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Effective Modeling of Multidirectional CFRP Panels Based on Characterizing Unidirectional Samples for Studying the Lightning Direct Effect

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Abstract

The electrical conductivity of a carbon fiber reinforced plastic (CFRP) panel is highly anisotropic due to its varied fiber orientations. This paper presents an effective modeling method for studying the lightning direct effect on a multidirectional CFRP panel based on an electrical conductivity characterization of unidirectional samples. The characterization using 4-probe method is done with a simple measurement setup. The measured DC conductivity is validated by comparing the sample's behavior in AC regime (lightning spectrum) obtained from measurement and simulation. It is subsequently used in the modeling of a 32-layer multidirectional CFRP panel excited by a lightning current. Simulation results show that the proposed method is able to effectively model multidirectional CFRP panels, which might be useful to studying the current-carrying capacity of CFRP panels under lightning strikes.

1. Introduction

Carbon fiber reinforced plastic (CFRP) panel has been increasingly employed in aeronautic industry due to its high strength to weight ratio. Since it is less conductive than its metallic counterpart, it is likely to be damaged by lightning attachments due to the accumulated currents [1]. A modeling of the CFRP panel is thus desirable for studying its current-carrying capacity. However, practical CFRP panels with multi-layers and multi-directions exhibit strong anisotropic electrical conductivity according to the fiber orientation in each layer, which makes it difficult to characterize the layered structure. Park *et al.* [2] compared the 2-probe and 4-probe method in characterizing the electrical behavior of CFRPs and confirmed the 4-probe method provides more accurate measures. However, their 4-probe measurement requires a complex configuration of electrodes. Piche *et al.* [3] proposed a 4-probe measurement setup to extract the anisotropic conductivity of unidirectional CFRPs. By metalizing the two ends of a CFRP sample, the current is forced to flow from one end to the other in the measurement and the contact resistance is reduced concurrently. Though the measurement setup is simple and effective, only a loose validation of the measured conductivity in the AC regime (lightning spectrum) is provided.

This paper proposes to model a multidirectional CFRP panel using a layered structure whose anisotropic conductivity is from an electrical characterization of its unidirectional samples. The same measurement setup in [3] is employed. However a more thorough validation of the measured conductivity in the AC regime is performed, followed by a discussion on correctly modeling the AC measurement setup. The measured conductivity is subsequently used in a finite element simulation of the lightning current in a 32 layer quasi-isotropic (QI) CFRP panel with the same dimensions in [4]. Reasonable current density distribution is obtained for fiber directions of 0°, 45°, −45°, and 90°, which proves the whole modeling method is effective. The proposed method may help in understanding the current-carrying capacity of multidirectional CFRPs under lightning strikes.

2. Electrical Characterization of the Unidirectional CFRP Samples

2.1 DC Measurement

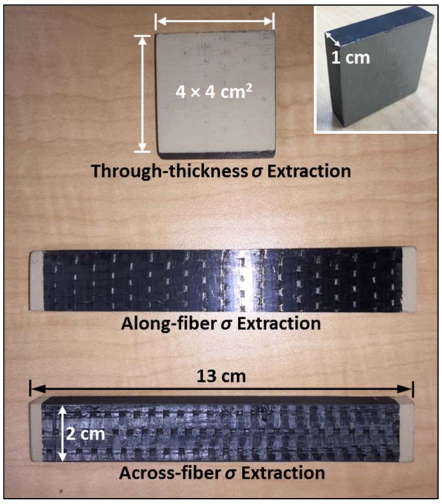


Figure 1. Photo showing the three CFRP samples for characterizing the electrical conductivity of three different directions. The samples were metalized with silver paste at their terminals.

Figure 1 shows three samples cut from a large unidirectional CFRP panel for characterizing the anisotropic electrical conductivity. The panel is prepared with high tensile strength carbon fiber Toray T700S and epoxy resin D.E.R. 332. Two bar-shaped samples (13 cm × 2 cm × 1 cm) are used to extract the conductivity along and across the fiber direction, while a square sample (4 cm × 4 cm × 1 cm) to extract the conductivity through thickness direction. Note that the two terminals of each sample are metalized with silver paste and thus appear in yellow color. This is to ensure an equipotential and conductive surface for further injecting current source in the resistance measurement.

