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On the electromagnetic shielding properties of carbon fiber materials

Introduction. *Due to the good electrical and thermal properties of carbon, carbon-based materials represent a major trend is various applications, including electromagnetic compatibility. Among carbon-based materials, graphite-impregnated woven fabrics represent a new trend in the field of electromagnetic shielding, with the perspective of being used for protective clothing.* ***The novelty*** *of the proposed work consists in the exhaustive comparative analysis of various carbon-based sample shields by employing both simulation and experimental methods. The selected configurations included a simple graphite plate, a graphite powder strip network, and a graphite-impregnated fabric with 2×2 twill weave.* ***Purpose.*** *The main scope of the analysis is to prove the efficiency of the graphite-impregnated twill woven fabric in the field of electromagnetic shielding.* ***Methods.*** *Two main research methods were employed: simulation and experiment, both following the same protocol: the shield placed in the middle, with the excitation (transmitting antenna) on one side and the measurement / receiving antenna on the other. The experimental stage was thorough, being performed in two different laboratories and by applying the double transverse electromagnetic (TEM) cell method and the shielded box method.* ***Results.*** *A significant difference yielded from the comparison of the simulation and experimental results for the shielding effectiveness, probably due to the fact that the virtual model is an idealized version of the physical one, not taking into account its imperfections. The virtual analysis yielded the graphite plate shield as the most efficient, followed closely by the twill fabric. The graphite strip network had significantly poorer performance compared to the other two shields, probably due to the electrical contact imperfections between the graphite strips and the optical transparency of the shield. The main focus of the analysis was the twill woven graphite-impregnated fabric; therefore, its shielding effectiveness was determined through simulation and experiment. The experimental analysis was performed in two stages in two different electromagnetic compatibility laboratories, by employing the double TEM cell method and the shielded box method, respectively, both methods providing similar results and classifying the shielding performance as good.* ***Practical value.*** *The paper provides an accurate analysis of the graphite-impregnated 2×2 twill woven fabric in terms of electromagnetic shielding effectiveness, by employing both simulation and experimental methods, and comparing its performance to the one other graphite-based shields.* References 14, tables 2, figures 14.

Key words: **carbon fiber, double TEM cell, electromagnetic shielding, graphite, shielded box method, shielding effectiveness.**

Вступ. *Завдяки хорошим електричним і тепловим властивостям вуглецю, вуглецевмісні матеріали являють собою основні напрямки у різних застосуваннях, у тому числі в області електромагнітної сумісності, завдяки хорошим екрануючим властивостям. Серед матеріалів на основі вуглецю просочені графітом тканини є новою тенденцією в області електромагнітного екранування з перспективою використання для захисного одягу.* ***Новизна*** *запропонованої роботи полягає у вичерпному порівняльному аналізі різних зразків екранів на основі вуглецю з використанням як моделювання, так і експериментального методів. Вибрані конфігурації включали просту графітову пластину, сітку зі смуг з графітового порошку і просочену графітом тканину з переплетенням саржею 2×2.* ***Ціль***. *Основною метою аналізу є доказ ефективності саржевого полотна, просоченого графітом, у галузі електромагнітного екранування.* ***Методи***. *Використовувалися два основних методи дослідження: моделювання та експеримент, обидва слідували одному й тому ж протоколу: екран розташовувався посередині, з збуджуванням (передаючою антеною) з одного боку і вимірювальною/приймальною антеною з іншого. Експериментальний етап був ретельним і проводився у двох різних лабораторіях із застосуванням методу подвійної поперечної електромагнітної (ПЕМ) комірки та методу екранованої скриньки.* ***Результати***. *Порівняння результатів моделювання та експериментів стосовно ефективності екранування демонструє суттєву відмінність, ймовірно, через те, що віртуальна модель є ідеалізованою версією фізичної, не враховуючи її недосконалості. Віртуальний аналіз показав, що екран із графітових пластин є найбільш ефективним, за ним близько слідує саржева тканина. Мережа з графітових смуг мала значно гірші характеристики порівняно з двома іншими екранами, ймовірно, через недосконалість електричного контакту між графітовими смужками та оптичною прозорістю екрана. Основним предметом аналізу була тканина саржевого переплетення, просочена графітом; тому її ефективність екранування визначалася шляхом моделювання та експерименту. Експериментальний аналіз був виконаний у два етапи у двох різних лабораторіях електромагнітної сумісності з використанням методу подвійної ПЕМ комірки та методу екранованої скриньки, відповідно, обидва методи дали аналогічні результати та визначили характеристики екранування як хороші.* ***Практична цінність.*** *У статті наведено точний аналіз просоченої графітом саржевої тканини 2×2 з точки зору ефективності електромагнітного екранування з використанням як моделювання, так і експериментальних методів, а також порівняння її характеристик з іншими екранами на основі графіту.* Бібл. 14, табл. 2, рис. 14.

