Experimental Electrical Characterisation of Carbon Fibre Composites (CFCs) for use in Future Aircraft Applications

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Experimental Electrical Characterisation of Carbon Fibre Composites (CFCs) for use in Future Aircraft Applications

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Abstract: This paper presents experimental testing of samples from two unidirectional Carbon Fibre Composite (CFC) panels to determine the factors that influence the electrical properties of CFCs and to also determine the temperature co-efficient of resistance. The CFC panels were manufactured by two different techniques to compare the impact of the manufacturing process on the electrical properties. Various electrical conductivity measurement methods were evaluated to determine the most consistent and accurate technique. The influence of sample geometry on the measured electrical conductivity was also investigated. Thermal imaging was used to image resistive losses and illustrate the current paths through the fibres within the CFC test samples. Finally, the effects of increasing temperature on the CFC samples are presented, illustrating that CFCs have a negative temperature co-efficient.

1. Introduction

Composite materials are revolutionising the aircraft industry, in both military and commercial aircraft applications [1, 2]. The percentage of carbon fibre composites (CFCs) used in aircraft structures has increased in recent years targeting weight reduction to meet global emission requirements. The Advisory Council for Aeronautical Research in Europe (ACARE) targets a 75% reduction in greenhouse gases from aircraft by 2050.

There are many motives for the growth in the use of CFCs. Replacement of ‘traditional’ metal materials with composites is a significant benefit to the aircraft industry. A comparison of CFCs to aluminium and steel are given in Table 1.

Table 1 Comparison of carbon fibre, steel, aluminium

<table>
<thead>
<tr>
<th>Material</th>
<th>Tensile Strength (kPa)</th>
<th>Weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Fibre</td>
<td>x</td>
<td>y</td>
</tr>
<tr>
<td>Steel</td>
<td>0.1x</td>
<td>5y</td>
</tr>
<tr>
<td>Aluminium</td>
<td>0.125x</td>
<td>1.5y</td>
</tr>
</tbody>
</table>

The weight reduction has been a major impetus in the commercial aircraft sector because it can result in a reduction in fuel costs per passenger. The Airbus A380 for example, presently the world’s largest passenger aircraft, uses composite materials in its wings. This resulted in a 17% reduction in fuel costs and associated emissions per customer [1]. Another example is from Rolls-Royce; their CTi (Carbon/titanium) blades are a key feature of the Advance engine design (AED) which provides 20% less fuel burn and CO₂ emissions.

The fan casing is also being proposed for manufacture using CFCs [3]. This could result in a weight reduction of up to 1,500 lbs per aircraft (the equivalent of carrying approximately seven more passengers and their luggage). As a further example, the percentage distribution of composite materials presently used in two aircraft designs is given in Table 2.

Table 2 Composite Materials Used in Two Aircraft Designs [4, 5]

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>% Distribution of Structural Material</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Comp.</td>
</tr>
<tr>
<td>A350</td>
<td>52</td>
</tr>
<tr>
<td>B787</td>
<td>50</td>
</tr>
</tbody>
</table>

Various application studies have been conducted on CFCs. It has been used for rotor banding on high-speed electric machines for containment [6]. Research has also been conducted on lighting strike protection where CFC’s have been used in aircraft structures and wind turbine blades [2, 7]. Research has also been for aircraft applications where CFCs have been investigated for potential use in de-icing applications. Detecting internal damage of CFCs using numerous non-destructive techniques has also been investigated [8-9]. However, the electrical behaviour of carbon fibre composites (CFCs) has received relatively little research attention and requires experimental testing to understand the factors that influence the electrical properties of the material such as geometry and temperature. Understanding the material electrically and in particular the current flow is important for many of the research applications discussed.

Given the strongly anisotropic nature of CFCs, varying fibre orientation and the difficulty making contact between
the carbon fibre strands and the measurement electrodes, measuring the electrical conductivity is not straightforward. To date there is no standardized method for electrical characterization of CFCs. This is, therefore, the main focus of this paper.