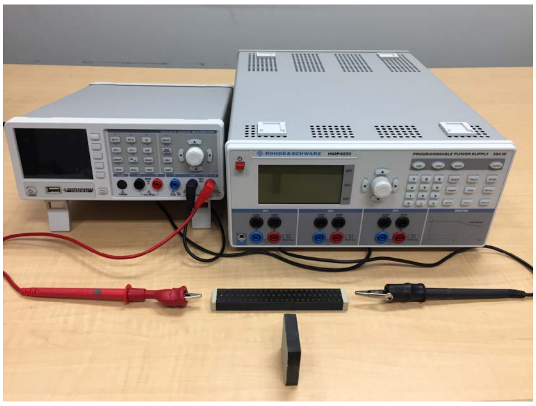


Figure 2. Photo of the measurement facilities including one power supply (R&S HMP4030) and one digital multimeter (R&S HMC8012).

The four-probe method is employed to retrieve the resistance between the two terminals, which is then converted into conductivity. Its measurement facilities are shown in Figure 2. The power supply (R&S HMP4030) provides steady current up to 10 A and also measures the actual current flowing though the sample, while the digital multimeter (R&S HMC8012) measures the voltage drop between the two terminals of the sample in this case. Alternatively, we use the digital multimeter's 4-probe function to measure the resistance directly. Note that this digital multimeter only provides a resolution of 1 mΩ.

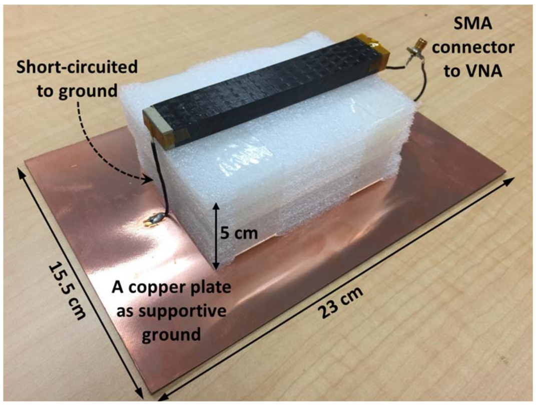
Table I. The measured resistances and computed conductivities according to three directions (along fiber, across fiber and through thickness).

	Power Supply + Multimeter		Multimeter	
	R (Ω)	σ (S/cm)	R (Ω)	σ (S/cm)
Along	0.0132166	453.972	0.013	461.538
Across	0.7054	8.50581	0.708	8.47458
Thickness	0.0133533	4.92358	0.014	4.69616

Table I lists the measured resistances as well as the computed conductivities at the three different directions – along fiber, across fiber and through thickness. From the table, the conductivity along fiber is much larger than that across fiber and through thickness, which is reasonable. In addition, good agreement between the results from two measurement setups is observed, indicating the proposed measurement method is able to effectively characterize the anisotropic electrical conductivity of the CFRP.

2.2 AC Validation

To validate the measured DC electrical conductivity, we look at the AC impedance of the CFRP within the frequency of interest for lightning (100 kHz to 10 MHz). Figure 3(a) shows the measurement setup we employed. The CFRP bar is in parallel with a flat copper ground plane, supported by a piece of foam of height 5 cm. The ground plane was 23 cm in length and 15.5 cm in width. Insulated wires of radius 0.65 mm connect the CFRP bar, the ground plane, and a SMA connector in a closed loop. The input impedance at the SMA connector is of interest. It actually comprises the contribution of the CFRP bar, the wires and the ground plane. Figure 3(b) shows the vector network analyzer (R&S ZNB20) for measuring the input impedance.



(a)

(b)

Figure 3. Photos showing (a) the setup of the AC measurement of a CFRP bar and (b) the measurement facility – vector network analyzer (R&S ZNB20).

We reproduce the measurement setup in the commercial software CST [5] as shown in Figure 4. The CFRP bar sample with metallization, the wires, the copper ground plane and even the SMA connector are fully modeled, except for the foam which has little effect on the result. The measured conductivity is input as the material property. It is worth highlighting that the dimensions (length, radius, curvature) and medium (conductivity) of the insulated wires should be accurately represented in the computer model to match the measured and simulated input impedances, because these parameters can largely vary the simulated results. For instance, a smaller wire radius results in larger resistance and larger reactance (inductance), a smaller conductivity leads to larger resistance and a shorter wire length provides both reduced resistance and inductance.

