Electromagnetic Shielding Properties of Carbon Fibre Composites in Avionic Systems

Simon Rea[1], David Linton[1], Eddie Orr[2], Jonathan McConnell[2]

Abstract − **The shielding properties of carbon fibres in composite materials are compared for two particular lamination examples used in avionics. Plane wave shielding theory and effective medium theory are compared in this work and found to provide the same theoretical shielding level. Measurements have been performed on samples at both X-band and S-band providing shielding effectiveness greater than 70 dB. This work has found that reflection is the main shielding mechanism for this particular type of carbon fibre composite material. Measurements have also been performed on reduced thickness laminates to test the simulated results. This also provided up to 70 dB of shielding across the measured frequency band.**

Keywords – **Carbon Fibre, Electromagnetic Shielding, HIRF, Avionics.**

I. INTRODUCTION

The avionics industry are making more and more use of carbon fibre in composite materials today. There is an increasing urgency to reduce aircraft weight using innovative materials and also provide reliable mechanical properties combined with the same level of electromagnetic shielding provided by comparable metallic alloys.

Compression strength and tensile strength are still the most important properties associated with Carbon Fibre Composite (CFC) materials when used in aero structures. Combined with this today it is necessary to also examine electrical characteristics of the composite materials as well. Important to those involved in the placement and shielding of avionics systems within aircraft structures, is the shielding effectiveness provided by the composite and assemblies made from the CFC laminate. This is a measure of the CFC's ability to attenuate electromagnetic radiation across the known threat bandwidth [1].

High Intensity Radiated Fields (HIRF) cause large electromagnetic fields to exist close to sensitive control systems that are safety critical within aircraft. It has been known for the control parameters and read-outs within the cockpit to be adversely affected by radiation both within the aircraft (onboard avionics or passenger mobile phones) and external to the aircraft (high power radar and lightning strikes).

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This work will address both unidirectional (UD) and bi-directional (BD) carbon fibre composites using a known woven format. These will be applied in moulded CFC laminates to provide the HIRF protection required in the aerospace industry.

It is a simple step to convert the unidirectional laminate to a bidirectional by layering the laminate in different directions usually at 90°as shown in Fig. 1.

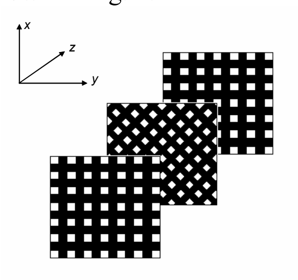

Fig. 1. Carbon Fibre Composite ply organisation (0°/45° "Composite A" or 0°/90° "Composite B")

The bidirectional laminate is both stronger and has a number of advantages that promotes niche markets within aerospace applications. The main advantage is in the manufacture of components within large structures. As most aerospace assemblies are curved, this suits bidirectional laminates whereas unidirectional composite will split easily over a curved surface. Other advantages cover resistance to bird strikes and better thickness of laminate.

This paper will consider the measured and simulated shielding effectiveness of a number of different CFC composite laminates. Standard shielding theory and the effective medium theory have been used to calculate the shielding effectiveness. Measurements are performed at both X-band and S-band for laminates with a thickness d = 1.14 mm and a comparison made with conventional aerospace alloys. Return loss has been assessed using a novel test jig for the laminates under consideration. The reflection coefficient is measured for the CFC samples and has been compared and contrasted with simulated predictions computed using a 3D full wave TLM simulation method.

II. THEORETICAL ANALYSIS

The composite laminates are made up from three plies of woven CFC. The first ply runs at 0°, the second ply runs in the direction -45°/+45° for Composite A and –90°/+90° for Composite B with respect to the y-axis. The carbon fibres have been bundled into tows of 6000 individual fibres. The fibres have a diameter of 7 µm. The tows have been woven using a five harness satin weave. This is made up of parallel tows called warp tows and the tows at right angles to these are called the weft tows.

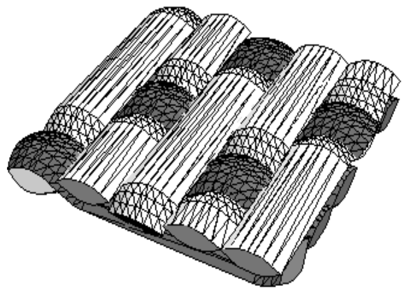

Fig. 2. CFC Laminate with 7 µm fibre tow bundles (satin weave)[5]

The dielectric constant of the resin has been measured to have a value of 4.0. The percentage weight of carbon in both the unidirectional and bidirectional CFC has been targeted to be approximately 58%. The conductivity of carbon used in this work is 55,555 S/m for a substrate thickness of 1.14 mm.

