, tab material, tab angle, tab adhesive, grip type, grip pressure, and grip alignment, should be re-examined. It is possible that in this case the problem is related to grip pressure and alignment. Some specimen failed as AGM (Angled - Gage – Middle). The failure type is angled. The failure area code G means that the failure is in the “gage zone”, close to the center of the specimens. The failure location code M means that the failure is in the middle of the specimen. Some other specimen failed as an LGM (Lateral - Gage - Middle); the fracture describes a line perpendicular to the longitudinal direction, dividing the specimen in two equal parts. The failures on the specimens are sudden and catastrophic, and confined to the vicinity of the break. From surface inspection of the failed coupons, it is noticed that fracture tends to follow the path that free from the fiber in the direction of laminated angles. This also means that the matrix materials fail first before the fiber. The matrix is weaker than the fiber except for 0^0 specimens the fibers do not fail.

CONCLUSIONS

a. The test results show that the load in the tensile test for the matrix and for the glass/epoxy and carbon/epoxy composites increases linearly for θ = 90° and non linearly for θ = 0° to its maximum value then drops suddenly at final fracture load. The maximum tensile loads for both carbon/epoxy and glass/epoxy composites in case of θ = 0° are higher than that for θ = 90°. The tensile test for θ = 45° for both composite materials show nonlinear behavior up to fracture and the shear modulus is represented by the slope of the first portion of shear stress shear strain response [9].
b. The test results also show that different fracture modes were observed like brittle fracture of the matrix and breaking of the fibers gradually depending on the fiber orientation angle. For θ = 90° the failure occurs by breaking of the matrix and the crack propagates in direction perpendicular to the load direction while for θ = 0° the failure was irregular and the crack propagates in different directions because of the high strength of the fiber in the longitudinal direction [10]. While for θ = 45° the failure starts by shear and splitting of the matrix parallel to the direction of reinforcement.
c. Good agreement was achieved when comparing the results from the experimental tests results with the theoretical results.

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Appendix-I. Analysis of Static Test

The constitutive equation of composite laminates as described by (Jones, 1998) [11] is

$$\begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_{xy} \end{Bmatrix} = \begin{bmatrix} c_{11} & c_{12} & c_{16} \\ c_{12} & c_{22} & c_{26} \\ c_{16} & c_{26} & c_{66} \end{bmatrix} \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \sigma_{xy} \end{Bmatrix} = \begin{bmatrix} \frac{1}{E_{xx}} & \frac{-\nu_{yx}}{E_{yy}} & \frac{\eta_{x,xy}}{G_{xy}} \\ \frac{-\nu_{xy}}{E_{xx}} & \frac{1}{E_{yy}} & \frac{\eta_{y,xy}}{G_{xy}} \\ \frac{\eta_{xy,x}}{E_{xx}} & \frac{\eta_{xy,y}}{E_{yy}} & \frac{1}{G_{xx}} \end{bmatrix} \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \sigma_{xy} \end{Bmatrix} \quad (1)$$

The engineering application to the static tensile test is obtained by setting, $\sigma_x = F/A$, $\sigma_y = \sigma_{xy} = 0$, where F is the applied load and A is the original cross-section. From equation (1) we obtained

$$\varepsilon_x = c_{11}\frac{F}{A}; \qquad \varepsilon_y = c_{12}\frac{F}{A}; \qquad \varepsilon_{xy} = c_{16}\frac{F}{A} \quad (2)$$

The normal strain of arbitrary orientation,θ, in *x-y* coordinates is

$$\varepsilon_\theta = \varepsilon_x \cos^2\theta + \varepsilon_y \sin^2\theta + \varepsilon_{xy}\sin\theta\cos\theta \quad (3)$$

At $\theta = 45^o$, the strain ε_C is equal to $(\varepsilon_x + \varepsilon_y + \varepsilon_{xy})/2$.
Let $\varepsilon_A = \varepsilon_x$ and $\varepsilon_B = \varepsilon_y$ as shown in Figure-12,
Then we have $\varepsilon_{xy} = 2\varepsilon_C - \varepsilon_A - \varepsilon_B$.

