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Analysis of Electrical Conductivity for Carbon Fibre Reinforced Polymer Composites

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Abstract— *Carbon fibre composites are generally used in aerospace for its high structural properties. These fibres have a very good electrical conductivity and bring anisotropy in the system when imbedded in polymer matrices. Polymer matrices have very low conductivity and they are generally insulative in nature. Hence, carbon fibre reinforced polymer composites do not have as good conductivity as carbon fibres. Many a times, electrical conductivity of composites may play a crucial role such as under lightning strike. In this paper, Model parameters such as curing pressure, resistivity of carbon fibre, waviness of composite fabrication and diameter of carbon fibre are used to analyze conductivity of carbon fibre composites. Experimental results are presented for stacking sequence* $[0^o/0^o/0^o/0^o]$ *and compared with numerical simulation.*

Nomenclature

L_c	Characteristic length of carbon fibre, (mm)
$R_a = R_b = R_L$	Resistance of carbon fibre having characteristic length (Ω)
R_c	Contact resistance between carbon fibre (Ω).
I_a	Current flowing in Resistance, R_a (A).
I_b	Current flowing in Resistance, R_b (A).
I_c	Current flowing in Resistance, R_c (A).
I_{In}	Input current towards Node 1, (A)
I_{Out}	Output Current From Node 1, (A)
d_f	Diameter of carbon fibre, (μm)
d_s	Waviness height, (mm)
β	Fibre waviness factor
E	Elastic modulus of carbon fibre, (GPa).
L	Length of sample, (mm)
B	Width of sample, (mm)
T	Thickness of sample, (mm)
P	Processing pressure (Bar)
ρ	Resistivity of composite lamina, (Ωm)
A_c	Cross-sectional area of composite, (mm^2)
σ_L	Conductivity of CFRP composite lamina in longitudinal direction, $(\Omega m)^{-1}$
σ_T	Conductivity of CFRP composite lamina in transverse direction, $(\Omega m)^{-1}$
$\sigma_{Thickness}$	Conductivity of CFRP composite lamina in thickness direction, $(\Omega m)^{-1}$

1. INTRODUCTION

CFRPs have been widely used in automobiles, aviation, structural and other industries for its high corrosion resistance and strength to weight ratio. From the last few years, Electrical property in CFRP may be gainfully employed in carbon fibre assisted heating during composite manufacturing[1], self-sensing of damage of composite structures [2], lightning strike protection of composite structures [3].There is a large difference between the conductivity of carbon fibre with polymer matrix. Electrical conductivity of carbon fibre is of the order of 10^5 $(\Omega m)^{-1}$while the polymer matrix is almost behaves as insulator with an electrical conductivity of the order of $10^{-10}(\Omega m)^{-1}$ to $10^{-20}(\Omega m)^{-1}$[4,5]. Conduction mechanism of electrical conductivity is explained as continuous in longitudinal direction while it has shortest conduction path in the transverse and through-thickness directions. Thermal conduction and mechanical behaviour studies have been performed using microstructure based modeling for CFRPs [6]. Generally, it is assumed that the fibres are thin (of the order of 10^{-6} to 10^{-9} m) and long cylinders and are placed parallel to the length direction of the composite. Microstructure is represented by fibre spacing and packing pattern information of the cross-section of the composite. Straight fibre model is relaxed by Gutowski *et al.*[7] by introducing a new assumption in model parameter for making multiple connecting points along its length with the neighbouring fibres due to fibre waviness. Waviness in carbon fibre provides a continuous conduction path in transverse as well as in thickness direction.

A 2D micro-mechanism model of electrical conductivity is presented with equivalent electrical resistance model built by describing the microstructure relationship between waviness and their contact points. Waviness model approach predicts electrical conductivity of CFRPs as a function of fibre volume fraction, intrinsic carbon fibre properties, fibre waviness and processing pressure etc.

