Modeling and experimental analysis of polypropylene honeycomb multi-layer sandwich composites under four-point bending

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Abstract

The behavior of a simple and innovative multi-layer sandwich panels having a polypropylene honeycomb core has been investigated carefully, theoretically and experimentally. A four-point bending test was performed to detect the mechanical characteristics of the multi-layer core. The experimental results emphasize a better rigidity of the multi-layer structure compared to the weakness displayed by the single-layer configuration. In fact, a small increase in the final weight of the component leads to a significant increase of the mechanical properties. In the second part of this study, analytical and numerical homogenization approaches were developed to compute the effective properties of the single polypropylene honeycomb core. The numerical model complies with the experimental protocol, and the simulation conducted is aiming to reproduce a typical four-point bending test on a polypropylene honeycomb multi-layer sandwich panel. Both numerical and experimental results are presented in details and a good correlation between them is highlighted.

Keywords

Composite, honeycomb, multi-layer, sandwich, bending, modeling

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Introduction

Sandwich composite structures should be considered a special class of composite materials due to their performance in terms of very high strength capabilities and relevant bending stiffness allowance. The low density of these materials makes them especially suitable for use in the aeronautical industry, in space and in marine applications [1–3]. Sandwich panels are composite structural elements, consisting of two thin, stiff, strong faces separated by a relatively thick layer of low-density stiff material. The faces are commonly made of steel, aluminium, composite and the core material may be foam, honeycomb or balsa wood. The faces and the core material are bonded together with an adhesive to facilitate the load transfer between the components. This particular coated composition creates a structural element with a very good balance between high bending stiffness—weight and bending strength—weight ratios. The general concept of classic sandwich structures and analytical methods has been investigated and developed by many researchers over the past 50 years; see for example Zenkert [4], Allen [5] and Gay et al. [6]. Gibson and Ashby [7] studied the in-plane stiffness of honeycomb cores according to the bending model of cell edges. Masters and Evans [8] developed a theoretical model to predict the in-plane elastic stiffness of honeycomb cores based on the particular approach of deformation of honeycomb cells. Becker [9] studied the effective in-plane stiffness of honeycomb cores and the thickness effect using the closed-form description. Meraghni et al. [10] presented a new analytical method to analyze the out-of-plane stiffness of honeycomb cores based on the modified laminate theory. Concerning the modeling of the sandwich composites, a complete review of the various kinematics and theories can be found in the work of Hu et al. [11]. Rao and Manujesh [12] have studied the effect of the core density of a foam cored sandwich beams by using a flexural strength routine for specific cases. They demonstrated the possibility to improve the flexural strength of the compound by using the high-density foam cores for sandwich structures. It is obvious that when the mechanical properties are modified, even for a single-core material, the flexural strength of the sandwich beam can be changed to a very large extent with only a little weight.

In recent years, researchers have increased their interest in studying the mechanical response of the multi-layer sandwich panels. Harisha and Biradar [13] have developed different models to predict the response of composite sandwich as well as single- and multi-layer under static bending conditions. Arbaoui et al. [14–16] have studied the mechanical behavior of sandwich beams, having a honeycomb multi-layer core using three- and four-point bending. After testing it, they observed a positive influence of the multi-layer configuration over the final mechanical properties. Salami and colleagues [17,18] investigated the effect of adding an extra layer within a sandwich panel while putting the core-types in top and bottom cores, the research carried out by using a quasi-static loading condition and on a low-velocity impact response. They discovered that the core material type has had a significant role in improving the sandwich panel's behavior compared with the effect of the extra layer location. Aqhil et al. [19] studied numerically by Finite Element Method (FEM)/ANSYS software, the flexural behavior of multi-layer PUF cored sandwich beam under three-point bending procedure. The results show a positive influence of the multi-core over the performance of the specific parameters such as face sheet stress (σ_f), core shear (τ) and beam deflection (y), indicating a better performance compared to single-layer core. Dongmei [20] studied the compressive behavior of multi-layer corrugated sandwich structures experimentally and concluded that compressive resistances were similar for the same type of corrugated sandwich structures with different layers; the energy absorption of the multi-layer corrugated sandwich structures can be significantly greater than the monolayer one and had compression resistance capability for repetitions shock. Lakreb et al. [21] studied the influence of the number of layers on the mechanical behavior of the sandwich panels. Ali et al. [22] have studied the behavior of multi-layer composite structures under dynamic loading.

It is clear from the above reviews and studies that the flexural behavior of sandwich structures can be improved considerably by modifying the core properties. In the present study, the author introduced an innovative idea to obtain a step-change component with better mechanical properties of composite structures, the single-layer core being replaced by a multi-layer core of different thickness. The sandwich structures used in the present work are formed as a result of adhering two high-stiffness glass/polyester thin face sheets with a low-density polypropylene honeycomb core characterized by less strength and stiffness.

