ELECTRICAL RESISTANCE MEASUREMENTS OF CARBON FIBRE REINFORCED POLYMER (CFRP) MATERIALS.
MEASUREMENT TECHNIQUES, METHODS AND PITFALLS TO AVOID: A CASE STUDY

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1 Abstract

Lightning strikes are a relatively common event to aircraft and can cause considerable damage due to high energy electrical current passing through the aircraft structure. Traditionally composite aircraft are protected from lightning strike by expanded metal foil mesh embedded in the composite. Alternatively, metallic lightning strike protection (LSP) coatings have also been investigated [1, 2]. Current aircraft design incorporates a range of mechanically fastened structural joint assemblies, which are often located in the electrical current path and these joints may reduce electrical conductivity performance. On post lightning strike inspection, these joint assemblies are sometimes subject to damage and require repair [3, 4].

Maintaining electrical continuity across joints in composite panels can be quite difficult to achieve. Electrical continuity is important for lightning strike protection (LSP) and for protection against High Intensity Radiated Fields (HIRF).

Innovative jointing techniques were explored and developed under the Clean Sky 2 project "C-JOINTS". A follow-on project named "D-JOINTS", currently in progress, is examining mathematical modelling and software development of a design tool to aid in the sizing of certain components associated with these joints.

As part of the mathematical modelling of the design tools for predicting the lightning and HIRF behaviour of these composite aircraft panels and components, it is clear that electrical resistivity, or its reciprocal, conductivity, is an essential parameter to quantify. However, electrical resistivity values for CFRP materials are very difficult to find in the literature. One the major reasons for this apparent lack of data is perhaps that the electrical properties of CFRP materials are enormously variable and are very dependent upon both the composition and fabrication methods of the material itself. Moreover, it is well known that the electrical properties of CFRP panels are anisotropic, i.e., the lengthwise properties are quite different from the through-thickness properties, but this difference is not often quantified.

Given the apparent lack of data in the literature, but, more importantly, the inherent material and process dependability of the parameters, it becomes apparent that these parameters need to be determined individually for each material composition and its manufacturing process.

This case study describes the development of relatively simple-to-implement measurement tools and procedures. Perhaps more importantly, it highlights some of the pitfalls encountered in evolving these test methods and describes how the problems were resolved. Once developed, these test methods gave encouragingly consistent results over a range of panel thicknesses. The electrical resistivity data for the composite material employed in the project is presented with the caveat that this data is particular to this material and its manufacturing methods. Both lengthwise and through-thickness measurements are presented.

A brief description of the D-JOINTS project and its progress to date will be included to provide some background information as to the requirement for these measurements.

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2 Introduction

The prospective pulse current across a joint in the lightning strike protection during a lightning event is of the order of many tens of kiloamps. Although the lightning event itself is of very short duration, perhaps a couple of hundred milliseconds, the energy dissipated even in a slightly resistive joint can be very large and can lead to the generation of "hot-spots" or arcing. It is very important, therefore, to ensure that contact resistances across any joints are appropriate for the magnitudes of the current expected across the joint.

Maintaining lightning strike protection (LSP) and protection against High Intensity Radiated Fields (HIRF) across apertures and panel joints in aircraft structures can be quite difficult. The panel joints must usually be capable of carrying a share of the very large lightning current and must also avoid the creation of parasitic antennas when exposed to HIRF. Furthermore this protection must continue, often without any maintenance, for a significant proportion of the life of the aircraft. This difficulty is nowadays even further compounded by the increasing use of composite structures. Frequently, these composite structures must interface with traditional metallic structures. However, the implementation of LSP and HIRF protection for composite structures is usually very different from that of the more familiar metallic structures, and it is at the interfaces or joints between these two different types of structure where most of the difficulties arise.

In an attempt to begin to resolve these difficulties, some innovative jointing techniques were explored and developed under the Clean Sky 2 project “C-JOINTS”. This C-JOINTS project focussed on the problems of joining metallic to composite structures as well as composite to composite structures while maintaining continuity of LSP and HIRF protection across the joints. Whilst this was difficult enough in itself to achieve, the typical airframe constraints of weight, maintenance, verification, cost and reparability were always also kept in mind.