2. MODELING

Percolation theory helps to explain electrical conductivity In CFRPs. Critical loading known as percolation threshold, enhances the conductivity to several order of magnitude. Fibres waviness leads to a number of contact points along the fibre direction with neighbouring fibres. Hence, the CFRP structure has a larger electrical network. A resistor network model has been devised using the existing microstructure model [7].Cross-sectional fibre arrangement perpendicular to the fibre length is generated to build a 2-D fibre arrangement. This 2-D fibre network is extended along the length with fibre waviness information to describe a full 3-D micro-structure. Fibre arrangements and fibre waviness parameters are described experimentally and numerically. It is assumed that square, hexagonal or random packing orders help in generation of 2-D fibre arrangement of the composite micrograph. Waviness parameters may be obtained experimentally from compression behaviour model developed by Gutowski[7].It can also be obtained using a numerical simulation. Each carbon fibre of CFRP composite is divided into small section with fibre contact point throughout length of the fibre. Contact point in carbon fibreis considered as a node in the electrical resistor network model. Carbon fibre divided in a number of sections in which each section modeled as a resistor whose value can be determined by the length of carbon fibre segment, carbon fibre diameter and the intrinsic resistivity of the carbon fibre. A contact resistor added in electrical resistor network model which represents contact point as in 3-D micro-structure. It means that there are two types of resistors in the electrical resistor network model.

a) Resistance which represents a length of carbon fibre(R_L).

b) Resistance which represents a contact resistance between carbon fibres(R_C).

Kirchhoff's law helps to solve resistor of fibre and contact resistance of carbon fibres. According to Kirchhoff's current law which states that the total charge(current) entering in a circuit junction for a parallel path is equal to the total current leaving the same junction as it has no other place to go or no charge is lost.

Mathematically,

$$\Sigma I_{in} = \Sigma I_{out} \quad \text{..........(1)}$$

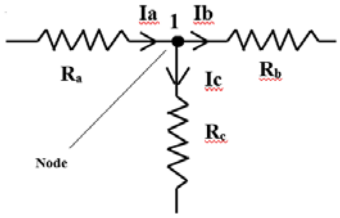

Figure 1: Fibre and contact resistance arrangement at node1.

In Figure 1, when potential difference is applied across the terminal, first current passes through fibre resistor (R_a) and reaches node 1 to get divided into two parts, one is fibre resistor and second is contact resistor. According to Kirchhoff's current law, algebraic sum of current entering at node 1 is equal to current leaving the node, i.e.

$$I_a = I_b + I_c \quad \text{.....(2)}$$

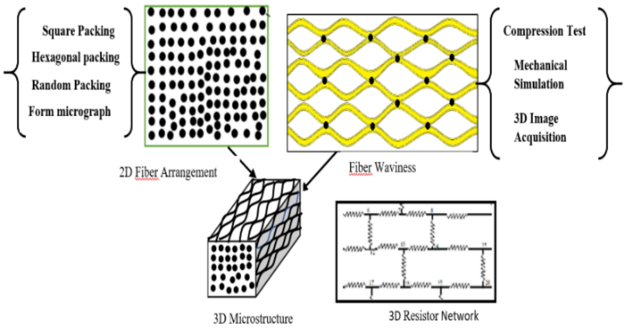

Figure 2: Resistor network model formation from 2-D fibre arrangement and fibre waviness parameter

3. RESISTANCE ANALYSIS OF CFRP COMPOSITES

Fibre resistance and contact resistance in each direction have been evaluated using following assumption:

- Fibres are not straight but they have waviness across the sample.

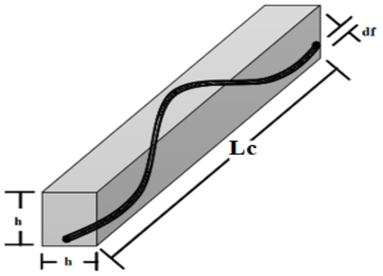

Figure 3: Representation of fibre waviness

Fibre waviness (β) = $\frac{L_c}{d_s} = \frac{L_c}{h-d_f}$

- $d_s = 2 \times d_f$
- Distribution of fibre is the same throughout in sample.
- Contact between the fibre is uniform and perfect(direct contact of carbon fibre) in a composite sample.
- CFRP compositesare orthotropic and carbon fibres are anisotropic.
- Matrices are insulative in nature and hold the carbon fibres securely.

