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Electrical Conductivity and Electromagnetic Shielding Effectiveness of Bio-Composites

Konstantinos Tserpes [1,*], Vasileios Tzatzadakis [1] and Jens Bachmann [2]

1 Laboratory of Technology & Strength of Materials (LTSM), Department of Mechanical Engineering & Aeronautics, University of Patras, 26504 Patras, Greece; mead6256@upnet.gr
2 German Aerospace Center (DLR), Institute of Composite Structures and Adaptive Systems, Lilienthalplatz 7, 38108 Braunschweig, Germany; jens.bachmann@dlr.de
* Correspondence: kitserpes@upatras.gr; Tel.: +30-2610-969498

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Abstract: In this paper, the electrical conductivity and electromagnetic shielding effectiveness of two bio-composites are studied by experimental testing and numerical models. Two monolithic composites with partly bio-based content were manufactured. The first bio-composite is made of a carbon fiber fabric prepreg and a partly bio-based (rosin) epoxy resin (CF/Rosin). The second bio-composite is a combination of prepregs of carbon fiber fabric/epoxy resin and flax fiber fabric/epoxy resin (CF-Flax/Epoxy). A single line infusion process was used prior to the curing step in the autoclave. Both variants are exemplary for the possibility of introducing bio-based materials in high performance CFRP. In-plane and out-of-plane electrical conductivity tests were conducted according to Airbus standards AITM2 0064 and AITM2 0065, respectively. Electromagnetic shielding effectiveness tests were conducted based on the standard ASTM D 4935-10. Materials were prepared at the German Aerospace Center (DLR), while characterization tests were conducted at the University of Patras. In addition to the tests, numerical models of representative volume elements were developed, using the DIGIMAT software, to predict the electrical conductivity of the two bio-composites. The preliminary numerical results show a good agreement with the experimental results.

Keywords: bio-composites; electrical conductivity; electromagnetic shielding effectiveness; rosin; flax

1. Introduction

Carbon-fiber reinforced plastics (CFRPs) are increasingly replacing metallic materials in lightweight structures, such as aircrafts, since significant weight savings can be achieved. Bio-composite materials derived from natural, renewable sources such as bio-fibers and bio-resin have received significant interest in recent years, mainly due to the increased awareness of environmentally sustainable technologies, the weight reduction they offer, the added functionality and the occupational health benefits. Bio-based composites and polymers could be an alternative to manufacturing lightweight structures. The fossil-based products could be replaced by bio-based ones, not only because of the abovementioned arguments, but also because of the economic uncertainty of the petrochemical industry by means of price and petroleum availability [1–5]. Moreover, the environmentally friendly polymers and composite production satisfy the demand for plastic products and, at the same time, protects the environment [6]. However, they have not yet found their way in aircraft structures, mainly due to their low mechanical properties, the lack of experience and confidence regarding their durability and the unknown electromagnetic properties [7,8].

Electromagnetic (EM) penetration of aircrafts mainly comes from lightning effects. On the other hand, lightning discharges do not necessarily have to hit the aircraft structure directly to create EM fields. Intracloud discharges, for example, might produce intense high-frequency radiation [9]. Additionally, to the lightning effects, an electromagnetically disturbed environment for the aircraft is developed from the infrastructure of all communication, entertainment and surveillance. EM radiation penetrates the aircraft from outboard ground-based transmitters for navigation, communication, radar surveillance from other aircrafts or satellite propagation, as well as from onboard generated interferences appearing by the carried onboard communication and entertainment equipment. Whereas a metallic aircraft fuselage principally counters these EM fields like a faraday cage—through its high electrical conductivity is able to deflect and absorb the radiation and provides an EM shield—a composite fuselage is not able to counter EM fields without enhancement [10,11].