Subsequent to some very encouraging results from the C-JOINTS project, a follow-on project named “D-JOINTS” is currently in progress. The D-JOINTS project is exploring mathematical modelling and the software development of a design tool to aid in the sizing of certain components associated with these jointing techniques developed in that previous project.

Clearly, a mathematical model is of little use unless the values of the parameters used in the model are known. Some of the parameters can be easily measured, or may perhaps be fundamental constants but others can be enormously variable and are very material and process dependent.

One such parameter is the electrical resistivity of the material. Resistivity is obviously a critical parameter in the mathematical model and, in the case of metallic structures, is quite easy to look up in any of numerous relevant technical data books. However, the resistivity of composite structures can vary by up to two orders of magnitude and resistivity is dependent, not only on the materials of construction, but also significantly upon the manufacturing processes. Complicating matters even further, the resistivity is significantly different in the transverse (or through-thickness) direction from that of the in-plane direction.

The purpose of these resistivity measurements is to compare the performance of different designs of LSP. In order for these measurements to be meaningful, it is necessary first to establish the parameters of the baseline configuration, i.e., the composite with no LSP application.
Then the conventional LSP (embedded copper mesh) parameters were measured. This configuration was then compared to a carbon composite with a metal-sprayed surface. Each composite test was performed on several different, but well defined, thicknesses of composite panel.

The thicknesses ranged from one layer of carbon weave, at approximately 0.3mm thick, to six layers of carbon at approximately 2mm thick.
Lightning strike protection consisted of six samples of different thicknesses with the traditional expanded copper mesh and a further six samples with thermally-sprayed aluminium. Six uncoated samples (panels without any LSP) were also measured as a baseline reference.

3 Methods

Although final demonstration or qualification of any assembly would necessarily be carried out on a lightning simulator, it is clearly impractical, and prohibitively expensive, to do this for every joint during the development process. Consequently, an alternative means of verifying and comparing the integrity of the joints during development was required. Since the requisite joint resistances are necessarily extremely low, it would be impractical to use a conventional ohmmeter, so a resistance test was developed which uses a much higher test current than is generated by conventional resistance measuring instruments.

The panels were tested by applying a defined current of one hundred amps across the panel under test, and the small voltage drops generated across the panels were measured. While this test current is very much smaller than the prospective lightning current, the heating effects of the current and contact resistances are largely scalable.

The results of this lower current testing were then used to compare the effectiveness of various configurations of joint against a baseline configuration and are also used to rank the quality of the joints and LSP coatings against one another.

3.1 Test Setup

To achieve this, a conventional low voltage, high current bench power supply was used to supply the current, ensuring personnel safety during testing. Voltage drop measurements were made using a conventional millivoltmeter. See Figure 1.

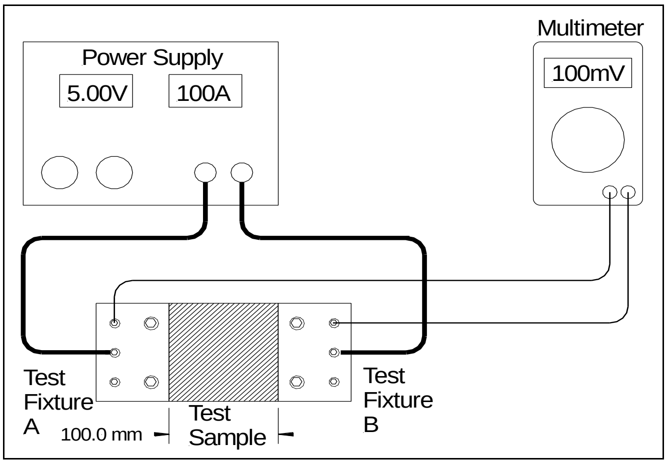

Figure 1. Low-voltage Test Configuration

In this test configuration a sample panel is clamped between two electrodes. A defined current of 100Amperes is applied through the sample and the voltage drop across the panel measured. This is the classic four-terminal resistance measurement technique adapted for the measurement of very low resistances.