Sample model of composite with above assumptions is shown in Figure 4. Mechanical properties and conductivity of CFRP are shown in Table 1.

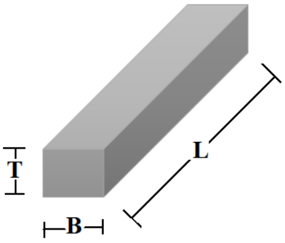

Figure 4: Sample model of CFRP composite

a) Calculation for Fibre Resistance (R_L)

The resistance (***R_L***) of characteristic length of carbon fibre is calculated from the intrinsic carbon resistivity, carbon fibre diameter and characteristic length (***L_c***):

$$R_L = \rho \frac{4*L_c}{\pi*d_f^2} \quad ....(3)$$

Contact resistance (R_c) may be calculated with the help of Hertz contact theory:

$$R_c = \frac{\rho}{\sqrt[3]{\frac{3P*(d_f+d_s)*d_s*\beta*d_f}{2E}}} \quad ....(4)$$

4. EFFECT OF PROCESS PARAMETER ON RESISTANCE

In proposed model, the effect of processing parameters is estimated. Processing parameters such as pressure, diameter of carbon fibre, fibre resistivity and waviness etc. These parameters are showing variation in the resistance. Model parameters for this analysis are shown in Table1.

Table 1. Model parameter of CFRP composites [8]

Description	Parameter	Typical value for A S4 Carbon Fibres
Processing pressure	Pressure	8bar (Autoclave)
Fibre waviness term	Beta	~300.
Averagefibre diameter	Fib_Dia	7 µm.
Elastic Modulus of fibre	E_Mod	231GPa.
Electrical resistivity offibre	Fibre_Rho	1.7x10^{-5}Ωm.

a) Pressure

Processing parameters help in decreasing the resistivity with an increase in process pressure. Withincrease in pressure, excess matrix material between the carbon fibres and fibres layer are removed. This results in better contact between the fibres and CFRPs are compact and stiffer with high strength. Equation4 shows that increase in processing pressure results in increased contact force leading to decrease in contact resistance and resistivity in transverse direction.

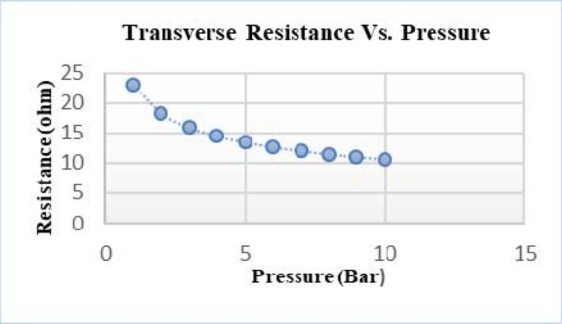

Figure 5: Variation of processing pressure with resistance

Increase in processing pressure also helps in decreasing resistivity in longitudinal direction because it systematically aligns all the fibres along the longitudinal direction.

b) Fibre Waviness

Contact portion between the fibres depends on processing pressure. An increase in pressure results in an increase in contact portion while reducing resistivity. Smaller contact portions have a greater resistivity as it is difficult for electrons to pass through the contact area.

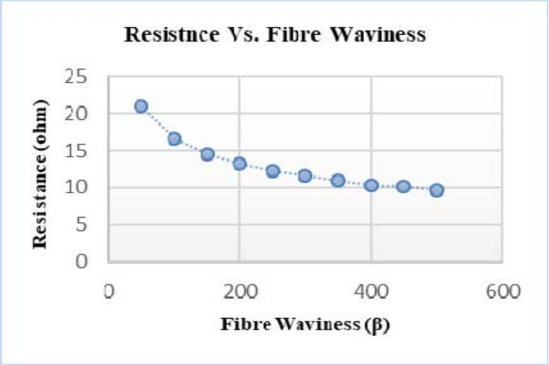

Figure6. Variation of fibre waviness with resistance

c) Fibre Diameter

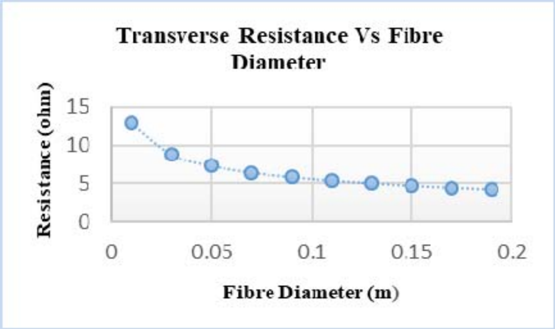

Figure 7: Variation in transverse resistance with fibre diameter

Fibre diameter plays important role in transverse and longitudinal direction.