In this paper, we present the experimental results from the three series of the multi-layer sandwich panels having different configuration. An analytical and numerical homogenization approach was implemented to determine with accuracy the effective properties of polypropylene honeycomb. The numerical simulations were developed using two commercial finite element software ANSYS and Castem 2000.

Experimental procedure

Material and specimens

The multi-layer sandwich panels samples used in our experiment were manufactured for building applications. The materials of the skins and the intermediate layers consist of fiberglass woven roving mat 0°/90° and fiberglass mat, respectively, being reinforced by polyester resin matrix composite laminate. The ply sequence and the thickness of the top and bottom face sheets are the same but have different specifications from the intermediate sheet. The mechanical properties of composite laminated sheets are summarized in Tables 1 and 2. Polypropylene-based core material includes a hexagonal cell configuration with

Table 1. Mechanical properties of the intermediate layer.

Mechanical properties	Values
Young's modulus (MPa)	5500
Tensile strength (MPa)	200
Shear modulus (MPa)	2115
Face thickness (mm)	0.05

Table 2. Material properties of the skin.

E_1 (MPa)	E_2 (MPa)	E_3 (MPa)	ν_{11}	ν_{23}	ν_{13}	G_{12} (MPa)	G_{13} (MPa)	G_{23} (MPa)
9135	9135	4000	0.2	0.3	0.3	1616	1769	1769

an average cell size of 8 mm (Figure 1) provided by P.A Technology. Five different core thicknesses (5, 10, 15, 20 and 40 mm) were used in the fabrication of the three series of the multi-layer composite sandwich panels:

1. **Series of 10 mm**
   - M10 represents a stacking of a single honeycomb of 10 mm;
   - M5:5 represents a stack of two layers of honeycomb with 5 mm each.
2. **Series of 20 mm**
   - M20 represents a stacking of a single honeycomb of 20 mm;
   - M10:10 represents a stack of two layers of honeycomb with 10 mm each;
   - M5:10:5 represents a stack of three layers of honeycomb; two layers with 5 mm and one of 10 mm positioned in the middle;
   - M5:5:5:5 represents a stack of four layers of honeycomb with 5 mm each.
3. **Series of 40 mm**
   - M40 represents a stacking of a single honeycomb of 40 mm;
   - M20:20 represents a stack of two layers of honeycomb with 20 mm each;
   - M15:10:15 represents a stack of three layers of honeycomb; two layers with 15 mm and one of 10 mm positioned in the middle;
   - M10:10:10:10 represents a stack of four layers of honeycomb with 10 mm each.

The mechanical properties of polypropylene honeycomb which were used in four-point bending test are shown in Table 3. The specimen's shape of the multi-layer sandwich is presented in Figure 2.

Figure 1. Polypropylene honeycomb.

Table 3. Mechanical properties of a polypropylene honeycomb core.

Mechanical properties	Values
Density (kg/m^3)	80
Compressive strength (MPa)	1.3
Shear strength (MPa)	0.5
Elastic modulus (MPa)	15
Shear modulus (MPa)	8

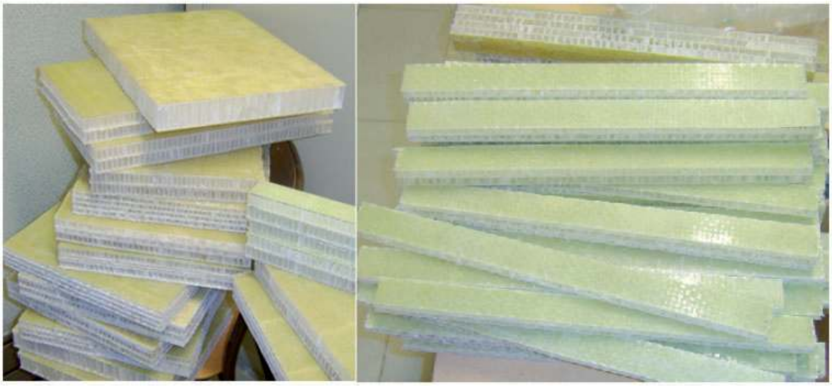

Figure 2. Multi-layer sandwich panels.

Four-point bending test

The bending strength and the stiffness of multi-layer sandwich panels were detected using a standard four-point bending test cited in the literature. The different types

Table 4. Specimen dimensions of the three series of 10, 20 and 40 mm.

