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FINITE ELEMENT PREDICTION OF MECHANICAL BEHAVIOUR UNDER BENDING OF HONEYCOMB SANDWICH PANELS

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ABSTRACT

This paper outlines a finite element procedure for predicting the mechanical behaviour under bending of sandwich panels consisting of aluminium skins and aluminium honeycomb core. To achieve a rapid and accurate stress analysis, the sandwich panels have been modelled using shell elements for the skins and the core. The effects of expanding orientation angle, wall thickness, edge length ratio and honeycomb cell size on the mechanical properties of honeycombs were studied. Sandwich panels were modelled by a three-dimensional finite element model implemented in Abaqus/Standard. By this model the influence of the components on the behaviour of the sandwich panel under bending load was evaluated. Numerical characterization of the sandwich structure, is confronted to both experimental and homogenization technique results.

Keywords: sandwich composite, aluminum honeycomb, finite element modelling.

INTRODUCTION

The use of sandwich composite structures in aeronautics and astronautics engineering is increasing. Sandwich structures have long been recognized as one of the most weight-efficient plate or shell constructions for resisting bending loads. The aerospace industry, with its many bending stiffness dominated structures, and its need for low weight, has employed sandwich constructions using aluminum honeycomb cores extensively (Palazotto, 2000). The metal honeycombs are frequently used as core materials for sandwich structures, in various engineering applications, because of their high strength-to-weight ratio.

The characterization of mechanical properties of sandwich structures poses special challenges due to their heterogeneity and considerable mismatch in properties between core and face sheet (Ravichandran, 2012). The need to an efficient numerical modeling for predicting the mechanical behavior of the sandwich structures is still an open area of research. Extensive work (Rahman, 2011) has been carried out on the development of computational models for studying the response of sandwich panels and shells in an attempt to make their use more widespread. Nowadays, numerical simulations based on the finite element (FE) method have become a standard tool in the development process of the aircraft industry (from the material level over the component level up to the full aircraft). Therefore, it is reasonable to use this technique also for the characterization of cellular sandwich core structures (Heimbs, 2009). Fan et al. (2006) investigated the out-of-plane compressive properties of honeycombs by linear and nonlinear finite element analysis (FEA). Aktay et al. (2008) built a micromechanics FEA model and a homogenized model, and compared the numerical results with the experimental results. They concluded that the micromechanics model was more suitable for honeycomb design since it gave good agreement with the experimental data. Pugno and Chen

(2011) calculate analytically the in-plane linear-elastic properties of a new class of bio-inspired nano-honeycomb materials possessing a hierarchical architecture, which is often observed in natural materials. A parametrical analysis reveals the influences of relative density and of two key geometrical parameters on the overall elastic properties. They discover optimal values for some of the mechanical properties, e.g. stiffness-to-density ratio. Furthermore, Out-of-plane shear modulus of the honeycomb core of a sandwich panel and the Young's modulus in the thickness direction were determined by experimental methods, an analytical approach and by the finite element method by Mujika et al (2011). They showed that FE characterization or the analytical model can be a reasonable alternative to experimental methods.

Analysis of load-deflection behavior of a composite sandwich beam in three-point bending was described by Gdoutos et al. (2001). They found that the effect of material nonlinearity on the deflection of the beam is more pronounced for shear-dominated core failures in the case of short span lengths. The authors thought that it is due to the nonlinear shear stress-strain behavior of the core. For long span lengths, the observed nonlinearity is small and is attributed to the combined effect of the facings nonlinear stress-strain behavior and the large deflections of the beam.

Thereby, numerical models allow for efficient parameter studies or optimizations. The method of determining the mechanical properties of honeycomb core of different geometries using tensile and shear test simulations is here discussed covering a number of important modelling aspects: the influence of cell wall thickness, expanding angle, edge length ratio, etc. A comparison of numerical and experimental results is given for aluminium facings and aluminium honeycomb core structures. In the present work, a numerical model is used to examine the behavior of sandwich panels made of aluminum skins with aluminum honeycomb core under four bend loading.

ANALYTICAL MODELS AND NUMERICAL SIMULATIONS

Analytical models

Many authors have developed theoretical approaches for determining the equivalent orthotropic mechanical properties of honeycomb cores (Schwingshackl, 2006). The nine basic material characteristics are as follows: two in- plane Young's moduli E_x and E_y, another out-of-plane Young's modulus E_z, the in-plane shear modulus G_{xy}, the out-of-plane shear moduli G_{xz} and G_{yz} and three Poisson's ratios ν_{xy}, ν_{xz}, ν_{yz}.

One of the analytical approaches mentioned in the work of Schwingshackl (2006) was developed by Gibson and Ashby (2001). They described the honeycomb core as a cellular solid consisting of an interconnected network of solid structures that form the edges and faces of cells (Fig. 1).

Analytical relations given by Gibson and Ashby (2001) of the nine material properties are listed below (Table 1).

