AIAA 2008-1917

Electrical Characterization of Electrified Composite Plates

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Building on recent published work by the Air Force Research Laboratory, the electrical behavior of a composite plate is investigated in the context of understanding the possible implications for damage resistance and tolerance. It appears that the DC resistance of the plate is not constant and depends on number of times and degree of intensity of the applied current. Dependence of the measured resistance on plate temperature is characterized. This will lead to an enhanced understanding of the electromechanical behavior of the plate upon transverse loading.

I. Introduction and previous work

A serious design concern for use of advanced composite materials as structural elements in aerospace applications is that they are more susceptible to damage due to foreign object impact. Recent analytical and experimental work by the Air Force Research Laboratory (AFRL) Munitions Directorate has found that a carbon fiber reinforced plastic (CFRP) laminate becomes more resistant to impact damage when significant values of DC current are applied [1-5]. Although experimental results are limited and need further investigation, the potential impact of this phenomenon could be dramatic. For example, localized electrification of a composite skin by means of a distributed network of electrical leads underneath the skin surface could provide improved damage resistance in case of an impact event (for example a ballistic strike during flight). Multifunctional composites therefore have the potential to dramatically reduce platform weight and increase survivability. In general, multifunctionality in composites may be achieved through coupling of structural behavior with electric, magnetic, and thermal capabilities.

In particular, the existing experimental evidence suggests that exposure of CFRP to the electromagnetic field leads to changes in the material's strength and resistance to delamination. Snyder et al. [6] conducted a series of impact tests on unidirectional CFRP plate with and without an applied direct current (DC) electric current of 20A and 40A introduced through the fibers. Their results indicate that the strength of a composite material and its low-velocity impact damage resistance may be improved by application of an electromagnetic field. The factors contributing to this complex phenomenon may be related to the coupling of mechanical and electromagnetic fields and/or changes in the material properties associated with Joule heating produced in the conducting carbon fibers. Sierakowski et al. [1-5] have demonstrated that an electromagnetic field, depending on the direction of its application and its intensity, may significantly amplify or reduce the effect of mechanical load in composites. Their experimental data showed dramatic improvements in failure initiation force as well as ultimate force with increasing current intensity for unidirectional plates. However, when a limited set of cross-ply laminates was tested the results were less than evident.

Application of an electric current at opposite clamped ends of a composite plate generates a magnetic field, which in turn induces a Lorentz force in the plane of the plate:

$$\bar{F}^L = \rho_e\left(\bar{E}+\frac{\partial\bar{u}}{\partial t}\times\bar{B}\right)+\left(\boldsymbol{\sigma}\cdot\left(\bar{E}+\frac{\partial\bar{u}}{\partial t}\times\bar{B}\right)\right)\times\bar{B} \;\Big|\; +\left(\left(\left(\boldsymbol{\varepsilon}-\varepsilon_0\cdot\mathbf{1}\right)\cdot\bar{E}\right)\times\bar{B}\right)_\alpha \nabla\left(\frac{\partial\bar{u}}{\partial t}\right)_\alpha+\left(\bar{J}^*\times\bar{B}\right), \quad (1)$$

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The Lorentz force depends on the external electric and magnetic fields, magnitude and orientation of the electric current with respect to the magnetic field, and rate of deformation of the plate (du/ dt). According to AFRL researchers, the Lorentz force acts to bring the longitudinal fibers together, in the same way that a rubber band keeps a bunch of flowers together and resists the any force attempting to pull them apart. Damage resistance is then increased because the fibers are more effective in resisting the influence of the transverse indenter trying to separate them by moving through the laminate. This result seems to suggest that the effects of the Lorentz force are more pronounced if the plate experiences a so-called high velocity impact event, such a ballistic impact, rather than during a low-velocity event, such as a drop test.

Future work will need to extend the present experimental investigation from a large, heavy impactor moving at 4 ft/s (1.22 m/s) to a small, light impactor moving at 70-100 ft/s (21.34-30.48 m/s). It is known that although the projectile moves at a much greater speed with respect to the target, the deformation of the target itself is actually much smaller and more localized than in the case of a low velocity impact event, where global plate deformation occurs. Therefore, the interaction of these two effects needs to be studied.

On the opposite end, quasi-static indentation tests will need to be performed to verify if the Lorentz force has any effect in the range of 0.02 in/min (0.51 mm/min) up to 1 in/ sec (25.4 mm/s). It has been shown that quasi-static tests offer greater understanding in the damage response of a plate than drop tower impact tests [7,8], and that for composite plates low-velocity tests and quasi-static indentation tests produce identical damage states and measurements [7,8].