Series	Specimen	Width, *b* (mm)	Height, *h* (mm)	Core thickness, t_c (mm)	Skin thickness, t_f (mm)	Length, *l* (mm)
10	M10	35	12	10	1	440
	M5:5	35	12.05	10.05	1	440
20	M20	35	22	20	1	440
	M10:10	35	22.05	20.05	1	440
	M5:10:5	35	22.1	20.1	1	440
	M5:5:5:5	35	22.15	20.15	1	440
40	M40	35	42	40	1	440
	M20:20	35	42.05	40.05	1	440
	M15:10:15	35	42.1	40.1	1	440
	M10:10:10:10	35	42.15	40.15	1	440

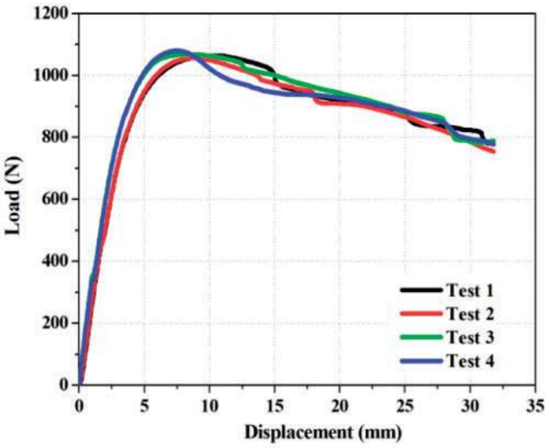

Figure 3. Test reproducibility.

of sandwich composite panels are tested in four-point bending conditions according NFT54-606 norm. A particular device, especially designed for such tests, was connected to a servo-hydraulic universal testing machine INSTRON 4302 controlled by an INSTRON electronic unit. To check the reproducibility of the results, four beams per composite type were tested. The crosshead displacement rate was settled at 3 mm/min. The sample dimensions are presented in Table 4.

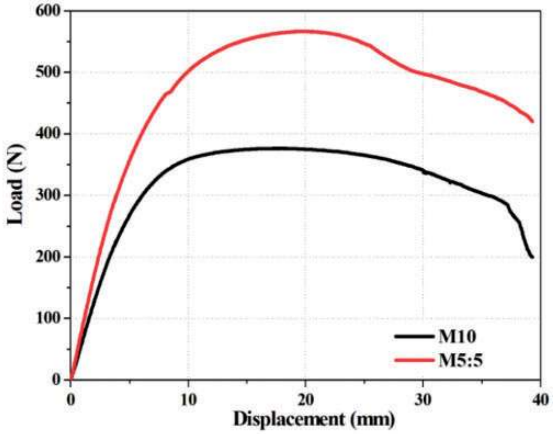

Figure 4. Typical load–displacement curves for series of 10 of the sandwich multi-layers.

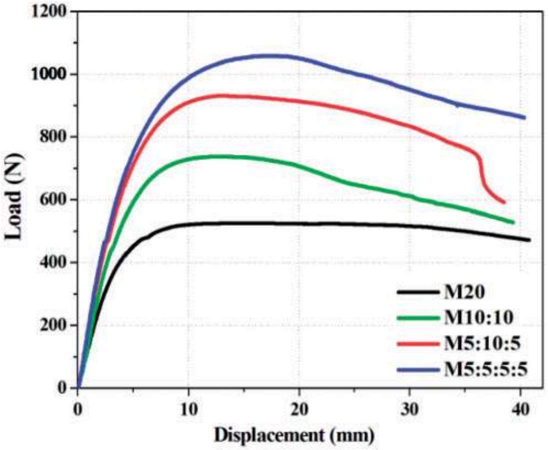

Figure 5. Typical load–displacement curves for series of 20 of the sandwich multi-layers.

Results and discussion

In a preliminary stage in order to ensure the accuracy of the results, a minimum of four tests were carried out in order to analyze the tests reproducibility. Figure 3 confirms a good repeatability of the applied routine. This testing protocol was implemented for each test. Figures 4–6 depict the load–displacement curve of multi-layer honeycomb composite structures solicited in four-point bending for three series of 10, 20 and 40 mm, respectively. The bending behavior presents similar trend and can be described in three principal phases: the first phase is an initial linear elastic behavior followed by a phase of nonlinear one in which the maximum

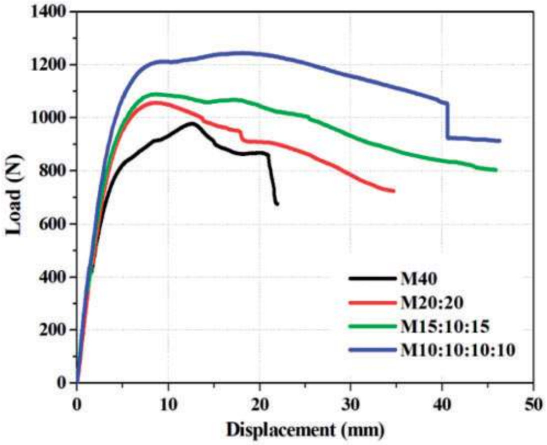

Figure 6. Typical load–displacement curves for series of 40 of the sandwich multi-layers.

