

# MULTIFUNCTIONAL SANDWICH STRUCTURE FOR ELECTROMAGNETIC ABSORPTION AND MECHANICAL PERFORMANCES

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## Abstract

*A sandwich panel based on a multiscale architected material is developed for structural and EM absorption performances. At the nanoscale level, carbon nanotubes are dispersed in a polymer to obtain a conductive material. This composite is then foamed into a micro porous solid to improve EM absorption and to decrease the density. The foam is inserted in a millimeter scale hexagonal metallic honeycomb lattice. The combination of the metallic honeycomb and the polymeric foam provides high bending, impact and crushing performances and a moderate thermal conductivity. This hybrid is used as core for sandwich panels, produced by the addition of two EM transparent face-sheets made of glass fiber reinforced polymers. EM absorption around 90% is achieved in the 10-40 GHz frequency band with a 8.8 mm thick sandwich panel.*

## 1. Introduction

Electromagnetic (EM) interferences are ubiquitous in modern technologies with an impact on the reliability of electronic devices and on living cells. Shielding by EM absorption, which is, in some circumstances, preferable over reflection, is attained by simultaneously minimizing the reflection and transmission. In the gigahertz range, this requires combining a low dielectric constant with an electrical conductivity around 1 S/m which are antagonist properties in the world of materials. For some transport applications, the need for EM shielding goes along with structural performances and lightness.

A multimaterial has been developed based on new multiscale architected material concept with optimized mechanical and EM absorption performances. The strategy starts at the nano-scale, by the use of a CNT reinforced polymer leading to an increase of the conductivity in

the range 1 S/m with 1 to 2% of fillers. However, the dielectric constant is also increased by the fillers which results in a higher reflectivity. Foaming the nanocomposite polymer into a microscale porous structure reduces the permittivity. The foam is inserted in a millimeter scale metallic honeycomb lattice, which acts as an hexagonal waveguide. The absorption of incoming EM waves with frequencies above the waveguide cut-off frequency is improved for the resulting hybrid material compared to the composite foam alone. But waves with frequencies below the cut-off frequency are reflected. In addition, the combination of the metallic honeycomb and the polymeric foam provides high crushing performance. Indeed, the presence of the foam positively impacts the energy dissipation of Al honeycomb faces by enforcing shorter wavelength buckling modes. At the centimeter scale, the hybrid is used as the core of a sandwich panel, obtained by the addition of two EM transparent face-sheets made of glass fibers reinforced polymers. A careful selection of the face-sheets preserves and can even improve the absorption of the hybrid in a specific frequency range.

The sandwich offers high bending stiffness versus density performance as well. Compared to a foam core, the hybrid core reduces the transverse shear deflection thanks to the presence of the honeycomb. Also, the large surface area offered by the foam filling the honeycomb cells facilitates the bonding of the faces and prevents the delamination of the core. The analysis of the experimental data is supported by finite element simulations which are also used to guide the multiproperty optimization.

This designed structure constitutes a new class of sandwich panels combining high EM absorption with mass efficiency, stiffness, impact resistance and thermal management.

## **2. Manufacturing of the sandwich panels**

The manufacturing process of the core is divided in two steps. In a first step, 1wt% multiwalled carbon nanotubes (CNT) (Nanocyl NC 7000, 90%) and 7.5wt% chemical foaming agent (CFA) (Hydrocerol HK40B, Clariant) are dispersed in polycarbonate (PC Makrolon 2805, Bayer) using a corotating twin-screw minicompounder (DSM Xplore Microcompounder 15cm<sup>3</sup>) with a bypass allowing continuous recycling of the material at the head of the mixing chamber. The temperature is set at 270°C and the compounds are mixed for 3 min at 100rpm. The composite is then foamed inside the honeycomb. To achieve this, a nanocomposite powder is poured in the honeycomb cells, which is itself inserted in a mold inside a 15 tons hot press. The amount of powder is calculated to reach a foam density of 0.5g/cm<sup>3</sup> each time. In situ foaming is performed for 2 min at 280°C, above the decomposition temperature of the foaming agent (> 230°C). Honeycombs (CRIII-3/8-5052-.004-5. 4, HexWeb, Hexcel), made of 100-μm-thick aluminum (5052) sheets forming 5.5 mm-sided (instead of 4.76 mm as nominal value in datasheet) hexagons are used.