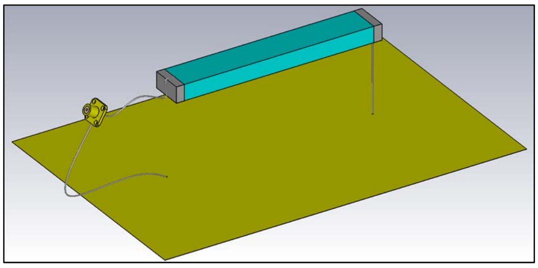
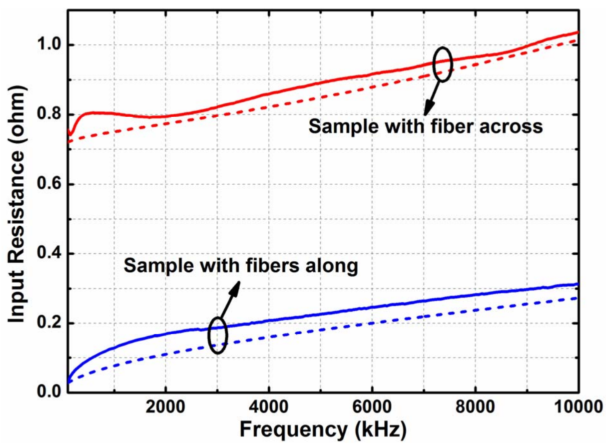
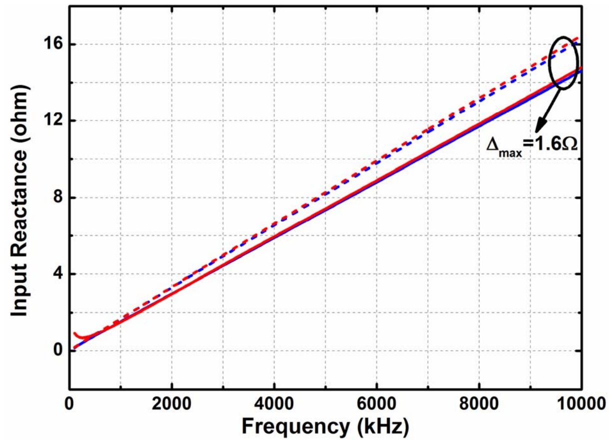


Figure 4. The simulation model of the AC measurement setup in CST.

Figure 5 shows the measured and simulated input impedance against the frequency. The two bar samples having fibers along and across the length are considered. The measured results are in good agreement with and simulated results. In particular, the input resistances at lower bound (100 kHz) are very close to their measured DC resistance shown in Table I, which indicates a consistent AC and DC measurement of the resistance. The slightly lower simulated AC resistance may be because the contact resistance that commonly exists in the measurement is not considered in our simulation. As for the input reactance, we manage to match the results between measurement and simulation well, which can be attributed to the full modeling of the whole measurement setup. The reactances of the two samples are very close to each other, indicating reactance is not related to medium conductivity.



(a)



(b)

Figure 5. The measured (solid lines) and simulated (dash lines) (a) input resistance and (b) input reactance of the bar samples with fibers along (blue color) and across (red color) the length.

3. Modeling of a Multidirectional CFRP Panel under Lightning Strikes

The measured conductivity of the unidirectional CFRP sample is used to model a 32-layer QI CFRP panel with fiber orientations from 45°, 90°, −45°, to 0° and so on. The panel is of 100 mm × 100 mm × 6.4 mm where each carbon fiber layer has a uniform thickness of 0.2 mm. Note that each layer of the QI CFRP panel must have identical material properties to that of the unidirectional CFRP sample such that the measured conductivity can be used. Figure 6 shows the model for studying the lightning direct effect on the 32-layer QI CFRP panel. A 200 kA lightning current at 25 kHz, specified in IEC 62305-1 for representing the first return stroke for lightning protection level 1, is injected at the center of the panel's top surface and extracted at the four corners of panel's bottom surface.

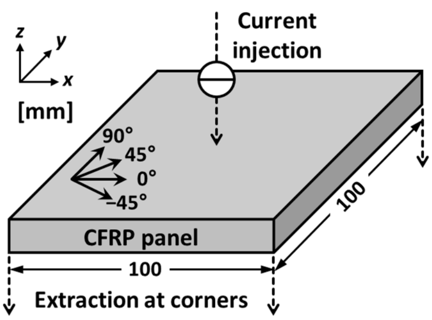


Figure 6. Lightning model for the 32-layer QI CFRP panel with the dimensions of 100 mm × 100 mm × 64 mm. Lightning current is injected at the center of the top surface and extracted at the four corners of the bottom surface.

