Impact of Composite Materials on the Shielding Effectiveness of Enclosures

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Abstract **─** This paper investigates and compares the electromagnetic behavior of different shielding enclosures built with composite panels (dielectric materials with conducting inclusions, carbon-fiber, fiberglass, conductive materials). The numerical model is based on a full wave finite element method taking into account the geometrical details of the walls and avoiding the use of the classical equivalent layer approach. A 2D composite enclosure with two wall structures is modeled: fiber rods shielding and metal screen shielding. Impacts of conductivity and rod diameter on the shielding effect are investigated. Concerning metal screen, the shielding effectiveness is studied for different metals with the same mass, leading to identify the most effective metal. The influence of the angle of incidence and the number of apertures is also studied. Finally, a comparison is performed considering the same mass of the two composite wall structures, each composed of fiberglass and carbon fiber.

Index Terms **—** Composite materials, finite element analysis, shielding effectiveness.

I. INTRODUCTION

Advanced composite materials become widespread in the aerospace, aircraft industries [1] and wireless communications [2]. They are typically composed by a resin matrix reinforced by high strength fibers, such as graphite, boron, glass, or carbon. With respect to metals, these materials offer lower weight, higher stiffness and strength, lower corrosion etc. Despite these advantages, composite materials are not as electrically conductive as traditional metallic ones. The shielding effectiveness of composite structures is strongly affected by the fiber-composition fraction or percentage. So these composite materials may have a significant impact on the electromagnetic compatibility constraints.

Generally, electromagnetic modeling studies of composites materials have been carried out concerning the characterization of the reflection, transmission, and shielding properties of such materials, with reference to canonical configurations having either planar or cylindrical symmetries [3-6]. In these analyses, the composite is replaced by an equivalent layer model where the composite is an effective medium. This makes easier the electromagnetic modeling with analytical or numerical methods.

For the packaging of practical structures, the performance of a shielding enclosure is quantified by its shielding effectiveness (SE), defined as the ratio of field strength in the presence and absence of the enclosure. The value of SE is closely related to the dimensions of the enclosure and the possible resonance effect for specific frequency ranges. The variation of SE versus frequency can be efficiently evaluated with a convenient modeling technique like the method of moments (MoM) [7-9], the Fourier transform and the mode-matching technique (MMT) [10], the finite-difference time-domain method (FDTD) [11-15], the transmission-

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line modeling method (TLM) [16, 17] or the finite element method (FEM) [18-20]. Most of these studies are devoted to metallic enclosures. They do not investigate the impact of new composite materials on the frequency response of the structure.

The aim of this paper is to emphasize the impact of composite materials used for shielding effectiveness of enclosures. It shows with an adequate finite element modeling that composite materials modify the wide band frequency response of the structure when compared to a metallic one. The analysis is performed for a 2D enclosure made of the carbon fiber composite material described in [4]. In order to avoid the classical assumption relevant to the use of an equivalent layer model, the finite element approach takes into account the fine features of the composite. The computational model clearly underlines the influence of the diameter and the electrical conductivity of the rods on the resonances of the SE. Another composite screen constituted with a metal sheet embedded in dielectric materials is also studied for comparison.

Shielding Effectiveness is defined as the ratio (in decibel unit) of the total field existing in the presence of the enclosure to the incident field:

$$SE_{dB} = \text{-}10 \, \log_{10}\left(\frac{P^t}{P^i}\right) = \text{-}20 \, \log_{10}\left(\frac{E^t}{E^i}\right), \quad (1)$$

where P^i and P^t are respectively the incident and transmitted electromagnetic power, also for the electric field E.

II. ELECTROMAGNETIC PROBLEM AND VALIDATION OF THE MODEL

The transverse magnetic (TM) case is considered where the incident electric field and scattered electric field have only one component in the z direction denoted E^i and E^s , respectively.

The total electric field $E^t (E^t = E^i + E^s)$ satisfies:

$$div\left(\frac{1}{\mu} gradE^t\right) + \left(\varepsilon\omega^2 - i\sigma w\right) E^t = 0. \quad (2)$$

Consider the 2D scattering of a plane wave by a 2D enclosure. The shape of the studied enclosure is described in [10-18] (Fig. 1).