Ключові слова: **вуглецеве волокно, подвійна ПЕМ комірка, електромагнітне екранування, графіт, метод екранованої скриньки, ефективність екранування.**

Introduction. Carbon exists in nature in different forms with different physical properties: as diamond, as graphite (also called amorphous carbon), as fullerene – geodesic dome-type structures and in cylindrical structures – as carbon nanotubes. Graphite is one of the two allotropic states of carbon, in which the atomic lattice – also known as stratified lattice – occupies a volume of space formed by parallel planes of carbon atoms arranged in a regular planar hexagonal structure. The planar two-dimensional structure of graphite, actually having a monoatomic thickness, is called graphene and has superior properties in terms of electrical and thermal conductivity. It was obtained in 2004 by Andrei Geim through an exfoliation technique. The research undertaken by Andrei Geim and Konstantin Novoselov on this type of material brought them in 2010 the Nobel Prize [1].

The low mass density and high tensile strength of carbon fiber recommend it for the use in aerospace industry, in automotive industry (the sports competition sector), or sports articles, while the high electrical conductivity of carbon turns it into a solid option for electromagnetic shielding materials. Although metals are traditionally used in electromagnetic shielding, their high mass density prevents using them in applications where the shield portability is required. Another limitation of the metal shield is given by the fact that the shielding mechanism relies mostly on reflection, which renders such shields inadequate for stealth applications, for instance. Conductive polymers come as an alternative for electromagnetic shielding, but with the inconveniences of low thermal stability and high processing cost. Carbon-based polymer nanocomposites offer the advantages of both conductive polymers and carbon, having low mass density, high electrical conductivity, and a shielding efficiency based on absorption and multiple internal reflections mechanisms [2].

Depending on the application, several types of carbon-based shielding materials such as polymer composites, cellulose composites, woven fabrics, or fabric/epoxy composites are investigated in [2-9]. Carbon-based technical textiles have also proved their economic efficiency in the aerospace industry, yielding a 20 % fuel saving for aircrafts with wing movables made of carbon fiber epoxy composites instead of aluminum [7].

Referring to carbon woven fabrics, several papers report the results of their analyzes on the impact of weave type, the number of carbon fiber layers, as well as their direction. In [9], Rea et al. investigate the shielding effectiveness (SE) of two woven carbon fiber composites used in aerospace industry, and placed in satin weave. Both samples are made of three plies, the difference between samples consisting in the direction of the middle ply.

The twill weave was analyzed in terms of shielding effectiveness in the frequency band up to 3 GHz, when compared to the plain weave and the uniform direction weave [6, 8, 10, 11]. In [10], Pamuk et al indicate the 2×1 twill structure has higher shielding effectiveness compared to a plain 1×1 weave and a satin 6 weave.

The goal of the paper is to perform a comparative analysis in terms of electromagnetic shielding effectiveness, of various carbon-based materials through both numerical and experimental methods.

Subject of investigations. Due to its high absorption properties, carbon is extremely efficient in electromagnetic shielding [12]. In this paper, the properties of various carbon fiber materials are studied, including graphite powder and graphite impregnated woven fabric [12-14]. Since the textile carbon fiber materials represent a new tendency in electromagnetic shielding, a sample of twill woven fabric is analyzed with reference to other carbon-based screen types. The shielding effectiveness of three selected samples, for the 1 GHz frequency, is initially investigated through simulation in a commercial Finite Element Method (FEM) software, by following an approach similar to the standard experimental procedure. The carbon-based fabric is built in great detail in the virtual environment. The second research method described in this paper was experimental and it investigated the efficiency of two sample shields. The experimental stage was carried out in two different electromagnetic compatibility (EMC) laboratories employing different methods – the double transverse electromagnetic (TEM) cell method and the shielded box method, respectively. The results obtained for the same frequency as in the simulation stage are presented and discussed.