Table 5. Mechanical properties of the multi-layer sandwich structures.

Series	Specimen	Maximum load (N)	Facing stress (MPa)	Core shear stress (MPa)	Flexural rigidity (N.mm^2)
10	M10	378	88	0.50	451.89 10^5
	M5:5	567	132	0.70	619.65 10^5
20	M20	520	64	0.36	947.70 10^5
	M10:10	736	90	0.50	991.41 10^5
	M5:10:5	931	113	0.63	1151.82 10^5
	M5:5:5:5	1065	129	0.72	1406.97 10^5
40	M40	980	61	0.34	2150.55 10^5
	M20:20	1060	66	0.36	2114.10 10^5
	M15:10:15	1090	68	0.38	2354.67 10^5
	M10:10:10:10	1248	78	0.43	2332.80 10^5

loading is reached. In the last phase, a reduction in the load applied can be observed until the total rupture of the sample occurs. The linear behavior corresponds to the work of the skins in traction and compression, whereas the nonlinear behavior mainly depends on the core properties under the effect of the shear stress. These figures show also an increase of the maximum load and bending stiffness with increased number of layers from single to double for series of 10; and from single to quadruple of 20 and 40 series. From these figures, the facing stress, core shear stress and bending stiffness have been obtained and listed in Table 5.

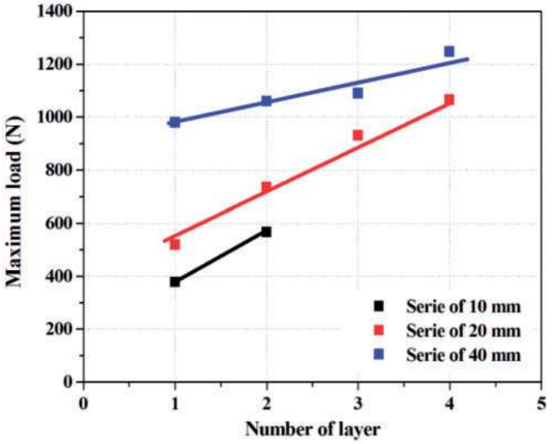

Figure 7. Maximum load versus number of layers of the sandwich multi-layers.

It may be relevant to note the increase of the facing stress, core shear stress and bending stiffness by about 50%, 51% and 33% for series of 20 and about 33%, 29% and 27% for series of 40, respectively, as the layers number increases from single to quadruple layers. When the number of the layers is increasing from single to double layers for series of 10, it has been observed an increase in the mechanical properties by about 33%, 29% and 27%, respectively. Figure 7 shows the maximum load/number of layer for three series of the multi-layer honeycomb composite structures. It is found that the higher is the thickness of the core and that the maximum load achieved is higher. A linear computation of the maximum load as a function of the number of layers was made. A correlation of the coefficients was established as well as $R^2 = 1$, 0.99 and 0.96, which confirm that the maximum load varies linearly with the number of layers of the series of 10, 20 and 40, respectively. The relations are

$$P_{\max} = 189 + 189\,\text{N} \quad (\text{series of } 10\,\text{mm})$$

$$P_{\max} = 355 + 183\,\text{N} \quad (\text{series of } 20\,\text{mm})$$

$$P_{\max} = 886 + 83\,\text{N} \quad (\text{series of } 40\,\text{mm})$$

The advantage of the multi-layer is that, for a given w deflection, the applied load P increases with the number of layers of the core. Thus, a sandwich structure with a double-layered core (M10:10 for example) can support a 30% higher load compared to a structure with a single core (20 mm). This technique of assembly allows reducing the thickness of the composite structures of a factor 2 while preserving an identical mass. For example, one configuration has a 5-kg/m^2 mass for a quadruple-layered structure of 20 mm whereas the mass of a single structure of 40 mm is 5.2 kg/m^2.

Mechanical properties of honeycomb core materials

The numerical simulation performed under the four-point bending of multi-layer sandwich structures were conducted as well. In this case, an analytical and numerical homogenization was carried out to determine the effective properties of polypropylene honeycomb, by using

- Analytical modeling based on Gibson and Ashby model;
- Numerical modeling with finite element based on ANSYS software.

By comparing the results obtained from these two methods, we can approximate the physical constants of the honeycomb.

Analytical approach

The development of constitutive material models for honeycomb materials is complicated due to highly anisotropic properties of the material. A computational efficient modeling method and the constitutive laws are required to reduce time and while being accurate enough to realistically represent the overall structural behavior. The analytical expressions used to determine the effective elastic properties of the cellular hexagonal honeycomb core are based on the works of Gibson and Ashby [7].