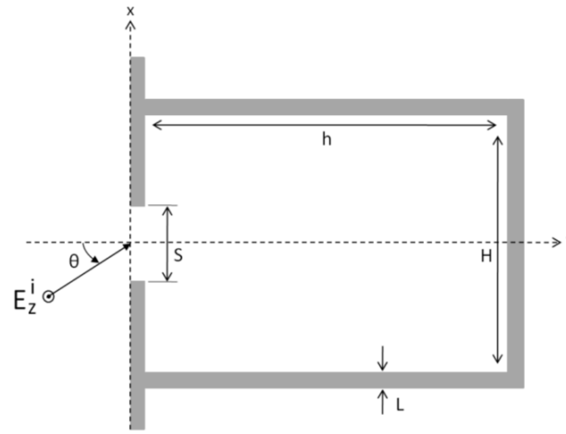

Fig. 1. 2D enclosure with h = 50 cm, H = 40 cm, S = 10 cm, L = 0.4 cm, θ = 0°.

Figure 2 illustrates a shielding composite wall where a thin copper screen ($\mu_r = 1$; $\varepsilon_r = 1$; $\sigma = 58\ 10^6$ S/m ; $e = 1\ mm$) is inserted in a dielectric resin with fiberglass reinforcements ($\mu_r = 1$; $\varepsilon_r = 4.3$; $\sigma = 10^{-11}$ S/m ; $L1 = L2 = 1.5\ mm$).

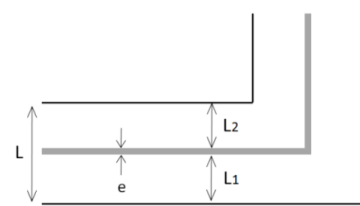

Fig. 2. Composite walls with copper screen shield and fiberglass reinforcements; L = 4 mm, L1 = L2 = 1.5 mm, e = 1 mm of copper.

The composite enclosure is illuminated by a plane wave in a frequency range between 100 MHz and 1.1 GHz. The shielding effectiveness is computed inside the enclosure on a line normal to the aperture, at the center, when the incident plane wave is *x*-directed. The computational domain is truncated by perfectly matched layers (PMLs). The results from the finite element method are compared to analytical formulae from [10] and experimental measurements [10, 18], obtained in the same conditions (geometry, plane wave…), but with a perfect electric conductor (PEC). The experimental process consists in placing a monopolar probe into the shielded enclosure to measure the inner field strength. The measurements were performed inside an anechoic chamber [18]. Results are shown in Fig. 3.

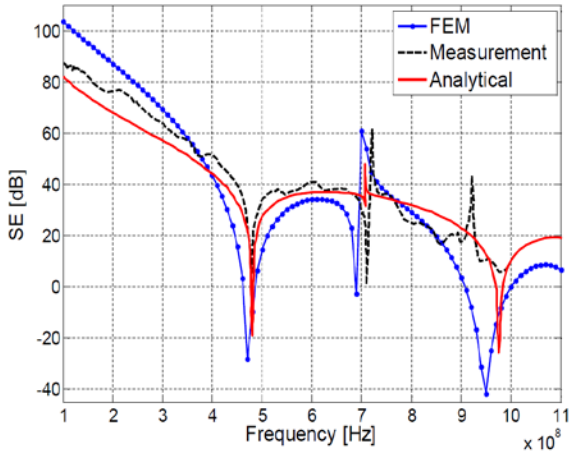

Fig. 3. Comparison of SE for different walls.

FEM results are in good concordance with the available analytical solution for 2D composite enclosure. Moreover, comparison of these results with those of experiments also shows good agreement, despite small shifts in inverted peaks (dips), which are due to the fact that the inner surface surrounded by the metal is a bit greater in the composite enclosure, considering the transparency of the fiberglass relative to the fields. This comparison justifies the use of FEM to simulate composite behavior in the following study. Two kinds of composite structure are next considered.

III. COMPOSITE WALL WITH FIBER RODS SHIELD

The walls include fiber rods ($\mu_f = 1,\ \sigma_f\ ,\varepsilon_f = 4$) embedded in a dielectric resin which is fiberglass ($\mu_d = 1,\ \sigma_d = 10^{-11}$ S/m , $\varepsilon_d = 5.5$) (Fig. 4).