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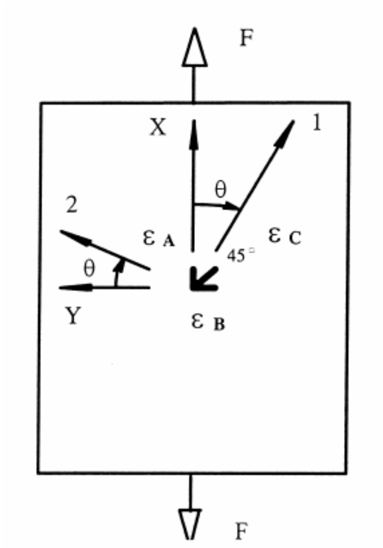

Figure-12. Orientations of the Strain Gauges, Loads and Principal Material Axes.
(Jen and Lee 1998) [8].

Equation (2) can be rewritten as

$$c_{11} = \frac{A}{F}\varepsilon_A ; \quad c_{12} = \frac{A}{F}\varepsilon_B ; \quad c_{16} = \frac{A}{F}\left(2\varepsilon_C - \varepsilon_A - \varepsilon_B\right) \tag{4}$$

After the substitution of equation (4) into equation (1), we obtain

$$E_{xx} = \frac{F}{A}\frac{1}{\varepsilon_A}; \quad \nu_{xy} = -\frac{\varepsilon_B}{\varepsilon_A}; \quad \eta_{xy,x} = \frac{\left(2\varepsilon_C - \varepsilon_A - \varepsilon_B\right)}{\varepsilon_A} \tag{5}$$

Thus, the three material constants can be calculated directly from equation (5) by the measurements of strain rosettes at locations A, B and C. The value of $\eta_{xy,x}$ should be zero due to stacking symmetry for $[0]_k$, $[90]_k$, cross-ply and quasi-isotropic laminates. According to the procedure the tensile tests of $[0]_k$ yield E_{11}, ν_{12} and the maximum tensile strength X^L, $[90]_k$ generate E_{22}, ν_{21} and maximum transverse strength X^T. Shear modulus G_{12} may be calculated from the data of $[45]_k$ or $[\pm 45]_{ks}$ as follows:

The stresses in principal material direction 1 and 2 are in the form:

$$\begin{aligned} \sigma_{11} &= m^2\sigma_x + n^2\sigma_y + 2mn\sigma_{xy} \\ \sigma_{22} &= n^2\sigma_x + m^2\sigma_y - 2mn\sigma_{xy} \\ \sigma_{12} &= -mn\sigma_x + mn\sigma_y + \left(m^2 - n^2\right)\sigma_{xy} \end{aligned} \tag{6}$$

Also, the strains have the same relation, where $m = \cos\theta$ and $n = \sin\theta$

$$\begin{aligned} \varepsilon_{11} &= m^2\varepsilon_x + n^2\varepsilon_y + mn\varepsilon_{xy} \\ \varepsilon_{22} &= n^2\varepsilon_x + m^2\varepsilon_y - mn\varepsilon_{xy} \\ \varepsilon_{12} &= -2mn\varepsilon_x + 2mn\varepsilon_y + \left(m^2 - n^2\right)\varepsilon_{xy} \end{aligned} \tag{7}$$

In the case of $[45]_k$ we let $\theta = 45^o$. Equations (6) and (7) become

$$\sigma_{11} = \sigma_{22} = -\sigma_{12} = \frac{1}{2}\frac{F}{A} \tag{8}$$

$$\begin{aligned} \varepsilon_{11} &= \frac{1}{2}\left(\varepsilon_x + \varepsilon_y + \varepsilon_{xy}\right) \\ \varepsilon_{22} &= \frac{1}{2}\left(\varepsilon_x + \varepsilon_y - \varepsilon_{xy}\right) \end{aligned} \tag{9}$$

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$\varepsilon_{12} = \left(\varepsilon_x - \varepsilon_y\right)$

Equation (3) associated with equation (9) yields

$$\varepsilon_{11} = \varepsilon_C \,;\; \varepsilon_{22} = \varepsilon_A + \varepsilon_B - \varepsilon_C \,;\; \varepsilon_{12} = \varepsilon_A - \varepsilon_B \qquad (10)$$