Numerical approach

The orthotropic properties of honeycomb core were determined through the numerical homogenization process applied to a representative volume element (RVE). Corroboration by an analytical modeling was performed then to prove the accuracy in the computation. The RVE (Figure 8) consists of 40 cells meshed with plate finite elements with four nodes and six degrees of freedom per node. Every foil contains 12 elements: 4 according to height and 3 to length. To estimate the various elastic moduli, a displacement was imposed on the face of the RVE in a given direction while the opposite face was fixed. The symmetry conditions were taken into account by using appropriate boundary conditions. In Figure 8, l_x, l_y and l_z are the lengths of the RVE, where $l_x = 64.7$ mm, $l_y = 36$ mm and $l_z = 10$ mm. The mechanical properties of the honeycomb are related to its geometrical characteristics which are $l = h = 4.6188$ mm, $t = 0.24$ mm, $h_c = 10$ mm and $\varphi = 30°$. The studied material was a polypropylene with the following characteristics: $E_s = 1.5$ GPa, $G_s = 0.5483$ GPa and $v = 0.36$.

Nine simulations were necessary to determine nine elastic constants of the polypropylene honeycomb. Three tensile simulations along the direction i ($I = x, y, z$)

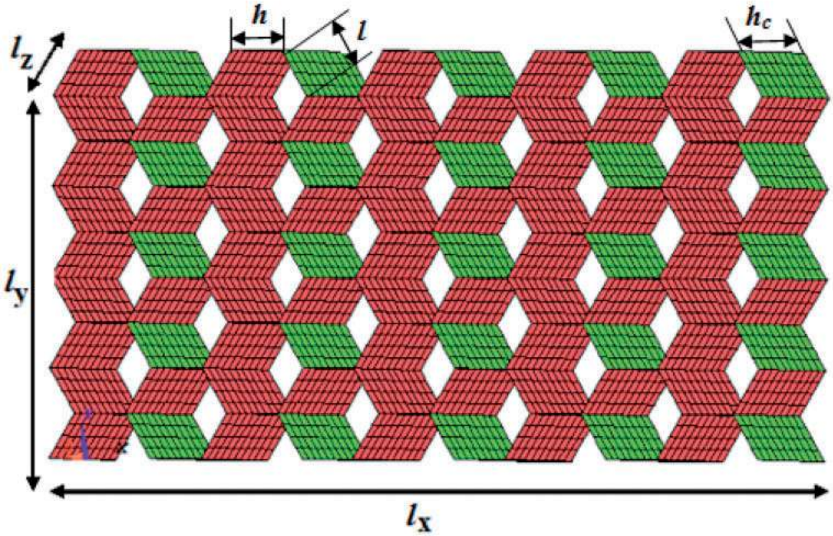

Figure 8. Representative volume element of the honeycomb core.

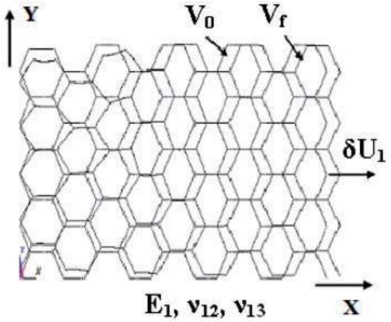

Figure 9. Representative volume element with the imposed displacement in the X direction.

which are used to determine the three elasticity moduli E_1, E_2 and E_3 and six Poisson's ratios.

$$E_i = \frac{\sigma_i}{\varepsilon_i} \tag{1}$$

where the tensile stress is deduced from the liaison efforts

$$\sigma_i = \frac{F_i}{S} \tag{2}$$

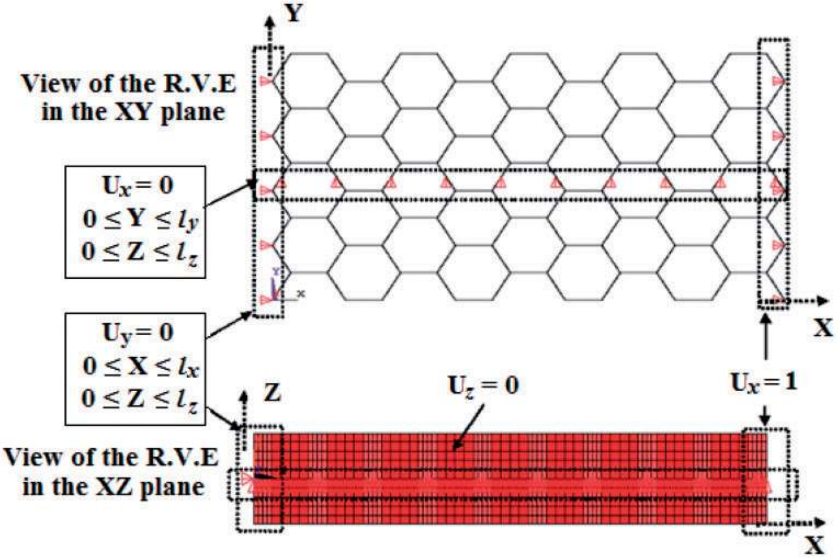

Figure 10. Boundary conditions for tensile in the direction X.