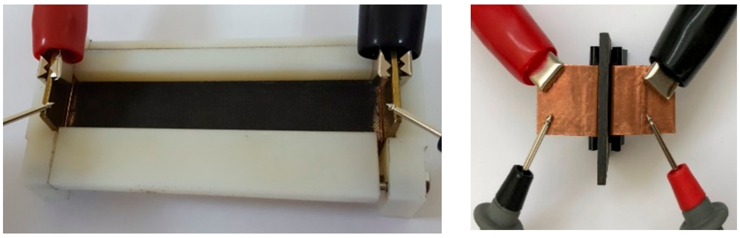
Studies have shown that there are several health effects caused by of electromagnetic fields. Sensitive individuals with electromagnetic field exposure from various sources experience ill health symptoms [12]. This phenomenon is called EHS (electromagnetic hypersensitivity), and according to WHO, 1%–3% of the population are affected by it [13,14]. Moreover, when passengers are exposed to the EM waves, the network of veins in high-risk organs, such as eyes, might be affected. This is due to heat build-up in the eyes by the EM waves, which could not be easily dissipated. Studies have shown that the EMF (electromagnetic fields) exposures have significant influence, even below the safety limits of energy that are capable of producing temperature changes in living tissues [15–20]. In order to avoid these hazards to passengers and to protect the sensitive equipment from undesired EM radiation [21], EM-interference shielding is essential. Moreover, there are indications that electromagnetic radiation could have a bio-physical effect on various animal and human organs. The organ exposure to electromagnetic radiation has shown that there are histological, hematological and histochemical changes which differ from normal [22–24]. In order to block the undesired EM radiation, one has to understand the electrical properties and EM behavior of structural materials. In this work, the electrical conductivity and electromagnetic shielding effectiveness (EMSE) of two bio-composites, which are destined for use in secondary aircraft structures, have been studied by tests and numerical models.

2. Materials

The first bio-composite is made of a carbon woven fiber fabric prepreg and a partly bio-based (rosin) epoxy resin (CF/Rosin of 10 layers). The second bio-composite is a combination of prepregs of unidirectional carbon fiber fabric (10 layers in 0° and 90° direction)/epoxy resin and flax plain weave fiber fabric/epoxy resin (CF-Flax/Epoxy). The epoxy resin, which was used to produce the second bio-composite, is the LY556 (HY+ DY). A single line infusion process was used prior to the curing step in the autoclave at 80 °C for 4 hours, with a post-curing at 120 °C for 4 hours. The prepreg layup of the first bio-composite was cured in the autoclave at 130 °C for 3 hours. Both bio-composites were manufactured at DLR (German Aerospace Center, Braunschweig, Germany).

3. Experimental

Electrical conductivity of bio-composites was derived from electrical resistivity. The electrical resistivity along X (longitudinal) and Z (normal) directions was measured according to AITM2-0064 [25] and AITM2-0065 [26] standards, respectively. To this end, a plastic test-jig and a probe ohmmeter were used. Figure 1a shows the specimen (coupon) used for the tests along the X axis inside the test-jig, while Figure 1b shows the specimen (plate) used for the tests along Z axis in between two brass plates.



(**a**) (**b**)

Figure 1. (**a**) The electrical resistivity test along the X axis; (**b**) the electrical resistivity test along the Z axis.

The resistance (in Ω) of a parallelepipedal sample made from an isotropic material may be expressed as follows:

$$R = \rho \times \frac{l}{s} = \rho \times \frac{l}{w \times t}, \quad (1)$$

where $\boldsymbol{\rho}$ is the resistivity of the material, expressed in ohm meter (Ω m); s the cross-sectional area of the specimen, expressed in squared meters (m^2); and l, w and t are, respectively, the length, the width and the thickness of the specimen, expressed in meters (m).

The resistivity is an intrinsic property of the bulk material and may be represented as the resistance between the opposite faces of a 1-meter edge cube from this material. The conductivity, σ, expressed in Siemens (S) per meter (S m^{-1}), is the inverse of the resistivity:

$$\sigma = \frac{1}{\rho}, \quad (2)$$

4. EMSE Tests

EMSE (electromagnetic shielding effectiveness) tests were conducted according to ASTM D4935-10 standard [27]. For each material, a set of a reference and a load specimen of circular shape were produced. The external diameter of the specimens is 133 mm, while the internal diameter of the reference specimen is 33 mm. The specimens used in the EMSE tests are shown in Figure 2. Both bio-composites are electrically thin, according to the measured frequency bandwidth, meaning that they are less than 0.01 times the electrical wavelength of the signal transmitted through the specimen.

Figure 2. The specimens used in the EMC (electromagnetic compatibility) tests (left: reference; right: load).

EMSE tests were conducted inside an anechoic chamber (Figure 3), in order to ensure a clear environment from other EM interferences (noise-free environment). The EM wave was produced from a signal generator and was transmitted through a double-shielded cable. The specimens were placed into the specimen-holder device. A set of N-type connectors were placed at both ends of the specimen holder, to ensure a constant 50 Ohm impedance. The signal was finally received by a receiver device.