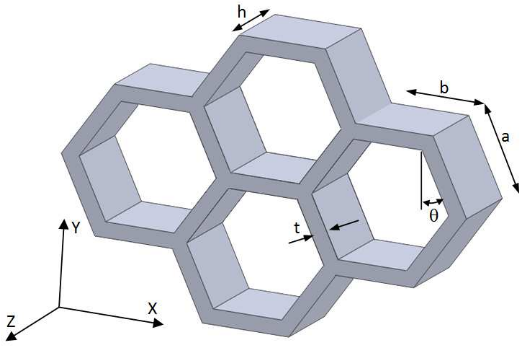


Fig.1 Honeycomb structure

Table 1 Analytical relations (Gibson, 2001)

In-plane and out-of-plane properties	Analytical relations
Young's modulus (x direction)	$E_x = E_0\left(\frac{t}{a}\right)^3 \frac{(b/a+\sin\theta)}{\cos^3\theta}$
Young's modulus (y direction)	$E_y = E_0\left(\frac{t}{a}\right)^3 \frac{(\cos\theta)}{(b/a+\sin\theta)\sin^2\theta}$
Young's modulus (z direction)	$E_z = E_0\left(\frac{t}{a}\right) \frac{(b/a+2)}{2(b/a+\sin\theta)\cos\theta}$
Shear modulus (xy plane)	$G_{xy} = G_0\left(\frac{t}{a}\right)^3 \frac{(b/a+\sin\theta)}{(b/a)^2(1+2b/a)\cos\theta}$
Shear modulus (xz plane)	$G_0\left(\frac{t}{a}\right)\frac{(b/a+\sin\theta)}{(1+b/a)\cos\theta} \le G_{xz} \le G_0\left(\frac{t}{a}\right)\frac{(b/a+2\sin^2\theta)}{\cos\theta(b/a+\sin\theta)}$
Shear modulus (yz plane)	$G_{yz} = G_0\left(\frac{t}{a}\right)\frac{\cos\theta}{(b/a+\sin\theta)}$
Poisson's ratios	$\nu_{xy} = \frac{(b/a+\sin\theta)\sin\theta}{\cos^2\theta}$ $\nu_{xz} = \frac{E_x}{E_z}\nu_{zx} \quad (\nu_{zx} = \nu \text{ of aluminium})$ $\nu_{yz} = \frac{E_y}{E_z}\nu_{zy} \quad (\nu_{zy} = \nu \text{ of aluminium})$

Finite element model

Several authors have performed numerical simulations by finite elements to determine the nine independent constants of this type of structure (Chamis, 1988, Martinez 1989). Similar studies were conducted later by Mistou et al. (2000) on honeycomb aluminum and Foo et al. (2007) on Nomex honeycomb. The finite element model used for the simulations of core structures honeycomb requires mesh generation for finite element structure, the allocation of behavior laws and the definition of boundary conditions and loading. The numerical model is based on the introduction of the geometric parameters of the unit cell of a honeycomb (Fig.1), the RVE size (length, width, height, or the number of unit cells), the size of the element and the type and boundary conditions. An elementary cell is generated from the geometric data and duplicated in the two directions of the plane depending on the size of the RVE.

For the sandwich structure, the two skins are generated by the upper and lower faces of the core, on which the loads are applied. The whole model is meshed with shell elements with 4-nodes depending on the size of the element, and the core and the skins are connected by nodes defining solider contact between these two bodies. Then the boundary conditions are applied to the skin of the sandwich structure.

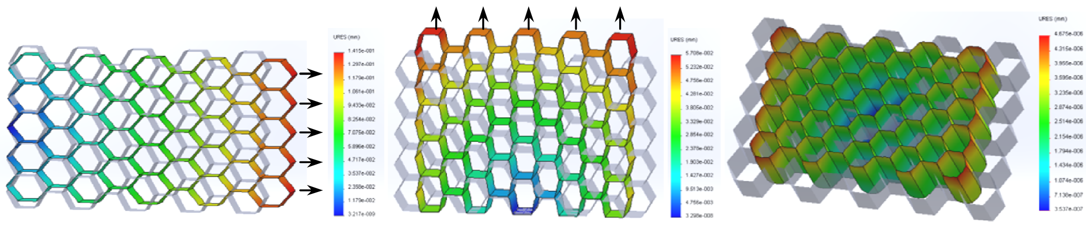
The analysis was performed by imposing known displacements or forces. The opposite side of the applied displacement is clamped and then the forces are obtained. The elastic moduli are obtained by measuring the slope of the linear stress-strain curve. Code Abaqus was used for the finite element calculation. The geometrical parameters are the same as the values used in the analytical approach and the geometric defects were not taken into account.

For the four-point bending test, only a quarter of the panel was modeled due to the symmetry of the problem. A non-homogeneous three-dimensional mesh is used. The adopted mesh contains 88,907 shell elements with 4-nodes reduced integration (S4R in Abaqus).

