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Electromagnetic shielding effectiveness of fiber-reinforced composites: a preliminary study

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Abstract

The use of Low power Radio Frequency (RF) based techniques as Non Destructive Testing (NDT) methods offers a potential solution for detecting defects and anomalies occurring in the structural integrity of composite based structures in real time, enabling better scheduling of servicing, repair and maintenance and eventual decommissioning of aircraft structures. Therefore preliminary results regarding the measurements of electromagnetic shielding effectiveness (SE) of diverse conductive fiber-reinforced composites will be reported. This investigation has been carried out with a coaxial transmission line testing chamber according to ASTM 4935 in the Radio spectrum, by means of comparisons between electromagnetic waves propagation in composites and traditional conductive materials, and through changes in electromagnetic shielding performances, based on the structural characteristics of the composite material.

1. Introduction

Composite materials are widely used in various industrial fields and especially in aerospace, as they offer high performances in terms of structural efficiency and lightness. In particular carbon fibre reinforced plastic matrix (CFRP) composites have always been used in load bearing components, and their applications is constantly increasing. Consequently a strong demand for non-destructive testing (NDT) methods has followed their application in order to guarantee the requirements of the materials, both during the manufacture and in service (1, 2). Most common techniques used in the industry are based on Ultrasound, Thermography, X-Ray Radiography and Computer Tomography, while electromagnetic based methods are mainly used for the analysis of metallic structures. However, lately conductive fabrics have been regarded as possible electromagnetic shields, because of their alluring properties of electromagnetic interference (EMI) and radio frequency interference protections, as well as their flexibility and thermal expansion matching (3). The high conductivity property of composite fibres could prove useful in developing a NDT method based on the electromagnetic shield behaviour displayed by these materials. In fact electromagnetic shielding is the act of obstructing the electromagnetic field by means of barriers consisting of conductive or magnetic materials, the shielding body is responsible to reduce the transmission of the electromagnetic energy. When the shielding body is used to block radio frequency electromagnetic waves, is acting as a RF shield (4, 5). The parameter which quantifies the ability of a material to work as an electromagnetic shield is the Shielding Effectiveness (SE). In accordance with the equations of shielding effectiveness as defined by Schelkunoff (6), it is possible to determine the SE of metals knowing their electrical and magnetic properties, such as magnetic permeability, dielectric constant and electric conductivity. When it comes to non-metal materials, like composites, the SE parameter can only be obtained due to experimental measures (7). In this work a preliminary study based on the possibility of determining experimentally the SE of high conductive carbon fibre composite sheets, according to the ASTM D4935 method, will be presented. The laminates contain standard reinforcements of high strength 210g 3k and 450g 12k carbon fibre, and can be applied for general engineering, robotics and aerospace purposes.

2. Shielding Effectiveness Theory

2.1 Plain-Wave Shielding Theory

The shielding theory is derived by Maxwell’s equations and can be expressed for infinitely thin plate according to Schelkunoff (6). A further description of this theory was illustrated by Ott and developed by Schulz, Plants & Brush (8-10). A shield is a medium used to control electromagnetic fields propagation between two regions. The SE is calculated as the ratio in dB of the electric (magnetic) field intensities measured before (subscript ‘‘0’’) and after (subscript ‘‘1’’) the installation of the shielding material:

$$SE = 20Log\left(\frac{E_0}{E_1}\right) \tag{1}$$

$$SE = 20Log\left(\frac{H_0}{H_1}\right) \tag{2}$$

Alternatively the ratio of the power of the incident and transmitted electromagnetic signal can also be used.

$$SE = 10Log\left(\frac{P_0}{P_1}\right) \tag{3}$$

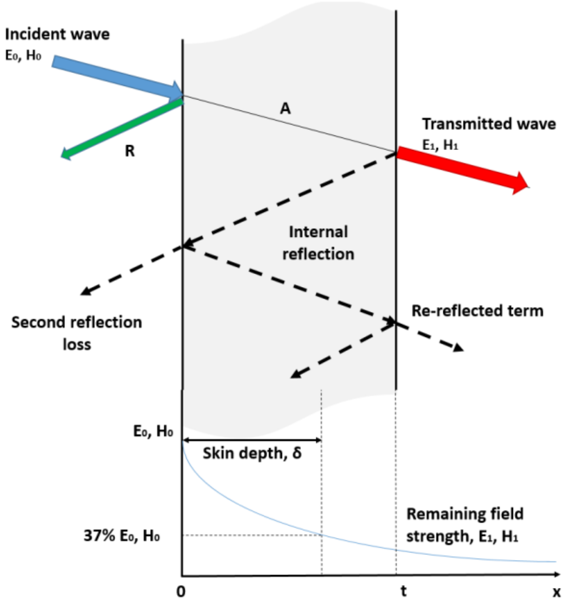

Figure 1. Concept of shielding effectiveness (SE) for a slab of conductive material, wave absorption, reflection, re-reflection and transmission processes at both boundaries of the shield.

