Correlation Study of IR TNDT Analysis with Structural Failure Modes of Carbon-Fabric-Reinforced Epoxy Composites

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ABSTRACT

In the present work, a generic experimental investigation procedure was developed on mechanical characterization and testing of carbon fabric/epoxy material under uniaxial tensile loading condition. In this study, using IR Thermographic NDT, the defects are identified by measuring changes in temperature online during testing and by taking temperature contour images on the surface of the composite samples. The unidirectional elastic properties such as tensile modulus, in-plane shear modulus, Poisson's ratio, and strength parameter like ultimate tensile strength, shear strength are reported. The estimated mechanical properties of carbon fabric/ epoxy composite were statistically analysed in this work using the Weibull distribution. In addition, emphasis on the microstructural investigation using Scanning Electron Microscope (SEM) is given, in order to study the fracture mechanism of the carbon fabric/epoxy composite under uniaxial tensile loading. The failure surfaces of the tensile tested carbon fabric/epoxy specimens were examined by SEM and the detailed fracture process such as matrix cracking, fiber pull outs and delamination are observed and discussed.

Keywords: Fabric Composite, Carbon fabric / epoxy, hand lay-up, Material Characterization, Tensile Testing, Scanning Electron Microscope (SEM).

INTRODUCTION

During recent decades, there has been an increasing interest in carbon fiber reinforcements with polymeric matrices. The polymeric matrix composite material [1, 2] (PMC) constituted by carbon fibers embedded in thermosetting resin system were first established to fulfil the high standards required in the design of aircraft structures. Fabric reinforced or Textile composites [3, 4] become applicable to a larger extent in many engineering applications like aerospace, automotive and naval due to its weight saving of the principal structural components and low processing cost. Plain weave fabrics [5, 6] are very popular in wet hand lay-up applications due to their rapid wet-out and dimensional stability. Plain-woven fabrics have been utilized as structural materials in space antenna systems [7]. The benefits of woven carbon fabric composites [8-10] have been established in principal parts for fighters, transport planes and light jet aircrafts. Carbon fabric/epoxy composites [11] have been well known for their properties like high specific strength, specific modulus, good chemical resistance and thermal property in elevated temperature conditions. Advanced composites [11] broadly used in aerospace structures include thin-walled laminated structures composed of layers of carbon fabric/epoxy material which excel over metallic counterparts. During the last decade there has been a growing application of IR thermographic [12-14] non-destructive testing (IR TNDT) in the inspection of metals. However, non-metals, particularly, fabric composite structures are still considered as the most successful objects for the application of TNDT procedures. Detection and Characterization of defects by specimen surface footprints is one of the fascinating research areas in TNDT. This paper also describes an IR TNDT procedure for the inspection of carbon fabric composite structures. Experimental investigation on the mechanical properties of fabric-reinforced composite materials through material characterization [15] is very essential for the evaluation of safety of any engineering composite structure.

Various test methods for the material characterization of composites are described in ASTM (American Society for Testing and Materials) standards. In addition to the available literature on analysis and mechanical characterization of uni-directional and laminated composite structures over the past 50 years, this paper presents another more recent approach to material characterization of carbon fabric composite structure. This study would be useful to understand the material characterization and various analysis procedures like IR TNDT, SEM, Weibull for carbon fabric composite structures which could be employed in aircraft and spacecraft structural applications. The mechanical characterization of fabric or textile composite materials and its constituents have appeared in the literature [15-20]. The investigations of the fracture behavior [21] of fabric reinforced composites are necessary for the enhancement of reliability of the composite material and the composite structural components. The main objective of the present study carried out deals with the following phases of work:

- Fabrication of the carbon fabric/epoxy composite test coupons as per ASTM Standards from a carbon fabric /epoxy composite laminate using hand lay-up technique and subsequent NDT inspection of test coupons by Thermography technique.
- Mechanical testing of carbon fabric /epoxy composite with no defects has been carried out using material characterization wherein uniaxial tensile tests were conducted for the estimation of unidirectional elastic properties and strength parameter of carbon fabric /epoxy composite material. The variations of unidirectional mechanical properties have been statistically analysed.
- SEM observation of microstructures of carbon fabric /epoxy composite material tested under uni-axial tensile loading for qualitative analysis of the fractured surfaces.

MATERIALS, FABRICATION AND EXPERIMENTAL PROCEDURES

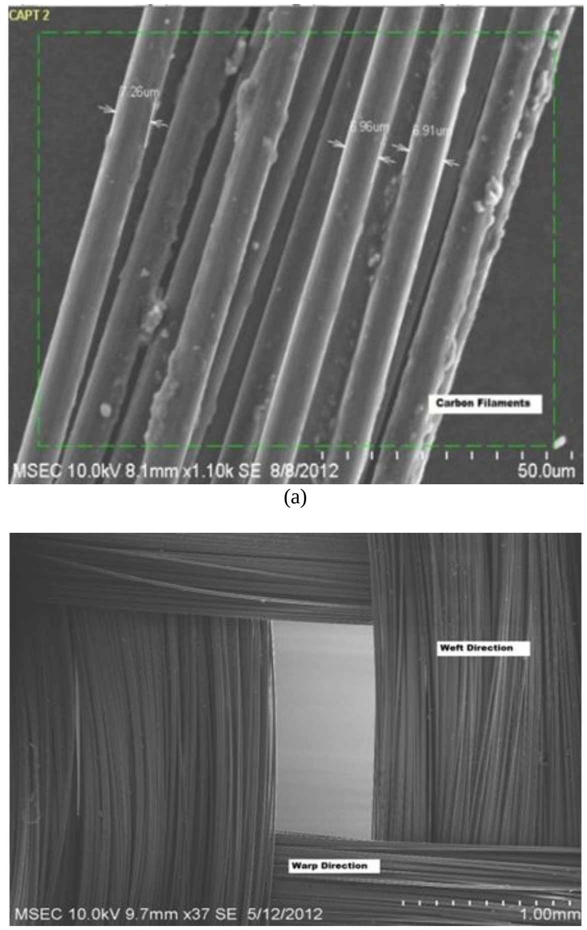
Materials

The fiber material used in this study was plain weave carbon fabric. The carbon fabrics were 3k count along warp and 3k count along weft directions.