With respect to laminate lay-up, it is also expected that the resistance of unidirectional $[0]_n$ plates be much lower than cross-ply $[0/90]_{ns}$ plates, and that any electromagnetic coupling effect may be strongest due to the greater electrical conductivity of the plate. However, $[0]_n$ laminates have a unique tendency to fail by transverse cracking prior to fiber breakage, while $[0/90]_{ns}$ laminates as well as any multidirectional laminate will fail through a more complex failure sequence and combination due to the presence of fibers in multiple directions. It is therefore expected that the effects of the electromechanical coupling be less pronounced, but at the same time the nature of the cross-ply laminate may be more representative of general laminates (such as quasi-isotropic) than unidirectional ones.

The purpose of this study is to explore the fundamental DC electrical behavior of the electrified composite plate.

II. Experimental Setup

Carbon fiber/ epoxy laminates where constructed from unidirectional prepreg tape, TORAYCA T700/ 2510, a material system designated for General Aviation and certified during the FAA-sponsored AGATE program. Although the system is designed for 270° F (132.2° C) vacuum bag and oven cure, for this study the laminate are press-molded at 85 psi (586 kPa) for 1 hour in a matched mold aluminum tool. The lay-up for the laminates is $[0/90]_{6s}$ and the dimensions of the cured laminate is 7 in x 7 in (177.8 mm x 177.8 mm) with a thickness of 0.133 in (3.378 mm).

The test fixture consists of Type I PVC electrically insulating material along with conductive copper bars used as electrodes (Figure 1). The CFRP laminate rest on two L-shaped copper electrodes. The two L-shaped copper electrodes are electrically insulated from the rest of the fixture by the PVC material. Adjustment screws are used to generate firm contact pressure between the copper electrodes and the CFRP plate ends. The ends of the plate were machined to size but not polished. A square copper electrode is used to clamp the panel from the top and provide additional electrical contact. A rectangular PVC beam is used to electrically insulate the top square copper electrode from the rest of the fixture. An additional steel beam is used on top of the PVC beam to facilitate the transfer of contact pressure from the clamping bolts to the interface of the square copper electrode and the CFRP laminate. The apparent electrical contact area between the copper electrodes and the CFRP laminate is approximately 7.93 in^2 (51.16 cm^2) on each conducting side. To improve the conductivity between the CFRP panel and the copper electrodes 3M XYZ-Axis Conductive Tape is placed at all interfaces between the copper electrodes and the CFRP laminate. According to AFRL researchers [5], the 3M XYZ-Axis Conductive Tape did not help to improve conductivity as well as other media such as silver filled epoxy and indium foil.