The face sheets used for the sandwich are 0.3 mm, 0.5 mm and 1 mm thick glass fiber reinforced E-glass/Epoxy composite panel (SI403240, Goodfellow). Bi-components epoxy glue (3M™ DP 460) mix with glass beads of 0.2 mm diameter is used to bond the face sheet and the core (here honeycomb filled with nanocomposite). The thickness of the glue is equal to 0.2 mm.

### 3. EM performance

The main functionality of the material is the ability to absorb electromagnetic radiation. In order to measure the level of absorption, a Vector Network Analyzer (VNA) Model Wiltron (Anritsu) 360, covering the 40MHz - 40GHz frequency range is used. The four scattering parameters ( $S_{11}$ ,  $S_{21}$ ,  $S_{12}$ ,  $S_{22}$ ) of the hybrid and sandwich panels were measured by inserting the sample between a coaxial-to-waveguide transitions. The extracted S parameters were de-embedded to take in account the loss in the measurement set-up [1].

The absorption index  $A$  is the ratio between the absorbed power  $P_{abs}$  and the incident power  $P_{in}$ :

$$A = \frac{P_{abs}}{P_{in}} = 1 - \frac{P_{ref}}{P_{in}} - \frac{P_{tr}}{P_{in}} = 1 - |S_{11}|^2 - |S_{21}|^2. \quad (1)$$

Equation (1) shows that to maximize the absorption,  $A$ , both the reflection and the transmission of the panel have to be kept close to zero. Equation (1) also provides the relationship between the reflected power  $P_{ref}$ , the transmitted power  $P_{tr}$  and the S parameters  $S_{11}$ ,  $S_{22}$ , respectively.

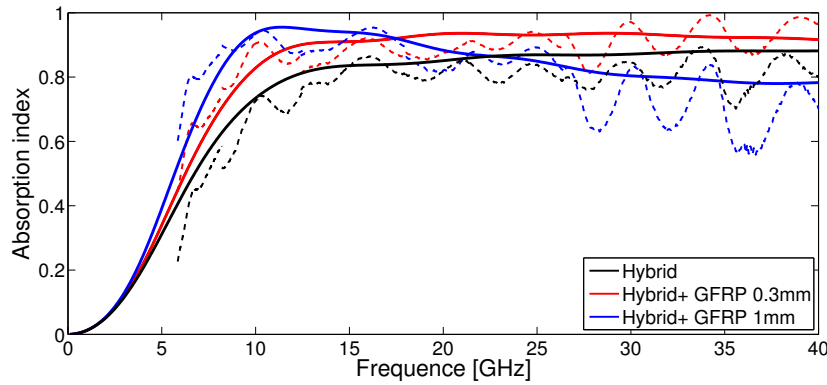
An analytical model of the absorption of the hybrid panel has already been developed in earlier studies [2]. In this model, the metallic honeycomb is associated to an hexagonal waveguide with an effective complex permittivity expressed as:

$$\varepsilon_{effw} = \varepsilon_{r,foam} - \frac{5}{4} \left( \frac{\pi}{X} \right)^2 \left( \frac{c_0}{\omega} \right)^2 - j \frac{\sigma_{foam}}{\omega \varepsilon_0}. \quad (2)$$

where  $\varepsilon_{r,foam}$  is the dielectric constant of the filler (here nanocomposite foam),  $X$  the length of the cell wall,  $\omega = 2\pi f$ ,  $f$  is the frequency,  $c_0$  is the speed of light and  $\varepsilon_0$  the dielectric constant of the vacuum. In the following, only the dominant transverse electric  $TE_{10}$  mode of propagation will be considered. A closer look to equation (2) indicates the existence of a cutoff frequency where  $\Re(\varepsilon_{effw})$  is equal to zero. At lower frequencies,  $\Re(\varepsilon_{effw})$  is negative which implies a high reflection of the incident waves. On the contrary, at higher frequencies,  $\Re(\varepsilon_{effw})$  is always smaller than  $\varepsilon_{r,foam}$  which means a lower reflectivity for the hybrid compared to the foam alone.

In order to compute the absorption index of the sandwich panel with an hybrid core, one can use the product of chain matrix for a multilayer of dielectric material [3] based on equation (2) applied to the core [4]. Figure 1 shows the experimental and predicted absorption level of panels made of 7 mm thick hybrid core in black, sandwich with this hybrid as core and with a 0.3 mm thick GFRP skin in red and with 1 mm GFRP skin in blue. The complex permittivity used for the analytical calculation of the sandwich panel absorption was determined by experimental measurement. For the hybrid sample,  $\varepsilon_{r,foam}$  is equal to 3.5 and  $\sigma_{foam}$  is a linear fit of the measurement, 2 S/m at 10 GHz and 3.5 S/m at 40 GHz. In this experiment, the cutoff frequency of the core (hybrid) is around 10 GHz with a rapid decrease of the absorption at lower frequency. Adding the glass fiber reinforced polymer skin improves  $A$  above the cutoff frequency compared to the hybrid alone. The improvement is high over a narrow band or smaller but over a broader band for thick and thin face sheet, respectively.