The plane wave shielding theory developed by Schelkunoff [2] and Schultz, Plantz, and Bush [3] has been used in this work. The shielding effectiveness *S* is defined as

$$S = A + R + B \tag{1}$$

where *B* is the internal reflection resultant inside the shield, *R* is the reflection from the shield and *A* is the absorption. It is assumed that the shielding level from the composite is ultimately the same as the conductivity of an isotropic metal. The role of mixtures [4] has been used to compute the conductivity of the CFC material.

$$\sigma_{composite} = V_{fiber}\sigma_{fiber} + V_{resin}\sigma_{resin} \tag{2}$$

The conductivity of the composite laminate is equal to the conductivity of its component parts weighted by the volume fraction V_{fiber}, V_{resin} of each individual part.

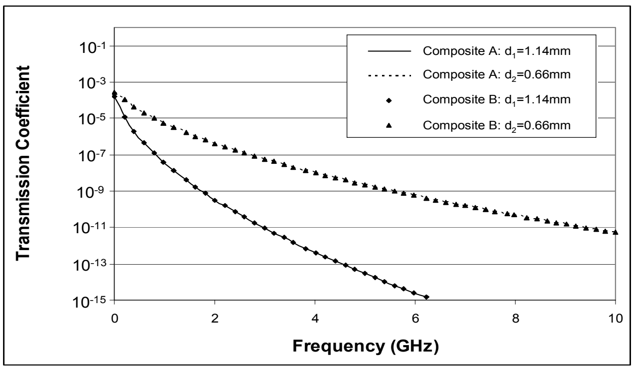

Fig. 3. Simulated transmission coefficients for CFC composites A and B for two different laminate thicknesses

In an iterative process the volume fractions have been found by adjusting the percentage and specific gravities of its component parts. In this way the volume fractions of carbon and resin have been found to be 0.505 and 0.495 respectively. Using this theory the shielding effectiveness (1) of the composite is refined for the individual sample thicknesses of 1.14 mm and 0.66 mm.

The effective medium theory stems from the theory of an exactly solvable configuration, that of a simple cubic lattice of points with lattice constant *a* and polarizability α In this case the material is considered to be homogeneous with a mixture of polarizable points and an empty void. The dielectric response is given by

$$\frac{\varepsilon - 1}{\varepsilon + 2} = \frac{4\pi}{3} n\alpha \tag{3}$$

where $n = a^{-3}$ is the volume density of points. This is known as the Clausius-Mossotti formula [4]. This can be developed further by summing points of two different polarising abilities α_{a} and α_{b} randomly assigned within the lattice.

$$\frac{\varepsilon - 1}{\varepsilon + 2} = \frac{4\pi}{3}(n_a\alpha_a + n_b\alpha_b) \tag{4}$$

where ε becomes the effective dielectric constant of the composite. The theory of CFC interweave is now applied.

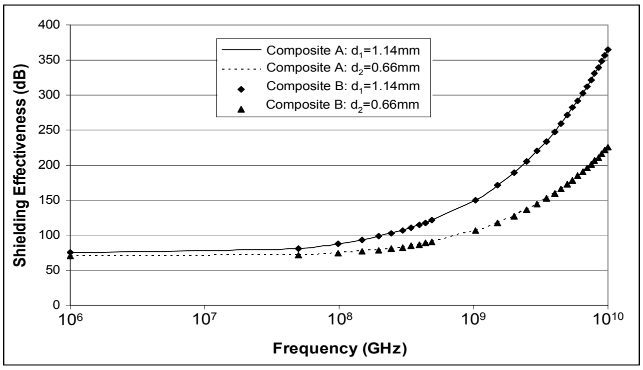

Fig. 4. Composite A and Composite B simulated shielding effectiveness using plane wave theory

The electromagnetic transmission coefficient computed from the previous theory has been plotted in Fig. 3 for material thicknesses of 1.14 mm and 0.66 mm. The simulated transmission coefficient is dependent directly on the absorption in the composite.

Uberall et al. [6] and Stoyanov et al. [7] believe the imperfect contact between individual carbon fibres must be taken into account by reducing the value of conductivity σ_{m}. However it should be remembered that much of the published work [8] has concentrated on carbon fibre polymers which use short cut (less than 5 mm length) sections of carbon fibre mixed with a polymer resin. This is not the case for this application where the carbon fibres are long and bundled into tows with in access of 6000 fibres.