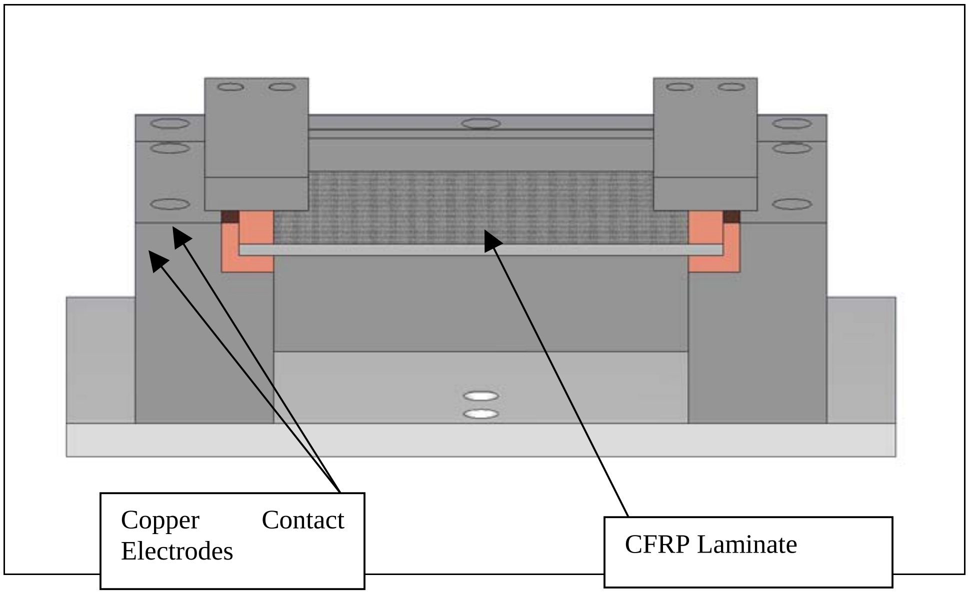


Figure 1. Cross-sectional illustration of the test fixture

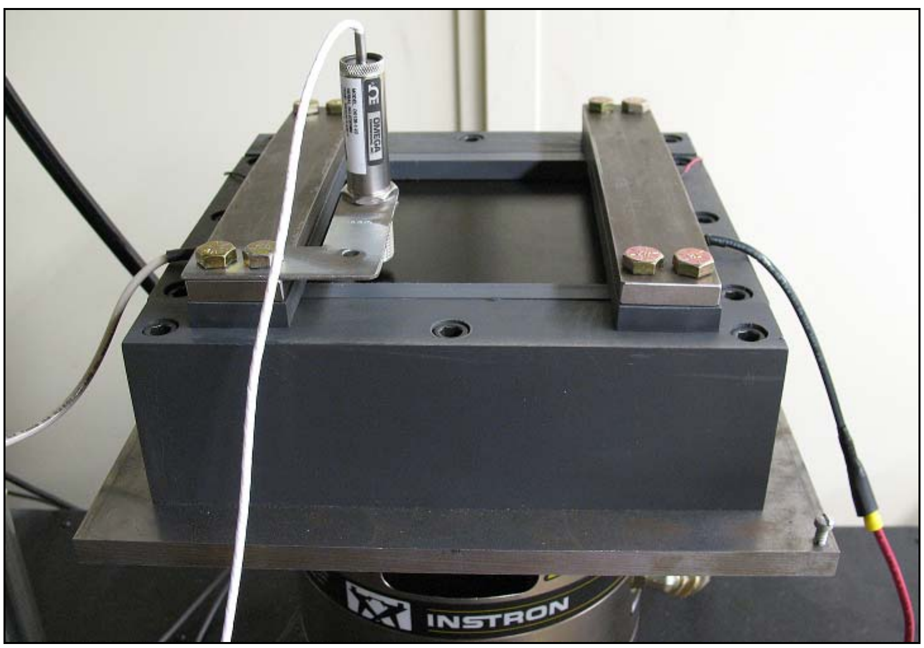


Figure 2. Photograph of Test Fixture

However it has been found for this study that the 3M XYZ-Axis Conductive Tape helped to improve repeatability and conductivity over just relying on direct contact between the copper electrodes and the CFRP laminate. *It should be emphasized that achieving good contact (repeatable, constant) is the key to for obtaining significant results.*

A Sorenson DCR-B 2700 Watt power supply is used in order the supply the required DC current to the CFRP laminate. The power supply operates in a constant current mode, in the range 0-100 A, and is controlled by a command voltage signal. The current flow, voltage drop and surface temperature of the laminate are monitored and recorded using an A/D converter and Labview software. The current flow through the CFRP laminate is monitored utilizing an internal current shunt in the power supply. The voltage drop across the laminate is measured through a 4-to-1 voltage divider circuit. The surface temperature of the laminate is measured using an Omega OS-136 infrared temperature sensor with a range from 0° F to 400° F (-17.78° C to 204.44° C), which is mounted approximately 1.5 in (38.1 mm) away from the conducting edge and 1.5 in away from the insulated edge (Figure 2).

III. Results

Dependence of CFRP Laminate Resistance on Applied Current

In order to understand the electrical response of the electrified laminate it is necessary to measure its resistance, which can be calculated by the linear slope of a voltage vs. current plot (Figure 3). The instantaneous resistance of the laminate can also be calculated for any given time by dividing the voltage drop across the laminate by the current flow in the laminate using Ohm's law (Figure 4). During the investigation it is discovered that the resistance of the CFRP laminate is not constant, but is affected by the applied current.

Applying a value of maximum current to a pristine laminate (i.e. it has never experienced electrical current), for a controlled duration of 10 seconds, the resistance is measured. The laminate is then allowed to cool back to room temperature, and a new, lower value of electrical current is applied. In the case of Figure 3, the blue line indicates a highest applied current of 30A, which is first tested. At a later time, the same plate is loaded with 20A and then 10A, and is allowed to cool to room temperature between the applications. It can be seen in Figure 4 that the measured resistance varies substantially between the three values of applied current (from 0.146 Ohms at 30 A to 0.165 Ohms at 10 A). Following the curve below, the laminate is loaded up to a maximum applied current of 50A, then cooled off, and loaded at 40, 30, 20, and 10 A. The resistance varies again between each applied current level, from 0.120 to 0.141 Ohms (Figure 4). Furthermore, it can be seen that for the same applied current, the resistance for the upper curve (30A-max applied current) is higher that for the one below (50A-max applied current). The same phenomenon is observed for the other two curves (70A- and 90A-max applied current).