Presentation of the selected samples. The following types of screens are investigated:

- a shielding material consisting of graphite impregnated fabric with twill weave (Fig. 1);
- a graphite plate;
- an orthogonal grid graphite powder screen (Fig. 2).

From the materials listed above, the fabric and the graphite strip mesh have been practically made and studied both theoretically and experimentally. The graphite plate was investigated only in the simulation.

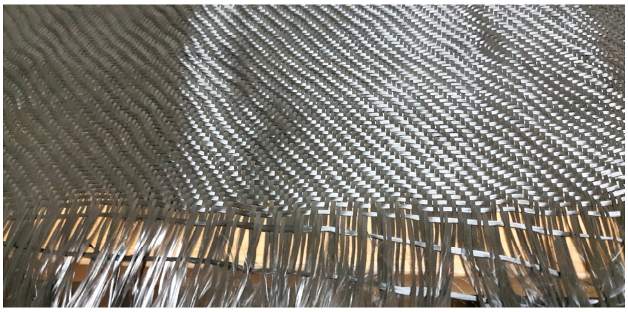

Fig. 1. The 2×2 twill carbon-based weave

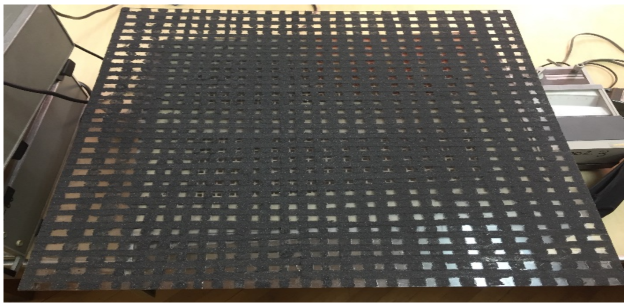

Fig. 2. Orthogonal grid with graphite powder strips

Description of the twill weave. Twill weave is a diagonally woven fabric and is characterized by the interweaving of warp and weft yarns at a specific angle. In this case, the two categories are perpendicular. This characteristic binding gives the fabric a particular appearance. Diagonal weaves can be: diagonal weft (when the weft yarns are visible on the face of the fabric and outnumber the warp yarns), diagonal warp (when the visible warp yarns are predominant on the face of the fabric) and diagonal balanced. The cross stitches are fewer than in the woven pile bond and therefore the fabric will be smoother, looser, softer and less durable than woven pile bond fabrics. Diagonal-bonded fabrics are softer, suppler, with more friction-resistant stitches. Diagonal bonded fabrics do not have high bond strength like woven bonded fabrics and therefore these fabrics will have mechanical properties inferior to the ones of woven bonded fabrics. The 2×2 twill weave is widely used in the decoration field and in the automotive industry and is made according to the following pattern: the warp yarns are arranged in the Ox direction, at a fixed distance, and the warp yarns are arranged perpendicularly, in the Oy direction, so that the warp yarn passes over two warp yarns, then under two other warp yarns. The 2×2 twill fabric model was built in the Ansys HFSS simulation environment (Fig. 3), following textile industry standards. The model characteristics are given in Table 1.

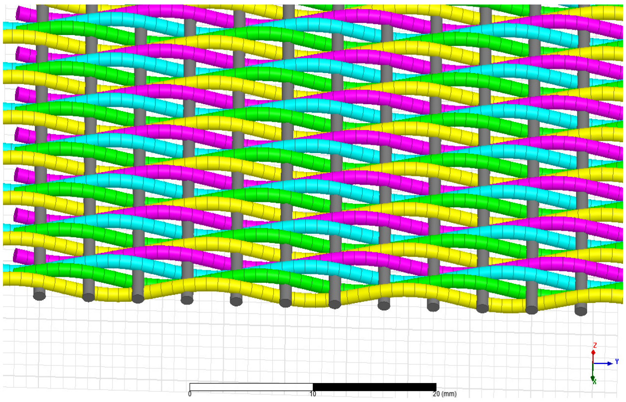

Fig. 3. Geometric pattern of 2×2 twill fabric

Table 1

Virtual twill fabric model parameters

Parameter specification	Value
Threads diameter	1 mm
Distance between warp threads	3 mm
Distance between batting yarns	0.1 mm
Shield width	20 mm
Shield length	1000 mm

Calculation of shielding effectiveness by means of simulation. To obtain the shielding effectiveness (SE), the procedure is similar to the experimental method: place the shield in the middle of a field, with excitation at one end, and determine the field or power level at the other end, with respect to the no-shield situation.