RESULTS

Mechanical behaviour of honeycomb core

The determination of the nine elastic constants characterizing the mechanical behavior of the honeycomb core using finite element simulations (Fig.2) is confronted with the analytical values of Gibson and Ashby (2001). We are interested primarily in the study of the influence of the expanding angle θ on the mechanical properties of the honeycomb. It should be noted that the in-plane shear modulus G_{xy} is very low.



x direction Tensile (Ex) y direction Tensile (Ey) z direction Tensile (Ez)

Fig.2 Tensile simulations in x, y and z directions

Figure 3 shows the evolution of in-plane and out-of-plane Young's moduli (E_x, E_y et E_z). It must be noted that the honeycomb exhibits remarkable out-of-plane stiffness (z, thousands of MPa) in comparison with in-plane Young's moduli (x and y, about ten MPa). We note the good agreement between finite element model and analytical values of Gibson (2001).

We notice that E_x and E_y show evolutions inverse one to the other; if one of the properties exhibits growing values, the other shows decreasing values. The cell regular polygon (θ=30°) put on display a quasi-isotropy in (x,y) plane ($E_x \approx E_y$). The curve of "bathtub" shape related to E_z, is due mainly to the cross-section area and its variation in function of θ. Indeed, this area (xy plane) increases when θ takes the values [0° to 30°], and decreases hereafter, what engender a decreasing way of E_z curve until θ = 30°, and then increases after θ = 30°.

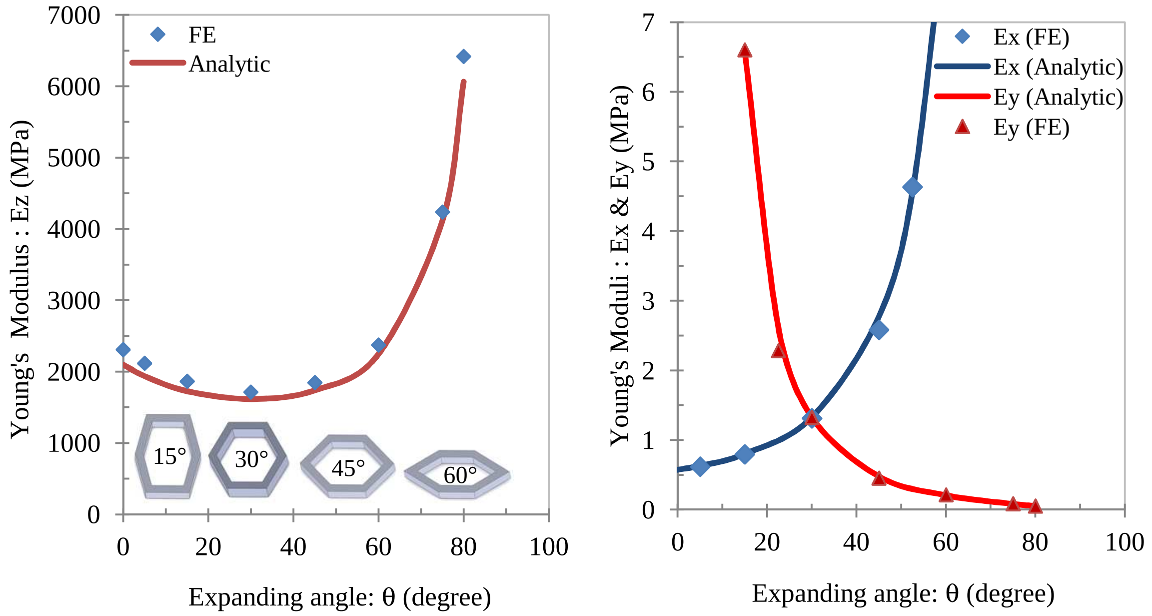


Fig.3 Influence of expanding angle on out-of-plane and in-plane Young's moduli

The out-of-plane shear moduli (G_{xz} and G_{yz}) display sensible growth in function of expanding angle θ (for G_{xz}), and a decrease rather pronounced (for G_{yz}) (Fig.4).