where F_i is the liaison force of RVE in the direction i (deducted from the imposed displacement δUi) and S is the surface perpendicular to the imposed displacement δU_i. Figure 9 presents an example of the tensile simulation along the direction X which was used to determine the elastic modulus E_1. In such cases, one blocks the left face in the direction X ($U_x = 0$) and one imposes a displacement of 1 mm on the right face (opposite face). The nodes of the planes of symmetry of the honeycomb serve for blocking the displacements U_y and U_z as is given in Figure 10. Similarly, the determination of shear modulus G_{ij} requires the use of the elastic behavior laws. Shear simulations are essential for determining the shear modulus G_{ij}, into blocking the displacement of one face and into applying a shear on the opposite face. The behavior law in the case of a shear stress is given by the following equations

$$G_{ij} = \frac{\tau_{ij}}{\gamma_{ij}} \quad i \neq j \ et \ i,j = x,y,z \tag{3}$$

where τ_{ij} is the shear stress and is given by

$$\tau_{ij} = \frac{F_i}{S_{ik}} \quad i \neq j \neq k \ et \ i,j,k = x,y,z \tag{4}$$

Figure 11 presents an example of the shear simulation in-plane X–Y which was used to determine the elastic modulus G_{12}. The method used for determining this modulus consists of blocking the face translation and applying a displacement to

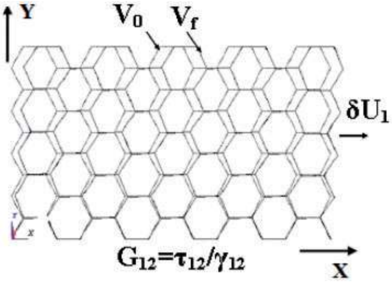

Figure 11. Representative volume element under shear loading.

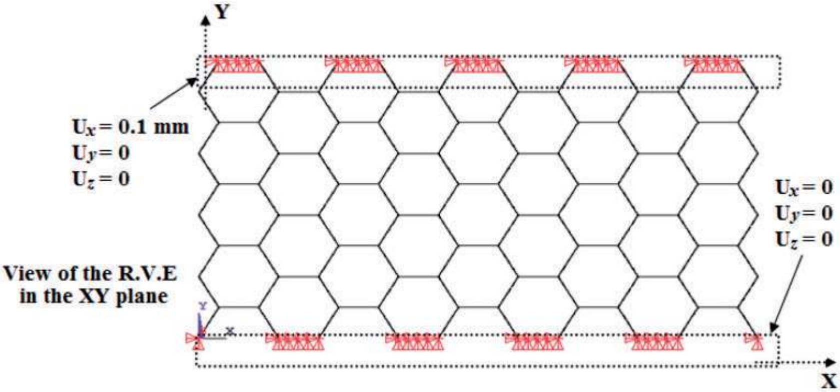

Figure 12. Boundary conditions for determining G_{12}.

the opposite face. The boundary conditions that have been applied are presented in Figure 12.

Comparison of analytical and numerical results of the mechanical properties of single honeycomb

The numerical and analytical results of the mechanical properties of single honeycomb are depicted in Table 6. A comparison between the results of Gibson analytical model and those obtained by numerical simulation allows determining with accuracy the values of the elastic moduli. To be noted the small variation of the results, between the numerical simulation and the analytical model that is approximately 7.8% for E_1 and 5% for the Poisson's ratio, results which are relatively acceptable having the module of Gibson like reference. In the case of traction following Y, we can notice the variation of the results between two models is approximately 12% for E_2 and 25% for the Poisson's ratio. For simulation according to Z, the variation is approximately 7% for E_3. On the other hand, the

Table 6. Mechanical properties of a single polypropylene honeycomb core.

Honeycomb	FE code (Ansys)	Gibson	Error (%)
E_1 (MPa)	0.448	0.486	7.8
E_2 (MPa)	0.545	0.486	12
E_3 (MPa)	96.30	90	7
ν_{12}	1.05	1	5
ν_{13}	0.002	0.002	25
ν_{23}	0.002	0.002	0
ν_{31}	0.4	0.4	0
ν_{32}	0.4	0.4	0
G_{12} (MPa)	0.1292	0.1214	0
G_{21} (MPa)	0.0664	–	6.4
G_{23} (MPa)	16.93	16.44	–
G_{32} (MPa)	1.2698	–	2.9
G_{13} (MPa)	17.11	–	
$G_{13\text{-min}}$ (MPa)	–	24.673	30
$G_{13\text{-max}}$ (MPa)	–	27.415	–
G_{31} (MPa)	1	–	–

variation on the Poisson's ratio is very weak. Concerning the shear modulus G_{12}, the variation of the results between Ansys and Gibson are approximately 6.4%. This important error relates to a low value of module that is not dominating in the mechanical properties of the sandwiches. The error on G_{23} is of 2.9%. The moduli of rigidity G_{21}, G_{31} and G_{32} are obtained only by numerical simulation. Gibson does not give comparative values.