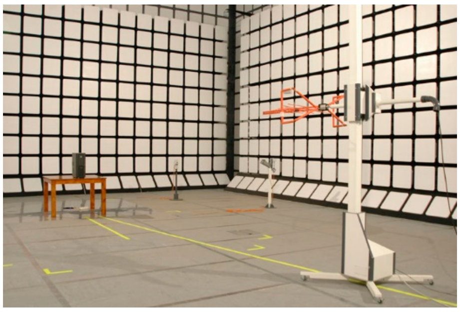


Figure 3. The anechoic chamber used for the EMSE tests.

The specimen holder (Figure 4) is made of bronze, and it was manufactured according to the ASTM D 4935-10 standard. A coaxial signal transmission is realized, as the device has a constant 50 Ohm impedance through its perfectly symmetrical structure (the calibration of the device was a mandatory step). The mounting of the specimen with the holder was accomplished with a set of four plastic fasteners. The leakage caused by the plastic fasteners is characterized as negligible.

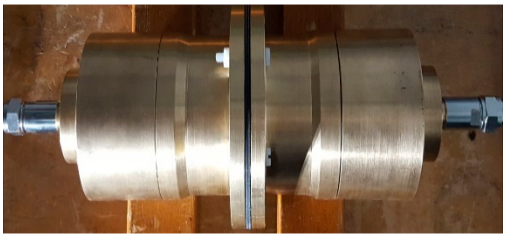


Figure 4. The specimen apparatus used for the EMSE tests.

The signal generator was set to produce an EM wave of 1 s total duration, starting from 30 MHz to 1.5 GHz, with a step increment of 0.5 MHz. The system was calibrated, in order to avoid an energy leakage or a component mismatch (a constant value of 50 Ohm is required). Inside the specimen holder (blank space), a far-field EM wave is formed that traverses through the testing material (load material case), in order to reach the holder's end. The receiver records the signal's power in dBm units (frequency bandwidth of 30 MHz to 1.5 GHz). The measurements are made for both reference and load specimens. Shielding effectiveness (SE) can be calculated directly from the dBm values or through conversion to mWatt units [8]:

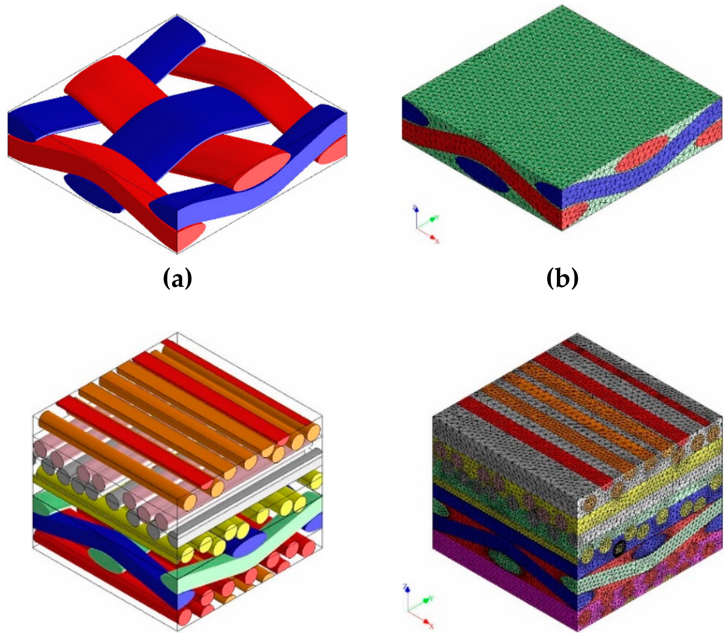
$$SE = -(\mathrm{dB}m_{ref} - \mathrm{dB}m_{load}), \tag{3}$$

5. Numerical Analysis

In addition to the tests, the electrical conductivity of bio-composites was predicted by numerical analysis, which is based on representative volume elements (RVEs). To this end, the DIGIMAT software [28] was used. For the development of the RVEs, it was crucial to have information on the microstructure and electrical properties of the materials (Table 1) given by DLR (German Aerospace Center). The developed RVEs are shown in Figure 5. The RVEs were meshed by using a built-in mesh generator with second-order tetrahedral elements, instead of voxel elements [10]. The FE meshes of the RVEs are also illustrated in Figure 5. The RVEs were loaded by using periodic boundary conditions, to achieve homogenization.

Table 1. Physical and electrical properties of materials.

