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EXPERIMENTAL BENDING BEHAVIOUR OF MULTI-LAYER SANDWICH STRUCTURES

ZACHOWANIE WIELOWARSTWOWYCH STRUKTUR SANDWICHOWYCH PRZY EKSPERYMENCIE ZGINANIA

Sandwich panels have the best stiffness over lightness ratio. It's what makes them very useful in industrial applications for instance aerospace, transport and maritime fields. The influence of a multi-layer core is analyzed using a three-point bending test and the results correlated to the final properties of the composite. Sandwich composites with glass/polyester skins and polypropylene honeycomb cores are explored. This experimental study shows that the multilayer structure is more rigid. A small increase of the final weight leads however to significant increase of the mechanical properties.
Keywords: sandwich, multi-layer, polypropylene honeycomb, bending

Panele sandwiczowe posiadają najlepszy stosunek sztywności do lekkości. Ta cecha nadaje im dużą przydatność w zastosowaniach przemysłowych, takich jak przemysł lotniczy, transportowy czy morski. Wpływ wielowarstwowej wkładki jest analizowany przy wykorzystaniu testu trzy-punktowego zginania, a wyniki są powiązane z końcowymi właściwościami kompozytu. Badane są kompozyty sandwiczowe z powłokami szklanymi/poliestrowymi i polipropylenowymi wkładkami komórkowymi. Niniejsze badania eksperymentalne wskazują, iż struktura wielowarstwowa jest bardziej sztywna. Mały przyrost końcowej wagi prowadzi jednak do znacznego wzrostu właściwości mechanicznych.

1. Introduction

Typical sandwich composites consist of two thin, stiff and strong skins separated by a thick, light and weaker core. The faces and the core material are bonded together with an adhesive to facilitate the load transfer mechanisms between the components. This particular layered composition creates a structural element with both high bending stiffness – weight and bending strength – weight ratios. Sandwich structures are often used in the marine, aerospace, train and automotive industries [1-3]. The general concept of sandwich structures has been investigated and developed by many researchers over the past 50 years, see for example Zenkert [4-5], Allen [6] and Gay [7]. The structures used in the present work are formed by two high-rigidity glass/polyester thin-facings adhering to a low density polypropylene honeycomb core characterized by less strength and stiffness. Varying the thickness of the core and the walls allows to reach a large range of mechanical properties such as a high strength-to-weight ratio [8]. The materials of this work are developed in the framework of a comparison with previously studied structures [9-10].

Our purpose in this work is to replace a single honeycomb core by a multi-layer core. This multi-layer core is obtained by using several honeycomb layers of different thicknesses. The honeycomb is built from hexagonal cells with isotropic shear properties. The evolution of the mechanical properties with some typical sequences is shown in Fig. 3. A particular attention is also applied to the influence of the interfaces that are created in such structures. The final goal is to work out a material of low density well adapted to industrial applications. The mechanical test retained to specify the variations of the multilayer composite is a three-point bending test.

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2. Sandwich construction

2.1. Mechanical properties of fully bonded sandwich structures

Thin stiff faces are glued on a lightweight, low modulus thick core to obtain a composite structure with a high bending stiffness. The behaviour of such structures has been extensively investigated [11-12].

Some of the most important relations describing the properties of such structures are summarized in the following section. For common engineering applications it is a requirement that the stiff faces be perfectly bonded to the core. That means a complete transfer of stresses between layers of the sandwich structure. The flexural rigidity of a sandwich structures is obtained using the sum of the flexural rigidities of the constituent parts, throughout the centroidal axis of the beam, as shown in Eq. (1) [13]

$$\begin{aligned} D &= \int Ez^2 bdz = \int_{-t_f-h_c/2}^{-h_c/2} E_f z^2 bdz + \int_{-h_c/2}^{h_c/2} E_c z^2 bdz + \int_{h_c/2}^{h_c/2+t_f} E_f z^2 bdz \\ &= 2\int_{-t_f} -h_c/2^{-h_c/2+t_f} E_f z^2 bdz + 2\int_{0}^{h_c/2} E_c z^2 bdz \\ &= E_f \frac{bt_f^3}{6} + E_f \frac{bt_f d^2}{2} + E_c \frac{bh_c^3}{12}. \end{aligned} \tag{1}$$