The difference between the theory and experiment can be due to some variability in the size and regularity of the hexagons. Also, even if the global density is kept equal between sample, the density of the foam from cell to cell may slightly vary, inducing different local dielectric constant and electrical conductivity.



**Figure 1.** Variation of the measured (dashed lines) and predicted (solid lines) absorption index as a function of the frequency for panels made of 7mm thick hybrid core (black), and of a 0.3mm (red) or 1mm (blue) GFRP skin.

## 4. Structural performances

### 4.1. Flexural rigidity

A series of four points bending test has been performed with a mechanical testing machine ZWICK 250kN on the sandwich beams in order to determine the flexural rigidity. The displacement at the center of the beam,  $\delta$ , is measured with an extensometer. The length of the beam is 150 mm and the width is around 25 mm for the foam and 45 mm for the hybrid core (equal to 5 hexagonal cell). The span lengths for the testing setup are 50 mm for the shorter,  $l$ , and 100 mm or 120 mm for the longer,  $L$ . By assuming the sandwich panel to an homogeneous beam and neglecting the displacement due to transverse shear load, the equivalent flexural modulus,  $E_{eq}$ , is extracted from [5]:

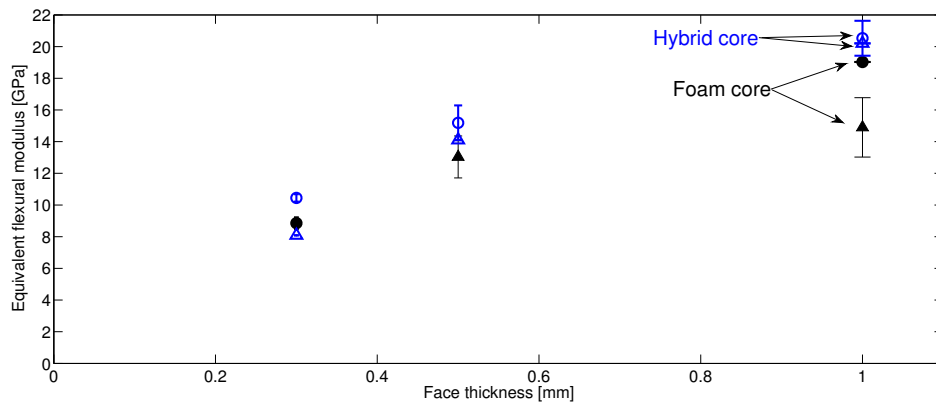
$$\frac{\partial \delta}{\partial F} = S = \frac{(L - l)(2L^2 + 2Ll - l^2)}{48} \frac{1}{E_{eq}I} \quad (3)$$

with  $I$  equal to the second moment of area.  $S$  is calculated with a linear fit of the force-deflection curve between 0.65 mm and 1 mm.

Figure 2 shows the equivalent flexural modulus in function of the face thickness for test carried with a span length of 100 mm (triangle dot) or 120 mm (circular dot). As expected, using an hybrid core over a foam core improves the rigidity of the panel. This increase can be attributed to an higher shear modulus of the core. Indeed, most of the time in sandwich panel, the flexural load is carried by the faces whereas the transverse shear load is carried by the core.