Note that, in making these resistivity measurements, there are three separate and usually quite different values that are important to know.

First is the skin resistance or surface resistance. Since the resistance of carbon composite is anisotropic, the surface resistance may be very different from the bulk resistance of the composite sheet. Therefore, it is necessary also to measure the bulk resistance of the composite material. However, the bulk resistance in the in-plane direction is normally very different from the through-thickness resistance. Hence, three separate values are required and a different method of measurement is necessary for each one.

a. Surface Resistance

This test is intended to measure the surface resistance of a typical composite panel. Surface resistance is a good indicator of lightning strike survivability and also of electromagnetic shielding effectiveness.

The method for measuring surface resistance was developed under the C-JOINTS project. This Clean Sky 2 project was developing innovative jointing techniques between composite panels for aircraft. The aim was to maintain lightning strike protection and HIRF protection across the joints and to compare the results of these measurements with those of the more conventional copper mesh protection methods. The test configuration of figure 1 was used. For this measurement, electrical contact was made only to the top surface. The other side of the clamp electrode was insulated with two layers of polyimide (Kapton^{TM}) tape.

NOTE: Although the dimensions of surface resistance are in Ohms, it is important to understand that skin resistance is usually given in Ohms per square. It should be clear that the electrical resistance across a rectangle depends upon the orientation of the rectangle in relation to the current flow. However, measured across a square, the skin resistance will be constant, regardless of the size of the square. It is for this reason that the units are given in Ohms per (dimensionless) square. See Figures 2 and 3

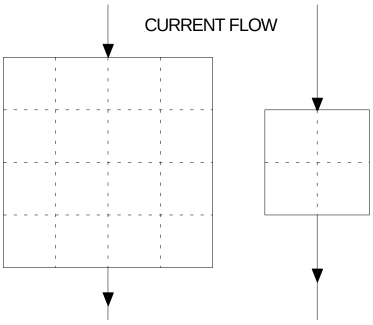

Figure 2. Surface Resistance different sized squares.

In the samples in figure 2, it is clear that the two panels are of quite different areas. However, it is also clear that the samples are square and have the same resistance. This is true for any size of square.

However, this is not true for samples that are not square, see figure 3.

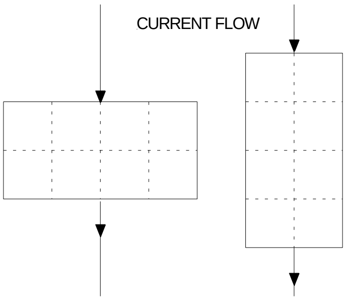

Figure 3. Surface Resistance, same areas, not square.

In figure 3 above, the panels are obviously of the same area, but it is also clear that despite this, the resistance of the right hand side panel, in the orientation of the current flow, is four times that of the left hand side.

b. Bulk Resistivity

This test is intended to measure the bulk (in-plane) resistivity of a typical composite panel. Bulk resistivity is useful for modelling current distribution in the panels under lightning strike conditions.

The method for measuring bulk resistivity was developed under the D-JOINTS project using measurement methods based upon test jigs developed under the C-JOINTS project. The test configuration of figure 1 was also used. However, for this measurement, electrical contact was made to both top and bottom surfaces.

Note that, because of the anisotropic nature of carbon composite materials, the bulk resistivity resistance measurement is expected to be different from the surface resistance.

c. Transverse Resistivity

This test was intended to determine the transverse, or through-thickness, resistivity of the carbon composite structure.

It is well known that the through-thickness resistivity of carbon composite is significantly different from the bulk lateral resistivity. This group of tests attempts to quantify that difference.

Flat test sample panels of dimensions 40mm x 40mm and of several different thicknesses were prepared for measurement.

The test equipment and experimental method of determining through-thickness resistivity are outlined below. See Figure 1.