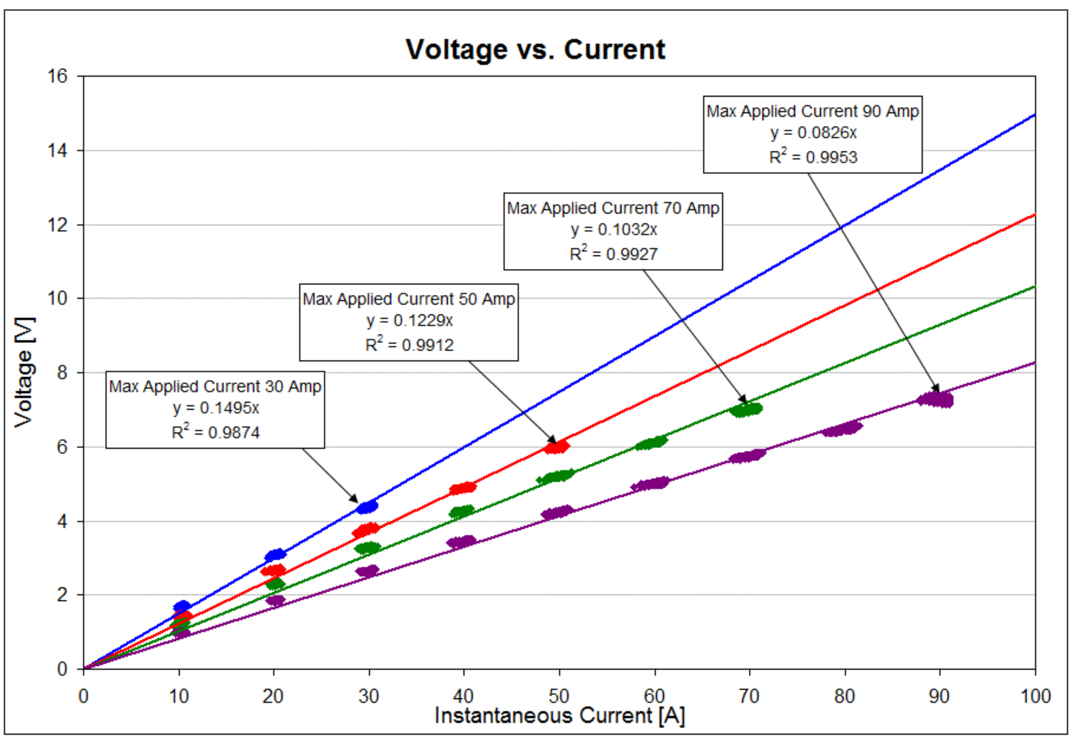


Figure 3. Voltage vs. Current Characteristics of a CFRP Laminate

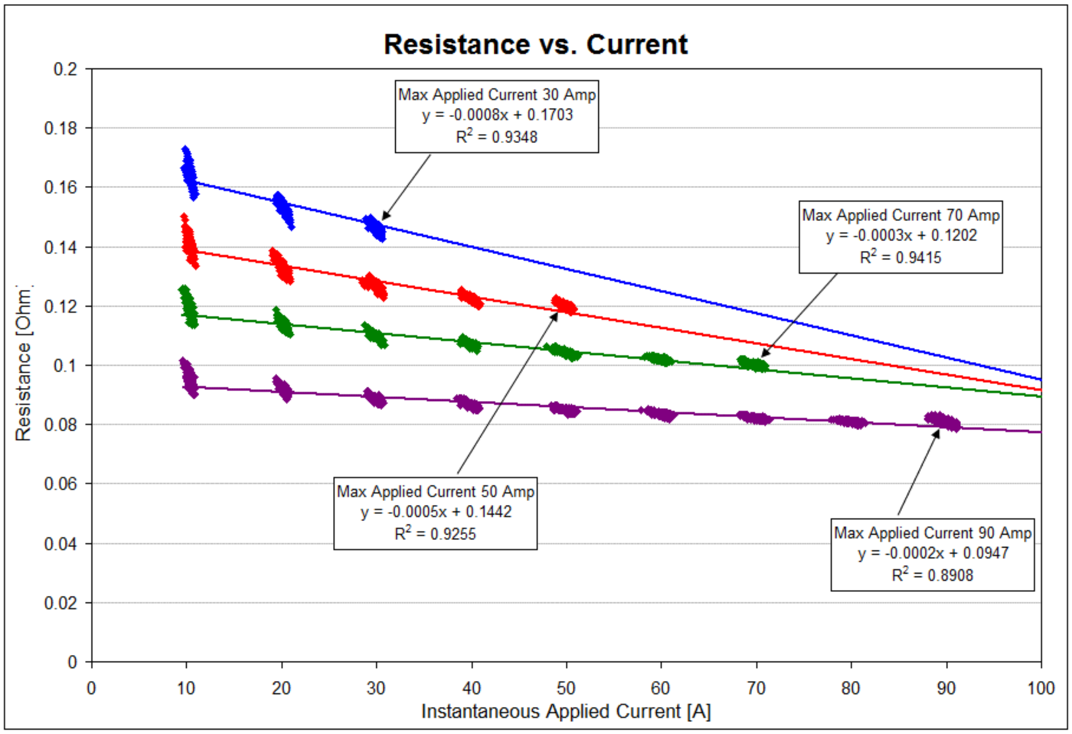


Figure 4. CFRP Resistance vs. Current

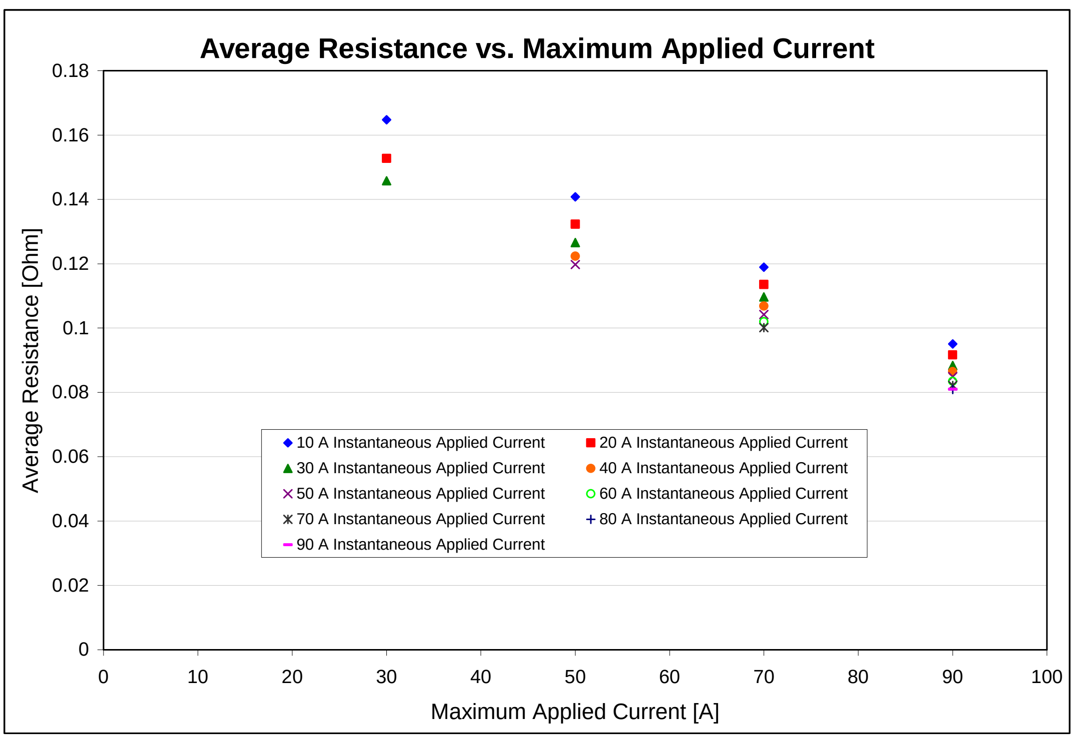


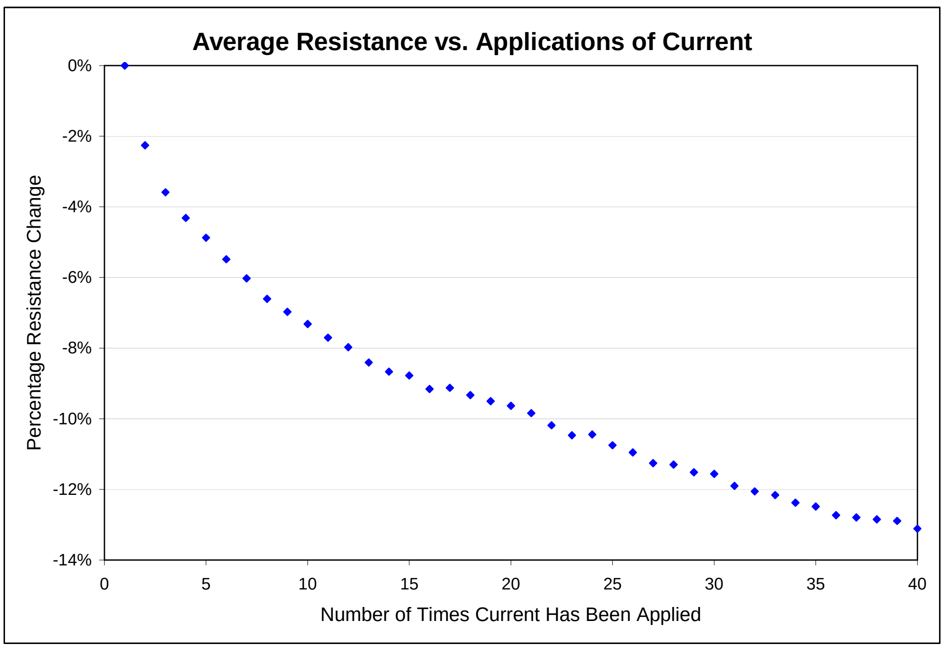
Figure 5. Average Laminate Resistance vs. Maximum Applied Current

Two values of applied current become important when addressing the electrical behavior of a composite laminate: the instantaneous applied current I_i, and the maximum applied current I_{max}. *The resistance of the laminate varies significantly with both.* For the same I_i the resistance of the laminate decreases as the I_{max} increase (Figures 4 and 5). Additionally for the same I_{max} the resistance decrease for increasing I_i (Figures 4 and 5). However it should be noted that increasing I_{max} has a greater effect on reducing the resistance of the laminate than increasing I_i.

Figure 3 illustrates that the resistance of the laminate irreversibly decreases as it has been exposed to a progressively higher I_{max}. The slope of the voltage-current curve decreases by nearly 45% when the I_{max} changes from 30 to 90 A.