TABLE I. Properties of carbon fabric, Epoxy resin.

Carbon Fabric		Matrix	
Width of the fabric	1000 mm	Type	Epoxy
Thickness, mm	0.25	Curing Temperature	20^0C - 180^0C
Weight per sq.meter,g/m²	640	Density,kg/m³	$1.06x10^3$
Tensile Strength,MPa	225 along Warp, 225 along Weft	Tensile Strength,MPa	33
Filament Diameter,µm	6.96		

The matrix material** used was AW106 type [22] epoxy resin with hardener HV 953 U. The physical properties of carbon fabric and epoxy resin employed in this study are presented in *Table I*. *Figure 1(a)* shows the surface morphology of carbon fiber.



(a)

(b)

FIGURE 1. SEM Photograph of Carbon Fabric.

Figure 1(b) shows the typical SEM image of carbon fabric in 0°-90° orientations which are used for the fabrication of test coupons. The warp and weft directions of the carbon fabric are clearly shown in the SEM photograph.

Test Specimen Configuration

In the current work, four types of carbon fabric /epoxy composite laminates with two layers cured at room temperature were evaluated by mechanical testing. The *Table II* describes the configuration of composite test samples taken into account for the present characterization study.

TABLE II. Test Specimen Configuration.

Sample No.	STANDARD	CFRP Test coupon Configuration	Range of averaged Thickness, mm	Qty.
#1	ASTM D3039 (Fig.2a)	Coupon Without End Tab	2.56-2.99	5
#2	ASTM D638 (Fig.2b)	Dumbbell Shape Coupon	2.31-2.64	5
#3	ASTM D3039 (Fig.2c)	Coupon With End Tabs	2.29-2.86	5
#4	ASTM D3518 (Fig.2d)	$\pm 45^0$ Coupon With End Tabs	2.8-3.26	5

The dimension represented in this paper indicates the range of variation of averaged thickness among specimens of the same configuration. In each test coupon the thickness was measured by a digital Vernier Caliper* after cutting from the laminate at different locations of same specimen. The *Table III* highlight the intra-individual and inter-individual differences of the carbon fabric/epoxy test coupons in terms of thickness.

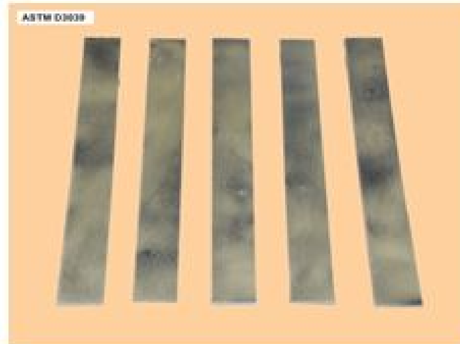
TABLE III. Intra/Inter Differences of Test Specimen

Sample No.	Averaged Thickness of Coupons, mm				
	1	2	3	4	5
#1.	2.56	2.60	2.74	2.80	2.99
#2.	2.31	2.43	2.47	2.54	2.64
#3.	2.29	2.32	2.55	2.74	2.86
#4.	2.8	2.86	3.06	3.14	3.26

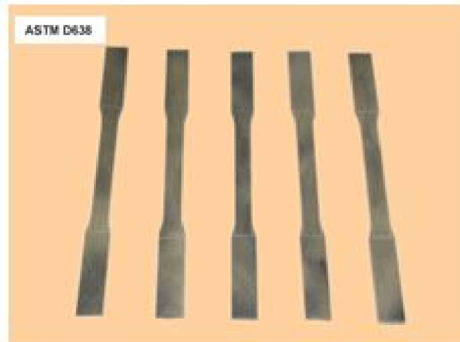
*ABSOLUTE Digimatic, Mitutoyo, Japan

Composite Laminate Fabrication

The ASTM standards of the various tensile test specimens which are shown in *Figure 2a*, *2b*, *2c* and *2d* are referred from literatures [15-17]. All the specimens have an overall length of 250 mm. The composite test coupon specifications and mechanical testing procedures are detailed in the proceedings of ASTM [14-16]. In the present work, the carbon fabric/epoxy test coupons in four configurations were fabricated by hand lay-up technique [10, 23] at room temperature curing.



(a)CFRP Plain Coupon



(b)CFRP Dumb Bell Coupon

(c)CFRP Coupon with End Tab

(d)CFRP ±45˚Coupon

FIGURE 2. Carbon Fabric/Epoxy Composite Test Coupons.

Figure 3 shows the schematic arrangement of the hand lay-up process. The hand lay-up process was the predominant fabrication process for making reliable composite specimens. The required carbon fabric in the desired orientation is laid over the mould, which is a flat plate required for the fabrication of carbon fabric/epoxy flat laminate.

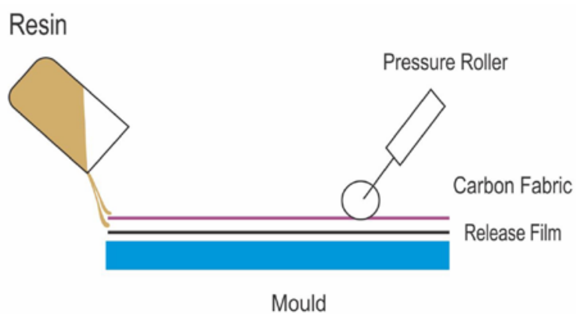


FIGURE 3. Schematic Diagram showing the Hand lay-up process.

The mould plate is tightly covered with a release film or milder sheet so as to enable ejection of carbon fabric/epoxy laminate. The epoxy resin and hardener mixture of ratio 100:27 is applied over the release film and above the laid carbon fabric. A gentle pressure is applied with the aid of a pressure roller to impregnate the carbon fabric with the epoxy resin. Initially, the carbon fabric/epoxy laminate with two layers were fabricated and the test coupons of ASTM standards were cut by using a FRP cutting machine. *Figure 4* shows the typical SEM image of the carbon fabric/epoxy material across the cross-section. It has been studied that, the microstructure of composite laminate reinforced with carbon fabric significantly differs from that of the uni-directional counterparts due to the distribution of carbon fiber in warp and weft directions.