Property	Carbon	Flax
Density (g/cm^3)	1.8	1.54
Electrical conductivity (S/m)	70,000	100
Dimensions of yarn (mm)	0.15 × 0.5	0.15 × 0.4



(a) **(b)** **(c)** **(d)**

Figure 5. (**a**) RVE of CF/Rosin bio-composite (twill carbon fabric); (**b**) FE mesh of the RVE of CF/Rosin bio-composite; (**c**) RVE of CF/Flax-Resin bio-composite; (**d**) FE mesh of the RVE of CF/Flax-Resin bio-composite.

6. Experimental Results

6.1. Electrical Conductivity

The measured electrical conductivity values of the bio-composites are displayed in Figure 6. The average conductivity of the CF/Rosin bio-composite is 11491 S/m, and the standard deviation is 558 S/m. The average conductivity of the CF/Flax-Epoxy bio-composite is 15104 S/m, and the standard deviation is 4858 S/m. The relatively high standard-deviation electrical conductivity for the CF/Flax-Epoxy material is due to the variation of metallization quality of the flax fiber surface and due to the variation of fiber volume fraction through the dimensions of the specimens. Figure 7 shows a metallized flax fiber surface with many defects, because the nickel deposit of the metallization procedure could be perfectly attached on the carbon fibers' surface, but it could not be attached on the flax fibers' surface. The measured electrical conductivities of the bio-composites lie in the area of the lower limit of the electrical conductivity of CFRPs (~12,000 S/m) [29,30].

6.2. EMSE

EMSE tests were conducted under continuous loading, from 30 MHz to 1.5 GHz, with increment steps of 0.5 MHz for both reference and load specimens. Inside of the specimen holder, a far-field wave is formed that propagates through the testing material (when load specimen is tested) and reaches the receiver, which records the signal's power. The received signals are plotted in Figures 8 and 9, in terms of the signal's amplitude versus frequency. The SE is derived from Equation (2). The results show that both materials exhibit a higher SE at high-frequency EM waves. More specific, the maximum SE for the CF/Rosin material is 81.05 dB at 1363 MHz, and for the CF/Flax-Epoxy material, it is 86.15 dB at 1417 MHz. The minimum SE values for the two materials are 38.89 dB and 36.68 dB, respectively, both achieved at 30 MHz (low EM frequencies). The values above 60 dB (up to 90 dB) provide sufficient EM protection [31].

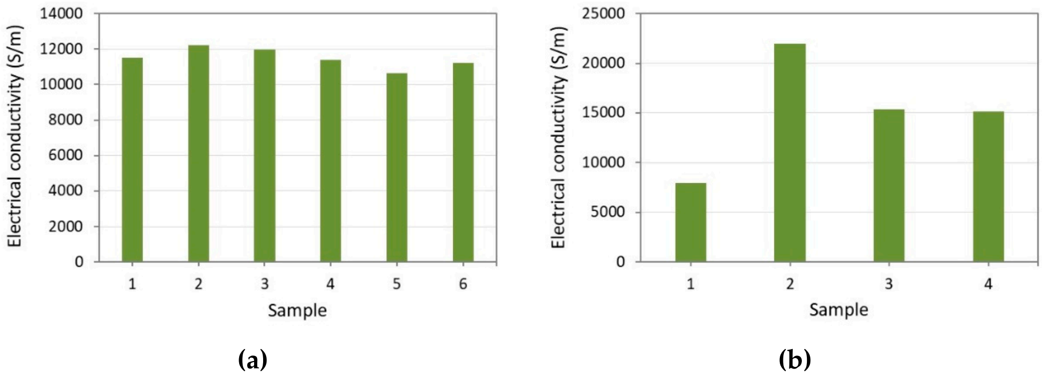


Figure 6. Electrical conductivity values of bio-composites: (**a**) CF-Rosin; (**b**) CF-Flax/Epoxy.

Figure 7. Metallization of the hybrid (Carbon/flax composite).