Considering a plain-wave propagating in a region with certain electrical properties which encounters a barrier with different electrical characteristics, the electromagnetic interference phenomenon consists of reflection, absorption and transmission of the incident field. Some of the energy in the incident wave is reflected at the first interface of the material $x = 0$. A part enters the barrier and is attenuated (absorbed) and successively reflected at the second interface corresponding to the thickness of the material $x = t$, creating a process of absorption, reflection and re-reflection inside the material. The last part of the wave's energy is transmitted (11).

Therefore the SE can be calculated as the sum of three different parameters, the absorption loss A, the reflection loss R, and the term due to successive re-reflection B (9, 10):

$$SE = A + R + B\ [dB] \tag{4}$$

Given the definition of impedance of the sheet material as follows:

$$\eta = \sqrt{\frac{j\omega\mu}{\sigma + j\omega\varepsilon}} \tag{5}$$

where for air $\sigma \to 0$

$$\eta_0 = \sqrt{\frac{\mu}{\varepsilon_0}} \tag{6}$$

for:

$$k = \frac{\eta}{\eta_0}, \qquad p = \frac{4k}{(k+1)^2}, \qquad q = \frac{(k-1)^2}{(k+1)^2} \tag{7}$$

the components A, R and B assume the following forms:

$$\begin{gathered} A = 20Log\left(e^{\frac{t}{\delta}}\right) \\ R = -20Log|p| \\ B = 20Log|1 - qe^{-2\gamma t}| \end{gathered} \tag{8}$$

For materials with high conductivity $\sigma \gg \omega\varepsilon$, the most consistent terms are the absorption loss A caused by the conversion of power into heat as the field propagates through the material, and the attenuation due to the reflection at the first interface R. The absorption loss is dependent on the skin depth δ, i.e. the distance required for the wave to be attenuated inside the material to $1/e$ or 37% of its original value, the transmitted wave amplitude will decrease exponentially along the thickness of the material due to heating and Ohmic losses ($\sigma \neq 0$), and γ is the propagation constant.

$$\delta \cong \frac{1}{\sqrt{\pi f \mu \sigma}} \tag{8}$$

$$\gamma = (1 + j)\sqrt{\pi f \mu \sigma} \tag{6}$$

where:

$\omega = 2\pi f$ is the pulsation,
ε is the dielectric constant,
μ is the magnetic permeability,
σ is the electric conductivity,
t is the thickness of the shield material.

2.2 Plain-Wave SE measurements

The notion of EMI shielding could be befitting for NDT approaches because SE is a function of only the thickness and the intrinsic (electric, mechanical) properties of the material. For carbon fibres composite materials the SE can be determined actually measuring it. Methods to measure the SE of a planar material under normal incidence of a plane, far-field EM wave, involve the transition of a guided TEM wave in a coaxial transmission line according to ASTM D4935 standard, generally employed for comparative testing. This test gives the net SE due to the absorption and reflection losses and equations (4, 8) can be used to verify the experimental set up.

ASTM D4935 method consist of a specimen holder unit realized with an external and internal conductors made of brass, the outer conductor has been expanded to maintain throughout the entire length of the holder a 50 Ohm impedance (12). The equipment set up makes use of a signal generator/receiver, with an impedance of 50 Ω in output and input respectively, 10 dB attenuators at each end of the specimen holder with the function of insulators from the input and output signal. The inner conductor has a diameter of 1.3 in, while the outer flange has inner and outer diameter of 3 in and 5.24 in (13).

The voltage received at multiple frequencies is recorded and the SE is calculated by considering the Log magnitude difference of the incident power (input power from the source) and the transmitted power (power received) according to relation (3).