The mechanical properties of multi-layer honeycomb core materials

Theoretical model developed by Arbaoui et al. [14] makes possible to determine the elastic moduli of the multi-layer honeycomb core materials. The mechanical characteristics of the intermediate sheet (isotropic composite material) are presented in Table 2. The analytical expressions used to assess the effective elastic properties of the multi-layer honeycomb core are determined by the equation (5). The mechanical properties of these multi-layer honeycomb core materials are listed in Table 7.

$$X = \frac{1}{h}\sum_{i=1}^{n} X_i h_i \tag{5}$$

Table 7. Mechanical characteristics of the multi-layer core.

Multilayer cores	M5:5	M10:10	M5:10:5	M5:5:5:5	M20:20	M15:10:15	M10:10:10:10
E_1	27.8	14.2	27.8	41.4	7.3	14.2	21.0
E_2	27.8	14.2	27.8	41.4	7.3	14.2	21.0
E_3	116.9	103.4	116.9	130.2	96.0	103.4	120.2
ν_{12}	1	1	1	1	1	1	1
ν_{13}	0.003	0.002	0.003	0.002	0.002	0.002	0.003
ν_{23}	0.003	0.002	0.003	0.002	0.002	0.002	0.003
G_{12}	10.6	5.3	10.6	15.8	2.7	5.3	8.0
G_{23}	26.8	10.5	26.8	32.0	19.0	10.5	24.2
G_{13}	35.0	29.8	35.0	40.1	27.2	29.8	32.4

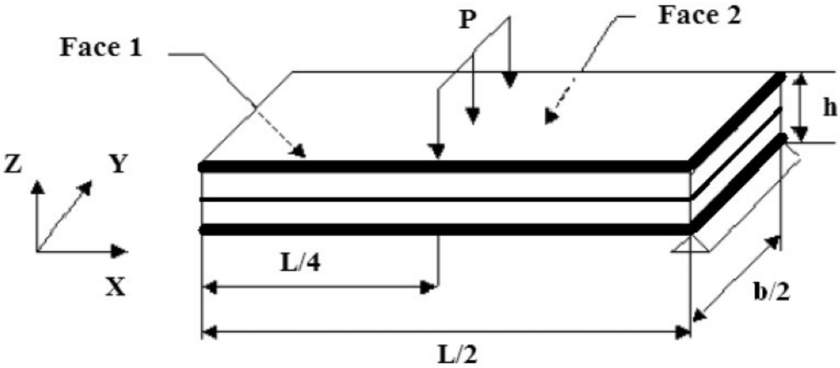

Figure 13. Four-point bending model developed on Castem 2000.

Numerical simulation of four-point bending

Once the honeycomb core is homogenized, the whole sandwich panel is likened to a beam constituted of three elastic layers: orthotropic/orthotropic/orthotropic that will be used in numerical models. Numerical simulations were conducted using the Castem 2000 finite element software. The honeycomb sandwich structure was modeled using 3D solid elements. For symmetry reasons, only a quarter of the sandwich panel was considered in the present analysis as given in Figure 13. The applied boundary conditions were imposed under the following manner: at the level of the support, the transversal displacement U_z was fixed to zero; at the symmetry level on the face 1, the in-plane displacement U_x and the rotations