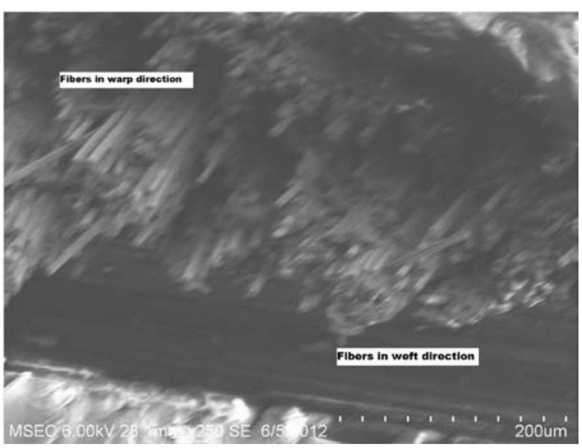


FIGURE 4. SEM image showing the carbon fabric/epoxy composite.

Infrared Thermography Analysis

Damage in a polymer composite can be caused during manufacturing or during service. Improper laminate fabrication or curing procedure can induce defects in the form of delamination, voids, debonds, wrinkles, inclusions, broken fiber, and fiber misalignment. *Figure 5* represents the schematic diagram of Infrared Thermography test set up. The process of infrared thermography testing of Composites is based upon the principle of thermal imaging wherein the thermal conductivity of the composite material would be altered due to the presence of defects such as crack, delamination etc.

Initially visual inspections were carried out to test the size and standards of the CFRP test coupons before setting up of IR Thermography test setup. A uniform heat source using a halogen bulb (up to 1kW) is applied on the front surface of the CFRP test heat source as 89cm. After continuous heating for 1 hour, the CFRP test coupons were taken to the dark room setup and the transient temperature contours on the surface of the composite test coupons were recorded using an infrared heat detection camera. An image of the surface temperature of the heated CFRP test coupon is monitored using an IR camera (Fluke Thermography Model Ti32), which collects IR radiation from the surface of the CFRP test sample. Defect areas exhibit irregular cooling behavior, which will appear in the temperature contours. The distance between the IR camera and the CFRP test coupons was maintained as 50cm. The IR camera records the transient temperature contours continuously when the temperature of the CFRP test samples drops using FLUKE Image Capturing software Finally the digital data from the IR camera is acquired and stored on a personal computer for the subsequent analysis.

Tensile Testing Procedures

The present study employs a FIE make UTE-40 Universal Testing Machine for the estimation of the fundamental material properties of the fabric composite material. The measurement of displacement is based upon an electronic extensometer with a standard gauge length of 50 mm. The mechanical testing of carbon fabric /epoxy composite material was conducted by applying axial tensile loading (*Figure 6*) of ASTM standard test coupons. The most commonly measured mechanical properties of fabric composite materials [15] are the longitudinal modulus, ultimate tensile strength, in-plane shear strength, shear modulus and Poisson's ratio.

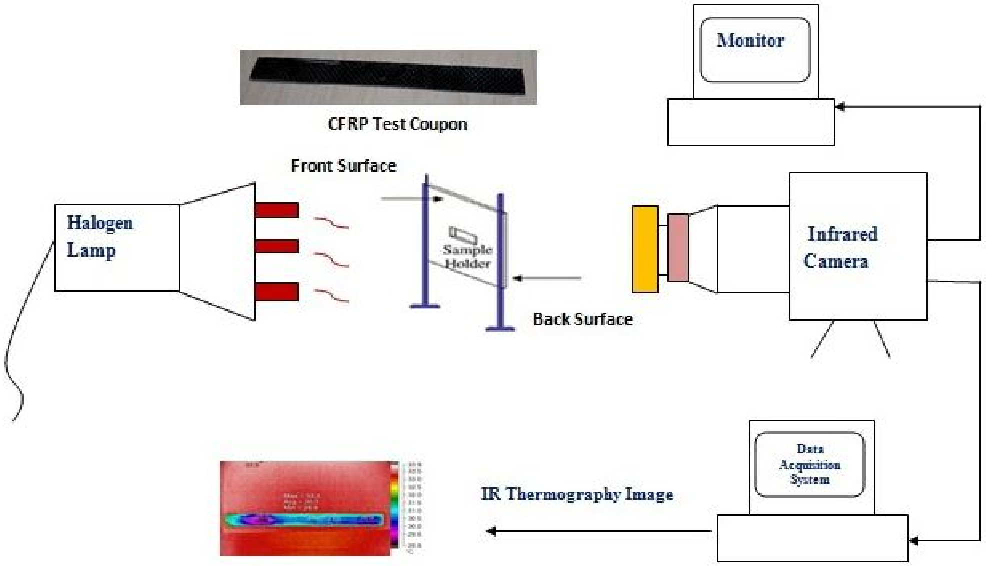


FIGURE 5. Schematic Representation of IR Thermography testing technique for Composites

Total of five tests under each of the four categories (*Table II)* of test coupons were taken into account for the present characterization study. In the UTM test setup (*Figure 6*), the carbon-fabric-reinforced epoxy composite test coupon is aligned in such a way that the tensile loading direction is in accordance with the fiber warp direction for the estimation of tensile modulus, tensile strength, Poisson's ratio and the tensile loading direction is in accordance with the laminate longitudinal direction for the estimation of shear property.

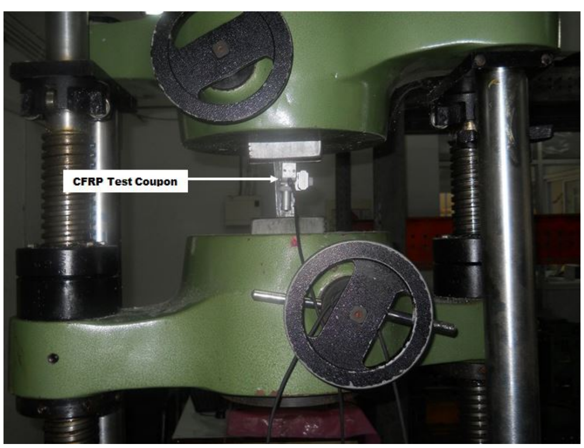


FIGURE 6. UTM Test Setup.