The model used is illustrated in Fig. 4 and is represented by a parallelepiped-shaped air box, with a square cross-section with a side equal to one screen side and a length of 1 m. The following boundary conditions were applied: on the top-bottom surfaces the «Perfect E» boundary condition was imposed, and on the front-back surfaces, the «Perfect H» condition, and thus waveguide propagation medium was obtained.

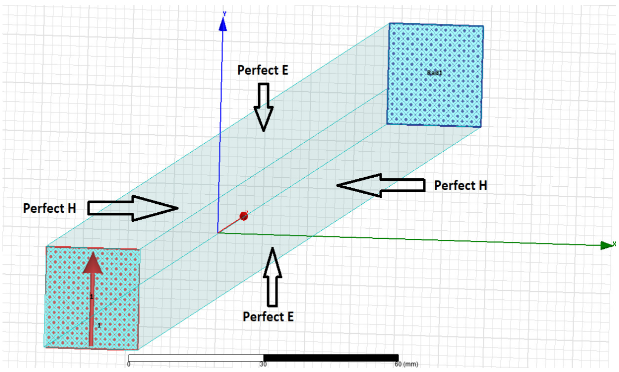

Fig. 4. Simulation domain, boundaries and excitation

«Wave Port» excitation is applied to one end of the domain, corresponding to the cross section of the domain and having the electric field distribution mode such that the curvilinear integral of the electric field along a vertical line is positive. At the opposite end of the excitation, a «Radiation» boundary condition was applied, which is actually an Absorbing Boundary Condition (ABC). This minimizes reflections of waves incoming from the perpendicular direction or nearly perpendicular to the boundary. Figure 4 shows the excitation applied to the near-plane base, the «Radiation» condition on the far-plane base, and the side surfaces with the «Perfect E» (top and bottom) and «Perfect H» (left and right) condition, respectively. The working frequency of the simulation is 1 GHz.

In the absence of the shield, the simulation domain behaves like a waveguide with the excitation on the left side, as shown in Fig. 5, which illustrates the electric field distribution in the longitudinal plane.

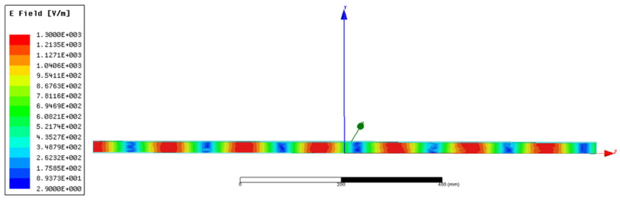

Fig. 5. Propagation of the electromagnetic field within the domain in the absence of the shield

Simulation of the shielding effectiveness of the graphite twill fabric. In the analysis of the shielding effectiveness of the carbon material, the 2×2 twill geometric model is extended to a 20 mm wide square-shaped screen, arranged in the air box at mid-length, and the excitation on the left side. The electric field distribution, illustrated in Fig. 6, highlights the mechanisms of electromagnetic field reflection and absorption. Thus, in the left half of the longitudinal plane, an increase of the electric field is observed – highlighted by the increase of the peak values compared to the previous case, due to the reflection process of the electromagnetic (EM) waves by the screen located in the middle. The right-hand side shows the electric field transmitted through the screen after the internal reflection, absorption and refraction mechanisms have occurred; it is approximately half compared to the situation without the shield.

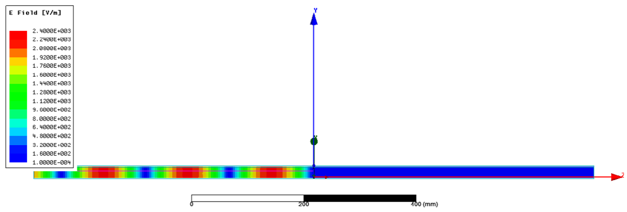

Fig. 6. Propagation of the EM field, with the shield placed in the middle of the domain

In both cases the same distance is observed between the maximum and minimum points, which means that the wavelength does not change, due to the fact that the propagation medium is the same (air) and the impedance of the medium is constant. For a more precise determination of the shielding effectiveness of the carbon fabric, the electric field strength E and the electromagnetic wave power density S are plotted on the central longitudinal axis. The variation of the two physical quantities on the central longitudinal axis in the two cases is given in Fig. 7, 8, respectively.