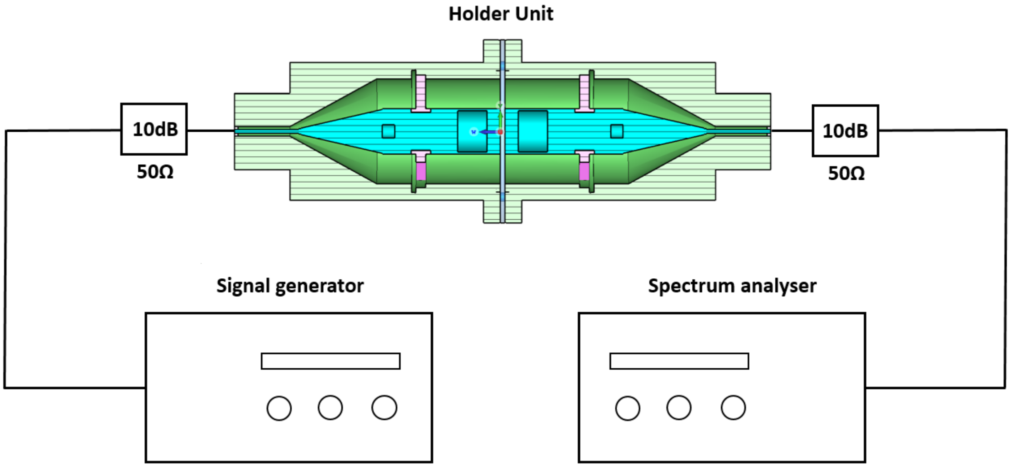

Figure 2. ASTM D4935: General Test Setup.

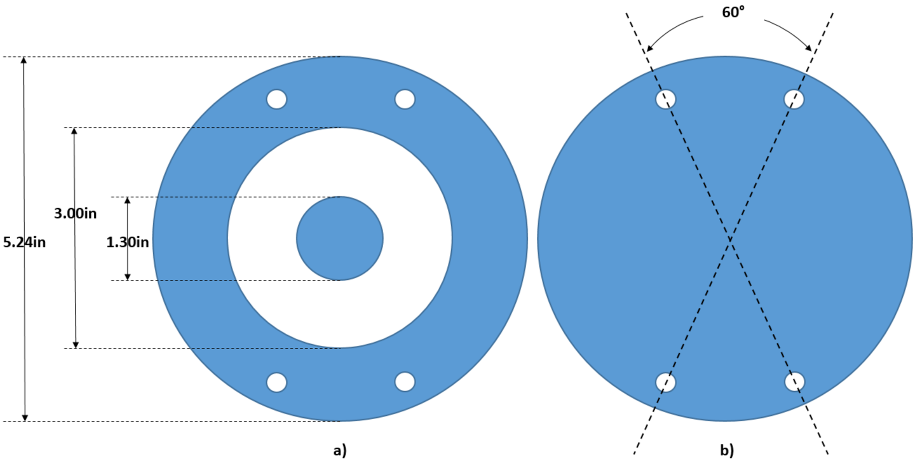

Figure 3. ASTM D4935: a) Reference specimen; b) Load specimen.

The samples to analyse are shaped in order to maintain a good electrical contact with the inner and outer conductors. From the material to be tested are cut both reference and load specimens of the same thickness, a description is provided in figure 3, where the reference appears to be constituted of two parts matching the inner and outer conductors, while the load is shown as a disk sample with same diameter than the external conductor. Both reference and load shapes are necessary to obtain the SE value, in fact the measurements are repeated twice, first using the reference in order to measure the value of the incident power P_0 and secondly with the load in place to measure the value of the power transmitted through the shield P_1 (12).

The valid frequency range to ensure TEM wave radiation goes from 30 MHz to 1.5 GHz. The thickness of the shielding materials should be decided according to equation 7 (12):

$$t \leq \frac{1}{100}\lambda \tag{7}$$

3. Experimental

3.1 Materials

Reference and load specimens with dimensions and shapes reported in figure 3 were obtained using water jet cut from Easycomposites high strength carbon fibre sheet 1 mm and 3 mm thick (testing samples A and B), and from Easycomposites high strength carbon fibre sandwich panel 6 mm thick (testing sample C). The high strength carbon fibre sheets are made of layer of XPREG XC130 210g and XPREG XC130 450g, with standard reinforcements Pyrofil TR30S 210g 3k and TR50S 450g 12k respectively. The carbon fibre sandwich panel is composed of 1 layer of 2/2 twill 3k carbon fibre fabric on each side. Specimens with only dry fibres Pyrofil TR30S 210g 3k and TR50S 450g 12k were also considered to verify the impact of the carbon fibres without the epoxy resin medium. Using fiberglass material as support both reference and load samples were prepared in laboratory gluing on a base of fiberglass a layer of Pyrofil TR30S 210g 3k (D specimens as shown in figure 4, 5).