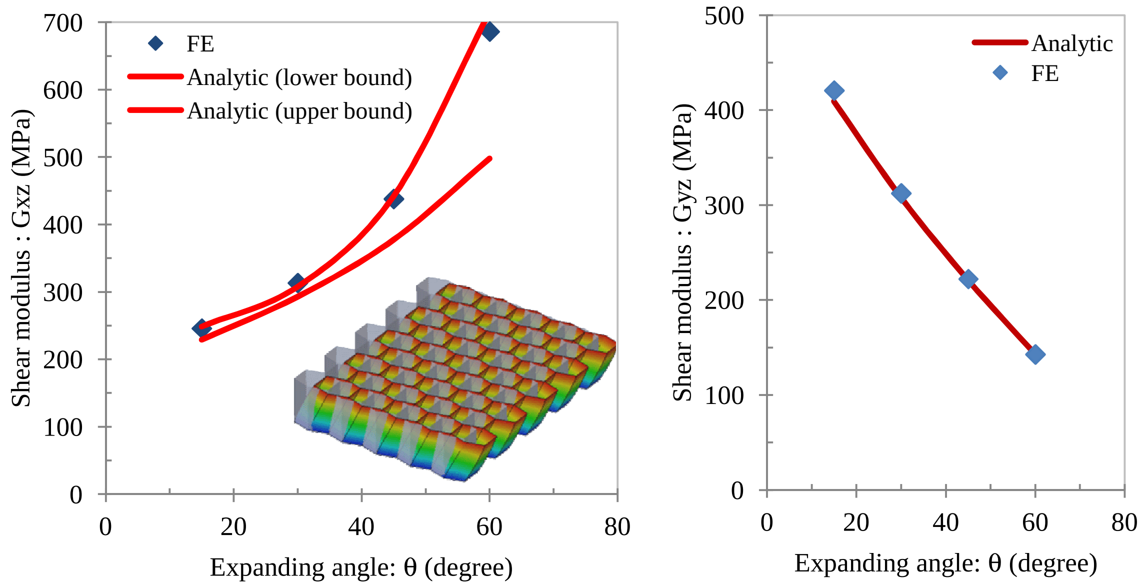


Fig.4 Influence of expanding angle on out-of-plane and in-plane shear moduli

Finally, Poisson's ratio in (x,y) plane reveals great strains in the two directions (x and y), following an applied load in one or the other direction (Fig.5). For the other Poisson's ratios related to z direction, it is clear that strain in this direction is weakness, because of the great stiffness of honeycomb in that direction (Fig.5).

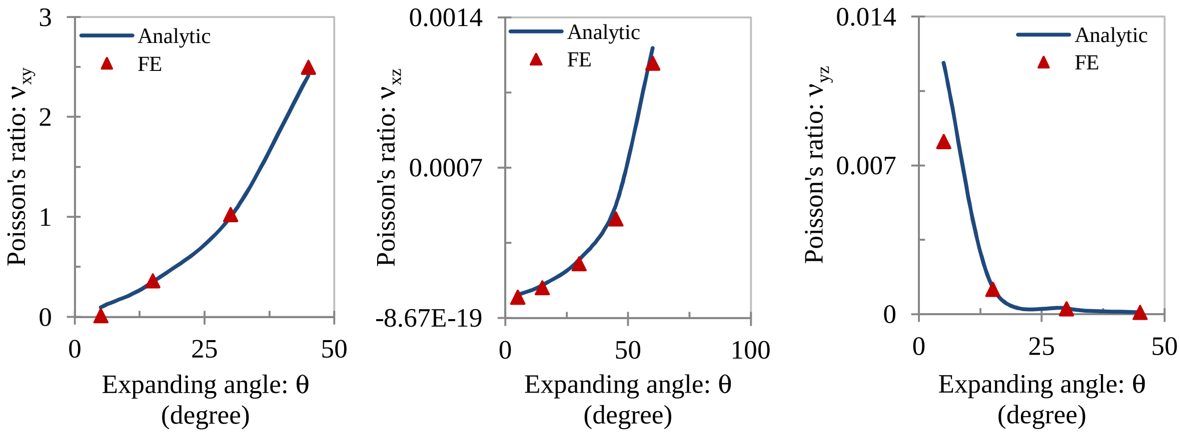


Fig.5 Influence of expanding angle on Poisson ratios

The parametric study associated to the three Young's moduli reveals an increase with regards to wall thickness (t) (linear for E_z and of 1/x function for the two others E_x and E_y, Fig.6). It must be noted that the honeycomb used in this section is constituted by regular polygon cells.