The shielding effectiveness of the test composites “A” and “B” is shown in Fig. 4 for both the 1.14 mm and 0.66 mm samples. The simulation environment assumes that the incident plane wave on the shielding laminate travels through the entire thickness of the material and exits on the opposite face. This suggests that as frequency increases the absorption loss will become the dominant effective shielding mechanism. This is directly related to the skin effect that bunches current near the surface of the conductor for the CFC laminate. In practice the energy decays essentially to zero very quickly and the shielding properties are not changed by the bulk material.

For the CFC laminates under scrutiny in this work, the skin depths are 55 μm at 3 GHz and 30 μm at 10 GHz. This results in the power density for a 1.14 mm thick CFC laminate being effectively zero within a small distance of the overall material thickness.

III. Measurements

In order to fully characterise the shielding performance of the CFC material, measurements were performed at both X-band and S-band. The composite as supplied from the manufacturer had a thickness of 1.14 mm and another sample was artificially thinned to a thickness of 0.66 mm for comparison. Further thinning of the CFC laminate was deemed impossible due to bowing and internal stresses being released within the sample as the outer layers of resin and carbon fibre tow were removed.

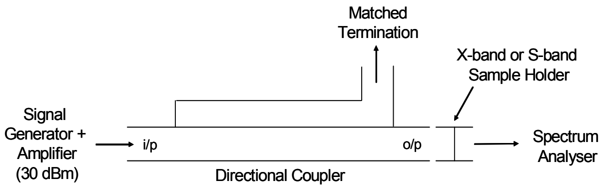

Fig. 5. Experimental setup for measurement of shielding effectiveness using a directional coupler

The experimental setup comprised of a synthesised signal source and a power amplifier to improve the dynamic range of the measurement system (Fig. 5.)

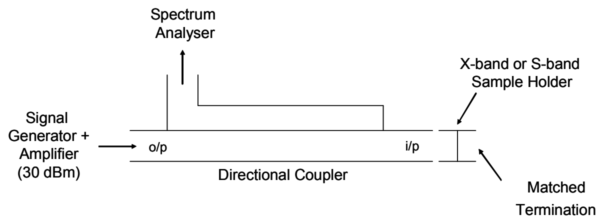

Fig. 6. Experimental setup for return loss measurement of CFC samples

This was fed into a coaxial directional coupler. Different sample holders were manufactured for the two waveguide bands (X and S) under investigation. A matched load was added to the coupled port of the directional coupler. Two sets of measurements were noted with the sample in position and with the sample removed. From this result the shielding effectiveness for the sample was calculated.

The measurement plan for the CFC under test called for three different samples of each composite material machined to fit into the waveguide sample containment jig. A small sample of aluminium of similar size was also tested for comparison as the new CFC structures are being compared directly with aluminium alloys.

The return loss for the composites was also considered. Now the directional coupler is being used as a reflectometer (Fig. 6). The position of the synthesizer and amplifier are repositioned into the main port of the apparatus. The CFC sample is mounted in a custom machined test jig connected to the main input port with the other side of the sample holder being left open. This can cause a small amount of residual fringing capacitance that must be removed from the jig by calibration. The power reflected from the CFC sample is measured using an Agilent spectrum analyser on a very narrow bandwidth for maximum signal to noise performance. The test system was calibrated by using a polished metal termination to provide a 0 dB return loss reference. Once the calibration procedure is completed the test sample is then placed into position and the experiment repeated.

At least three samples of the CFC were measured for each composite under study. The average return loss is shown in Fig. 9.

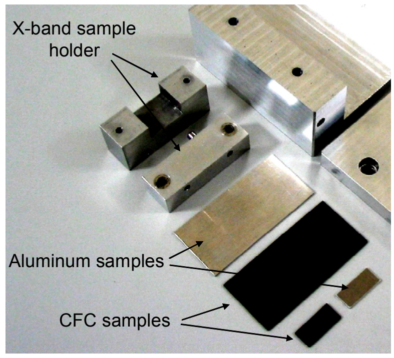

Fig. 7. Machined X-band CFC waveguide sample holder with aluminium and CFC samples

The shielding effectiveness for aluminium in Fig. 8 is the dynamic range of the system at X-band.