Figure 4 indicates the dependence of the laminate resistance on I_i for increasing values of I_{max}. For higher values of I_{max} the resistance of the laminate approaches a constant value for all I_i. The dependence of the laminate resistance (the slopes of the curves in Figure 4) on I_i decreases nearly 4 times as I_{max} changes from 30 to 90 A. *There is an apparent strong dependence between laminate resistance and applied current.* The overall electrical resistance of a composite laminate can be significantly reduced irreversibly if high values of current are applied to the laminate before being used in service.

To further investigate the dependence of laminate resistance on applied current, a fixed value of current is applied multiple times on the same panel. A current of 30 A is applied to a pristine panel for a duration of 10 s, then allowed to cool to room temperature, and loaded again with 30 A of current. In the present study the process is repeated 40 times, but further work should more systematically characterize time-dependent behavior. Between applications of the current the panel is not removed from it configuration in the test fixture. Figure 6 shows the percent reduction in resistance of the panel to be nearly 28% after 40 current applications.



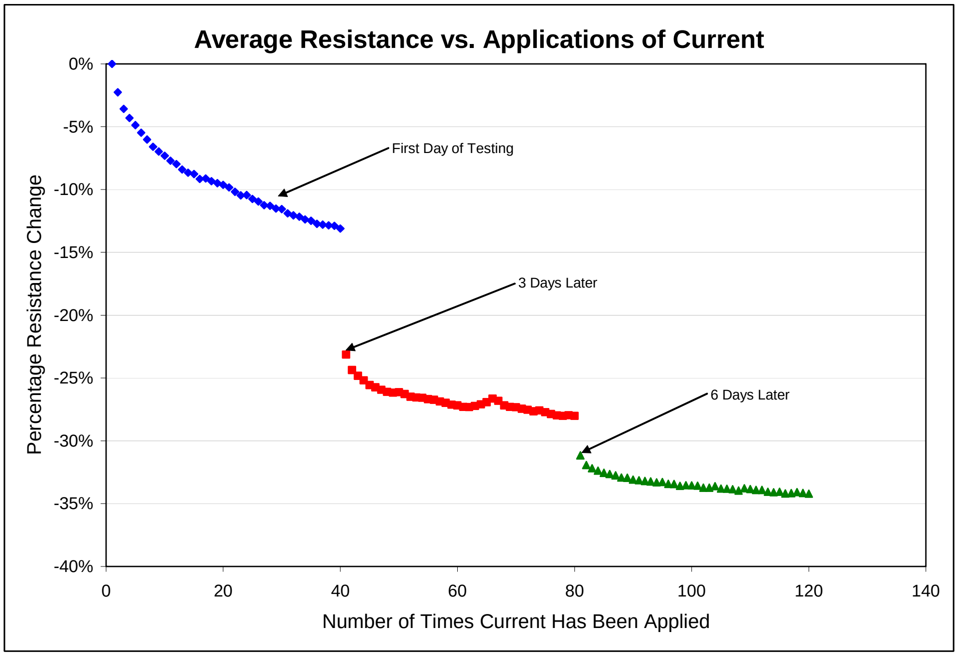


Figure 6 a and b. Percent Change in Laminate Resistance vs. Number of Times that a 30 Amp current is Applied a) in one day, b) after 3 and then 6 days

Dependence of CFRP Laminate Resistance on Temperature

Since it is possible that the trends reported in the previous sections may be influenced by heating effects, this portion of the study addresses the dependence of the measured resistance on temperature. The laminate used for this portion of the study has been previously loaded with high values of current (as described in the previous section) until the resistance of the laminate has reached an asymptotic value. To induce heating, a current of 10 A is applied to the CFRP laminate until the surface temperature at the location of the temperature sensor reaches a nearly steady state value (91° F or 32.8° C). The current is then increased to 20 A until the surface temperature reaches a nearly steady state value (130° F or 54.4° C). The current is then increased to 30A and applied until the temperature suddenly decreases and then the test is terminated. Figure 7 shows the surface temperature of the panel at the location of the sensor for three different values of current until termination of the test.

Figure 8 shows both surface temperature and resistance of the laminate as a function of time. The measured resistance of the laminate remains constant for a significant time, and up to relatively high surface temperatures. Once the surface temperature of the laminate approaches approximately 193° F (89.4° C), the resistance of the laminate begins increasing rapidly. Since Joule heating is proportional to the resistance the temperature begins to rise at a faster rate as the resistance increases.

The maximum surface temperature reached is approximately 310° F (154.4° C). The temperature at the center of the CFRP laminate is potentially greater than 2 times larger than this measured surface temperature [1]. It is clear that high temperature due to Joule heating severely increases the resistance of a CFRP laminate. The resistance of the laminate increases over 2 times as the temperature rises from room temperature (~80° F or ~26.7° C) to 310° F due to the effect of Joule heating.