Subscripts 'f' and 'c' refer to the skin and the core material. b is the width of the sandwich beam. t_f, and E_f are respectively the thickness and Young's modulus of each facing of the sandwich composite, while h_c and E_c are those of the core. $d = t_f + h_c$ is the distance between the facing centroids. Retaining the following remarks, the expression for the flexural rigidity can be reduced. The first term represents the flexural rigidity of the faces bending separately about their own centroidal axes while the second term represents the bending stiffness of the faces bended about the neutral axis of the complete sandwich element. The third term is connected to the bending stiffness of the core. If the sandwich element has a core which is much thicker than the face plates, then the error introduced by neglecting the first term is negligible provided that [6]

$$\frac{d}{t_f} > 5.77. \tag{2}$$

So on, the first term contribution is less than 1% of the second term in Eq. (1). The third term represents less than 1% of the second when [6]

$$\frac{6E_f t_f d^2}{E_c h_c^3} > 100. \tag{3}$$

Following these assumptions, the expression for the flexural rigidity of the sandwich reduces to

$$D \approx E_f \frac{bt_f d^2}{2} \tag{4}$$

and the shear rigidity Q is given by

$$Q = AG_c = G_c \frac{bd^2}{h_c}. \tag{5}$$

2.2. Bending behaviour

A simply supported honeycomb beam is subjected to a line load at its mid-span (Fig. 1). The stress distribution at the mid-span cross section of the honeycomb beam is described in Fig. 2. It is assumed that the facing plates carry only bending stresses σ_f. When the skin thickness t_f is small, the bending stress variation through the plate thickness direction may be ignored. It is also supposed that the honeycomb core carries only the vertical shear stresses τ_c.

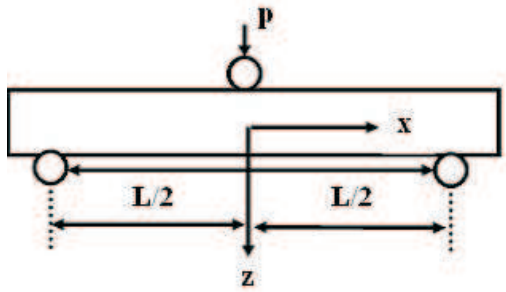

Fig. 1. A simply supported honeycomb beam

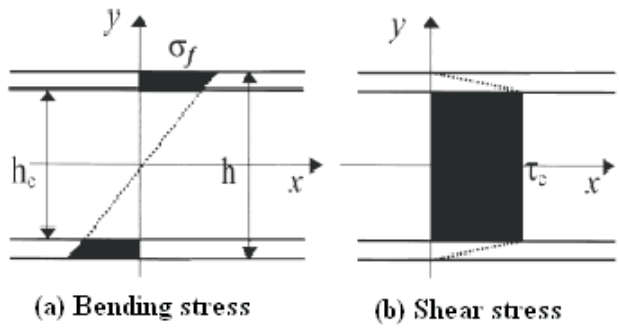

Fig. 2. Idealized distributions of bending and shear stresses in a polypropylene honeycomb beam

Considering the rotational restraints between facing plates and core, the distribution of shear stresses τ_c is assumed to be uniform through the core depth h_c. Kelsey et al. [14] provide a formula of the mid-span deflection for the sandwich beam in the linear elastic regime as follows

$$\boldsymbol{\delta} = \boldsymbol{\delta}_1 + \boldsymbol{\delta}_2 = \frac{\boldsymbol{PL}^3}{48\boldsymbol{D}} + \frac{\boldsymbol{PL}}{4\boldsymbol{AG_c}}. \tag{6}$$

The first term of the right hand side in Eq. (6) is due to the bending effect alone. The second term takes in account the shear effect.

3. Materials and experimental technique

3.1. Materials

This study only deals with polypropylene honeycomb cores (Fig. 3). The bonded assembly of the material is possible thanks to non woven polyester felt impregnated with a specific formulation and integrated between the honeycomb layers. The skins are of polyester resin/glass fibers (T800/M300). The composite structures are pressed in only one pass. The mechanical properties of the basic materials are summerized in Tables 1 and 2.