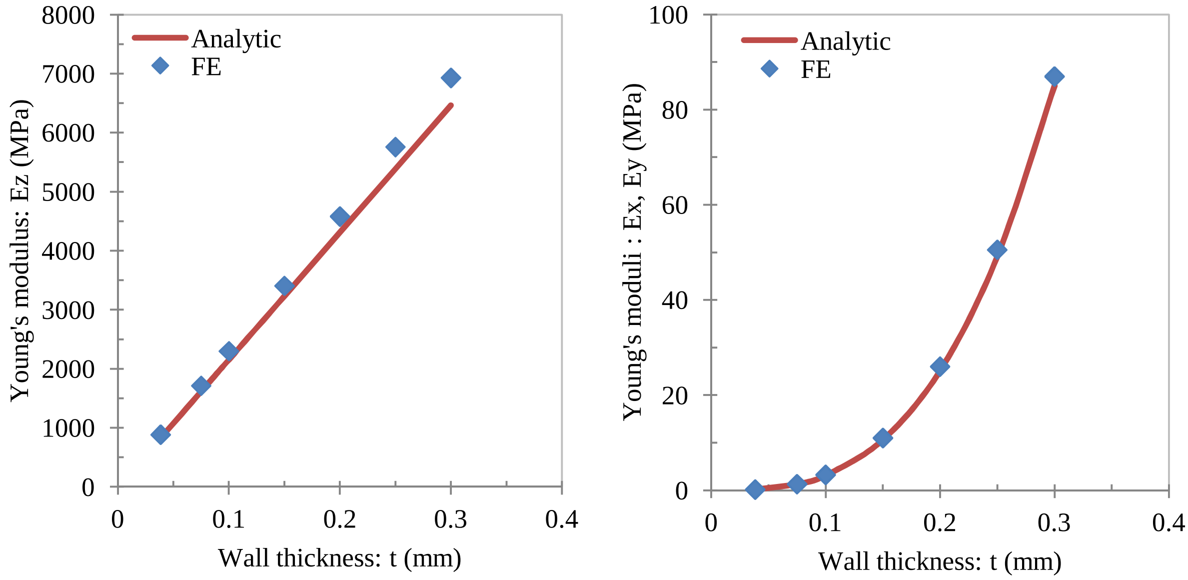


Fig.6 Influence of wall thickness on out-of-plane and in-plane Young's moduli

The growth of edge length ratio (b/a) engenders fall down of E_z and E_y properties, nevertheless E_x increases with this ratio (Fig.7).

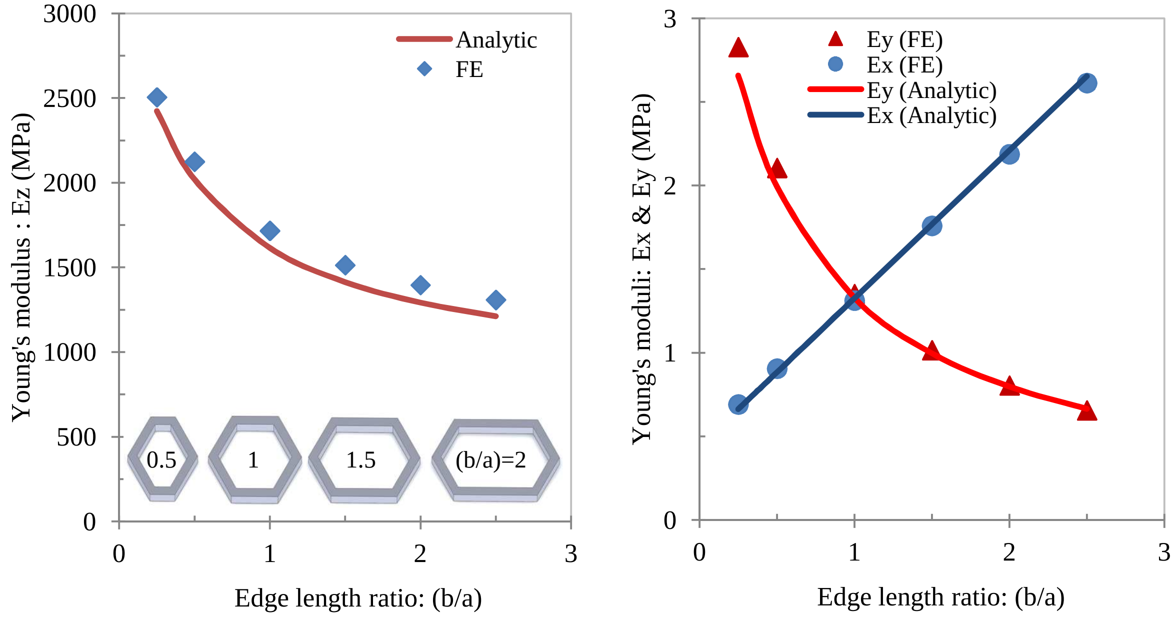


Fig.7 Influence of edge length ratio on out of-plane and in-plane Young's moduli

Comportement mécanique du panneau sandwich

In this section, we considerate the mechanical behavior of sandwich panel in function of some geometric parameters; such as: skin thickness, core expanding angle (θ), core wall thickness (t) and core edge length ratio (b/a).

Figure 8 illustrates linear evolution of Young's modulus according to x direction (Ex) in function of skin thickness. This explains the important effect of skins on in-plane properties. However, the expanding angle θ hasn't a great effect on these properties.