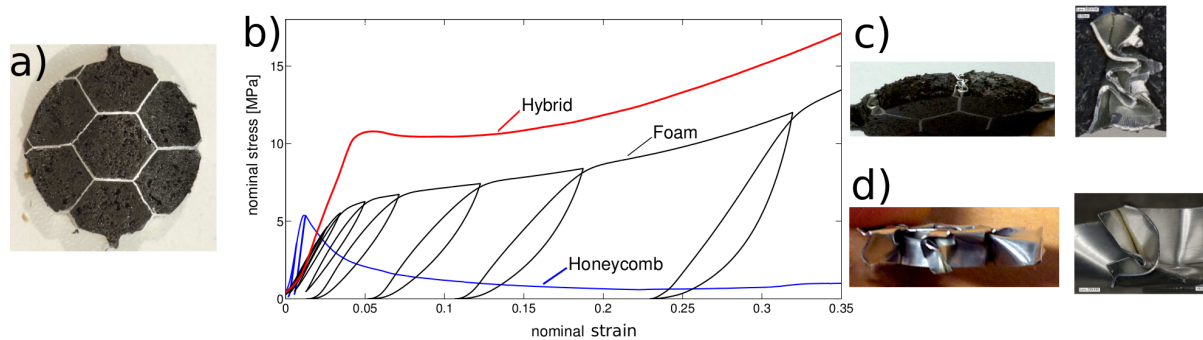
### 4.2. Compression

The combination of the foam and honeycomb provides high crushing resistance. The hybrid, the foam and the honeycomb without the glass fiber reinforced polymer faces have been tested in compression, with a mechanical testing machine ZWICK 250kN. All samples have a diameter equal to 24 mm. The initial height of the hybrid is 6 mm height (Fig. 3.a), the foam 7.64mm and the honeycomb 7mm. A precharge of 200N is applied before testing. Figure 3 shows the corresponding engineering stress-strain curves. Loading/unloading cycles are applied while



**Figure 2.** Equivalent flexural modulus in function of the face thickness for a span length of 100 mm (triangle dot) or 120 mm (circular dot).

deforming the honeycomb and the foam. The hybrid shows a higher crushing resistance equal to 10.8 MPa compare to the foam (6 Mpa) or HC (5.5 MPa). Even after the buckling of the honeycomb side in the hybrid, the crushing strength is 3 to 4 MPa above the one of the foam. Postmortem analysis (Fig 3.c and d) shows a buckling mode with smaller wavelength in the hybrid compared to the HC alone, in agreement with [6].



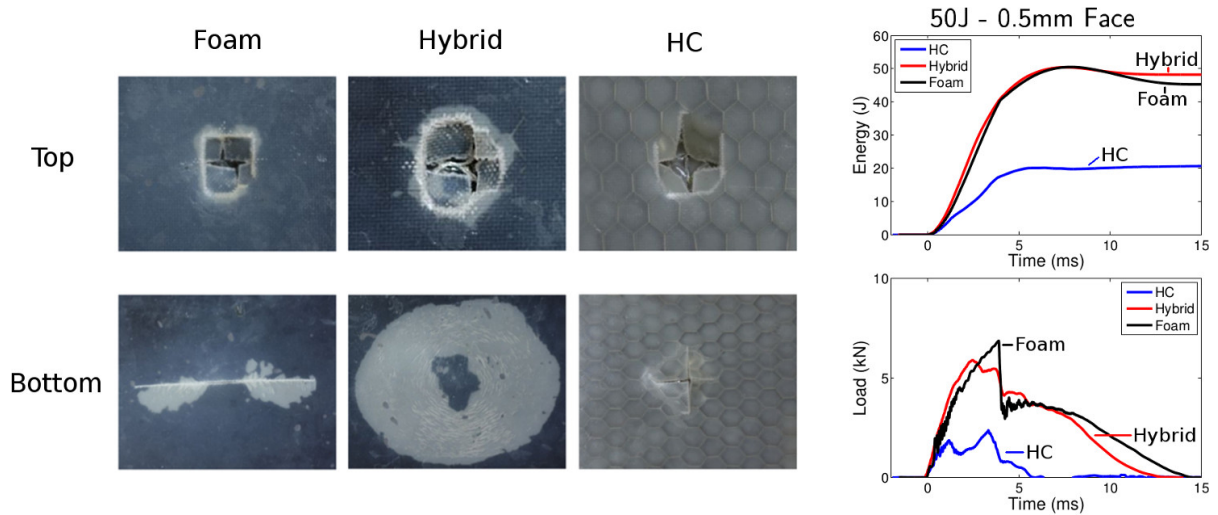
**Figure 3.** a) hybrid sample, b) engineering stress-strain curve, c) lateral view of the hybrid after the compression  $\varepsilon = 0.61$ , d) lateral view of the honeycomb after the compression,  $\varepsilon = 0.48$

This exhibits a true effect where the small increase in density associated to the HC is more than compensated by the increase in compression strength.