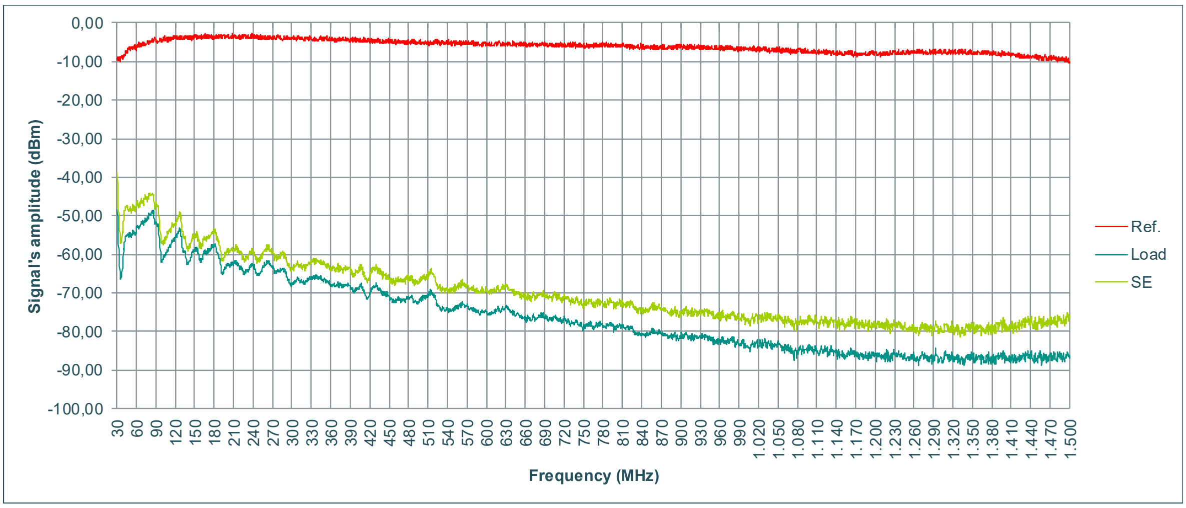


Figure 8. Signal's amplitude vs. frequency for the CF/Rosin bio-composite.

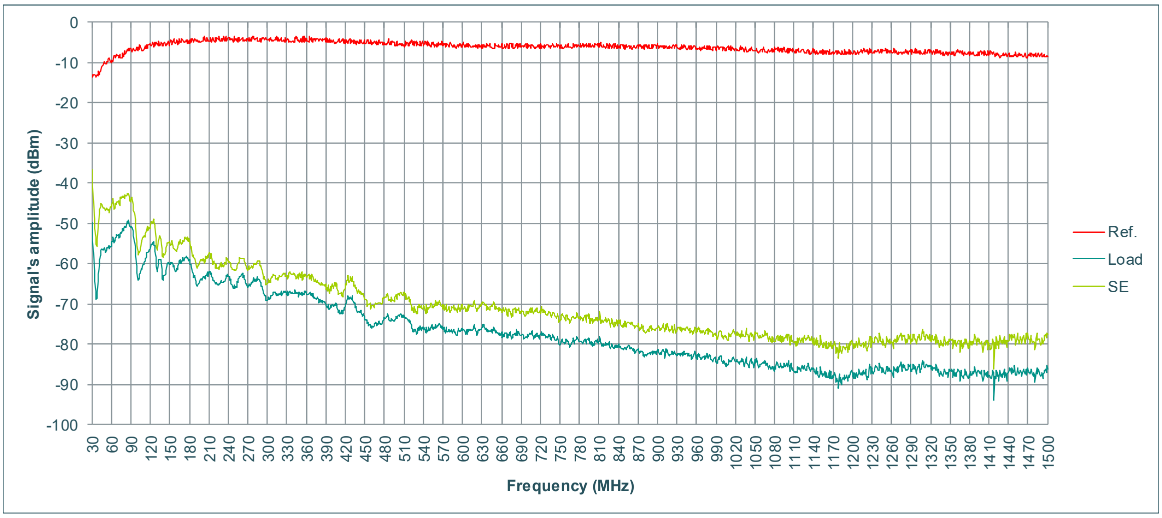


Figure 9. Signal's amplitude vs. frequency for the CF/Flax-Epoxy bio-composite.

7. Numerical Results

The computed electrical conductivity is 12,357 S/m for the CF/Rosin bio-composite and 14,333 S/m for the CF/Flax-Epoxy bio-composite. Both predicted values compare very well with the average experimental values (11,491 S/m and 15,104 S/m, respectively; see Figure 6).

8. Conclusions

In this paper, the electrical conductivity and EMSE of a CF/Rosin bio-composite and a CF/Flax-Epoxy bio-composite, which are intended for use in secondary aircraft structures, were studied by tests and numerical models. The findings show the potential of the bio-composites, since the measured electrical conductivities, and the SE, although being smaller than the respective values of CFRPs, are within the acceptable deviation range. Furthermore, the RVE-based numerical model gave very good predictions on electrical conductivity of the bio-composites.

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Conflicts of Interest: The authors declare no conflict of interest.

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