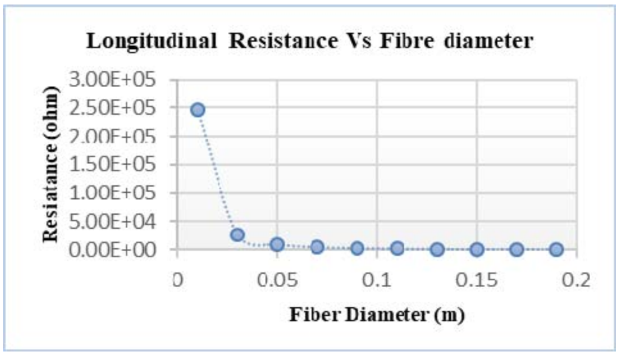

Figure 8: Variation in longitudinal resistance with fibre diameter

Equation 3 and 4 show that the increase infibre diameter leads to decrease in electrical resistivityin longitudinal and transverse directions.

d) Fibre Resistivity

Carbon fibre is conductive while matrices are insulating in nature. Hence, conductivity of CFRPs is mainly depended on fibre resistivity. Higher the fibre resistivity, lower is the conductivity in longitudinal and transverse directions. Equation 4 represents relation between fibre resistivity and resistivity of CFRP composites.

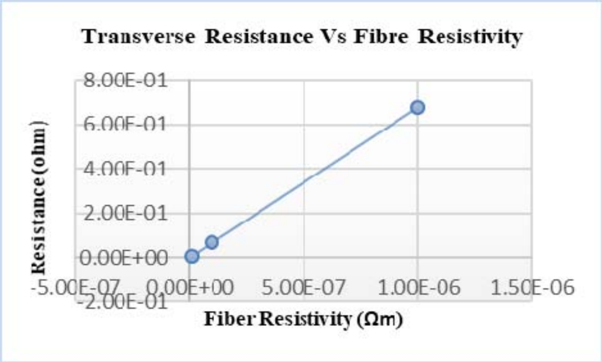

Figure 9: Variation in transverse resistance with fibre resistivity

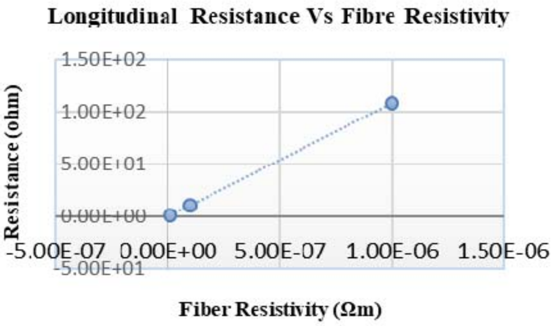

Figure 10: Variation in longitudinal resistance with fibre resistivity

5. EXPERIMENTAL ANALYSIS OF ELECTRICAL CONDUCTIVITY

CFRP composite samples have been prepared using unidirectional fibre by hand operated press. Parameter for sample prepared are shown in Table 2.

Table 2. Model parameters for experimental analysis.

S No.	Description	Typical Value
1	Fibrevolume fraction	~ 70 %
2	Sample thickness	2.45 mm
3	Sample length	100 mm
4	Sample width	20.0 m.
5	Processing pressure	100lbf/sq.intch.
6	Average fibre diameter	$7\text{x}10^{-6}$ m
7	Curing temperature	25^{o} C
8	Curing time	24 hour.