For the first case – in the absence of the shield, the maximum value of the electric field strength

E_{max} = 1315.34 V/m and S_{max} = 2423.35 W/m^2. As noted in Fig. 7, there is a natural fluctuation of the power density *S*, generated by the discontinuous structure of the discretization mesh. Depending on how the mesh was applied, only a portion of the mesh vertices are located on the longitudinal axis on which the *E* and *S* quantities were calculated. For points on the longitudinal axis that do not coincide with the mesh vertices, the *E* and *S* quantities are calculated by interpolating the values of adjacent vertices. The *S* graph in Fig. 7 shows an average value of the transmitted power and a peak deviation of 250 W/m^2 which, compared to the average value, indicates a relative deviation of approximately 10 %.

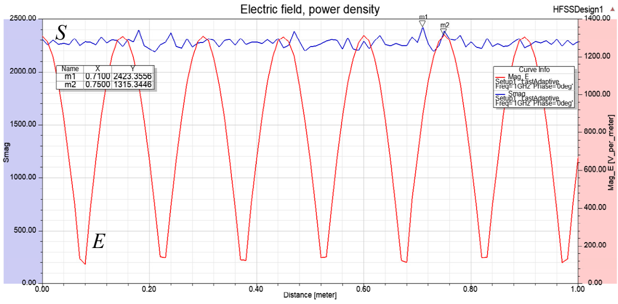

Fig. 7. The power density *S* (blue line) and the electric field strength *E* (red line) on the central longitudinal axis – in the absence of any shield

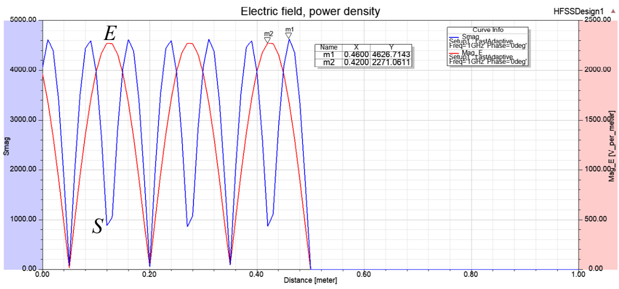

Fig. 8. The power density *S* (blue line) and the electric field strength *E* (red line) on the central longitudinal axis – in the presence of the fabric material shield

In the second case – in the presence of the shield, a significant reduction of the values of the two magnitudes in the second half of the axis and an increase of the values on the left side (compared to the first case) is evident, as shown in Fig. 8. On the right side, the value of *S* is zero and that of *E* = 0.06 V/m. Applying the formula for calculating *SE* based on the electric field strength, we obtained:

$$SE = 20 \cdot \lg\left(\frac{E_1}{E_2}\right) = 20 \cdot \lg\left(\frac{1315.34}{0.06}\right) = 86.8 \text{ dB}.$$

In this case, the value of SE indicates a very high degree of shielding.

Simulating the shielding efficiency of a graphite plate. To complete the analysis of the carbon powder fabric, we evaluate the results obtained from the simulation by comparing it with a shield consisting of a continuous graphite plate with the same dimensions as the first shield. The results for the two sizes considered are given in Fig. 9. Using the same formula and the same value for E_1, but modifying E_2 = 0.03 V/m, we obtain *SE* = 92.8 dB.