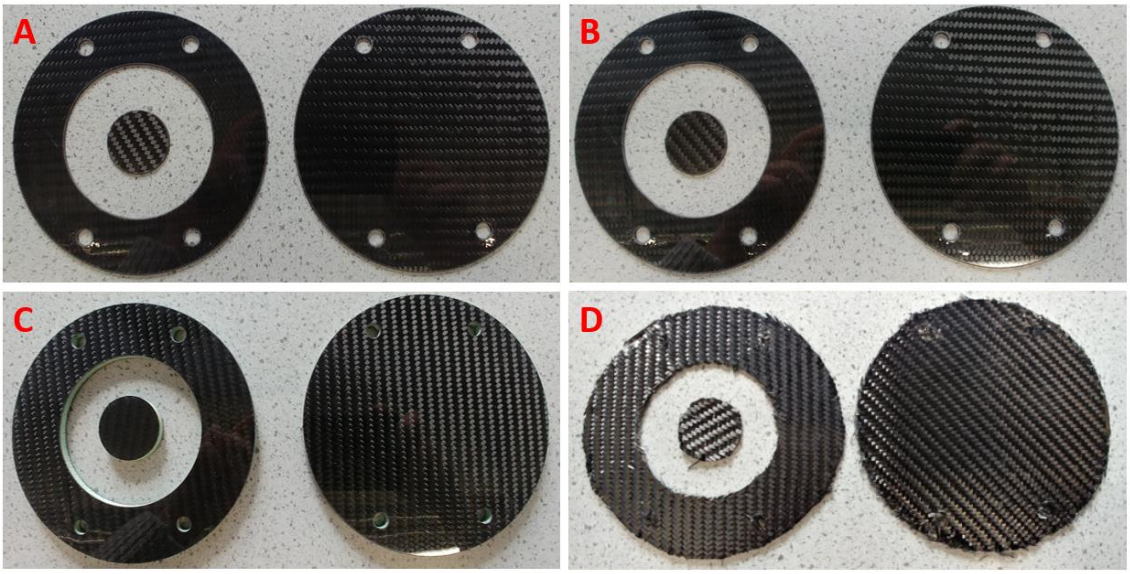

Figure 4. A) Carbon fibre sheet 1mm thick; B) Carbon fibre sheet 3mm thick; C) Carbon sandwich panel 6mm thick; D) 1 layer of dry fibres TR30S 210g.

Successively to mimic the stacking sequence of A a sample with 4 layers of dry fibres was prepared with 2 layer of TR30S 210g and 2 layer of TR50S 450g, E sample in figure 5.

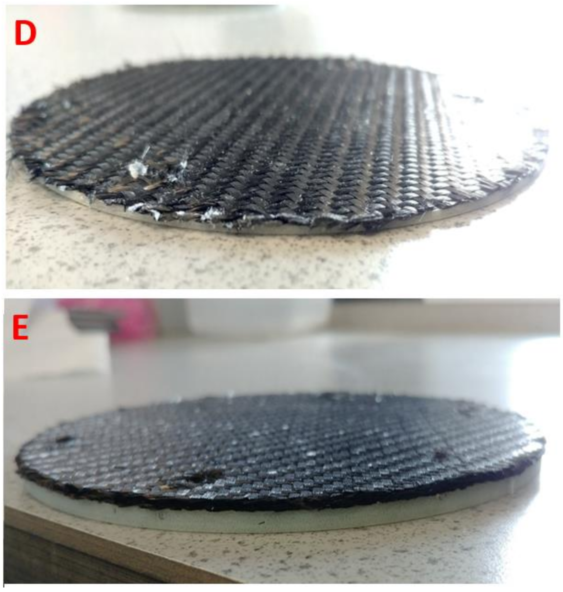

Figure 5. D) 1 layer dry fibres TR30S 210g; E) 4 layers dry fibres (TR30S/TR50S/TR50S/TR30S).

3.2 Measurements

Figure 6. Coaxial unit holder manufactured according to ASTM D4935-99. On the right 3mm carbon sheet specimen in place.