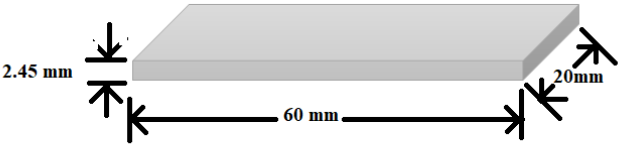

Figure 11: Dimensionof CFRP composite sample for experimental analysis

Figure 12: Actual fabricated CFRP composite sample for experimental analysis in laboratory

6. MEASUREMENT METHOD

Two-probe method has been used to measure the electrical resistance of CFRP composite samples shown in Figure 12.In two-probe method, a pair of electrodes with conductive wires are required to measure electrical resistance of CFRP composite samples. The two-probe method is based on Ohm's law, i.e.

$$V = I * R \quad ....(5)$$

Where V, I and R being voltage, current and resistance between the two electrodes respectively. Schematic diagram of two-probe method for longitudinal resistance is shown in Figure 13.

When the two electrodes are connected with DC power supply source as shown in Figure 13, a direct current is supplied to the samples. Using Ohm's law, a resistance is measured based on the current and voltage.

Total measured resistance, $\boldsymbol{R_T}$ also includes the resistance, $\boldsymbol{R_W}$ of electrodes with wires, the resistance $\boldsymbol{R_M}$ of the meter and the contact resistance, $\boldsymbol{R_{IM}}$ due to the imperfect bonding between the electrodes and the body.

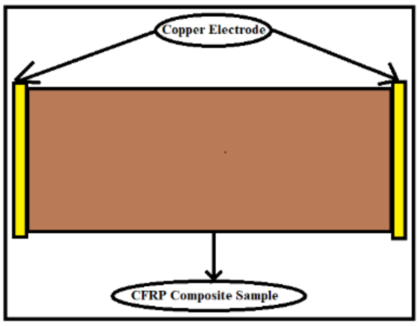

Figure 13: Schematic diagram of two-probe measurement

The measured resistance, R_S can be approximated as the specimen's resistance.

Mathematically,

$$\boldsymbol{R_T = R_S + R_W + R_M + R_{IM}} \quad ....(6)$$

As compared to R_S, it is assumed that the resistance R_W,R_M and R_{IM} are very small and may be neglected.

Electrodes are made of copper tape as shown in Figure 14. Advantage of copper tape electrodes is that they have higher electrical conductivity.

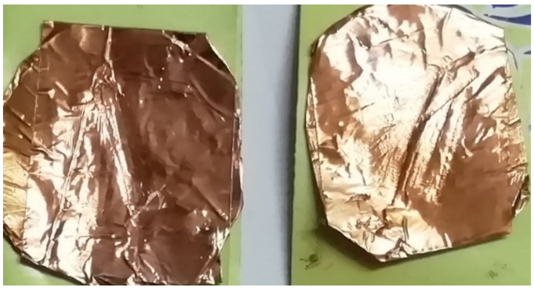

Figure 14: Copper tape electrode measuring longitudinal resistance

Figure 15: Copper tape electrode for measuring transverse and through thickness resistance

7. CONDUCTIVITY MEASUREMENT

In this research paper, the conductivity of CFRP composite samples with four layers of continuous carbon fibres in a polymer matrix with a rectangular shape is prepared with a stacking sequence of [0°/0°/0°/0°].This specimen ensures a uniform current density in the rectangular or strip panel. Copper tape electrode has been used. When the sample is connected to a DC power source, the conductivity of the composite panel,σmaybe determined using Equation[7]:

$$\boldsymbol{\sigma = \frac{L}{R*A}} \quad .....(7)$$

L and A are the length and cross-sectional area of the sample. Since the composite panel is orthotropic, the conductivities in the other two directions will be different and can be measured in the same fashion. A DC current of the magnitude of 5 ampere has been used.

a) Conductivity in Longitudinal Direction

Arrangement of CFRP sample with plate electrode is shown in Figure 13 to measure the electrical conductivity in longitudinal direction. Electrical conductivity is shown in Figure 16.