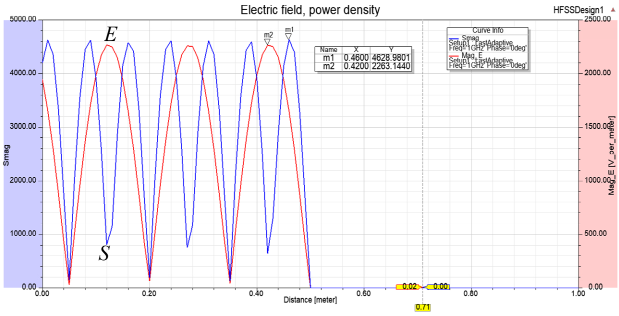

Fig. 9. The power density *S* (blue line) and the electric field strength *E* (red line) on the central longitudinal axis – in the presence of the graphite plate shield

Simulation of shielding effectiveness of an orthogonal network made of graphite powder strips. The shielding material is an orthogonal network of graphite powder strips of 1 mm thickness and 10 mm width. These are arranged in parallel at 10 mm intervals. The physical screen has been illustrated in Fig. 3. A mesh has been represented in the simulation (Fig. 10) which falls within the same simulation domain used in the previous cases.

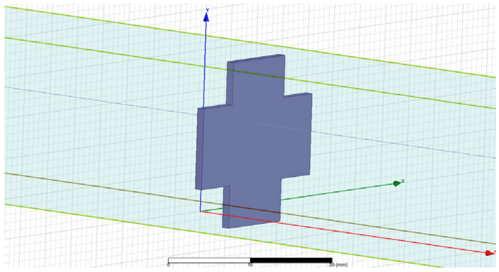

Fig. 10. The geometric pattern of the graphite mesh

The simulation results, shown in Fig. 11, indicate a maximum electric field level after the screen of E_2 = 10.3 V/m and also a good degree of shielding effectiveness of about 42.1 dB.

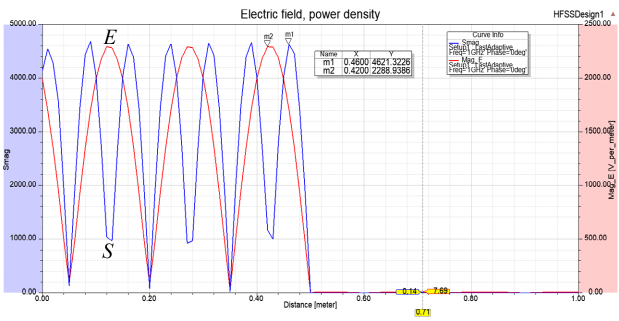

Fig. 11. Power density *S* (blue line) and electric field strength *E* (red line) on the central longitudinal axis – in the presence of a graphite strip grid shield

Experimental determination of shielding effectiveness. The experimental determination was carried out in two steps performed in two different EMC laboratories. Although the experimental investigation covered a wide band of frequencies, for the purpose of comparison with the numerical method only the SE values for the 1 GHz frequency will be presented.

In the first experimental stage, a double TEM (DTEM) cell from TESEO was used. A DTEM cell consists of two cells that provide a good approximation of the far field propagation and which are coupled through a rectangular aperture. The DTEM cell has two of its ports connected to a Rohde & Schwarz FSH3 spectrum analyzer with tracking generator. The textile shield was placed inside the DTEM cell, covering the common aperture between the two parts. The other two ports of the DTEM cell there were connected 50 Ω impedances. The input port was fed from the spectrum analyzer with signals in the 500 MHz – 1 GHz frequency range, and the transmitted signal was received at the output port of the cell into the spectrum analyzer. The measurement setup described above is illustrated in Fig. 12. This experimental stage was focused on the textile shield.

Fig. 12. The experimental setup used in stage 1

Second stage of the experimental investigation of the shielding effectiveness was based on the use of a steel box in a cubic shape with the side of 60 cm. The shield partly replaced one box side – as it can be noticed in Fig. 13. The measurements were performed in a different EMC laboratory and investigated both the textile material and graphite strips screen. The measurement setup drawn in Fig. 14 consisted in placing the transmitting (Tx) antenna outside the steel box and the receiving (Rx) antenna inside it, along with a Signal Hound BB60C SDR receiver, a personal computer (PC), and a media converter (MC). The MC was connected through optical fiber to another PC, and the Tx antenna was fed by a Rohde & Schwarz SMP04 signal generator. Both Tx and Rx antenna were Rohde & Schwarz HF906 horn type and were placed so as to have horizontal polarization.