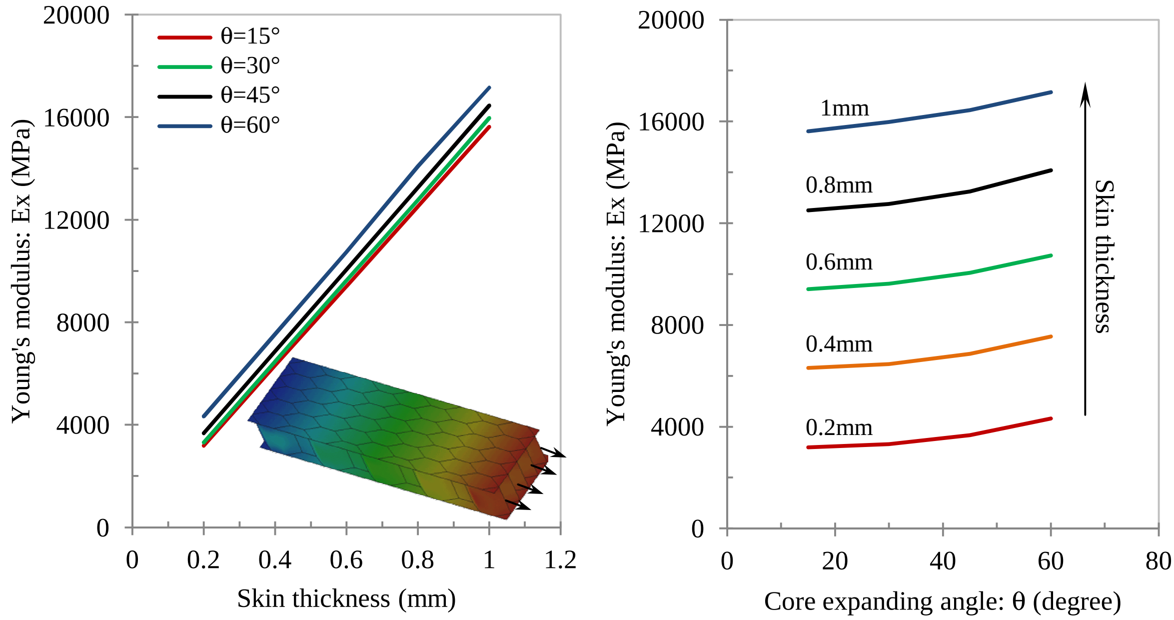


Fig.8 Influence of skin thickness and expandable angle on in-plane Young's modulus (Ex)

Similarly, honeycomb wall thickness has a moderate influence on the in-plane stiffness (Fig.9).

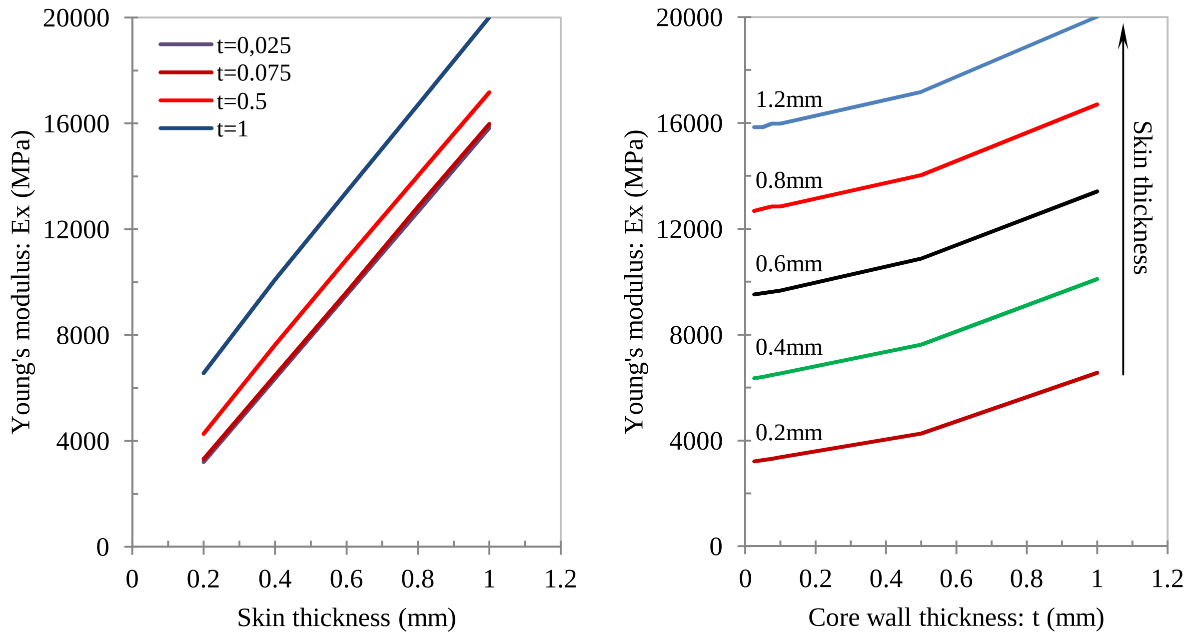


Fig.9 Influence of skin thickness and wall thickness on in-plane Young's modulus (Ex)

The mechanical behavior of panel sandwich is governed mainly by the skins properties. Figure 10 shows clearly this; the core edge ratio hasn't any influence on Young's modulus E_x of the sandwich.