In-plane tensile properties such as tensile strength, tensile modulus of flat carbon fabric/epoxy composite laminates are determined by static tension tests in accordance with dumb bell coupons (*Sample#2, Figure2b*) and coupons with end tabs (*Sample#3, Figure 2c*) simultaneously. The geometry shown in *Figure 2c* is similar to that presented in *Figure 2a*, except that the coupons are tabbed with CFRP end tabs for a length of 50 mm. The $\pm 45^0$ shear test (*Sample#4, Figure 2d*) has been conducted for the estimation of in-plane shear modulus, G_{12} [6] and shear strength, τ_{12} which involves uniaxial tensile testing of $\pm 45^0$ oriented carbon fabric laminate. For shear test, the specimen dimension, preparation and test procedure are the same as that of the tensile test method ASTM D3039.

Poisson's ratio has been estimated by carrying out tensile tests using plain coupon (*Sample#1, Figure 2a*) which makes use of flat laminate of 250 mm long, 25 mm wide by employing electrical strain gauges. In this test method, electrical strain gages (120 Ohms resistance with a gage factor of 2.15) are pasted along the longitudinal and transverse direction in carbon fabric/epoxy test coupon as shown in *Figure 7* for the evaluation of the Poisson's ratio value through the strain data acquisition system (Model – 5100B Scanner with 5 channels).

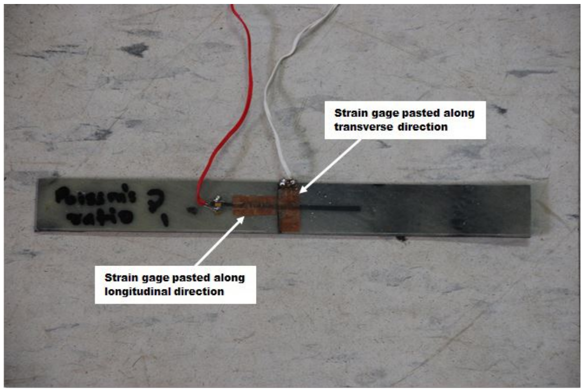


FIGURE 7. Poisson's ratio Testing.

WEIBULL ANALYSIS

The values of experimentally obtained mechanical properties viz. tensile modulus and tensile strength along longitudinal direction (Sample #2- 5 No's; Sample #3- 5 No's), shear modulus (Sample #4- 5 No's), Poisson's ratio (Sample #1- 5 No's) are being statistically analysed in the present study by Weibull distribution [24,25] using Microsoft Excel® spread sheet program. The (cumulative) distribution function of the three parameter Weibull distribution is given as,

$$F(x;a,b,c) = 1 - exp\left(-\left(\frac{x-a}{b}\right)^c\right) \quad (1)$$

where a, b, and c are the threshold, scale and shape parameters respectively. When a=0, Eq. (1) becomes two parameter Weibull distribution as given below,

$$F(x;b,c) = 1 - exp\left(-\left(\frac{x}{b}\right)^c\right) \quad (2)$$

In the context of this study, F(x; b; c), represents the probability that the estimated mechanical property is equal to or less than x. Using the equality F(x; b; c) + R(x; b; c) = 1 , the reliability R(x; b, c), that is, the probability that the material property is at least x, is defined as,

$$R(x;b,c) = exp\left(-\left(\frac{x}{b}\right)^c\right) \quad (3)$$

The method usually employed for the estimation of the parameters b and c of the distribution function F(x; b; c) is method of linear regression.

Method of Linear Regression

This method is based on transforming Eq. (2) into

$$1 - F(x;b,c) = exp\left(-\left(\frac{x}{b}\right)^c\right)$$

and taking the double logarithms of both sides. Hence, a linear regression model in the form Y = m X + r is obtained:

$$ln\left[ln\left(\frac{1}{1-F(x;b,c)}\right)\right] = cln(x) - cln(b) \quad (4)$$

F(x; b; c) is an unknown in (4) and, therefore, it is estimated from observed values: In order to compute b and c, the experimentally observed material properties are individually ordered from the smallest to the largest and (X, Y) values are computed. Then applying linear regression to these (X, Y) values, the linear regression model with the regression line (*Figure 12a-d*) is obtained. The slope of the regression line is the value of the shape parameter c. A c < 1 indicates that the material has a decreasing material property. Similarly c = 0 indicates constant P material property and c > 1 indicates an increasing material property rate.

TABLE IV. IR Thermography – Test Results of Sampe#1.

Test No.	T_{Avg}	T_{Min}	T_{Max}	Emissivity	Background Temp	Standard Deviation
CFRP1 F	86.4°C	45.1°C	97.0°C	0.98	20.0°C	9.63
CFRP1 B	75.5°C	58.2°C	83.0°C	0.98	33.3°C	6.17
CFRP2 F	110.8°C	45.6°C	118.4°C	0.98	33.3°C	8.85
CFRP2 B	83.8°C	61.7°C	88.2°C	0.98	33.3°C	5.15
CFRP3 F	110.4°C	42.9°C	122.5°C	0.98	33.3°C	13.25
CFRP3 B	88.4°C	40.2°C	98.9°C	0.98	33.3°C	10.26
CFRP4 F	99.9°C	75.4°C	108.3°C	0.98	33.3°C	8.04
CFRP4 B	75.6°C	56.8°C	81.5°C	0.98	33.3°C	5.71
CFRP5 F	101.2°C	69.3°C	110.5°C	0.98	33.3°C	10.52
CFRP5 B	80.9°C	58.9°C	88.8°C	0.98	33.3°C	8.00

The b value is computed using the point the regression line intersects the Y axis in
$b = e^{\left(-\frac{Y}{c}\right)}$.

SEM MICROSTRUCTURAL ANALYSIS

Scanning Electron Microscope* (Model: SU-1510, 2009) shown in *Figure 8* has been used for the observation of the fracture mechanism [26-28] of tested samples of carbon fabric/epoxy composites.