The experiments were conducted at room temperature, EMI SE was measured using a programmable E5062A ENA-L RF network analyzer, in compliance with ASTM D4935-99. The frequency range evaluated was from 30 MHz to 1.5 GHz, varying it according to the thickness of the material as stated in equation 7. The samples were clamped between the two mirrored halves of the holder unit, as shown in figure 6. As expressed in equation 3 the SE is given by the ratio between the incident power density and the transmitted power density with the load specimen in place. Via the analizer the SE can be opportunely measured in terms of scattering parameters S_{ij} (14). In a 2 ports network analizer the S –

parameter S_{21} is the forward voltage gain that is related to the ratio of the power transmitted from port 1 to port 2 divided by the input incident power wave:

$$|S_{21}|^2 \leq \frac{P_1}{P_0} \tag{8}$$

Then (14):

$$SE = 10\;Log\left|\frac{1}{|S_{21}|^2}\right| \tag{9}$$

4. Results and discussion

The aim is to verify the possibility to measure experimentally the SE parameter for commonly used carbon fibre composites with ASTM D4935 standard test setup. The minimum signal reached in the dynamic range (DR) of the system is obtained using a metallic specimen, if the values measured are within 10 dB from this limit, they exceed the DR of the system according to D4935. To increase the DR the receiver bandwidth can be decreased and the measurements repeated. A receiver bandwidth of 300 Hz was considered, after estimating that a further reduction of the band did not cause significant changes. To reduce the signal to noise ratio the signal power can be increased, a power of 5 dBm was set for the measurements.

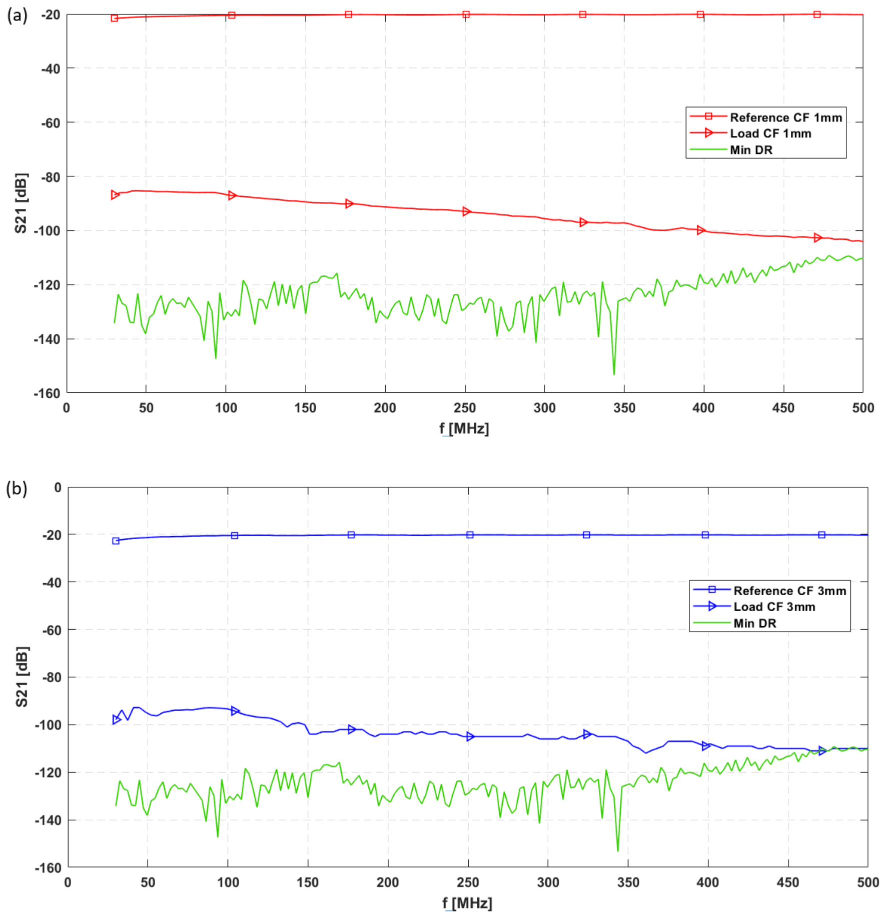

Figure 7. (a) Variation of S-parameter S_{21} over frequency of Carbon fibre-epoxy sheet 1mm thick. (b) Variation of S-parameter S_{21} over frequency of Carbon fibre-epoxy sheet 3mm thick.