From the definition of shear modulus G_{12} with the substitution of equation (11) into equation (10) we obtained

$$G_{12} = \frac{\sigma_{12}}{\varepsilon_{12}} = \frac{E_{xx}}{2\left(1+\nu_{xy}\right)} \qquad (11)$$

Where E_{xx} and ν_{xy} are determined from the tensile test of $[45]_k$ specimen. Alternately, we can also find G_{12} by using $[\pm45]_{ks}$ specimens according to the standards of ASTM D3518, (1994) [8]. Adopting the standards as that used by (Jen and Lee 1998) [12] and CLT, we have the stress and strain relations for each ply in $[\pm45]_{ks}$ laminates as

$$\sigma_{12} = -\frac{1}{2}\frac{F}{A} \,;\; \varepsilon_{12} = \varepsilon_B - \varepsilon_A \qquad (12)$$

Similarly, plugging the data of $[\pm45]_{ks}$ we calculate

$$G_{12} = \frac{\sigma_{12}}{\varepsilon_{12}} = \frac{E_{xx}}{2\left(1+\nu_{xy}\right)} \qquad (13)$$

It is difficult to measure the shear strength τ_o of unidirectional specimens in the laboratory. According to Jen and Lee (1998) [12] indirectly used the Tsai-Hill failure criterion with the measurement of tensile and compressive strengths of $[45]_k$ specimens to estimate τ_o. The Tsai-Hill failure criterion can expressed as

$$\frac{\sigma_{11}^2}{\left(X^L\right)^2} - \frac{\sigma_{11}\sigma_{22}}{\left(X^L\right)^2} + \frac{\sigma_{22}^2}{\left(X^T\right)^2} + \frac{\sigma_{12}^2}{\tau_o^2} = 1 \qquad (\sigma_{11} > 0,\ \sigma_{22} > 0) \qquad (14)$$

$$\frac{\sigma_{11}^2}{\left(X_C^L\right)^2} - \frac{\sigma_{11}\sigma_{22}}{\left(X_C^L\right)^2} + \frac{\sigma_{22}^2}{\left(X_C^T\right)^2} + \frac{\sigma_{12}^2}{\tau_o^2} = 1 \qquad (\sigma_{11} < 0,\ \sigma_{22} < 0) \qquad (15)$$

Where X^L and X^T are longitudinal and transverse tensile strengths, respectively, while X_C^L and X_C^T are respective compressive strengths. After the determination of the tensile and compressive strength X^L and X_C^L for the $[45]_k$ specimen, the corresponding stresses from equation (8) are

$$\sigma_{11} = \sigma_{22} = -\sigma_{12} = \frac{1}{2}X^L \qquad (16)$$

$$\sigma_{11} = \sigma_{22} = -\sigma_{12} = \frac{1}{2}X_C^L \qquad (17)$$

Substituting equation (16) into equation (14) or equation (17) in to equation (15) τ_o could be calculated without shear tests.

Appendix-II. Theoretical Equations

Modulus of Elasticity in principal coordinate system: (Jones, 1998) [11]

$$E_{11} = E_f \times v_f + E_m \times v_m$$

$$E_{11} = 72.52 \times 0.476 + 3.2 \times 0.524 = 36.196 GPa$$

$$E_{22} = \frac{E_f \times E_m}{v_f \times E_m + \left(1 - v_f\right) \times E_f}$$

$$E_{22} = \frac{72.52 \times 3.2}{0.476 \times 3.2 + \left(1 - 0.476\right) \times 72.52} = 5.872 GPa$$

Major Poisson's Ratio in principal coordinate system: (Jones, 1998) [11]

$$\nu_{12} = -\frac{\varepsilon_2}{\varepsilon_1} = v_f \times \nu_f + (1 - v_f) \times \nu_m$$

$$\nu_{12} = 0.476 \times 0.33 + (1 - 0.476) \times 0.28 = 0.304$$

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In-plane shear modulus: (Barbero, 1998) [13]

Because $G_m << G_f$

So $G_{12} = G_m \times \left(\frac{1+v_f}{1-v_f} \right)$

$$G_{12} = 1.25 \times \left(\frac{1+0.476}{1-0.476} \right) = 3.521 GPa$$