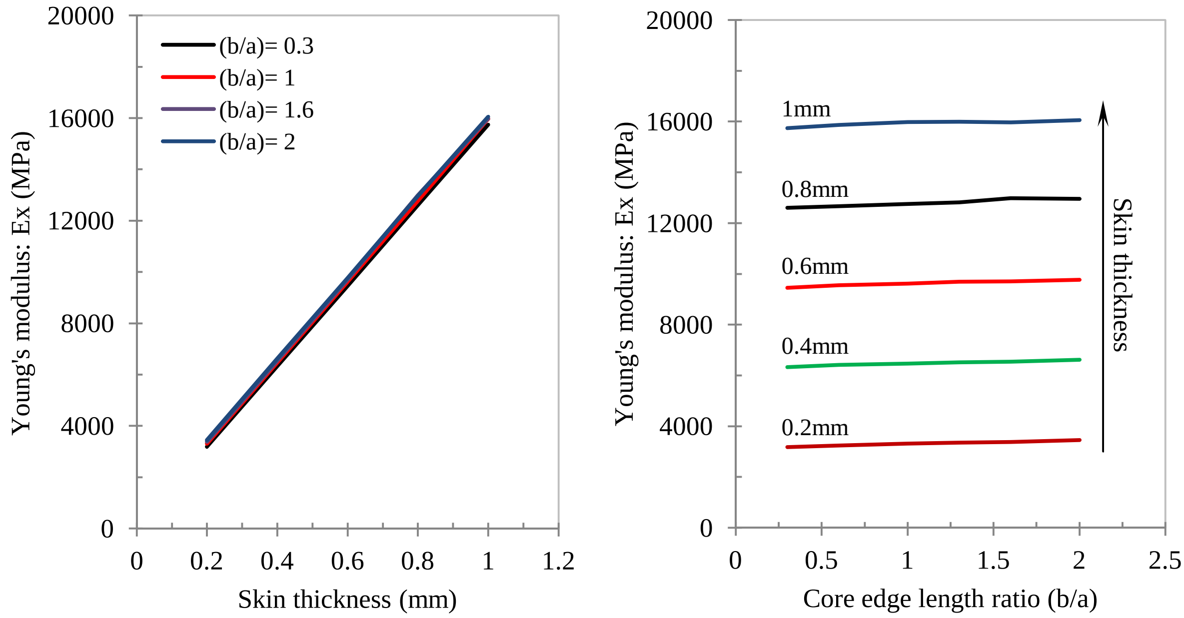


Fig.10 Influence of skin thickness and edge length ratio on in-plane Young's modulus (Ex)

In figure 11 below, we have plotted the in-plane Young's modulus (Ex) for an aluminium plate (skin), a honeycomb core structure and a sandwich panel. It indicates that the skins improve the in-plane properties of honeycomb structures.

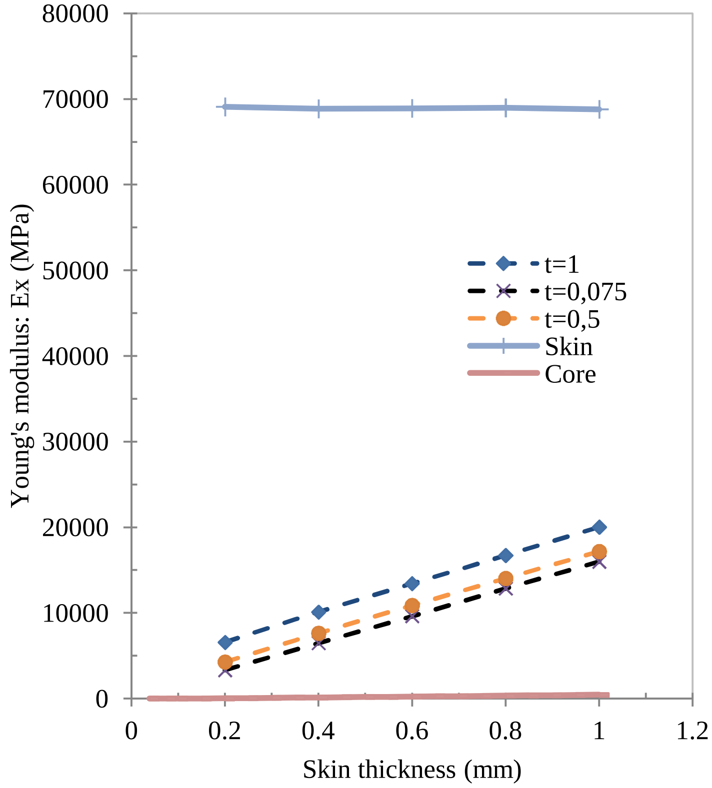


Fig.11 Influence of skin thickness on in-plane Young's modulus (Ex- comparison with those of the skins and core

The virtual simulation of a four point bending test on a sandwich beam shows the deflection of the beam, and a zoom of the central part reveals a cell with the attached skins (Fig.12).