The SU 1510 SEM utilizes an electron beam accelerated in the range of 300eV to 30keV. To prevent image interferences due to charging-up when a secondary electron image of a non-conductive specimen such as FRP specimen are observed with SEM, a metallic film of 2-25 nm thick of an alloy such as Au-Pd is coated on the effected portions of surface of the carbon fabric/epoxy composite specimen with the sample preparation instrument namely, Ion Sputter E-1010*. To enhance the image quality, the surface of the specimen is coated with Au-Pd.

FIGURE 8. SEM Test Setup.

*Hitachi High-Corporation Technologies, Japan

RESULTS AND DISCUSSION

Infrared Thermography Analysis Results

A sample of Thermograph image or surface mapping of isothermal contour lines of carbon fabric/epoxy test coupon are represented in *Figure 9a* and *9b*. During continuous heating of CFRP test coupons, the thermal energy from the heated front surface diffuses toward the cooler interior and back surface of the CFRP test coupons. It was found that the areas of the front surface that are located above subsurface defects (discontinuities in the material) cools at a different rate than the defect-free areas. *Figure 9(a)* and *9(b)* graphically illustrate the consequence for areas with and without subsurface defects respectively. *Figure 9(a)* infers that the infrared radiation is emitted inconsistently at the surface above a hidden defect (Voids at three locations from the left side of the CFRP test coupon in the front surface test) is due to the interruption of the flow of heat into the CFRP test sample by the defect. *Figure 9(b)* reveals that the infrared radiation is emitted consistently (uniform distribution of infrared radiation without any discontinuities in the back surface defect is seen in *Figure 9*) from the surface as the thermal energy from the surface distributes toward the interior of the CFRP test sample thereby presume that the surface is defect free. Many CFRP samples are tested using IR TNDT using front surface test and back surface test and coupons (20 nos. five per every four category) with no defects are selected for mechanical characterization. The transient temperature contours and IR Thermography test results of all the tested samples are not included in this paper just for the sake of brevity.

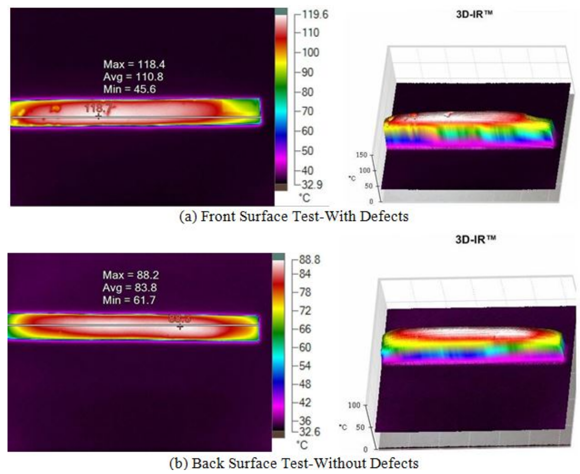
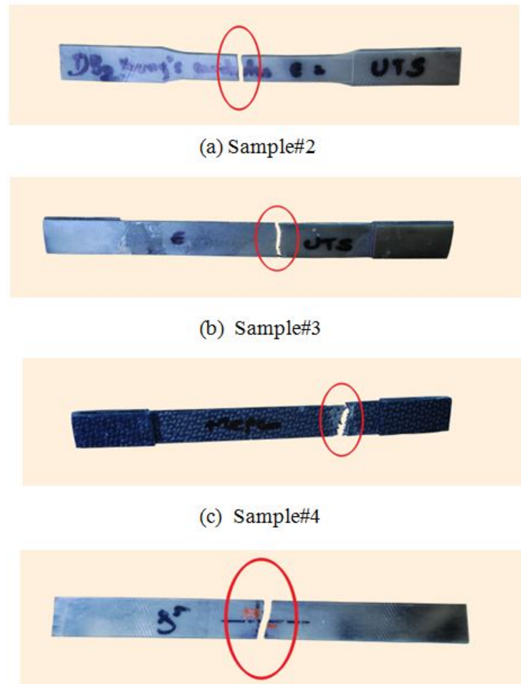


FIGURE 9. IR Thermography of Image of Test No.CFRP2.

Table IV indicates IR Thermography results (Both front surface test and back surface test) for five CFRP specimens under Sample#1.

Material Characterization Results

Typical failure modes of tensile tested carbon fabric/epoxy composite test coupons are shown in *Figure 10c* wherein the failure occurs near to the end tab. The typical failure mode of carbon fabric/epoxy composite coupons tested under uni- axial tension is shown in *Figure 10a, 10b and 10d*. It reveals that the failures occurs nearly at the centre of the laminate, which is an ideal failure [15].The consolidated test results of material characterization for the different samples of various carbon fabric/epoxy composite test coupons are listed in *Table V* and *Table VI*. The maximum extension indicates the displacement for the gauge length whereas the extension at Fm indicates the displacement value for the total length of the test coupon excluding the gripping length on both the ends. Fm is the maximum force that the test coupon sustains during the test. For every uni- axial tensile testing, the load-axial extension plots are recorded. The load-axial extension plot which is found to be linear for the four samples of carbon fabric /epoxy composite test coupons under uniaxial tensile tests is shown *Figure 11a* and *11b*. The experimental shear properties are found to be around 58-60 % of the literature test results [3] for the carbon fabric/epoxy composite which may be due to the scattering of thickness of test specimens. The experimental results are quite low compared to the literature counterparts which may be also due to the low values of span length to thickness ratio, the volume fraction not being constant in each specimen, weak matrix, or resin-rich outer surface of the test coupon. From a structural perspective, the matrix is typically both weaker and less stiff than the reinforcements in the composite. Failures often occur near the region where the load is transferred from the fibers to a week matrix.



(a) Sample#2

(b) Sample#3

(c) Sample#4

(d) Sample#1

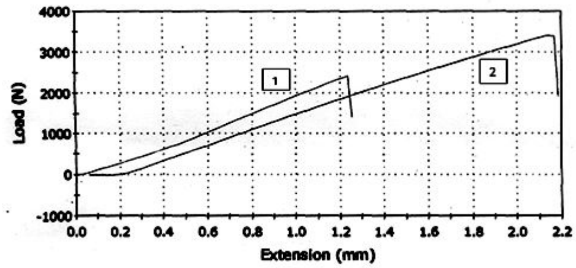
FIGURE 10**.** Failure mode of Carbon Fabric/Epoxy Composite.