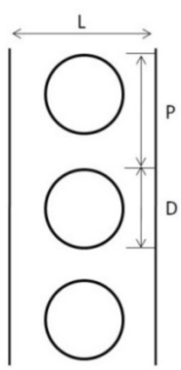

Fig. 4. Composite wall with fiber rods shield and fiberglass reinforcements; L = 10 mm, D = 4 mm, P = 8 mm.

Figure 5 shows the variation of SE versus the rod conductivity up to 1.1 GHz. For high values of conductivities the resonance peaks correspond to the theoretical values obtained in the case of a closed cavity. It can be pointed out that for conductivity lower than 10 S/m, the negative shielding near the resonances disappears, but SE is significantly reduced for those values. This can be explained by the fact that a low value of the conductivity leads to a low value of reflection loss inside the enclosure, thus minimizing the effect of resonances.

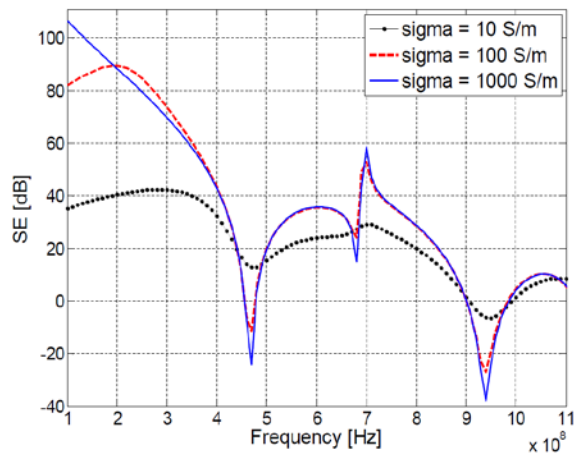

Fig. 5. Shielding effectiveness considering different conductivities of the rods.

One of the main advantages of composite materials is their low weight. The impact of the rod diameter D on the SE, directly related to the weight of the enclosure, is now investigated. Here, we consider that P = 20 mm and σ = 1000 S/m.

Figure 6 clearly shows that SE is significantly reduced when using rods with small diameter. In this case, the shielding effect is mainly governed by the ratio between the period of the rods and the wavelength.

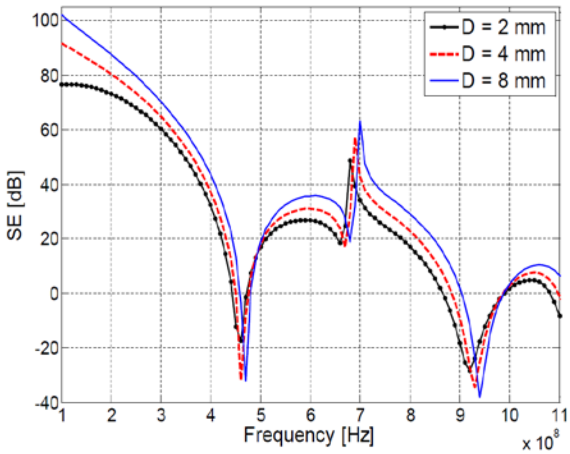

Fig. 6. Shielding effectiveness for different diameters of the rods.

IV. COMPOSITE WALL WITH METAL SCREEN SHIELD

The second structure is composed of walls, where a thin metal screen is inserted in resin dielectric fiberglass reinforcements.

A. Impact of the composite material

Figure 7 shows the variation of SE for several kinds of metallic screens with a same mass for the whole wall. In order to identify the most effective metal in term of electromagnetic shielding, the mass criterion seems to be suitable.

- Aluminum screen structure :
$\mu_r = 1$; $\varepsilon_r = 1$; $\sigma = 38\ 10^6$ S/m ; $\rho = 2700\ kg/m^3$.
- Copper screen structure :
$\mu_r = 1$; $\varepsilon_r = 1$; $\sigma = 58\ 10^6$ S/m ; $\rho = 8920\ kg/m^3$
- Iron screen structure :
$\mu_r = 400$; $\varepsilon_r = 1$; $\sigma = 10.3\ 10^6$ S/m ; $\rho = 7860\ kg/m^3$

The aluminum presents an efficiency slightly greater than other metals, in spite of its lower conductivity (38.10^6 S/m) comparing with that of copper (58.10^6 S/m). This can be explained by the fact that from a certain very high value of the conductivity, the thickness of the material will mainly influence the increase of the shielding effectiveness.