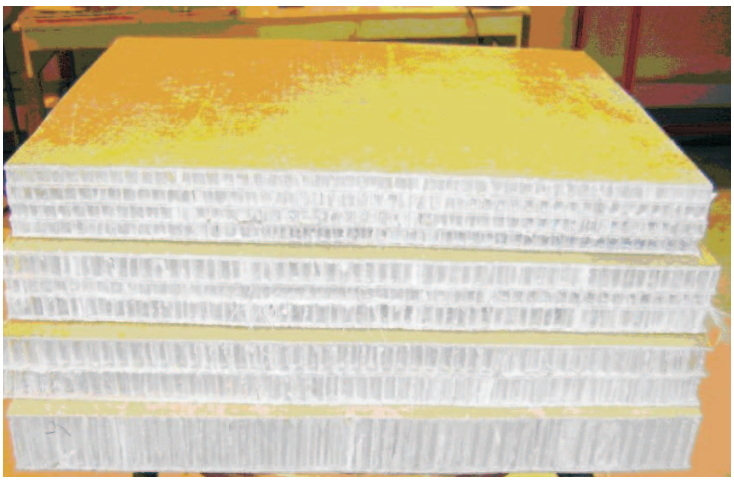

Fig. 3. Honeycomb multi-layer sandwich

TABLE 1
Mechanical properties of a polypropylene honeycomb core

Density [kgm^{-3}]	80
Compressive strength [MPa]	1,3
Shear strength [MPa]	0,5
Elastic modulus [MPa]	15
Shear modulus [MPa]	8

TABLE 2
Mechanical properties of polyester resin/glass fibers (T800/M300) laminates

Young's modulus [MPa]	9162
Tensile strength [MPa]	321
Shear modulus [MPa]	2101
Face thickness [mm]	1

3.2. Experimental technique

Fig. 4. Static three-point bending test

A three-point bending test allows to deduce the bending and shear rigidities. The test is performed with respect to the NFT54-606 norm on an INSTRON model 4302 machine (Fig. 4). To check the reproducibility of the results, a minimum of 5 beams by composite type is tested. The load displacement is constant during the test.

The dimensions of the samples are : length = 440 mm, width = 35 mm with a global thickness close to 20 mm.

4. Results and discussion

4.1. Influence of multi-layer cores

Fig. 5 shows the load versus bending curves obtained for specimen going from single to quadruple cores. The analysis of the curves leads to set up three principal ranges. At first we observe a linear increase in the applied load P with the bending δ. In a second step one can notice a slowing of the curve to a maximum load. In a last phase, the load decreases down to the total rupture of the specimen. The linear step corresponds to the contribution of the skins in tensile and compression likewise behaviours. The non-linear part mainly depends on the properties of the core under the effect of the shearing forces. The integration of a multi-layer core in the structure does not modify the general bending behaviour compared to a single core material. On the other hand with a constant thickness (close to 20 mm), the advantage of the multi-layer is that, for a given δ deflection, the applied load P increases with the number of layers of the core. Thus, a composite structure with a double-layered core (10 + 10 mm) can bear a 30% higher load compared to a structure with a single core (20 mm) (Fig. 5). This load is equivalent to that supported by a structure with a single core of 40 mm (Fig. 6). With this assembly technique it is possible to reduce the thickness of the composite structures of a factor 2 while preserving an identical mass. For example, a double-layered structure of 20 mm weighs 4.8 kg m^{-2} whereas a single structure of 40 mm reaches 5.2 kg m^{-2}.

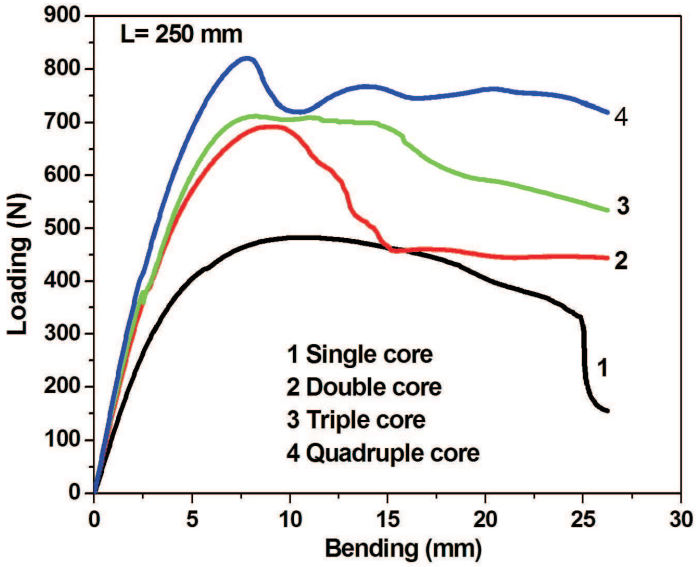

Fig. 5. Loading-bending curve measured under static three-point bending with L = 250 mm (L distance between the supports during the bending test)