TABLE V. Material Characterization Results.

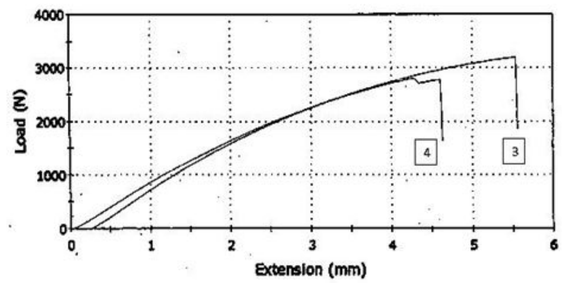
Sample No.	ASTM	Property Estimated	Test1	Test2	Test3	Test4	Test5
#1	D3039	υ_{12}	0.297	0.306	0.305	0.304	0.300
#2	D638	E_L,MPa	5225	5985	5065	5132	5610
#2	D638	σ_{12},MPa	96	97	100	85	90
#3	D3039	E_L,MPa	5874	5637	5632	5819	5721
#3	D3039	σ_{12},MPa	46	56	54	48	43
#4	D3518	G_{12},MPa	3660	3770	3520	3430	3590

TABLE VI. Tensile Tests Results.

Test No.	ASTM	F_m, N	Extension at F_m,mm	σ_{12}, MPa	% Elongation	Load at Break N	Max. Extension, mm	Modulus, MPa
1.	D3518	2418.649	1.233	29.317	0.88087	2418.649	0.470	3769.80259
2.	D638	3398.354	2.067	100.692	2.06681	3391.030	0.455	5609.77349
3.	D3039	2806.635	4.267	56.447	2.66659	2779.004	0.325	5637.29735
4.	D3039	3203.773	5.299	53.897	3.60504	3203.773	0.437	5632.31444



(a) *Test 1- Sample #4; Test 2- Sample #2*



(b) *Test 3- Sample #3; Test 4- Sample #1*

FIGURE 11. Load-Axial Extension Plot.

<u>**Statistical Analysis Results**</u>

a) Discussion on Tensile Modulus Model:

The slope of the regression line (*Figure 12a*) is found to be 18.407 which indicate that the material tends to have tensile modulus with higher probability for every unit increase in applied uni-axial tension. The computed b value is 5721.85 which measure the spread in the distribution of data. R (5721.85; 5721.85, 18.407) = 0.368. Therefore 36.8% of the tested carbon fabric/epoxy composite specimens have a tensile modulus of at least 5721.85 MPa.

The reliability curve in *Figure 13a* shows that tensile modulus values approximately less than or equal to 4000 MPa will afford high reliability. Considering reliability levels 0.90 and 0.95 in Eq. (3) the values for x, the tensile modulus are obtained as 5063.38MPa and 4869.2MPa respectively.

b) Discussion on Tensile Strength Model:

The slope of the regression line is (*Figure 12b*) 15.637 which indicates that the material tends to have tensile strength with higher probability for every unit increase in applied uni-axial tension. The b value is computed as b = 96.421. Therefore, R (96.421; 96.421, 15.637) = 0.368 which implies that 36.8% of the tested carbon fabric/epoxy composite specimens have a tensile strength of at least 96.421MPa.

The reliability curve in *Figure 13b* shows that tensile strength values approximately less than or equal to 70 MPa will provide high reliability. Also for 0.90 and 0.95 reliability levels from Eq. (3) the tensile strength values are obtained 83.497MPa and 79.74MPa respectively.

c) Discussion on Shear Modulus Model:

The value of the shape parameter c which is the slope of the regression line (*Figure 12c*) is 28.3636 and thereby indicates that the carbon/fabric epoxy composite material tends to have shear modulus with higher probability for every unit increase in applied uni-axial tension. The b value is computed as b = 3654.82 which measures the spread in the data distribution. R (3654.82; 3654.82, 28.3636) = 0.368, which infers that 36.8% of the tested specimens have a shear modulus of at least 3654.82.

The reliability curve in *Figure 13c* shows that shear modulus values roughly less than or equal to 3000 will provide high reliability. The shear modulus values are obtained 3376.05MPa and 3291.45MPa respectively by considering 0.90 and 0.95 reliability levels using Eq. (3).

d) Discussion on Poisson's ratio Model:

The slope of the Regression Line (*Figure 12d*) is obtained as 80.933, which is the value of the shape parameter c. The b value is computed as b = 0.3042 using the point the line intersects the Y axis (@ 96.3099) in $b = e^{\left(-\frac{Y}{c}\right)}$. Therefore, c= 80.933

indicates that the material tends to have Poisson ratio with higher probability for every unit increase in applied unidirectional tension. The scale parameter b measures the spread in the distribution of data. R (b; b, c) = R (0.3042; 0.3042, 80.933) = $exp\left(-\left(\frac{x}{b}\right)^{c}\right)$ = 0.368. Therefore 36.8% of the tested specimens have a Poisson ratio of at least 0.3042. The reliability curve (*Figure 13d*) shows that Poisson ratio values roughly less than or equal to 0.2 will provide high reliability. Considering 0.90 and 0.95 reliability levels for a more certain assessment. When these values are put as R(x; b, c) in Eq. (3) and the equation is solved for x, the Poisson ratio values 0.29586 and 0.29323 are obtained respectively.

There are uncertainties inherent in the constituent (fabric, matrix, and interphase) properties and uncertainties in the fabrication process that result in scatter of mechanical properties of the composite in this work. The experimentally observed material properties of the carbon-fabric-reinforced epoxy composite are found to display a considerable amount of scatter in the present work. The possible uncertainties leading to the scattering of testing result are presented in *Table VII.*

TABLE VII. List of Uncertainties.