Fig.12 Deflection of beam under four-point bending load

A good agreement can be seen in figure 13, between experimental bending tests (Abbadi, 2009) and the present work based on finite element model.

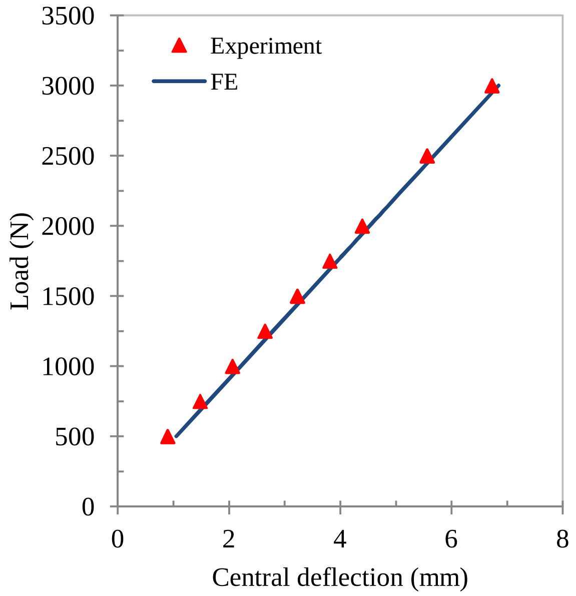


Fig.13 Confrontation diagrammes charge-déplacement under four-point bending (Experiment (Abbadi, 2009) and FE)

The central deflection decreases with cell wall thickness of the honeycomb (Fig.14), which is completely justified. However, the central deflection exhibits growing values when skin thickness decreases.

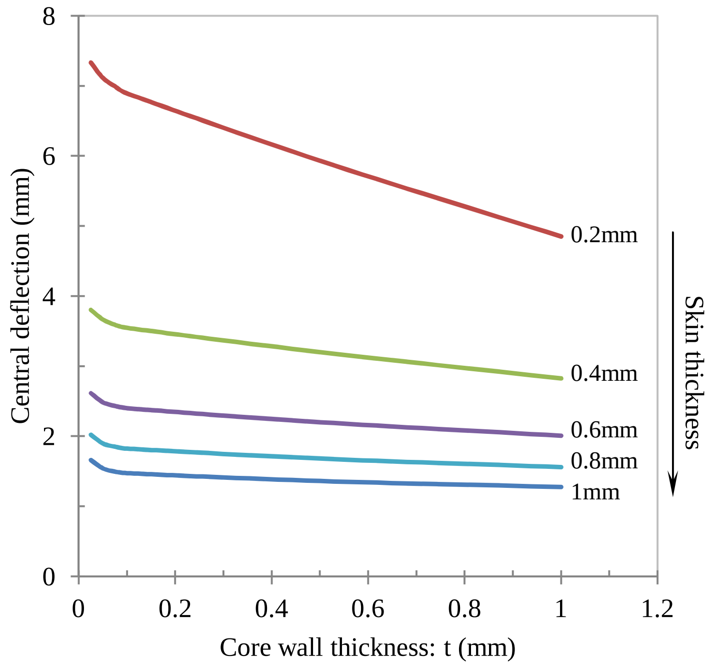


Fig.14 Central deflection vs core wall thickness (four point bending)

Figure 15 shows iso-values of the displacement at the cell level.

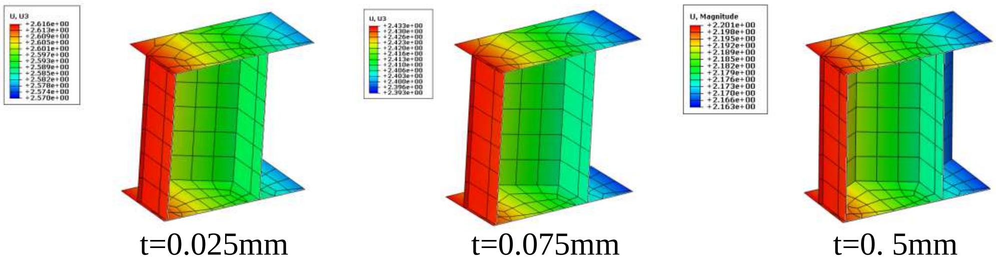


Fig.15 Effect of wall thickness on displacement at the cell level (skin of 0.6mm)

CONCLUSION

This study shows that there is a good agreement between the mechanical properties of honeycomb core and sandwich structure with analytical and experimental results.

E_x and E_y show evolutions inverse one to the other; if one of the properties exhibits growing values, the other shows decreasing values. The cell regular polygon (θ=30°) put on display a quasi-isotropy in (x,y) plane ($E_x \approx E_y$). The curve of "bathtub" shape related to E_z, is due mainly to the cross-section area and its variation in function of θ. Indeed, this area (xy plane) increases when θ takes the values [0° to 30°], and decreases hereafter, what engender a decreasing way of E_z curve until θ = 30°, and then increases after θ = 30°.

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