2. Factors Influencing the Electrical Conductivity of CFCs

In a composite, the electrical properties are a combination of its constituents. In CFCs, there are carbon fibres and epoxy resin. Epoxy resins are classified as insulators due to their low number of free electrons for conduction. The resistivity of resins is typically in the region of $\approx 7 \times 10^{11}$ $\Omega \text{m}$ [10, 11]. The electrical conductivity of CFCs therefore is predominantly in direct relation to the number of carbon fibres; the epoxy resin can effectively be ignored. The factors which influence the bulk electrical conductivity of CFCs are:

- Anisotropic nature
- Orientation of the carbon fibres
- Volume fraction
- Percolation threshold
- Length of the carbon fibres
- Fibre matrix adhesion

2.1. Anisotropic Nature

One of the most important factors when numerically modelling or manufacturing a CFC, is the orientation of the carbon fibres. CFCs are defined as an anisotropic material, which means that the properties of the material are orientation dependent [12]. The electrical conductivity for example is higher in the longitudinal direction of the fibres (parallel) but lower in the transverse direction (perpendicular) [13].

2.2. Orientation of the Carbon Fibres

The variation of electrical conductivity as a function of the carbon fibres orientation was investigated in [11]. The results in [11] stated that the smallest misalignment in the fibres (no longer parallel to each other) impacted the longitudinal and transverse electrical conductivities. This is supported by the work published in [14], where the authors illustrated that the anisotropic nature of CFCs is associated with the orientation of the carbon fibres.

2.3. Volume Fraction

The volume fraction in CFCs is related to the percentage of carbon fibres to resin, and is a significant factor in the electrical conductivity in both the longitudinal and transverse directions; this was experimentally confirmed by the work presented in [15]. The maximum conductivity can be calculated by multiplying the electrical conductivity of a single carbon fibre strand by the volume fraction. The ideal equation is referred to as the ‘rule of mixture’ [15], and can be calculated from:

$$\sigma_0 = \sigma_f V_f + \sigma_m (1 - V_f) \quad (1)$$

where: $\sigma_0$ is the electrical conductivity of a CFC in the direction of the carbon fibres (S/m); $\sigma_f$ is the electrical conductivity of the carbon fibre strands only (S/m); $V_f$ is the volume fraction (%); and, $\sigma_m$ is the electrical conductivity of the resin in a CFC (S/m). The conductivities are functions of temperature so (1) will be appropriate to any particular temperature.

The ideal linear relationship to determine the electrical conductivity in the longitudinal direction is:

$$\sigma_0 = \sigma_f V_f \quad (2)$$

and the electrical conductivity in the transverse direction is:

$$\sigma_{90} = \frac{\sigma_f \sigma_m}{\sigma_m V_f + \sigma_f (1 - V_f)} \quad (3)$$

where, $\sigma_{90}$ is the electrical conductivity of a CFC in the transverse direction of the fibres (S/m).

2.4. Percolation Threshold

The percolation threshold relates the conductivity of a CFC based on its volume fraction. The percolation threshold corresponds to a value of the volume fraction where the conductivity increases strongly due to the number of connection points between the fibres. It is difficult to determine the percolation threshold theoretically, i.e. to determine a preset volume fraction percentage which surpasses the percolation threshold. This is because each manufactured CFC is uniquely different in terms of the orientation of the carbon fibres [16]. However, typically a value of approximately 35-45% of the volume fraction generally meets this percolation threshold [16-18].

From the work published in [16, 17, 19, 20] once the volume fraction of CFCs exceeds 60%, it has surpassed the percolation threshold and it is considered to be conductive. A 60% volume fraction therefore was aimed for in the two panels manufactured for the experimental testing presented in this paper.

3. Measuring the Electrical Conductivity

To date, there is no standardized method for measuring and determining the electrical characteristics of CFCs. The U.S. Department of Defence’s (DoD) handbook on composites includes a section on electrical conductivity measurement but at present it is just a place holder in the document, as no details have been provided [21].

Previous research has used a conductive adhesive applied at the ends of the CFC samples to be tested, to enable a more accurate measurement of the electrical conductivity to be achieved [10]. A typical conductive adhesive for this measurement application is silver epoxy. The conductive adhesive improves the electrical connections between the ends of the carbon fibre strands and the measurement electrodes. In [7], copper foil was used, along with a bench vice, to connect the ends of the CFC samples and the measurement electrodes. However, this method introduced another unknown variable, namely the pressure applied to the CFC samples using the vice was unmonitored.
The work presented in [7] determined the electrical conductivity of CFCs. However, no work in the literature has presented the effect of the CFC sample length on the electrical conductivity, or the impact of temperature on the value of electrical conductivity.

4. Manufacturing Uni-Directional CFC Panels

The diameter of a single carbon fibre is normally between 5 µm and 15 µm, and is predominantly made of carbon atoms [22]. Typically 12,000 carbon fibres are combined together to form a bundle known as a tow, which is then embedded in epoxy (resin) to form a lamina. Laminas are then layered in different configurations/orientations depending on the intended application to form a CFC laminate, as illustrated in Fig. 1. The lay-up or component is then heated to cure the epoxy resin and form a solid structure.