Assuming the fiber direction of the unidirectional CFRP sample is aligned with that of the 0° fiber in the QI CFRP panel, the conductivity tensor is be obtained by rotating the coordinate system in the horizontal plane [6] as below

$$\begin{bmatrix} \sigma_{xx} & \sigma_{xy} & 0 \\ \sigma_{yx} & \sigma_{yy} & 0 \\ 0 & 0 & \sigma_{zz} \end{bmatrix} = \begin{bmatrix} \sigma_{\xi}\cos^2\alpha + \sigma_{\psi}\sin^2\alpha & (\sigma_{\xi}-\sigma_{\psi})\sin\alpha\cos\alpha & 0 \\ (\sigma_{\xi}-\sigma_{\psi})\sin\alpha\cos\alpha & \sigma_{\xi}\sin^2\alpha + \sigma_{\psi}\cos^2\alpha & 0 \\ 0 & 0 & \sigma_{\zeta} \end{bmatrix} \quad (1)$$

where σ_{ξ}, σ_{ψ}, σ_{ζ} denote the measured conductivities along fiber, across fiber and through thickness directions, respectively (c.f. Table I). α is the degree of fiber orientation. Table II lists the conductivity tensor elements (σ_{xx}, σ_{xy}, σ_{yx}, σ_{yy}, σ_{zz}) calculated using (1).

Table II. Key elements of the conductivity tensor for fiber orientations: 45°, 90°, −45°, and 0°. Units [S/m]

α	σ_{xx}	σ_{xy}	σ_{yx}	σ_{yy}	σ_{zz}
45°	231.239	222.733	231.239	222.733	4.92358
90°	8.50581	0	0	453.972	4.92358
−45°	231.239	−222.733	231.239	−222.733	4.92358
0°	453.972	0	0	8.50581	4.92358

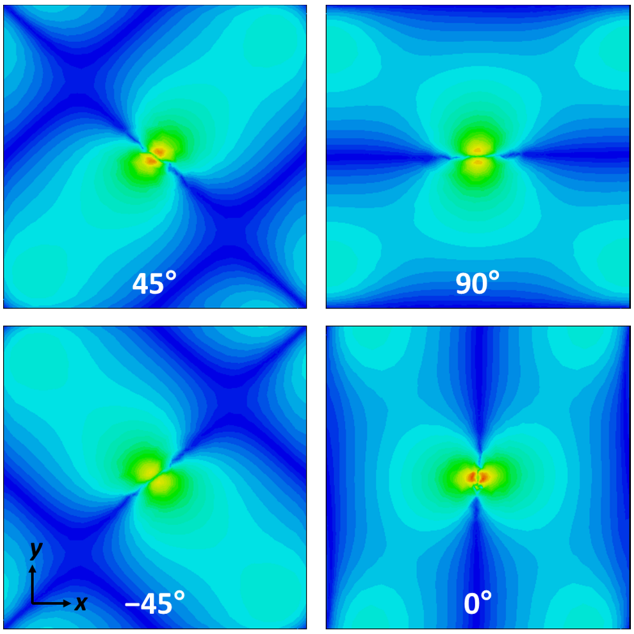


Figure 7. Distribution of current density of the top four layers of the 32-layer CFRP panel (45°, 90°, −45°, and 0° fiber orientations). The maximum magnitude denoted by red color is around 2×10^{11} A/m^2.

Figure 7 shows the results of the finite element analysis, where the current density distribution of top four layers with 45°, 90°, −45°, and 0° fiber orientations are plotted. It is seen that, for all four scenarios, the current concentrates in the center area because of the current injection; the current then flows along the fiber due to the high conductivity along fiber direction and finally finds its shortest way out at the corners. The reasonable results indicate that the modeling is able to predict the current distribution in multidirectional CFRP panels.

4. Conclusions

A modeling method for studying the lightning direct effect on a multidirectional CFRP panel has been proposed. The anisotropic electrical conductivity of the panel is obtained by characterizing unidirectional samples with identical medium properties to the one of each layer in the panel. A 32-layer QI CFRP panel excited by the lightning current is considered. Simulation results show that the proposed method is able to effectively model multidirectional CFRP panels, which might be useful to the current-carrying capacity study of CFRP panels under lightning strikes.

5. Acknowledgements

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6. References

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