List of Uncertainty
#1 Manufacturing defects such as matrix void, waviness, gaps
#2 The matrix void-volume ratio
#3 Resin-rich layer
#4 Composite Fabrication-related parameters
#5 Geometrical parameters of the laminate
#6 Cutting of the laminate

<u>SEM Microstructural Analysis Results</u>

The effected portions of the fractured face of the carbon fabric/epoxy composite samples were experimentally observed in SEM [29] in order to study the microstructure of the carbon fabric/epoxy composite material under load. *Figure 14* shows the typical microstructure of carbon fabric/epoxy composite material tested under uni- axial tension (*Sample#3*, *Sample#4*). From the above SEM analysis, it may be seen that the failure of carbon fabric/epoxy laminate under tensile loading takes place due to the shear mode failure with a large number of fiber pull outs (*Figure 14a*), with fiber debonding (*Figure 14b*), transverse fiber breakage (*Figure 14c*) and sequence of matrix crack propagation with fiber pull outs. (Missing of fiber is seen in the right side- *Figure 14d*).

Stress concentration from matrix cracks and fiber-matrix debonding can also provoke fiber breakage. Fiber breakage is commonly seen in composites containing brittle carbon fibers. Fiber breakage (*Figure 14c*) is an extensive mode of failure during high strain rate loading. Matrix cracking (*Figure 14d*) is characterized by microscopic cracks that form primarily in the matrix areas of the composite laminate under loading. The orientation of matrix cracking may be in any direction depending on the applied stress. Debonding (*Figure 14b*) arises due to the interfacial shear stress components. The degree of debonding is decided by the bonding between the matrix and the fibers. High interfacial bond strengths will display only a little fiber matrix interfacial debonding whereas low interfacial bond strength may exhibit interfacial debonding to a larger extent that combines with other damage mechanisms to speed up failure.

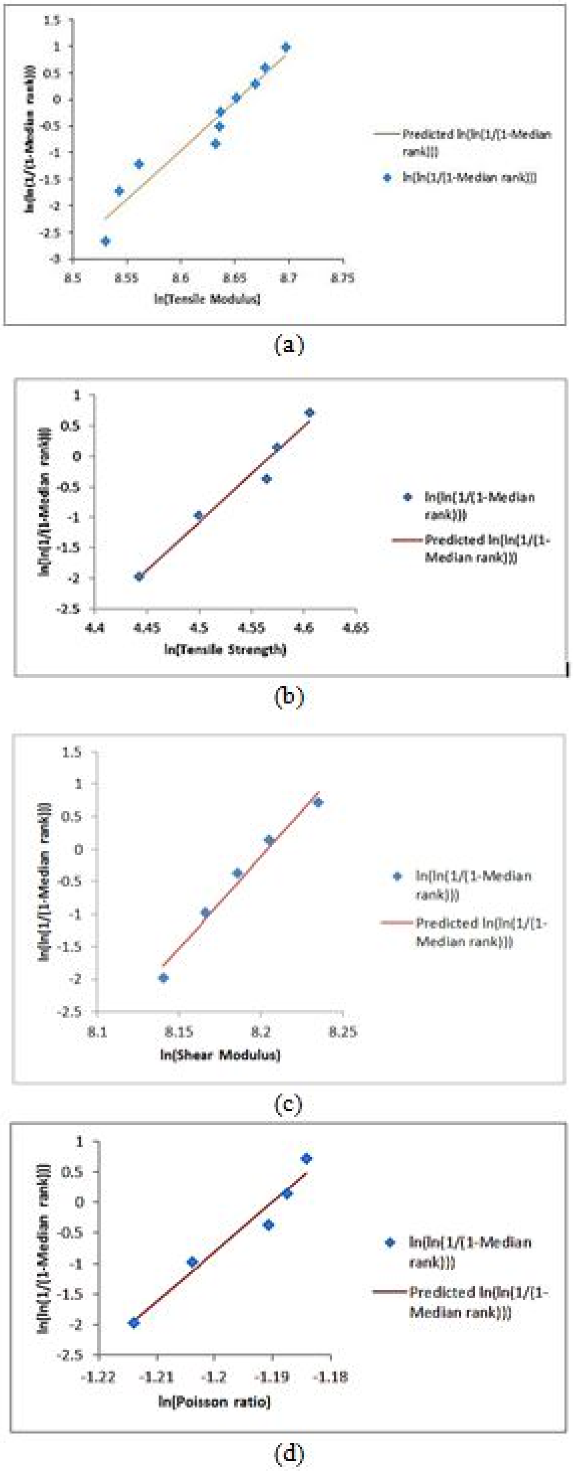


FIGURE 12. Regression Line.