![Fig. 1. Example layout of a CFC laminate [23]](image)

There are two types of resins that are typically used when manufacturing CFCs: thermoset and thermoplastic resins. Thermoset resins are liquid at room temperature, which makes them easier to work with because it allows for convenient impregnation of the carbon fibres. A CFC using thermoset resin is then hardened at a relatively high temperature (curing temperatures are typically 120 °C to 180 °C) [21, 24]. Conversely, thermoplastic resins are solid at room temperature. On heating a thermoplastic resin, it softens and a CFC can be manipulated to the shape/form required. The structures in aircrafts are typically manufactured using thermoset resins. Therefore, the two CFC panels investigated in this paper were manufactured using thermoset resins.

For the purpose of the research work presented in this paper, two uni-directional (UD) CFC panels were manufactured using different techniques: a resin infusion technique and a pre-impregnation (prepreg) technique. This was conducted to understand if the manufacturing process impacted on the values of electrical conductivity.

4.1. A CFC Panel Manufactured using the Resin Infusion Technique

The first CFC panel (Panel 1) was manufactured from carbon fibre fabric STS40 F13 24K 1600tex. The resin used was Araldite LY564 and the hardener was Aradur 2954. An explanation of the resin infusion manufacturing method can be referred to in [25]. The specific curing process chosen for the epoxy resin and hardener system from the datasheet was one hour at 80 °C followed by two hours at 140 °C, with a rise time of 30 minutes.

4.2. A CFC Panel Manufactured from PrePregs

The second CFC panel (Panel 2) was manufactured using T800SC/3900-2C Toray Composites prepreg (prepreg is a CFC pre-impregnated with epoxy resin). This is an aerospace grade composite made of ten layers of 0° UD fibres. The manufacturing process is explained in [26, 27]. The specific curing cycle conditions for Panel 2 used in the autoclave were:

- Pressurize to 6.95 bar
- Heat at 2 °C/min to 177 °C
- Dwell at 177 °C for 120 mins.
- Cool at 3 °C/min to 60 °C
- Depressurize and cool at 3 °C/min to 40 °C
- 100% vacuum applied for duration of cure

Four samples labelled (S1-S4) were cut from Panel 2 due to the limited availability of the prepreg material used. The initial length of the four samples was 150 mm each. After resistance measurement testing, the samples were cut to the lengths of 125 mm, 100 mm, 75 mm, 50 mm and 25 mm, respectively, to compare the results with the results obtained from Panel 1.

4.3. Dry Carbon Fibre Fabric
Electrical conductivity testing was also conducted on carbon fibre tows without epoxy resin. The diameter of a single strand of the carbon fibre fabric, STS40 F13 24K 1600tex, was 7 µm, which was difficult to work with for electrical conductivity testing. Therefore, a tow was used for each sample tested. Each tow consisted of 24,000 strands of carbon fibre. The cross-sectional area of each strand was $3.85 \times 10^{-11}$ m$^2$. The tows within the carbon fibre fabric were held together by fibre glass stitching. The lengths of the samples (S1 to S3) were 109 mm, 75 mm and 40 mm, respectively, as shown in Fig. 4.

**Fig. 4.** Three samples of tows consisting of 24,000 strands of carbon fibre

### 5. Experimental Test-rig

To measure the resistance accurately and hence, obtain the conductivity of the CFC test samples, the four-point resistance method was used. The method can eliminate or significantly reduce the effects of the contact resistance during the measurements. Two pairs of electrodes were used: the outer electrodes injected a current through the CFC samples and the inner electrodes measured the voltage across the test samples.

To ensure a uniform current was injected into the CFC samples tested, two copper plates at either end were used. The required length of the copper plates was determined by a finite element model which indicated uniform current flow was achieved approx. 20 mm from the current connection point to the copper plate. The length of the copper plates therefore was chosen to be 30 mm in length. The width of the plates was the same as the CFC samples, 20 mm; and the thickness was 2 mm. In addition, a copper wire was placed between the copper plates and the CFC samples as shown in Fig. 5 to measure the voltage across the CFC samples.