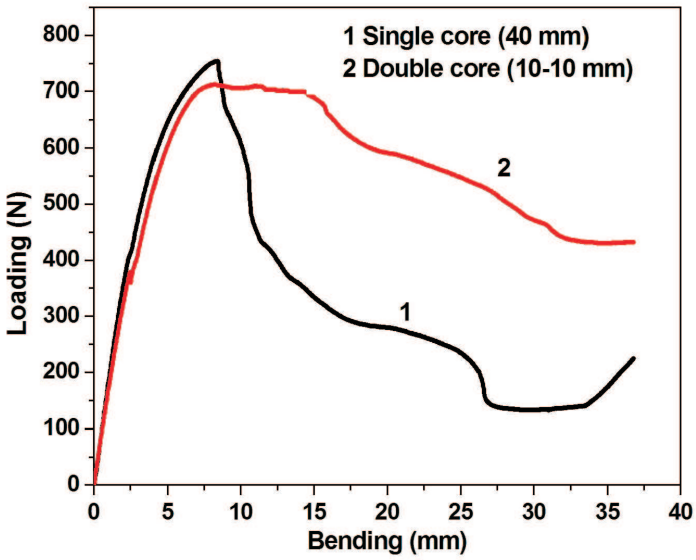

Fig. 6. Loading-bending comparison for a single and a double core

4.2. Properties of multi-layer core material

To determine the shear properties of a multi-layer core, we have carried out a series of measurements while varying the distance L between the supports (Fig. 7). This measurement technique enables us to determine an apparent rigidity modulus of the multi-layer core. Fig. 7 gives the results obtained with a single core. The different curves of Fig. 7 make it possible to represent the evolution of δ/PL versus L^2 for a single core (Fig. 8). The experimental data are then fitted by a linear law describing the evolution of δ/PL versus L^2. Extrapolation to L=0 gives the value of factor 1/4AG which is used to calculate the apparent shear modulus. A similar procedure is then applied to double, triple and quadruple cores. The values of the shearing rigidities are presented in Table 3 (calculations using the experimental data).

TABLE 3

Shear stiffness of the composite structures

Sandwich materials	Shear stiffness (N)
Single core	9338.2
Double core	12785.2
Triple core	14923.3
Quadruple core	17718.8

Fig. 9 represents the increasing evolution of the apparent modulus rigidity with the number of layers. A linear modelling with a correlation coefficient $R^2 = 0,99245$ makes it possible to consider that the rigidity modulus varies linearly with the number of layers N. The fitted relation obtained is

$$G_c = 3,05N + 9.45 \quad (7)$$

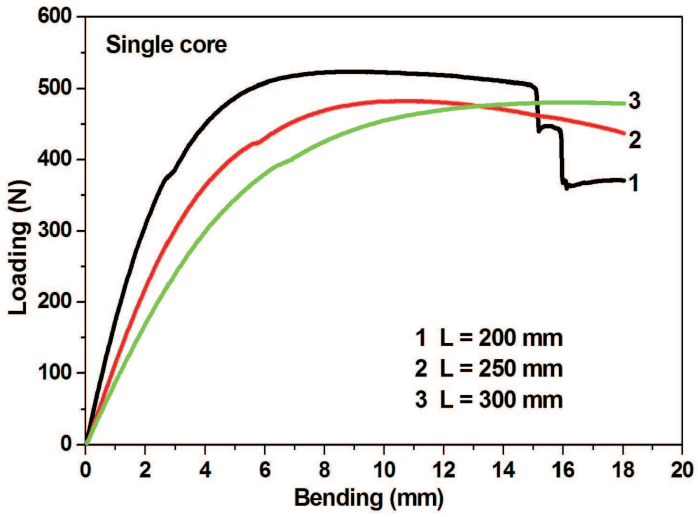

Fig. 7. Loading-bending curve measured under static three-point bending of a single core versus support span L