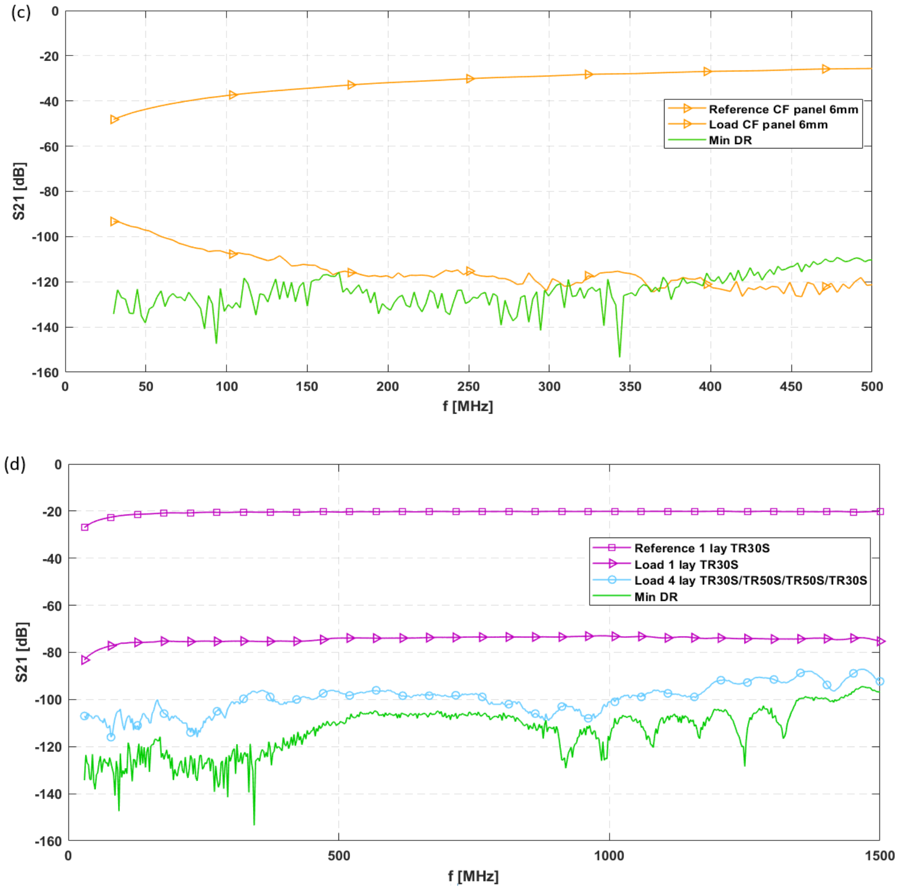

Figure 8. (c) Variation of S-parameter S_{21} over frequency of Carbon sandwich panel 6mm thick. (d) Variation of S-parameter S_{21} over frequency of dry fibres 1 layer TR30S 210g and 4 layers (TR30S/TR50S/TR50S/TR30S).

Using a narrower receiver bandwidth allowed to register S_{21} values for a range of frequencies up to 450 MHz for the composite laminates, and up to 125 MHz for carbon sandwich panel. The tests results confirm that carbon fibre are attractive for EMI shielding (15). In fact, the closer the results are to the lower measurement limit, the more the material's ability to act as an electromagnetic shield increases. The SE is given by the following difference, according to equation 9:

$$SE|_{dB} = \left|S_{21_{Load}}\right|_{dB} - \left|S_{21_{Ref}}\right|_{dB} \tag{9}$$

With a specimen of 1 mm thickness composed of 4 layers of 2/2 twill weave fabric prepreg, the SE measured assumes values from a minimum of 63.7 dB to a maximum of 82.3 dB in the range from 30 MHz to 450 MHz, having applied a second order polynomial interpolation to the data set measured. Using the same procedure for a specimen of 3 mm thickness with 8 layers of 2/2 twill weave fabric prepreg, the SE measured varies from 70.9 dB to 88.2 dB, in the frequency range from 30 MHz to 401.28 MHz. Increasing the number of prepreg layers of carbon fibres and consequently the thickness of the material raises the shielding power: SE curves of samples A and B have respectively a slope of 2.56° and 2.58° calculated considering a linear interpolation, and sample B has a value of SE higher than sample A of $\cong 10 \pm 4$ dB on average. It has been shown in the literature that a shielding level between 60 dB and 90 dB offers a significant protection from the electromagnetic radiation, while a level between 90 dB and 120 dB is considered excellent (16), therefore these materials possess an important shielding effect. However

with this experimental set up becomes difficult to measure SE values around 100 dB, using a bandwidth of 300 Hz it was possible to obtain consistent results only for less than 1/3 of the available band, as appears in figures 7,8 where the minimum S_{21} value is shown for a metallic specimen in green. Consequently this set up may not be sufficient to detect subtle variations of the parameter in question due to small structural defects.
To investigate the effect of the shielding properties of the fibres, specimen D and E were analysed. It was possible to measure experimentally a value of ≅ 54 dB in the whole range of frequencies (30 MHz to 1500 MHz) for specimen D, as shown in figures 8 (d),10.