A silver epoxy adhesive was used to create the electrical connection between the copper strip and the CFC test samples. Fig. 5 shows the FE model of the potential distribution and the CFC test sample ready for experimental testing. The method shown in Fig. 5 was the initial measurement technique used to determine the electrical conductivity of the CFC samples. This method, however, did not provide consistent results. The reasons for this were:

- The voltage measurement wires inserted between the copper plates and the CFC samples lead to variability in the contact area and hence, current flow into the CFC samples due to changes in the contact resistance
- No pressure could be applied to the connection area to ensure a good contact between the copper plates and the CFC samples during oven curing of the silver epoxy

**Fig. 5.** (a) FE model to determine length of copper plate for uniform current flow, and (b) one end of a CFC test sample (ready for testing)

After experimentation with different set-ups, a combination of the method shown in Fig. 5 and the technique of applying pressure discussed in [7] were used to provide consistent pressure and contact between the measurement electrodes and the CFC test samples.

An Agilent 34420A micro-ohm meter was used to perform the four-point resistance measurements. 200-grit emery paper was pasted along the edges of all the CFC samples in an attempt to expose the carbon fibre strands. Silver epoxy was pasted onto both ends of the CFC samples and then placed in an oven for 10 minutes at 100 °C to cure. Each CFC sample was placed between the copper foil strips and a bench vice was used to apply sufficient pressure to ensure good electrical contact, as shown in Fig. 6.

**Fig. 6.** Final experimental test-rig setup used to measure CFC test samples

To determine the electrical conductivity in the direction of the carbon fibres, a DC current was passed through the sample and the voltage was measured on the...
micro-ohm meter. The electrical conductivity was determined using the empirical formula:

$$\sigma = \frac{l}{V I} \times A \quad (4)$$

where $l$ is the length of the CFC test sample, $A$ is the cross-sectional area of the CFC test sample, $V$ is the measured voltage from the micro-ohm meter, and $I$ is the current set on the current controlled power supply.

6. Results and Discussions

6.1. Results from Electrical Conductivity Test on Carbon Fibre Strands Only

The electrical conductivity of the carbon fibre fabric tow without resin was measured initially. The tow was connected to the copper foil strips using electrical tape, since the carbon fibre strands were exposed. The result of electrical conductivity versus length is presented in Fig. 7.

The small variations in conductivity are attributed to experimental error mainly. The measured value was $\approx 3.83 \times 10^4$ S/m. The various datasheets and publications [7] suggest that the electrical conductivity of carbon fibre is in the range of 40,000 to 70,000 S/m, so the measured value is slightly below the minimum value in the range. However, it was difficult to ensure that all the fibres were connected to the electrical supply which results in a higher sample resistance and hence, lower conductivity value.

6.2. Results from Panel 1 and Panel 2

Figs. 8 and 10 illustrate the standard error deviation for the averaged values from all the tested CFC samples of the electrical conductivity for Panels 1 and 2, respectively.

Figs. 9 and 11 present the average results of the group of samples measured at two different temperatures: room temperature and after oven curing ($\approx 100 ^\circ C$) the silver epoxy.
The first point observed from the results was that the electrical conductivity increased with sample length. This was thought to be due to the following factors:

- The contact between the silver epoxy and the CFC test samples was not providing a consistent uniform contact.
- The current paths within the samples were not flowing uniformly throughout the samples as the length increases.

The results presented in Figs. 9 and 11 are the averaged results for Panels 1 and 2. The averaged results minimize the variation due to inconsistent contact points between the silver epoxy and the CFC samples. It is therefore clear that there is an increase in the electrical conductivity as the length of the CFC test samples increases for both of the manufactured panels tested. This was thought to be primarily due to a non-uniform current flow through the CFC samples. This was confirmed using a thermal imaging camera (FLIR A35sc), which captured the heat produced by the current flow, as shown in Fig. 12. The images presented in Fig. 12 were taken in increments of 0.16 seconds starting from time (t) = 0.

**Fig. 11.** Electrical conductivity variation with length for Panel 2 (pre-preg) measured at two different temperatures (100 °C and 20 °C)

Images 1 to 6 in Fig. 12 provide evidence that the current paths within the CFC samples are not uniform because the temperature is not predominantly constant throughout the sample. This was observed in all samples tested. The non-uniform current flow could be due to the random distribution of the resin through the CFC which can influence the number and distribution of contact points between the carbon fibres and thus, modify the current flow along the length of the samples. Another issue is the electrical contact to the carbon fibres at both ends of the samples.