B. Impact of angle of incidence

The variation in the angle of incidence (θ on Figure 1) also changes the shielding effectiveness (Fig. 8). In the previous simulations, the wave propagates initially to the shielding enclosure with an angle of incidence θ = 0°. It is shown that it corresponds to the worst case, because the incident wave penetrates directly into the aperture.

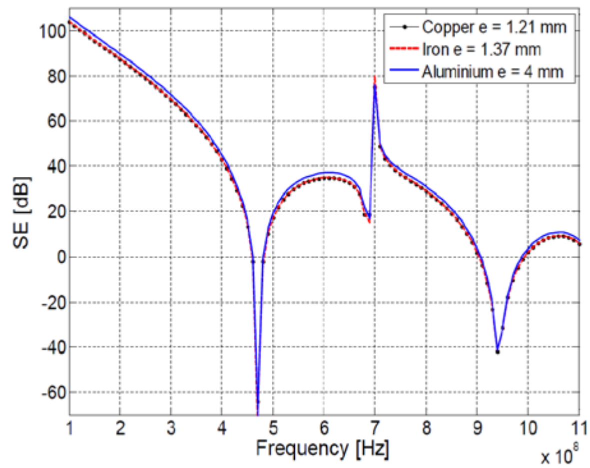

Fig. 7. Shielding effectiveness for various kinds of composite walls metal screen with equal mass; L1= L2 = 3 mm.

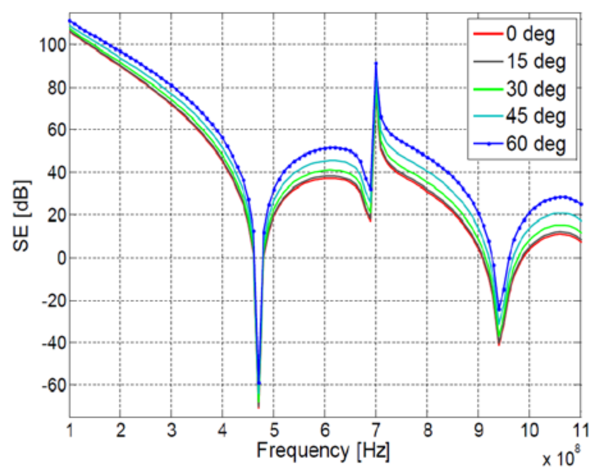

Fig. 8. Shielding effectiveness for various angles of incidence; S = 100 mm, L = 10 mm, L1 = L2 = 3 mm, e = 4 mm of aluminum.

C. Impact of multiple apertures

Initially, the structure of shield has an aperture of S = 100 mm to serve as an input for ventilation and cabling. Even with the best composite material, an opening of this size will weaken the shielding effectiveness, because it will allow the passage of an important flow of electromagnetic fields.

Two cases are now considered. In the first one, the size of an aperture is taken as 20 mm, and the impact of an increase of the aperture number is evaluated (Fig. 9). It is obviously shown that it reduces the shielding effectiveness, because the larger the total area of the apertures is, the higher the fields penetrate inside the enclosure. Figure 10 shows concordance between FEM simulations and analytical results proposed by [10].

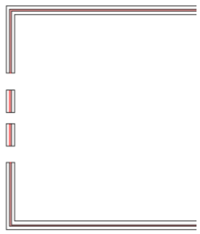

Fig. 9. Composite enclosure with three apertures.

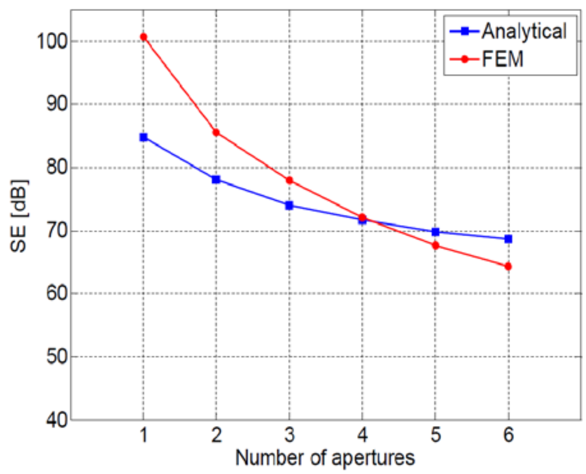

Fig. 10. Shielding effectiveness at 600 MHz vs. aperture number; S = 20 mm, L = 4 mm, L1 = L2 = 1.5 mm, e = 1 mm of aluminum, compared with analytical results.