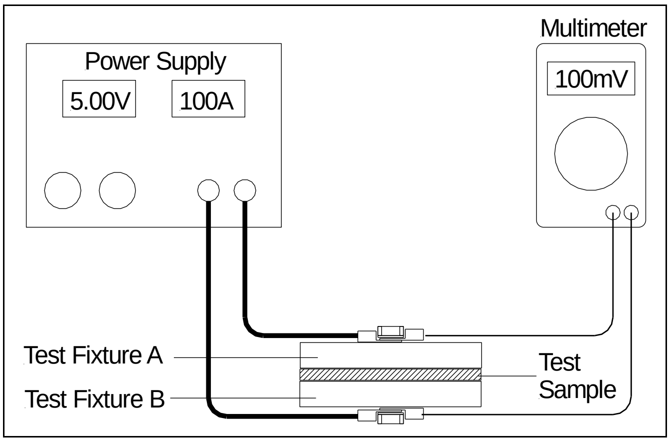

Figure 4. Through-thickness test configuration

The test samples were clamped between two aluminium plates as shown in figure 4. The spring clips were electrically insulated from the aluminium plates by two layers of polyimide (Kapton^{TM}) self-adhesive tape. Polyimide was chosen because of its puncture resistance and excellent electrical insulation properties.

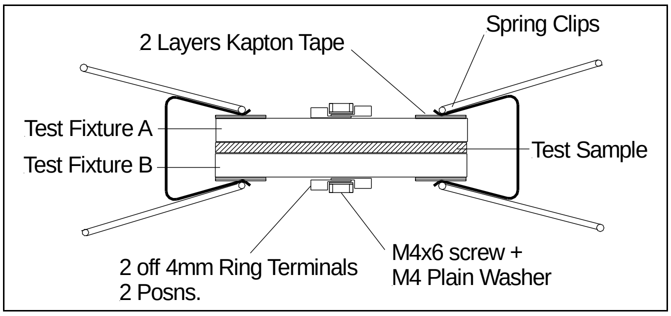

Figure 5. Through-thickness test sample mounting

It would, of course, have been possible to design the necessary electrical insulation into the test fixtures, but this test fixture needed only two 50mm square 6mm thick aluminium plates, some polyimide tape and a couple of document clips from the stationery cupboard, thus demonstrating that it is not always necessary to have expensive elaborate test rigs to perform good science.

Determination of Though-thickness Resistivity.

A defined current of 100 Amps was passed though the test samples and the small voltage drops across the samples were measured. Once again, the classic four-terminal technique was used to determine the electrical resistance. See figure 6.

From this resistance measurement, and knowledge of the physical dimensions of the samples, it is quite simple to determine resistivity.

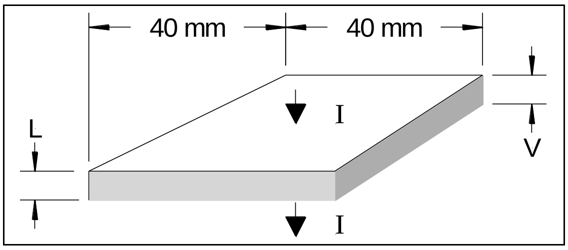

Figure 6. Through-thickness Resistivity Calculation

Calculation of Resistivity:
Resistance, $R = V/I$
Also, resistance, $R = \rho.L/A = \rho.L/(0.04^2)$
Where ρ = resistivity
L= length of conductor (m) [sample thickness]
A=Cross sectional area of conductor (m^2)
W=width of conductor (m)

Re-arranging for Resistivity

$$\rho = 0.0016\ R/L\ \ \Omega.m$$

4 Results

4.1 Baseline Resistivity

The measurement campaign began with the determination of the baseline resistivity of six different thicknesses of unprotected carbon composite, i.e. the basic panel composition without any form of lightning strike protection. The composite panel was clamped at each end between two 6mm aluminium plates. The inside edge of each plate was slightly rebated to locate a length of copper braid to help ensure good electrical contact between the test jig and the panel under test. The test samples were cut to 100mm width and 120mm long. 10mm of each end of the test sample was allocated as the contact area, so that the separation between test electrodes was set to be 100mm. Hence the tested area of each test sample was square. See figure 7.