Section IV discussed the manufacturing of the CFC panels. Both panels contained many tows of carbon fibre and each individual tow contained 24,000 strands of carbon fibre. A random number and distribution of thousands of carbon fibre strands therefore will be exposed and make contact with the silver epoxy, as illustrated in Fig. 12. However, the key point here is that a significant number of carbon fibre strands may not be exposed or make contact with the silver epoxy and it is worth considering what happens in this situation.

**Fig. 12:** Thermal images illustrating the non-uniform current paths in a CFC sample at various time stamps

**Fig. 13:** (a) Physical construction of the experiment and (b) illustration of carbon fibre strands contact to silver epoxy

Fig. 13 (a) represents the physical construction of the experiment. Let us assume that the electrical contacts at each end of the test sample make contact to a random number of carbon fibres, which are not necessarily the same. This is illustrated simplistically in Fig. 13 (b).

Despite the random connections at each end, we know that a total current (I) is carried through the carbon fibres of the test sample. The number of carbon fibres that make electrical contact at each end will determine the resistance per unit length. Fewer carbon fibres reduce the area and hence, produce a higher resistance per unit length. It is worth noting that the temperature plots in Fig. 12 indicate indirectly the joule heating losses in the fibres rather than the current immediately after connection and before heat starts to spread through the sample. Fig. 12, image 1, shows a higher temperature at the bottom edge compared to the top edge. The same total current must pass along the CFC sample so this would indicate a higher resistance per unit length at the bottom edge compared to the top edge. This in turn would indicate that fewer carbon fibres have made electrical contact at the bottom edge.

If there were no carbon fibre interconnections within the sample, the current would only flow in the carbon fibres that are connected at each end and the conductivity measurement would not vary with length. The fact that the conductivity measurements do vary with sample length tells us that carbon fibre interconnections exist within the CFC sample. The current, therefore, spreads out into other carbon fibres through these interconnections along the length of the sample, and the resistance per unit length starts to reduce.

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The temperature also reduces, as illustrated in Fig. 12, images 1 and 2.

The current continues to spread out along the CFC test sample but has to start spreading back into the carbon fibres that are connected at the other end. The resistance per unit length will then start to rise again. The thermal plots in Fig. 12 would suggest, therefore, that the resistance per unit length would vary approximately, as shown in Fig. 14 (a). For longer sample, the current can spread out along more of the sample, as shown in Fig. 14 (b), leading to a higher sample conductivity. The variation of the resistance per unit length will be dependent on the volume fraction. A high volume fraction will increase the number of fibre to fibre connections and this allows the current to spread quickly out into all fibres. This in turn increases the sample conductivity.

If we now consider the average resistance of a CFC sample, the average resistance reduces as the sample length increases. The apparent electrical conductivity is represented by the inverse of the resistance, so the measured conductivity increases as the sample length increases. Although the average conductivity along the fibre direction increases as the sample length increases, it will converge towards the conductivity value for the fibres. The final value, however, will be slightly lower due to higher resistivity per unit length seen at the entry and exit connections to the sample. This could be circumvented by ensuring that all fibres are exposed at both ends and connected electrically to the supply. In this situation the conductivity of the CFC along the fibre direction would be closely equal to the fibre conductivity and the resistance would be determined by the total fibre length and area unless there were a number of broken fibres in the sample.

The second point to note from the results is the difference between the electrical conductivity values of Panels 1 and 2. The electrical conductivity of Panel 1 was significantly lower than the electrical conductivity of Panel 2. The conductivity values shown in Figs. 9 and 11 represent the sample conductivity, \( \rho_e \), in (2). The carbon fibre conductivity \( \sigma_f \) is typically in the range of 40,000 to 70,000 S/m according to various carbon fibre manufacturer datasheets, so the sample conductivities in Figs. 9 and 11 would be expected to converge towards the fibre conductivity times the volume fraction which is typically around 60%.

For an assumed volume fraction of 60%, the sample conductivity would be expected in the range 24,000 S/m to 42,000 S/m as the sample length increases. The sample conductivity of Panel 1 (Fig. 9) appears to be significantly lower than Panel 2 (Fig. 11) and this would be consistent with a lower volume fraction for Panel 1. The lower volume fraction also reduces the number of fibre-to-fibre contact points which further reduces the conductivity by extending the region of higher resistivity per unit length at the connection ends of the sample. This would be consistent with the results in Figs. 9 and 11.

Panel 1 contains a fibre glass stitching that is used to hold the dry carbon fibres together. The glass fibre stitching would reduce the volume fraction and would likely reduce the number of fibre-to-fibre contact points. The final point to note from the results is that the manufacturing technique of the CFC panels did not affect the relationship between the electrical conductivity and length.