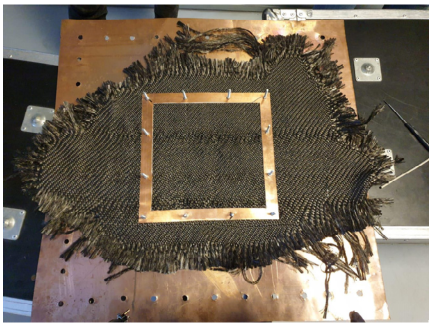

Fig. 13. Shield installation on one side of the steel box

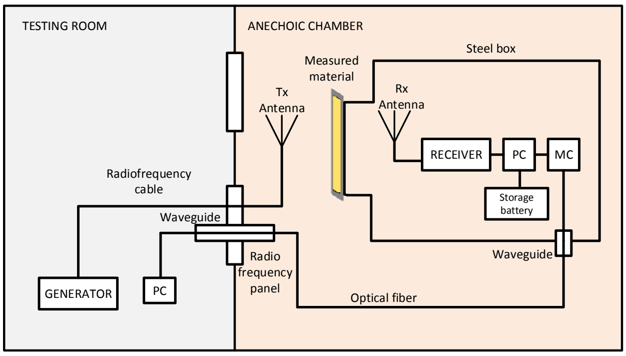

Fig. 14. The experimental setup used in stage 2

Shielding effectiveness results. In order to compare the simulation and experimental results, the SE values for the test frequency of 1 GHz are presented in Table 2.

Table 2

Values obtained for the shielding effectiveness of the three sample screens, at a test frequency of 1 GHz

Shield pattern	Simulation results	Experimental results	
		Stage 1	Stage 2
Twill weave	86.8 dB	57 dB	54.8 dB
Graphite plate	92.8 dB	–	–
Graphite strip network	42.1 dB	–	6.5 dB

Results discussion. Significant differences are observed between the simulation results and the experimental results. Among the three sample shields, the graphite plate was investigated only through simulation, but its shielding performance proved to be superior to the other ones, although closely followed by the carbon-based fabric. The superiority of the graphite plate is obvious due to the fact that there are no holes or apertures in the shield structure. Since the twill sample was the focus of the investigation, it was analyzed through both simulation and experiment – in both EMC laboratories. As it can be seen in Table 2, there is a slight difference between the SE results obtained through different methods. Although a 30 dB difference is noted when compared to the simulation results. A similar 35 dB difference between simulation and experiment is also obtained for the graphite strips shield. This difference could be explained by the virtual model construction, which does not include imperfections in electrical contact between strips and has a constant thickness on the entire surface of the screen.

Conclusions.

1. There is analyzed the shielding performance at 1 GHz of three types of carbon-based screens: a graphite plate, a network of orthogonal graphite powder strips, and a twill woven graphite-impregnated fabric. All screens were investigated by simulation means, following an approach similar to the experimental procedure. The second and third screens were investigated experimentally.

2. From the virtual analysis, the graphite plate shield was the most efficient, followed closely by the twill fabric. The graphite strip network had the poorest performance, 45-50 dB lower than the other shields, probably due to electrical contact imperfections between graphite strips and the shield optical transparency.

3. The main focus of the analysis was the twill woven graphite-impregnated fabric; therefore, its shielding effectiveness (SE) was determined through simulation and experiment – by employing the DTEM cell and the shielded box method. The experimental results of the two stages were similar: SE = 57 dB from the former and SE = 54.8 dB from the latter, respectively.

4. A significant difference yielded from the comparison of the simulation and experimental results for the SE. This is probably due to the fact that the virtual model is an idealized version of the physical one, not taking into account its imperfections.

5. Both from the simulation and experimental stages, the efficiency of the graphite-based twill fabric proved to be at least at a good level, with SE ≈ 55 dB.

6. Graphite has considerable advantages over other materials currently used due to its properties: high electrical conductivity, lower mass density than metals, corrosion resistance in hostile environments, mechanical flexibility, easy processing. Compact graphite structures have higher attenuation than other structures due to their low transparency to the electromagnetic field.

7. Properties related to the electromagnetic field absorption and the mechanical properties recommend the use of graphite fabric for protective clothing and electromagnetic security. The protective clothing has variable and dynamic geometric structure, and such qualities are provided by the carbon fiber fabric.

8. A further research direction consists in manufacturing a twill woven protective suit and investigating its shielding properties in terms of specific absorption rate reduction.

Conflict of interest. The authors declare that they have no conflicts of interest.

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