#### 4.3. Impact

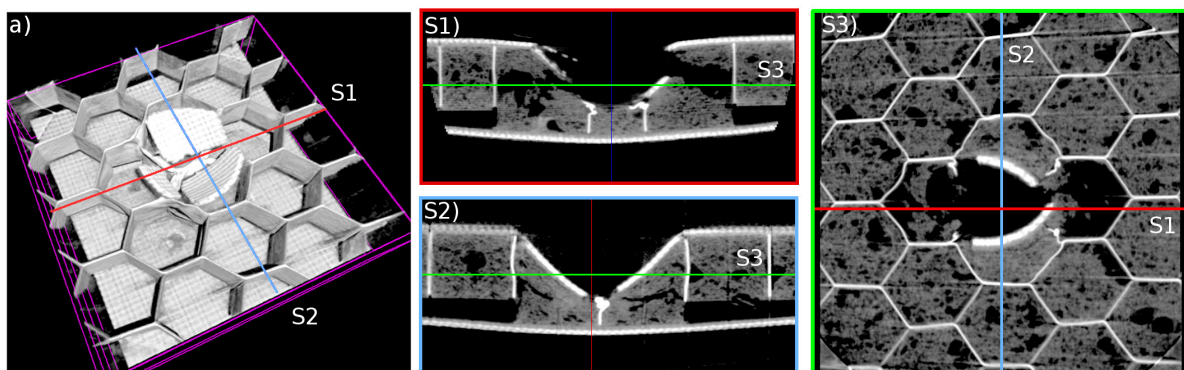
Three sandwich panels with 0.5 mm thick face but involving different 7mm thick cores, have been impacted at 50 J with a low speed impactor (Instron dynatup 9250HV machine). The diameter of the steel impactor is equal to 12 mm. The top and bottom faces of the impacted panel can be seen on the left part of Figure 4 whereas the absorbed kinetic energy and the force seen by the impactor is plotted on the right hand side as a function of time.

Only the foam core and hybrid core allow absorbing the impact. The load-time curve gives more insight about the behavior of the panels. The top face of the sandwich with the honey-



**Figure 4.** Low speed impact of 50J on sandwich panel made of 0.5mm GFRP faces sheets and 7mm thick core. The left hand side correspond to picture of impacted sandwich, 1st row is a zoom in of the top face and the 2th row shows the bottom face. The right hand side corresponds to the graphs representing the variation of the absorbed energy and of the force on the indent as a function of time.

comb core, has been penetrated at a load of 3kN quickly followed by the bottom face. The honeycomb has opposed little resistance to the impactor. The damaged zone is barely larger than the impact tip diameter. With the foam core, the panel fails at a load of 7 kN, at this load, a crack has propagated through the core and the faces. After the first failure, some delamination and/or crack propagation occur. The final crack at the back is equal to 85 mm. The analysis of the hybrid panel is more complicated due to a combination of several failure modes. A 3D tomography image of the impacted zone obtained with a Tomohawk system, see figure 5, shows that the foam in the cell under the impactor has been pushed out leading to a wide debonding of the bottom face. Moreover, the cross section views Fig.5.S1 and 5.S2 show the multiple folds of the honeycomb and the tearing of the foam in the cell under the impactor head. These two mechanisms dissipate a lot of energy and keep the damage in the honeycomb localized, see the 3D view Fig.5.a.



**Figure 5.** CT scan of the sandwich panel made of 0.5mm GFRP faces sheets and 7mm thick hybrid core impacted at 50J: a) 3D view of the bottom half of the sandwich (foam is not shown), S1) vertical cross section, S2) vertical cross section, S3) horizontal cross section

## 5. Conclusion

A combination of structural and electromagnetic functions has been achieved thanks to a multiscale multimaterial approach. Using a polycarbonate/carbon nanotubes foam as core of a sandwich panel made of EM transparent faces results in a light and stiff panel with a high EM absorption capacity. Despite the small increase in weight, experiment and model have shown that filling a metallic honeycomb with this foam is well rewarded in terms of structural rigidity and strength but also in terms of EM absorption in a selected range of frequencies. Indeed the honeycomb acts like a waveguide with an effective dielectric constant lower than the filling material above the cutoff frequency but with a total reflection below this cutoff. Moreover, the transparent face sheet of the sandwich also boosts the absorption in a range of frequencies which is smaller if the face is thicker. Four point bending test highlight the increase in shear stiffness induced by the presence of the honeycomb. In case of crushing, the honeycomb also has a positive role. The presence of the honeycomb increases the energy needed to crush the core, and the presence of the foam leads to a small wavelength buckling mode in the honeycomb wall, by increasing even more the energy needed to crush the core. If the panel is subject to impact, the hybrid core prevents the crack of the back face at the cost of a wider debonding area.

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