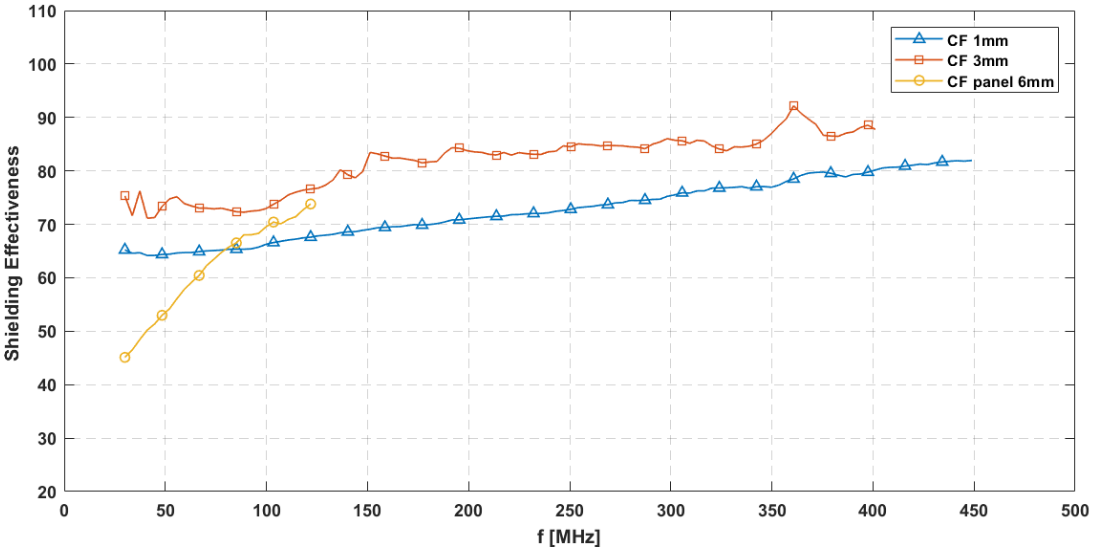

Figure 9. Variation of SE over frequency of Carbon fibre-epoxy sheet 1mm thick, Carbon fibre-epoxy sheet 3mm thick and Carbon sandwich panel 6mm thick.

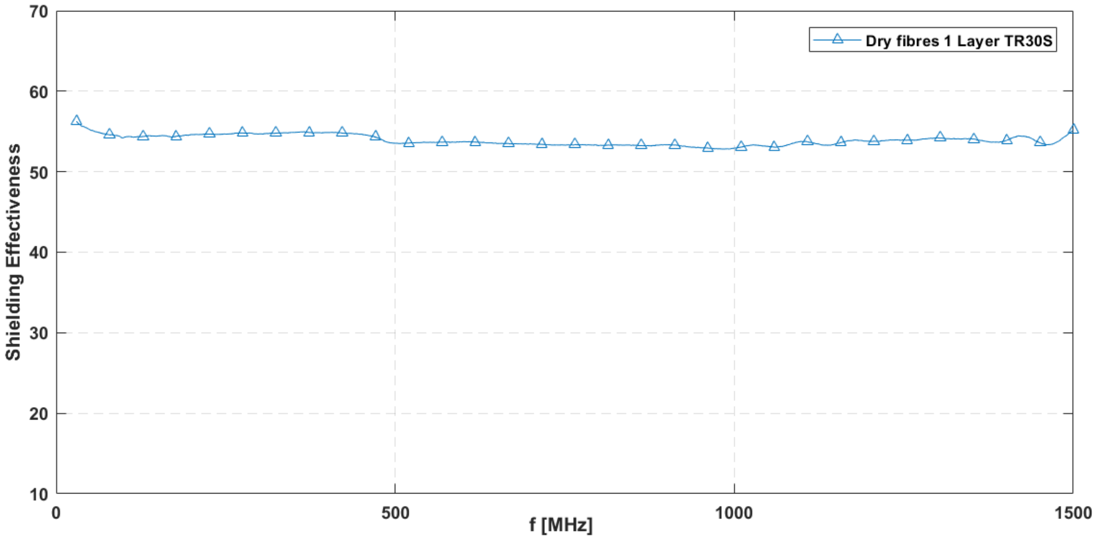

Figure 10. Variation of SE over frequency of dry fibres 1 layer TR30S 3k 210g.

A single layer of TR30S 3k 2/2 twill weave dry fabric alone provides more than 99% of attenuation of the electromagnetic field, an acceptable level for the majority of the electronic devices (16). The experiment was repeated using sample E with 4 layers of dry fibres, to compare the results obtained with the ones of specimen A. Without epoxy resin the contact points between conductive fibres increases, leading to a high shielding effect, as it appears in figure 8 (d) where S_{21} decreases in dB towards the lower measurement limit, therefore the presence of epoxy resin causes a decrement of the homogenized electric conductivity of the CF laminates.