However, given that the variation in temperature observed during the 10-second load cycles described in the previous section is negligible compared to the one described here, it appears that heating effects do not play an immediately obvious role in relating the laminate's resistance change with applied electrical current.

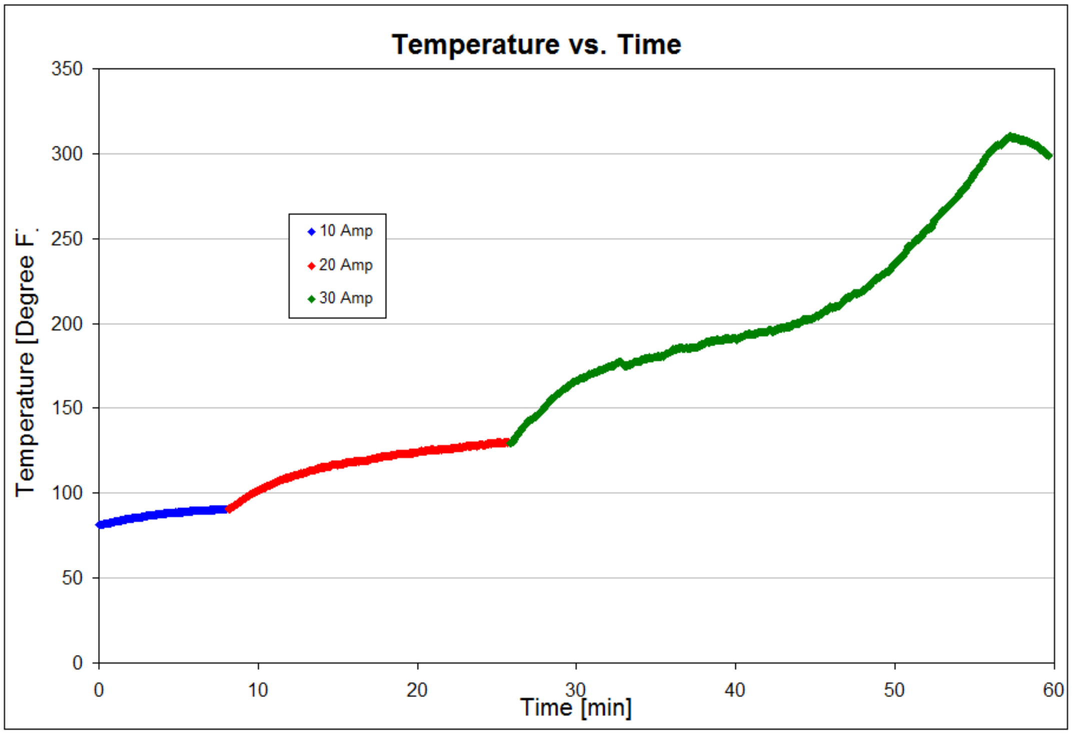


Figure 7. Surface Temperature of CFRP Laminate vs. Time

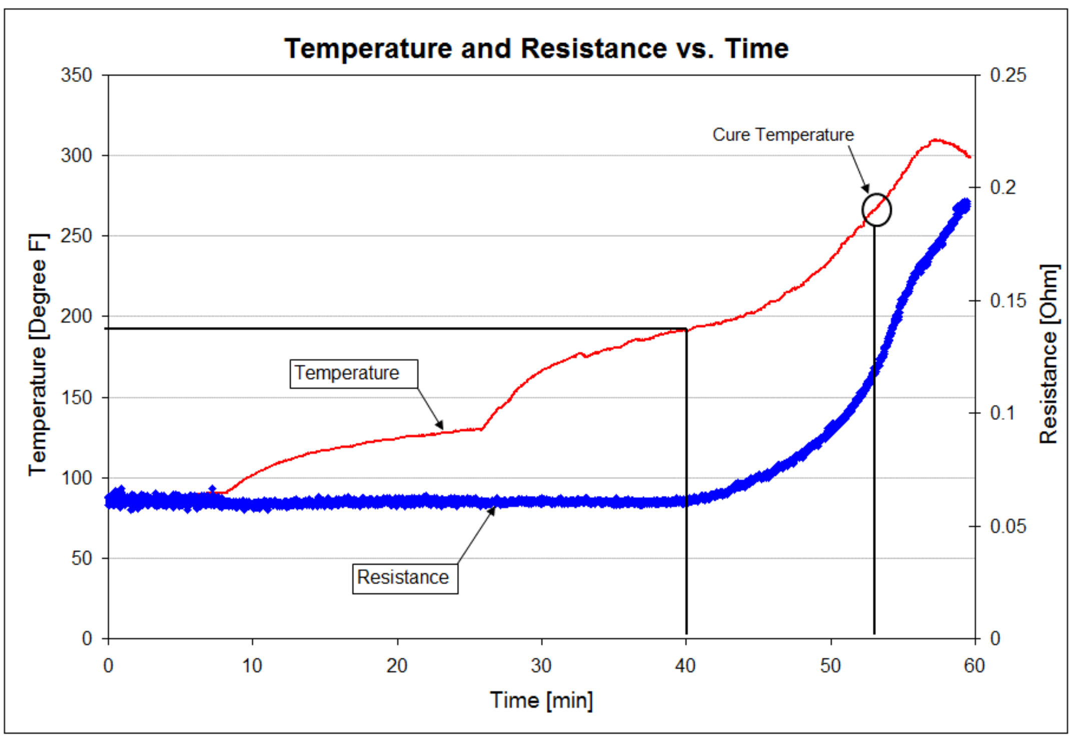


Figure 8. CFRP Laminate Surface Temperature and Resistance vs. Time

IV. Discussion

Several possible explanations can be offered for the observed phenomena of decreased resistance upon electrification, and include:

- Electron tunneling through thin films: it has been shown that resistance decrease with rising current is indicative of electron tunneling effects through a thin film [9]. This is consistent with observations of tarnish on the copper electrodes, and of adhesive in the conductive tape and epoxy covering the carbon fibers within the laminate.
- Matrix deterioration due to arcing: resistance decrease is associated to arcing between the carbon fibers, which may occur as a consequence of dielectric breakdown of the matrix. This latter possibility may be supported by the evidence of transverse cracking of the plies (figure 9).
- Micro-structural reorganization of the individual carbon fibers: upon electrification the carbon atoms in the molecular chain will realign to favor greater electron movement.
- Electron trapping within the individual carbon fibers: upon electrification the hexagonal stacking planes of carbon molecules may retain electrons (figure 10).
- Chemical modification of the polymer matrix or fiber/ matrix interface: upon electrification the dielectric matrix undergoes a restructuring of its electron configuration, thus becoming more conductive.

Further work must be conducted to clearly understand the observed phenomena.