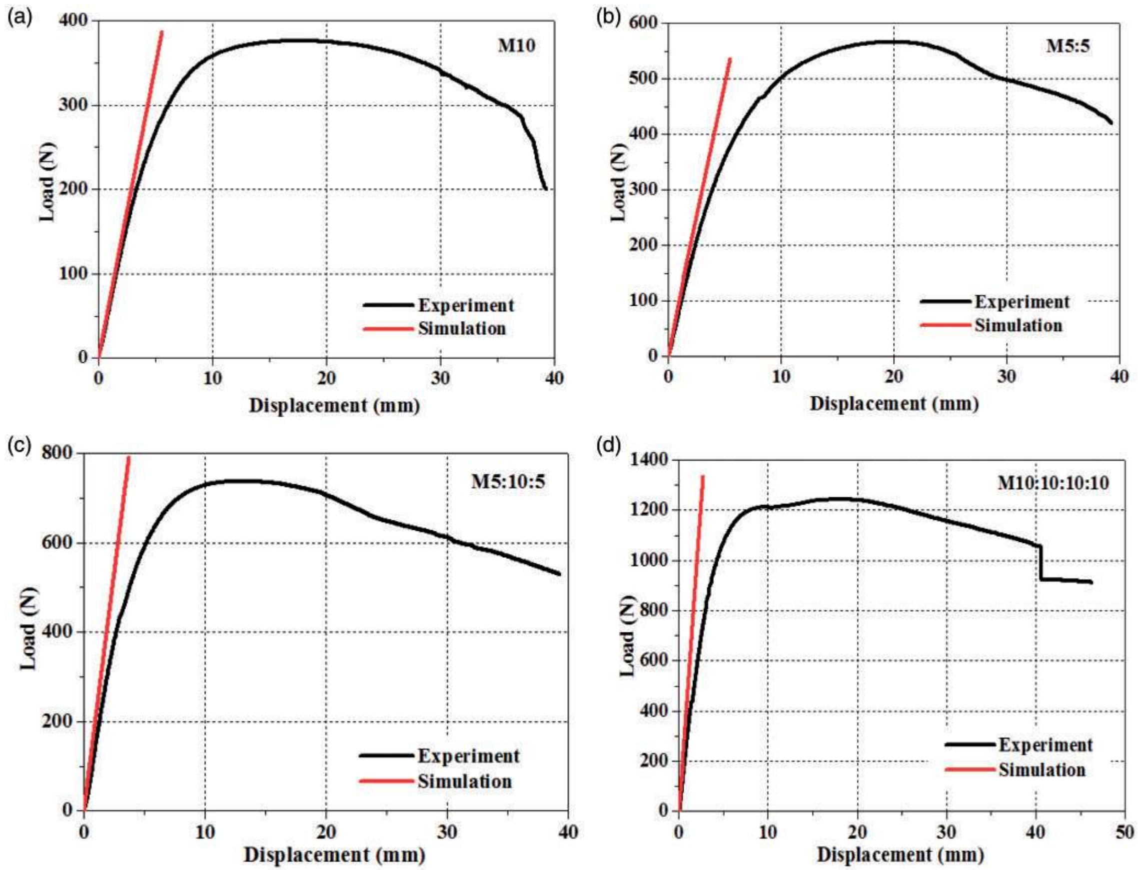

Figure 14. Comparison between the experimental and numerical results of multi-layer sandwich composite subjected to four-point bending: (a) single honeycomb with 10 mm, (b) double honeycomb with 10 mm, (c) triple honeycomb with 20 mm and (d) quadruple honeycomb with 40 mm.

h_y and h_z was fixed to zero as well; then on the face 2, the in-plane displacement U_y and the rotation h_x and h_z was likewise zero. The sandwich plate consists of composite face and multi-layer honeycomb core whose dimensions are length $l = 440\,\text{mm}$, width $b = 35\,\text{mm}$, core thickness $h_c = 20\,\text{mm}$, face thickness $t = 1\,\text{mm}$ and intermediate layer thickness $t' = 0.05\,\text{mm}$.

Prior to initiating the evaluation study, an analysis of mesh convergence was carried out to ensure the accuracy of the proposed finite element solution since it is considered a(s) reference in the present study. The convergence was achieved with 4200 elements: 20 elements following the x-axis, 15 elements in the thickness of the core, 3 elements in the thickness of each skin and 10 elements following the y-axis. The numerical modeling was simulated considering the four-point bending approach from the experiments protocol, conducted with single- and multi-layer sandwich structures. Later, the four-point bending experiments were compared with the numerical procedure and the results were presented in Figure 14. A good agreement between the experiment and finite element results can be observed with a minor difference of approximately 7%, which may be related to the experimental conditions such as a result of the systematic defects of the manufacturing process, in particular the air bubbles and uncertainties of the used devices.

Conclusion

A detailed experimental and numerical investigation was conducted on the behavior of multi-layer composite sandwich panels under four-point bending. The multi-layer sandwich panels were prepared with glass/polyester on top, bottom and intermediate face and polypropylene honeycomb in the multi-core. The experimental results confirm a positive influence of the multi-layer core over the performance of parameters such as face sheet stress, core shear and bending stiffness, performance compared to single-layer structure. The proposed assembly technique ensures a reduction in the thickness of the composite structures of a factor 2 while preserving an identical mass. In the second part of this survey, an analytical study based on the homogenization methodology was explained to determine the equivalent elastic properties of the single polypropylene honeycomb. The properties obtained analytically were successfully compared with the numerical solution. The four-point bending response was simulated using Castem 2000 structural analysis software. A numerical model without damage (i.e. assuming the material is free defect when is manufactured) was developed to detect with accuracy the elastic behavior of the materials. The results obtained by the numerical simulation are consistent with experimental results with a slightly difference, which may be related to the experimental conditions such as the systematic defects of the manufacturing process, in particular the air bubbles and uncertainties of the used devices.

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