Specimen C is composed of 1 layer of carbon fabric on top of a layer of fiberglass on each side (panels) with 5 mm of PVC foam core, the thickness dimension of the sample allows results only in the range from 30 MHz to 500 MHz according to equation 7. However substantial SE values were measured only up to ≅ 122 MHz. The slope of the curve is also different from the ones measured for samples A and B, with a calculated value of 17.10°, the SE increases more rapidly with the frequency from 44.6 dB to 73.2 dB.

The use of fiberglass in specimen C, D and E doesn't compromise the shielding properties of the carbon fibres, fiberglass material does not block the electromagnetic radiation as shown in figure 11.

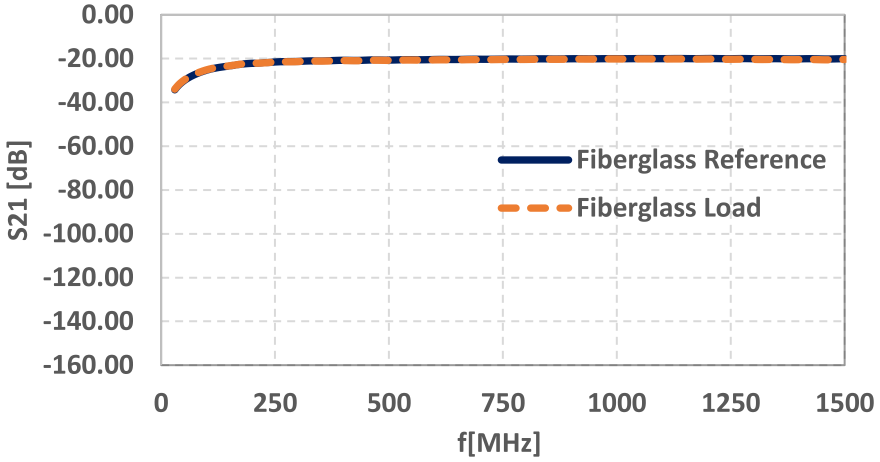

Figure 11. Variation of S_{21} over frequency of fiberglass 3mm thick.

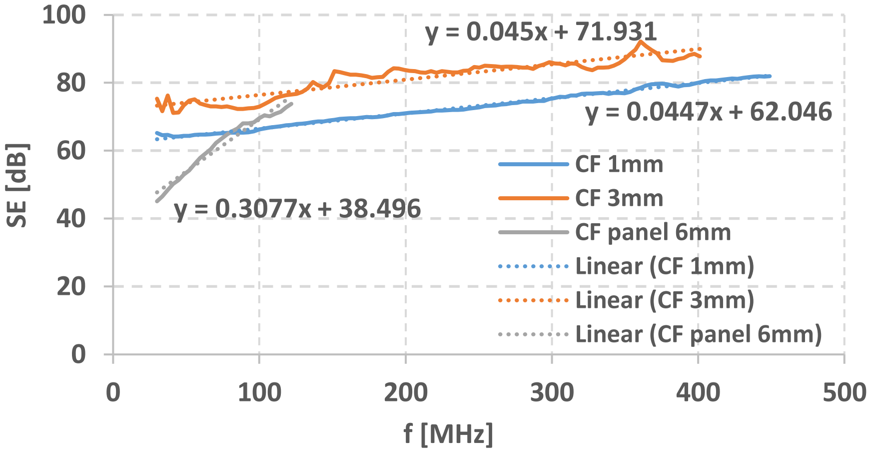

Figure 12. Linear interpolation of SE curves.

5. Conclusions

In conclusion the SE of carbon fibre/epoxy composites has been studied. These materials displays a significant ability to obstruct electromagnetic radiation, for example a carbon fibre laminate of 3mm thickness exhibits a shielding level between 70.9 dB and 88.2 dB. The EMI SE of composites increases with the thickness of the material, and increasing contact between the fibers. Therefore the results can suggest that not only increasing the fiber volume fraction has a positive effect on EMI shielding, but also the continuity of conductive fibers along the directions transversal and parallel to the incident radiation. Also the SE increases with frequency. The frequency range in which it was possible to obtain results for these materials is considerably reduced to the very high frequency band because of the allowed dynamic range and the precision of the results is inversely proportional to the thickness of the material, then a possibility to use this experimental set up to detect changes in SE due to the presence of defects inside the load specimens needs further investigation on its accuracy.

Acknowledgements

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