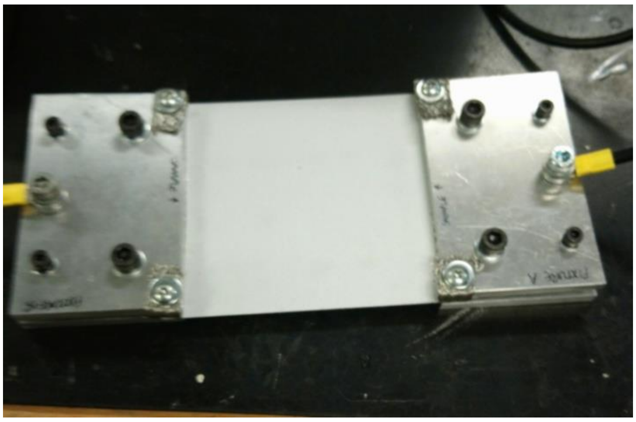

Figure 7. Test sample mounted in test jigs.

The test sample was mounted in the test jigs and the low-voltage power supply was set to deliver 100 Amps with a voltage limit of 5 Volts. These settings limit the maximum power dissipation in the sample to 500 Watts, a power density in the sample of up to 50kW/m^2. It is known from long personal experience in the discipline that this figure is typical of aircraft in-flight ice-protection power densities which have been demonstrated to be survivable without forced cooling for several seconds, i.e. for long enough to take meaningful voltage measurements.

However, when the power supply output was switched on, the current drawn was not the programmed 100 Amps, but only a few hundred milliamps.

Of course it is obvious in retrospect that the surface of any carbon fibre composite panel is filled with electrically insulating resin, and this resin covers most of the surface. Electrical contact to the conducting carbon fibres is very poor and both unreliable and unrepeatable. This was the first of many traps that were unforeseen, although obvious once encountered.

The measurements on these samples were ignored as meaningless, but were nonetheless recorded as part of the development process of a reliable, repeatable test.

After some thought, it was considered that metal-spraying the contact surfaces would improve electrical contact. The samples were suitably masked and thermally-sprayed with approximately 100µm of aluminium on the contact areas.

The tests were then repeated, this time with much more believable results.

This revised test regime repeats the determination of the baseline resistivity of the bare carbon composite structure due to the unreliability of the previous test results. The flat test sample panels of dimensions 120mm x 100m and of various thicknesses were prepared for measurement by applying a 10mm wide thermally-sprayed aluminium contact area on each of the short sides of the test panel. This metallic coating ensures good electrical contact between the test apparatus and the test sample panels.

Nevertheless, the resistance of the panels tested was such that it was still not possible to pass 100Amps through the test panels with a 5Volt voltage limit. Clearly our original estimate for resistivity was a little on the low side.

It should be noted, therefore, that for these tests, the test procedure was modified to increase the power supply voltage limit to 15Volts. The increased resistance of unprotected bare carbon composite meant that it was not possible to insert 100 Amps through the sample with the lower voltage limit. This modification does not in any way compromise the safety of the experiment but it does improve the accuracy of the result.

Here the next obvious but unforeseen problem was encountered. What happens when large currents are passed though an electrical resistance is that it heats up. This was entirely expected and suitable precautions were taken to avoid dangerous overheating, e.g. by limiting the duration of power application. What should also have been expected is that, when the resistance heats up, its resistance changes. The Thermal Coefficient of Resistance is, of course, well known but was entirely unforeseen in this case. Now came the problem of what to do about it.

The first thought was just to measure the voltage drop at a precise time in the process. This method has two problems. Firstly, it is somewhat complicated to arrange, needing timers and automatic voltage measurement and power switching. These are not insurmountable problems but there was a more fundamental problem. The thinner panels are clearly more resistive than the thicker panels, so at any given time after power application, the thinner panel will be significantly hotter than the thicker panel, skewing any measurements based on time interval. Measuring the temperature of thin panels is itself far from trivial, so another solution was required.

The solution itself is very simple: test the samples in a water bath.

The water maintains the samples at a near-constant temperature and although water is itself slightly conductive, its conductivity is about five or six orders of magnitude different from the resistances under evaluation. The conductivity of the water contributes about 10ppm error in the measurement results. Compare this 10ppm to an expected variability inherent in the composite manufacturing process of at least 10% and it becomes obvious that the water bath is an ideal solution to this problem.