The results for both Panels 1 and 2 showed consistent behaviour for two different manufacturing techniques. The measured electrical conductivity in the through-thickness and transverse directions was not affected by the sample length of the unidirectional CFC test samples either. This was expected as both directions are perpendicular to the carbon fibre strands. Table 3 summarises the electrical conductivities measured in the three axes of a UD CFC.

![Fig. 14: Predicted resistance distribution through CFC sample for (a) short vs. (b) long distance](image)

Table 3 Summary of electrical conductivity in a UD CFC

<table>
<thead>
<tr>
<th>Direction</th>
<th>Conductivity (S/m)</th>
<th>Varied with length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fibre</td>
<td>(0.4 to 3) \times 10^3</td>
<td>Yes</td>
</tr>
<tr>
<td>Transverse</td>
<td>15-20</td>
<td>No</td>
</tr>
<tr>
<td>Through-thickness</td>
<td>0.1-1</td>
<td>No</td>
</tr>
</tbody>
</table>

The upper values of the electrical conductivity in Table 3 correlated with the values published in [9]. However, the measurements have shown that attention is required in understanding the current flow path through the CFC.

6.3. Determining the Temperature Co-efficient

The variation of the electrical conductivity due to the increase in temperature during curing is another important criterion to consider. In metals, an increase in temperature generally results in a decrease in the electrical conductivity. The decrease in conductivity is predominantly due to electron mobility as the temperature increases. The relationship between the material resistivity and temperature can normally be approximated as:

\[
\rho = \rho_\text{rt}\left[1 + \alpha(T - T_\text{rt})\right]
\]

where: \( \rho \) is the electrical resistivity, \( \rho_\text{rt} \) is the electrical resistivity at 20 °C, \( T \) is temperature, \( T_\text{rt} \) is room temperature (20 °C), and, \( \alpha \) is the electrical temperature co-efficient

No information regarding the temperature coefficient for CFCs was found in the literature. However, it is well established that SP2 allotropes of carbon exhibit a negative temperature coefficient of resistance [28]. The CFC samples from Panels 1 and 2 were used, therefore, to determine the relationship between temperature and electrical conductivity. A temperature controlled oven was used to bring the CFC samples to various temperatures from 20 °C up to their curing temperature, in increments of 40 °C. The electrical conductivity was measured using the technique described previously in Section IV. Fig. 14 presents the
averaged results for the three CFC sample groups versus sample length for Panel 1.

Fig. 14: Impact of temperature and length on the electrical conductivity of CFCs from Panel 1

Fig. 15: Electrical conductivity variation due to temperature of the CFC samples from Panel 1 (wet lay-up)

Using the data from Fig. 15 and (5), the temperature coefficient of the UD CFC samples from Panel 1 was calculated to be an average of \(-4.57 \times 10^{-3} \, ^\circ C^{-1}\). Using the data from Fig. 16 and (5), the temperature coefficient of the UD CFC samples from Panel 2 was calculated to be an average of \(-1.59 \times 10^{-3} \, ^\circ C^{-1}\). The difference in temperature coefficient values could be due to the different carbon fibre strands, the different epoxy resins used or the curing temperature used to manufacture both panels. However, the values are relatively close in magnitude and both confirm that CFCs have a negative temperature coefficient within the temperature range of 20 °C to 140 °C.

7. Conclusions

A measurement technique has been proposed for determining the electrical conductivity of CFCs providing an accurate and consistent method, which is quick and simple to implement. The experimental testing was conducted on two CFC panels using different manufacturing techniques. The results showed that the measured electrical conductivity varied with sample length in the carbon fibre direction for the two different CFC panels. This was shown to be due to the poor electrical connection to all the fibres at each end of the samples and to the fibre-to-fibre contact, which allows the current to spread out into all fibres along the length of the samples.

The volume fraction is an important factor in the number of fibre-to-fibre contact points with a higher volume fraction improving the conductivity of CFCs. The conductivity in the two transverse axes was unaffected by sample length. Knowledge of the electrical conductivity is important for various applications. For example, aircraft lightning strike protection and de-icing models, aircraft engine cases, wind turbine blades protection models, etc. Another important parameter of note in applications using CFCs is the temperature coefficient of resistivity.

The results illustrated an increasing electrical conductivity as the temperature increases. The temperature coefficient of CFCs, therefore, was shown to be negative in the range 20 °C to 140 °C; this is consistent with other forms of carbon such as nanotubes.

8. Acknowledgment

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9. References