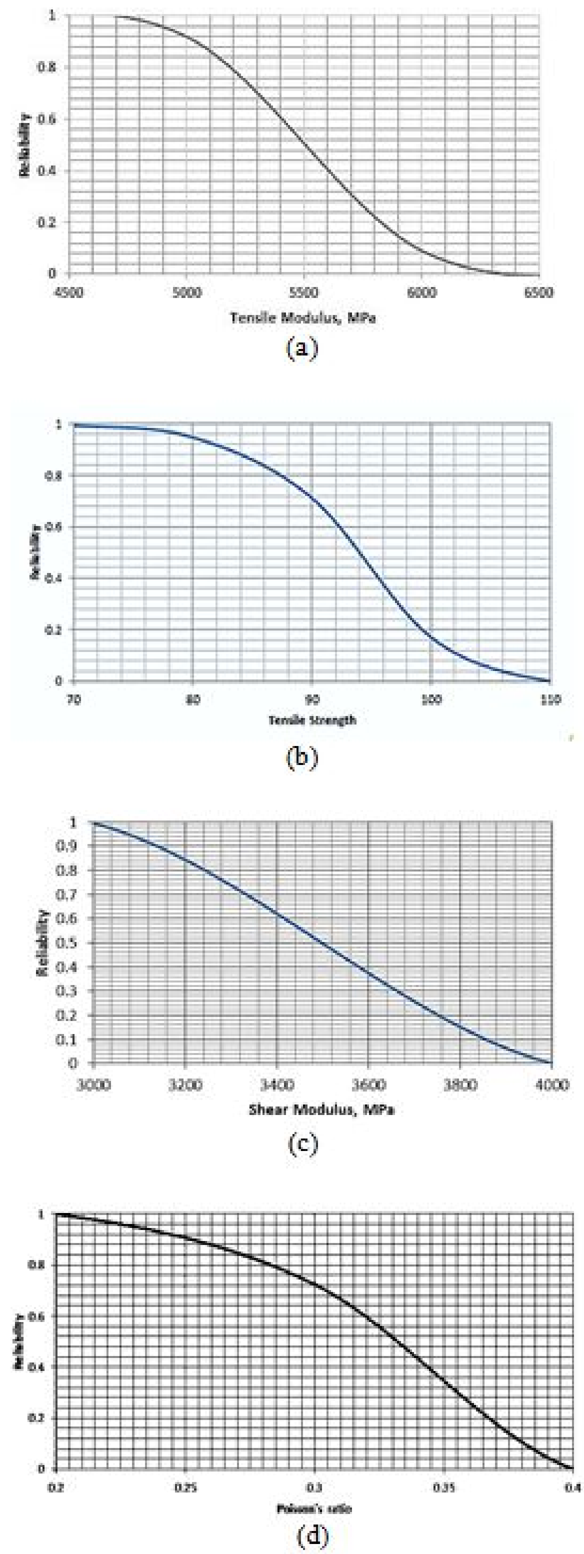


FIGURE 13.Weibull Reliability Distribution.

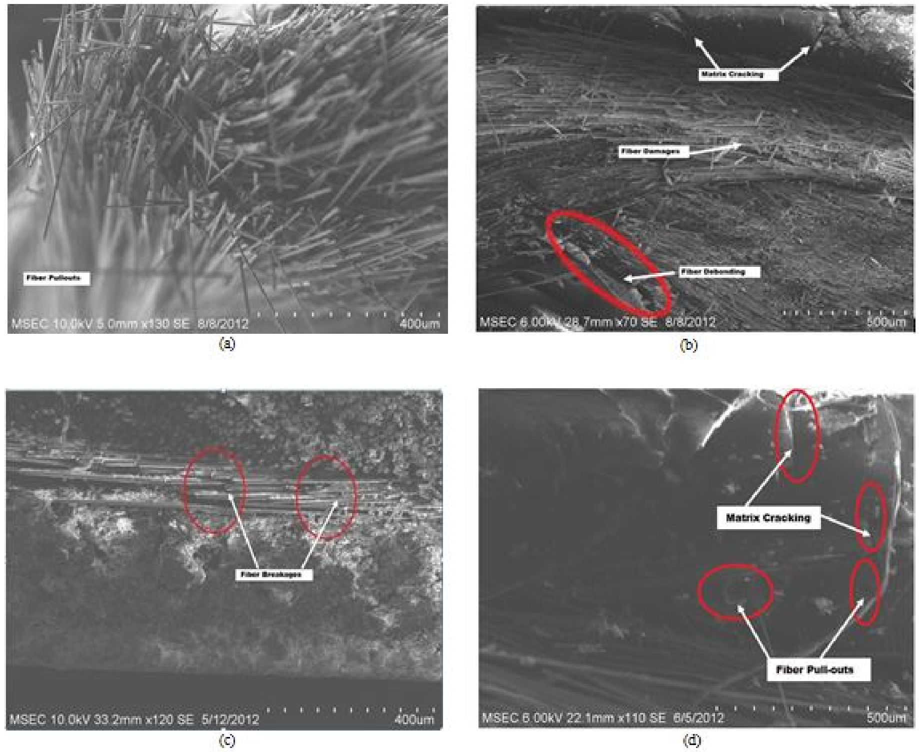


FIGURE 14**.** SEM Photographs of carbon fabric/epoxy composite.

CONCLUSION

A simple fabrication procedure by using hand lay-up technique for the fabrication of carbon fabric/epoxy test coupons is presented in this work with an emphasis on analysis and material characterization of plain weave carbon-fabric-reinforced epoxy composites. The characterization of fabric composite in this research has led to the following conclusions:

(1) The mechanical characterization of carbon-fabric-reinforced epoxy composite for the estimation of unidirectional elastic properties and strength parameter were carried out successfully only after conducting IR Thermographic Non-Destructive Testing.

(2) It was found that the novel infrared thermography technique could be an effective way for the practical inspection and detection of surface defects on expensive high liability carbon-fabric-reinforced epoxy structure.

(3) The load-axial extension curve for carbon-fabric-reinforced epoxy composite has been experimentally obtained under uni-axial tension.

(4) These experimentally observed material properties of carbon fabric/epoxy composites would be useful subsequent with the structural analysis and design techniques of the fabric composite structures.

(5) The Weibull distribution was employed for modelling the variation of mechanical properties of carbon-fabric-reinforced epoxy composite. Using Weibull distribution the composite materials reliability according to which the material will fail has been obtained.

(6) The surface of the carbon fabric/epoxy composite under uni-axial load was examined by Scanning Electron Microscope. The qualitative analysis of the fractured surfaces of the carbon fabric/epoxy composite was conducted. The SEM study reveals that the fracture of carbon fabric/epoxy composite is mainly due to fiber breakage, fiber pull-outs, fiber debonding and matrix cracking. The present study also reveals that the fracture behavior of carbon fabric/epoxy composites depends directly on the fabric/matrix interaction which governs the mechanical properties, thereby the complete performance of the fabric composites.

(7) The IR TNDT, Tensile testing, Statistical, SEM analysis and experimental procedures described in this work would be useful in the development process of fabric composite structural components in case of aircraft and spacecraft structures.

NOMENCLATURE AND UNITS

σ_{12}	Longitudinal Tensile Strength ,MPa
E_L	Elastic Modulus along longitudinal direction ,GPa
G_{12}	In-plane Shear Modulus ,MPa
τ_{12}	In-plane Shear Strength ,MPa
υ_{12}	Poisson's ratio
P	Axial compression, N
SEM	Scanning Electron Microscope
CFRP	Carbon Fabric Reinforced Plastic
PMC	Polymeric Matrix Composite
IR TNDT	IR Thermographic Non-Destructive Testing

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