For the sample thickness under investigation both CFC laminates were at the limits of the dynamic range. For the thinned sample at d = 0.66 mm the shielding was 20 dB below the level of the thicker material at d = 1.14 mm. Thus for both composite CFC laminates, the shielding is more than 70 dB in the X-band range and more than 85 dB in the S-band range. The thinned composite provided 70 dB of shielding in the S-band range. From theory for the d = 0.66 mm sample the shielding effectiveness should be approximately 150 dB at S-band. This will exceed the dynamic range of the measurement system. There were some problems measuring the shielding level of the thinner sample as there is less edge contact between the sample and the waveguide test jig that allows slightly higher leakage around the sample due to sample bowing. The return-loss measured for both composite materials is very close to 0 dB. This indicates that most of the incident material is being reflected rather than absorbed in the material.

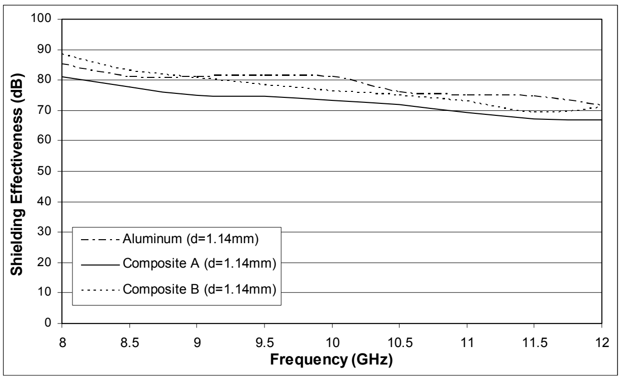

Fig. 8. Measured shielding effectiveness of the composites compared to Aluminium at X-band.

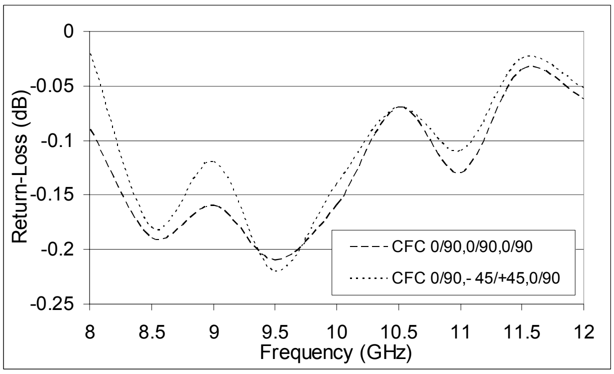

Fig. 9. Return loss for the CFC materials at X-band [9]

The very high carbon content in this CFC material means that the conductivity of the sample is very high and the properties have many similarities to a metal. The larger number of connected conduction paths in the sample, because of joined carbon fibre tows, results in only a small amount of absorption in the bulk CFC from an incident wave. The high level of reflection for both CFCs under investigation are shown in Fig. 9. The reflection coefficients are greater than 0.975 across X-band and greater than 0.987 across S-band.

IV. CONCLUSION

Plane wave shielding theory has been combined with Effective Medium Theory to investigate the shielding effectiveness of two commercial carbon fibre composite weaves. The two methodologies studied indicate the same shielding effectiveness value from the assumption that there is significant fibre parallel to the incident electric field vector. In both simulation studies it was assumed that the electric field vector is x-directed or y-directed.

From our measurement study the shielding effectiveness for the thicker laminate indicates that the results are at the limit of the dynamic range of the test system. Thus the CFC materials should in practice provide more shielding than this value. The thinner sample (d = 0.66 mm) that was studied suggested a lower shielding value than predicted from theory which may be due to the bowing in the sample because of stresses released during machining. This causes the sample to make a less reliable contact with the edge of the sample holder in the waveguide test system. The net result of this being more leakage.

The return-loss measurements have indicated interestingly that the main mechanism of shielding for this type of CFC material is reflection and not absorption. This is due to both the thickness of the CFC laminate and the high carbon content in the laminate. Due to the high connectivity of carbon fibres, the net conduction is high and the computed skin depth is low but still thicker than in a metal of comparable thickness. This again supports the view that the laminate will experience little absorption due to skin depth.

Overall both materials studied will provide high levels of effective electromagnetic shielding over the X and S bands that is comparable with that of aluminium alloys. The CFC materials will also provide a significant reduction in weight and the ability to form shaped assemblies due to moulding. The materials are already being studied for use as aircraft fuselage panels for areas where both weight and electromagnetic protection of sensitive onboard avionics are important.

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