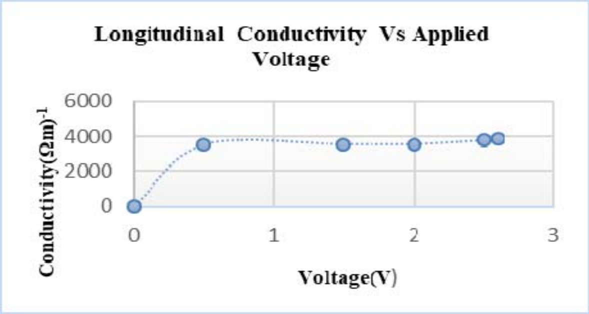

Figure 16: Experimental result of longitudinal conductivity with applied voltage for CFRP composite sample parameter shown in Table 2

b) Conductivity in Transverse Direction

Potential difference is applied across the width of the CFRP sampleto measure the electrical conductivity in the transverse direction. Resulting electrical conductivity is determined by Equation 7 and is presented in figure17.

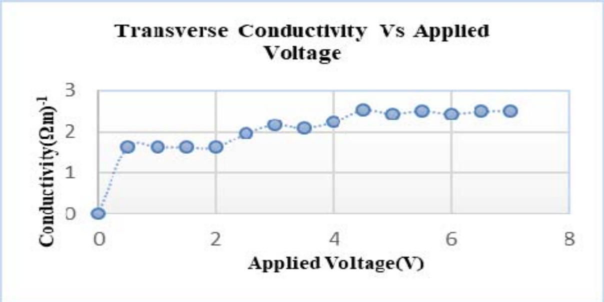

Figure 17: Experimental results of transverse conductivity with applied voltage for CFRP composite sample parameter as shown in Table 2

a) Conductivity in Thickness Direction

Variation in conductivity in through-thickness direction is shown in Figure 18.

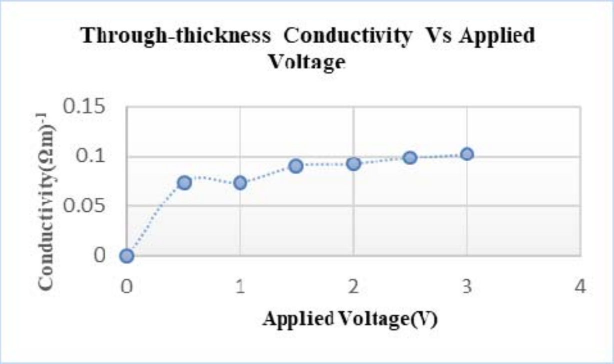

Figure 18: Experimental result of through-thickness conductivity with applied voltage for CFRP composite sample parameter as shown in Table 2

8. RESULTS AND DISCUSSION

Electrical conductivity of CFRP composites is orthotropic in nature, i.e, conductivity in longitudinal direction is very high as compared to other two directions (transverse and thickness directions). Conductivity in longitudinal direction is directly proportional to the intrinsic property of the carbon fibre. In transverse and thickness direction, the conductivity is lower than that in longitudinal direction because the gap between adjacent carbon fibres has been filled with epoxy in case of transverse direction. Epoxy is non-conductive in nature and only a few electrons are allowed to pass from one terminal to the other. In thickness direction, between the layer of carbon fibre epoxy is present causing decrease in conductivity. Presence of epoxy between layers of carbon fibre may be controlled by processing pressure as shown in Figure 5. Conductivity in thickness direction is low as compared to the transverse direction.

With the help of experimental investigation on CFRP composite samples shown in Figure12, it may be concluded that longitudinal conductivity is very high as compared to transverse and through- thickness directions. results are presented in Figures 16, 17 and 18.

Mathematically,

$$\sigma_L > \sigma_T > \sigma_{Thickness} \quad \text{..........(8)}$$

9. CONCLUSIONS

Experimental analysis on four layer CFRP composite sample with [$0^0/0^0/0^0/0^0$] stacking sequence has been presented. A waviness based model has been examined with various processing parameters. Following conclusions were made:

a) Experimental analysis shows a very high conductivity in longitudinal direction and fairly low conductivity in transverse and thickness direction. (Refer Equation (8)).

b) Electrical resistance depends on processing parameters such as pressure, fibre waviness, diameter of fibre and fibre resistivity etc. Fibre waviness model gives better prediction of conductivity in CFRP composite. However, it is fairly difficult to create waviness in the composite.

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