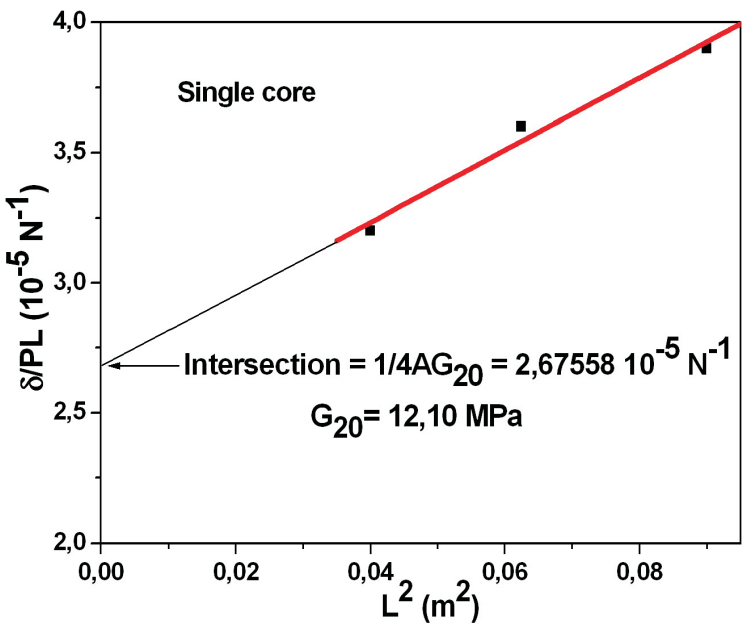

Fig. 8. Plot of δ/PL versus L^2 used to determine the apparent shear modulus of a single core

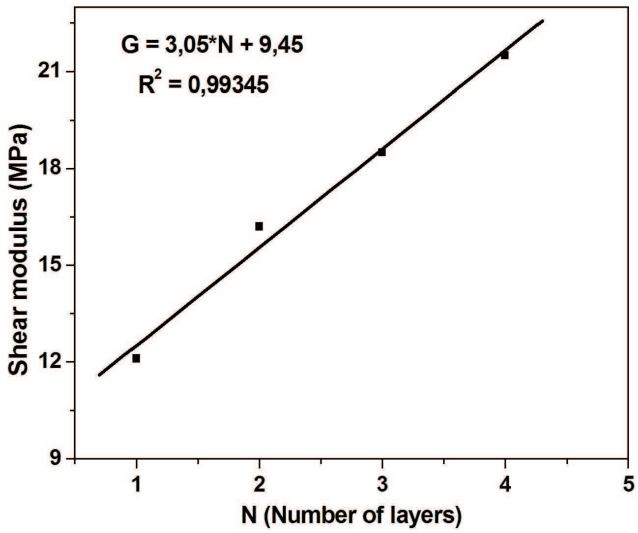

Fig. 9. Apparent shear modulus versus number of layers

5. Conclusion

The mechanical behaviour of composites with polypropylene honeycomb multi-layer cores has been explored via a three-point bending test. The experimental results show the positive influence of the increased number of layers over the final mechanical properties of the composite structure (Fig. 10). For a given deformation, the increase in the number of layers makes it possible to increase the applied load. Varying the support length permits to determine the apparent rigidity modulus of the multi-layer beam.

One can concluded that this technique of assembly gives very interesting results for many industrial applications. It allows in certain cases to obtain final thickness reduction by a factor 2 while preserving the mechanical performances. This study is to be completed by a comparison with different other panels with different cores and skins and with the results of theoretical simulations of the bending behaviour.

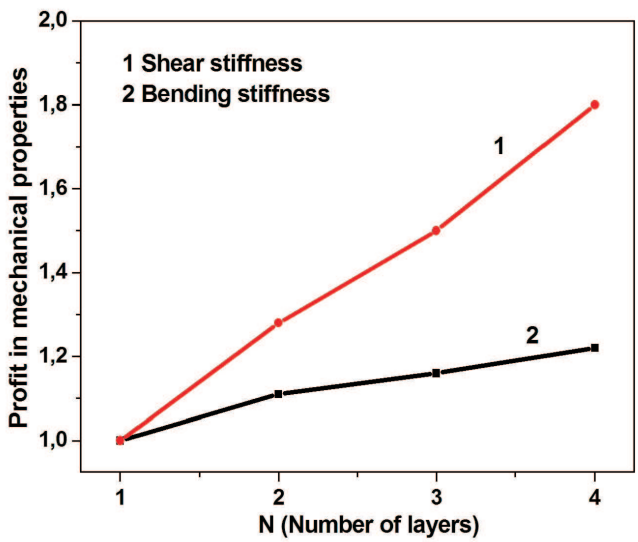

Fig. 10. Variation of the mechanical properties versus the number of layers

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Nomenclature

b – width of sandwich beam
h_c – thickness of core
t_f – thickness of face
d – distance between the facing centroids
L – support span
E_f – face Young Modulus
E_c – core Young Modulus
G_c – core shear modulus
τ_c – core shear stress
σ_f – bending stress of facing skin for a sandwich beam
P – load
δ_1 – bending or primary partial deflection
δ_2 – shear or secondary partial deflection
δ – total deflection
A – a geometrical parameter that depends on thickness of the core, skin materials and beam width
D – bending rigidity
Q – shear rigidity

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