Water is also, of course, not only far cheaper but is also easier and safer to handle and dispose of than insulating oil which had been suggested.

A water bath was acquired to immerse the test jigs and test samples the tests were continued.

Two sets of parameters were determined with this one set of measurements, Surface Resistance and Lateral Resistivity, i.e. the resistivity along the plane of the samples.

The results for Lateral Resistivity are presented in Figure 8 and Surface Resistance is presented in Figure 9.

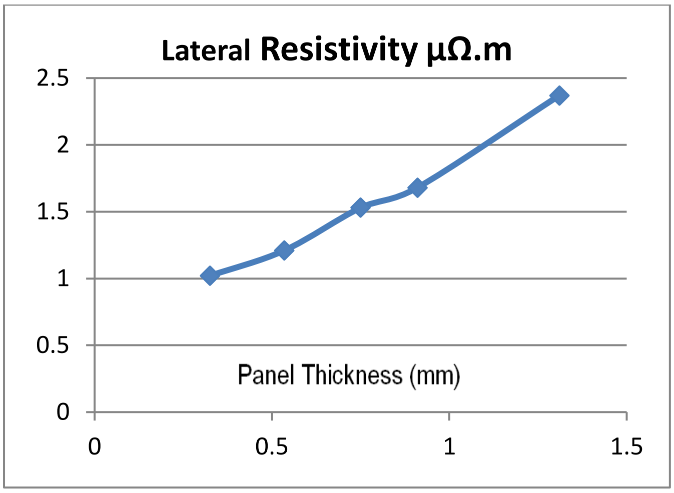

Figure 8. Lateral Resistivity v Panel Thickness

The apparent Lateral Resistivity increases with panel thickness because the material is not isotropic. The current is injected at the surfaces and the current path to the internal laminae is via the transverse resistance.

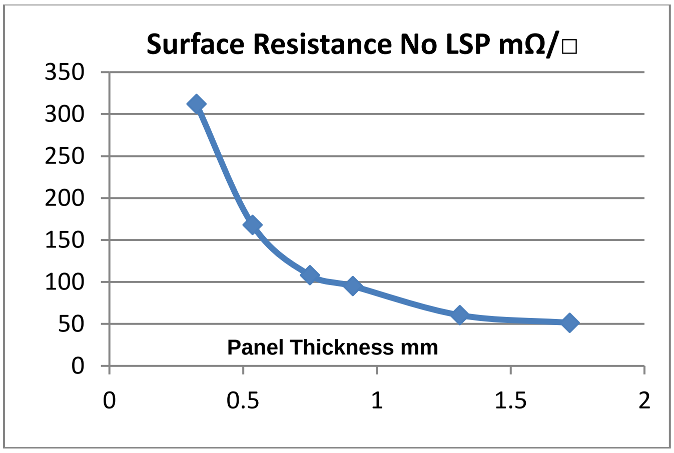

Figure 9. Surface Resistance of Baseline Panels

As expected, the Surface Resistance of the unprotected panels displays the classic 1/x curve as the resistance of the panels is inversely proportional to the thickness.

4.2 Resistivity of Panels with LSP

Having completed the baseline measurements, evaluation of two different types of LSP coatings was begun. Again, six different thicknesses of panel were evaluated in two distinct groups. One set was protected with the standard expanded copper mesh, and the other set was coated with four passes of thermally-sprayed aluminium. This thickness of metal-spray coating was found to be the optimum compromise between weight and conductivity in the previous C-JOINTS project mentioned earlier. A single layer of the expanded copper mesh was also measured in isolation in order to evaluate its contribution to the surface resistance when embedded in the CFRP composite.

The results are presented below in Figure 10.