For the second case, the initial 100 mm-opening is divided into several sub-apertures, so as to keep the same open area.

Figure 11 shows formally that this division of the opening increases the efficiency of shielding in a very striking way. Comparing a composite shielding with 6 sub-apertures to one with a single opening, the effectiveness increases with an average of 40 dB (this value is calculated over the frequency band of this study).

V. COMPARISON OF STRUCTURES

The comparison of the two structures, one with rods (Fig. 4) and the other with screen (Fig. 2), is now proposed considering the same mass and the same kind of conducting material, which is the carbon fiber ($\mu_r = 1$; $\varepsilon_r = 4$; $\sigma = 21200\ \mathrm{S/m}$) (Fig. 12). In both structures, carbon fibers are incorporated into glass fibers.

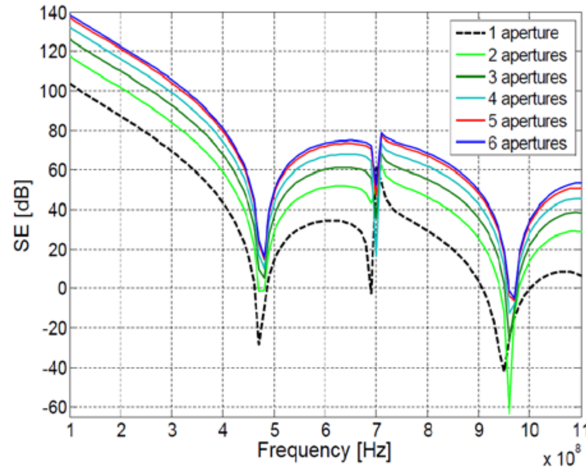

Fig. 11. Shielding effectiveness for various sub-aperture numbers with same open area.

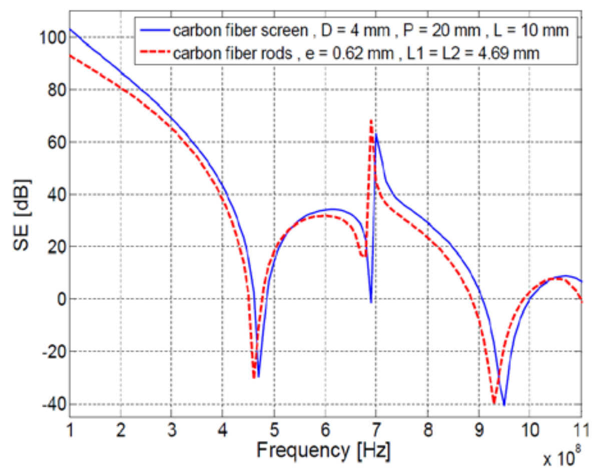

Fig. 12. Shielding effectiveness for composite walls with carbon-fiber rods and with carbon fiber screen.

Figure 12 illustrates that the shielding with screen composite walls is a little bit more effective than with rods. In fact, in the same conditions (equal masses for fiberglass and carbon fibers), over the entire frequency band, the screen structure displays an increase of effectiveness with an average about 2 dB compared to the rods. This can be explained by the fact that the structure with rods behaves like a screen structure since the distance between two rods is small compared to the wavelength. It is noted that the resonance inverted peaks are only slightly modified. However this result is highly dependent on the geometry, and particularly on the distance P.

VI. CONCLUSION

The shielding effectiveness of an enclosure with two different structures of composite walls was evaluated. Numerical results for the fiber rods show that the behavior of the wide band response is affected by their conductivity and their diameter. For the structure with a metal screen shield, comparison of the influence for different kinds of metals considering equal mass, has allowed equitably identifying the most effective metal in term of electromagnetic shielding. The influence of the incidence angle of the exciting wave has been illustrated. Moreover, higher SE was obtained using a composite enclosure with a subdivision of the aperture. Also, the comparison between fiber rod shield and fiber screen shield, with the same mass and with the same kind of conductive material, has shown that the second structure is less efficient than the first one.

The different simulations in this paper show that from the shielding point of view composite materials can be an excellent alternative to the conventional use of metal in enclosures. In addition, these materials have generally good mechanical and thermal characteristics. Ongoing works address practical 3D enclosures involving new conductive polymers.

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