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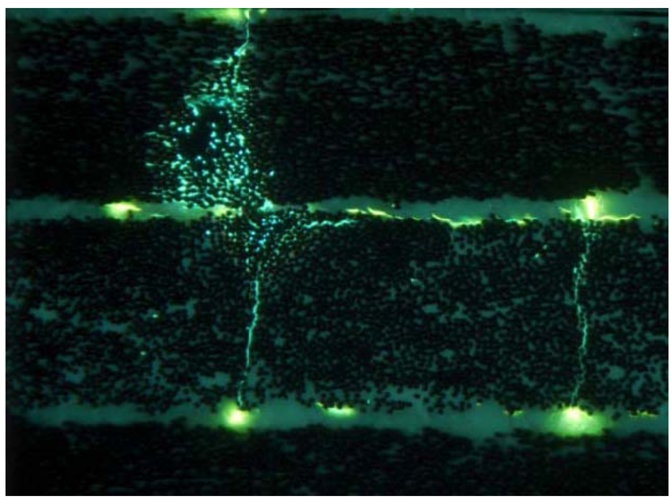

Figure 9. Micrographic picture of an interlaminar area of the plate after electrification.

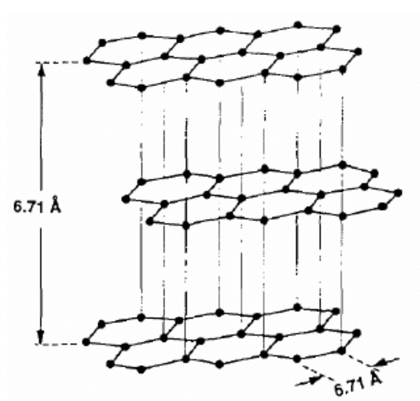

Figure 10. Hexagonal arrangement of carbon molecules.

V. Conclusions

It has been found experimentally that there is a dependence of the resistance of a cross-ply CFRP laminate on the applied DC current. As the laminate experiences higher values of applied current, the resistance of the laminate decreases irreversibly, and tends to an asymptotic value. Assuming that the CFRP laminate's electrical resistance is constant (does not vary with applied current intensity), and that such value remains constant (does not vary with the highest value of applied current or with number of applications of current) could mislead other observations. Although the results presented here are only preliminary, they offer potential benefits to a broad range of applications of electromechanical multifunctional composites, such as active ballistic protection systems and passive lightning strike protection systems. A detailed roadmap is identified that will lead to future enhanced understanding of the multifunctional response of electrified plates.

Acknowledgments

The authors would like to thank Les Lee (AFOSR), Bob Sierakowski (AFRL Munitions Directorate), Olesya Zhupanska (University of North Dakota), David Banks (Technical Fellow, Boeing Phantom Works), Diane Heidlebaugh (Senior Manager, Boeing Phantom Works), for the precious discussions that added experienced insight to the experimental observations. They would also recognize the contributions to the experimental work by undergraduate students David Medendorp and Andrew Southworth. Andrea Dorr and Leslie Cooke of Toray Composites of America are gratefully acknowledged for the donations of prepreg material.

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