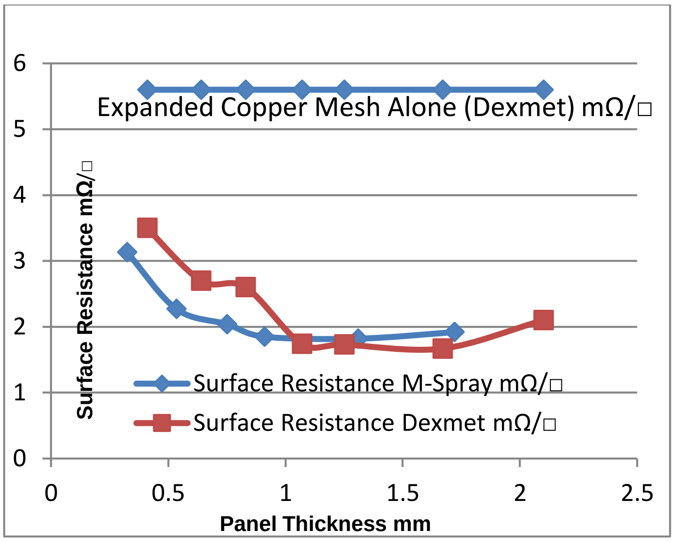

Figure 10. Surface Resistance of Panels with LSP

The six panels that were coated with expanded copper mesh were made with identical materials and processes to the baseline panels so that valid comparison of their electrical performances may be made. The six metal-sprayed panels were the actual baseline panels, thermally-sprayed after the baseline measurements had been completed.

Two things are clear from Figure 10. One is that the surface resistances of aluminium metal-spray and expanded copper mesh are almost identical. The second is that the carbon composite itself contributes significantly to the surface conductivity, the surface resistance of LSP coated composite being less than half that of the LSP in isolation.

Although not shown in the graph of Figure 10,it is important to mention that the mass surface density of the thermally-sprayed aluminium is also almost identical to that of the bare Dexmet^{TM} expanded copper mesh at around 160g/m^2. Lightning Simulator testing conducted during the C-JOINTS project demonstrated, perhaps counter-intuitively, that the aluminium LSP performed far better than the expanded copper mesh in direct effects testing.

4.3Transverse (through-thickness) Resistivity

Test laminates of the six various thicknesses were prepared, each as a 40mm square plate. The first sample was mounted in the test apparatus described in Figure 5 and Figure 6.

A preliminary test was conducted on sample the thickest of the through thickness samples without any surface preparation to enable an initial estimate of the resistance.

However, without any surface preparation, the resin coating on the surface of the sample was an effective electrical insulator and no measurable current was observed.

Consequently, all of the through-thickness samples were grit-blasted to enable electrical connection to the test apparatus.

Nevertheless, the through-thickness resistances initially measured were such that the applied current had to be reduced to 5 Amps to enable measurable voltages within the output voltage range of the power supply employed. All six thicknesses of panel were measured and the results are presented in Figure 11 below.

These test results were considered implausibly high and variable and, upon closer inspection of the test samples, it was ascertained that, despite the grit-blast surface preparation, the surface of the resin matrix of the sample panels was still higher than that of the carbon fibres and so the electrical contact to the test samples was still very poor.

This problem was one of those that was not quite so easy to foresee.

Intuitively, it would be expected that light grit-blasting the contact surfaces would remove the thin top layer of resin and expose the carbon fibres. This should ensure good electrical contact to the carbon.

Unfortunately, that was not the case. What actually happens is that the grit blasting does remove the top layer of resin, as would be expected, but what also happens is that, once the thin skin is eroded away by the grit-blast, the same grit-blast erodes away some of the carbon fibres, leaving the internal resin matrix still proud of the surface. It would appear that the carbon fibres are quite brittle when exposed to grit-blast but the resin matrix, bonding the fibres together, is tougher and more flexible and so not quite so easily eroded away by the grit.

These preliminary test results should therefore be disregarded but are included to show development of the test methodology and the significant difference between those preliminary results and the final measurements.

The test samples were then sprayed with 4 passes of aluminium on both sides to ensure good electrical contact. Any metallic over-spray bridging the two sides was carefully abraded away, and the resistivity tests were repeated, this time with more believable results. The results of both measurements are presented on the same scale in Figure 11 below.

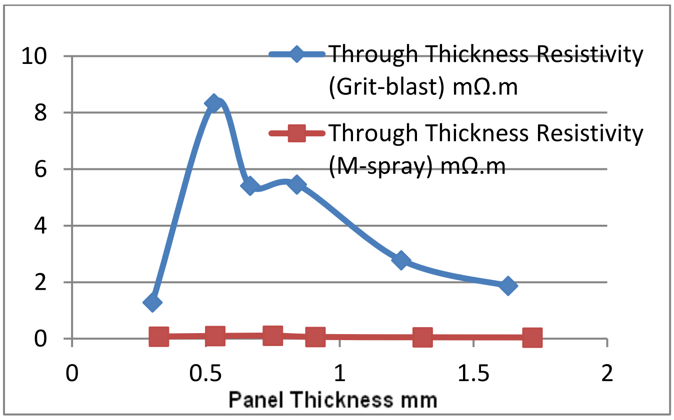

Figure 11. Through-thickness Resistivity Development

It is clear that the final measurements are significantly different from the preliminary tests. The final results are presented separately in a more meaningful scale in Figure 12 below.

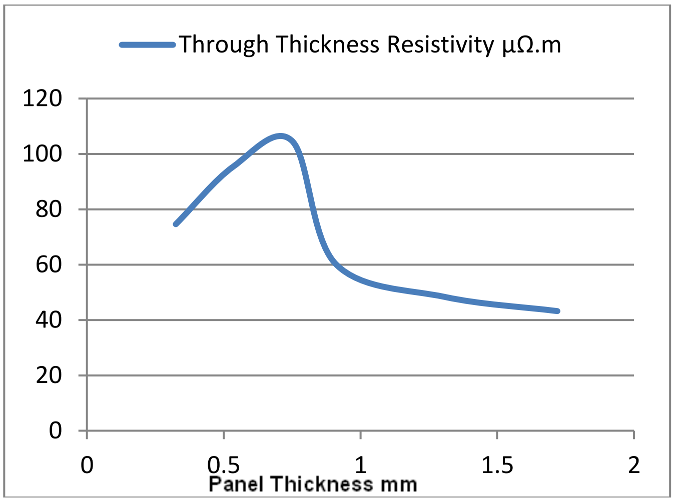

Figure 12. Through-thickness Resistivity Final Results

5 Conclusions

The consistency of the test results is very encouraging considering the large variability to be expected in the manufacture of composite structures.

The surface resistance of the thermally-sprayed aluminium LSP coating is closely comparable with that of typical expanded copper mesh, although it is less than half that of the copper mesh in isolation. This clearly shows the significant contribution of the conductivity of the carbon to the overall surface resistance figure.

The surface mass density of the thermally-sprayed aluminium LSP coating is comparable with that of expanded copper mesh.

These results would indicate, therefore, that the aluminium LSP would perform as well as a similar weight of copper. However, results of earlier full-threat lightning testing on similar LSP coatings in the C-JOINTS project indicate that the aluminium LSP performs much better in minimising substrate damage. Rationale for this is included in the C-JOINTS project reports.[3]

As would be expected, the effective surface resistance decreases slightly as the panel thickness increases, since the thicker carbon structure has lower resistance and carries a larger share of the current.

The difference between through-thickness resistivity and bulk lateral resistivity has been verified as roughly two orders of magnitude. The experimental results confirm what had been previously estimated but never verified.

The bulk lateral resistivity measurements are remarkably consistent, given the inherent variability in composite panel composition and demonstrate that the aluminium thermally-sprayed LSP coating is almost identical in electrical performance to the expanded copper mesh.

However, the aluminium coating is much simpler to apply over complex shapes. Based on the previous work[2], and the current project, the application of thermal sprayed LSP systems offers significant benefits in comparison to traditional expanded metal foil systems in terms of ease of application, higher productivity, reduced weight, superior finish, lightning strike performance and reparability. Nevertheless, due consideration must be given with respect to selection and manufacturing of composite materials, surface preparation and coating adhesion, galvanic interaction between metallic LSP and CFRP substrates, and mitigation solutions.

6 Acknowledgements

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