

# Investigation of mechanical properties of sandwich panels made of paper honeycomb core and wood composite skins by experimental testing and finite element (FE) modelling methods

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**Abstract** In this study, lightweight sandwich panels with different Kraft paper honeycomb core structures and wood composite skins were constructed. The influence of structural parameters, including core shape, cell size, core density, core and web thickness, and material properties of the core and skin layers on the mechanical behavior of these lightweight sandwich panels were studied by experimental testing and finite element modeling methods. The panels were subjected to compression and shear loadings. Test and simulation results indicated that core density and core shape mainly affected the panel stiffness under out-of-plane loading conditions (e.g.  $E_z$ ,  $G_{xz}$  and  $G_{yz}$ ). Material properties of the skin layer affected the panel stiffness both under in-plane and out-of-plane loadings if the skin layer was orthotropic.

## 1 Introduction

Over the years, the furniture industry has been increasingly adopting more and more lightweight sandwich panel type of structures to reduce material cost and product weight. These lightweight panels typically consist of a thicker and

lower density core layer, such as a paper honeycomb, sandwiched between two thinner and higher density skin layers (Petutschnigg and Ebner 2007).

The honeycomb core can have various configurations. A common open cell expanded honeycomb core can be reinforced by adding additional layers of paper along the ribbon direction (Bitzer 1997, Pflug et al. 2003) as the corrugated honeycomb cores (Fig. 1), and its interlaminar shear strength and modulus in the ribbon direction increase greatly by this reinforcement (Palei and Trepelkova 1965). However, the manufacturing process of the corrugated cores is more complicated than that for the expanded honeycomb core and the corrugated cores are more difficult to transport as they can not be folded for shipping (Pflug et al. 2004, Stosch 2008).

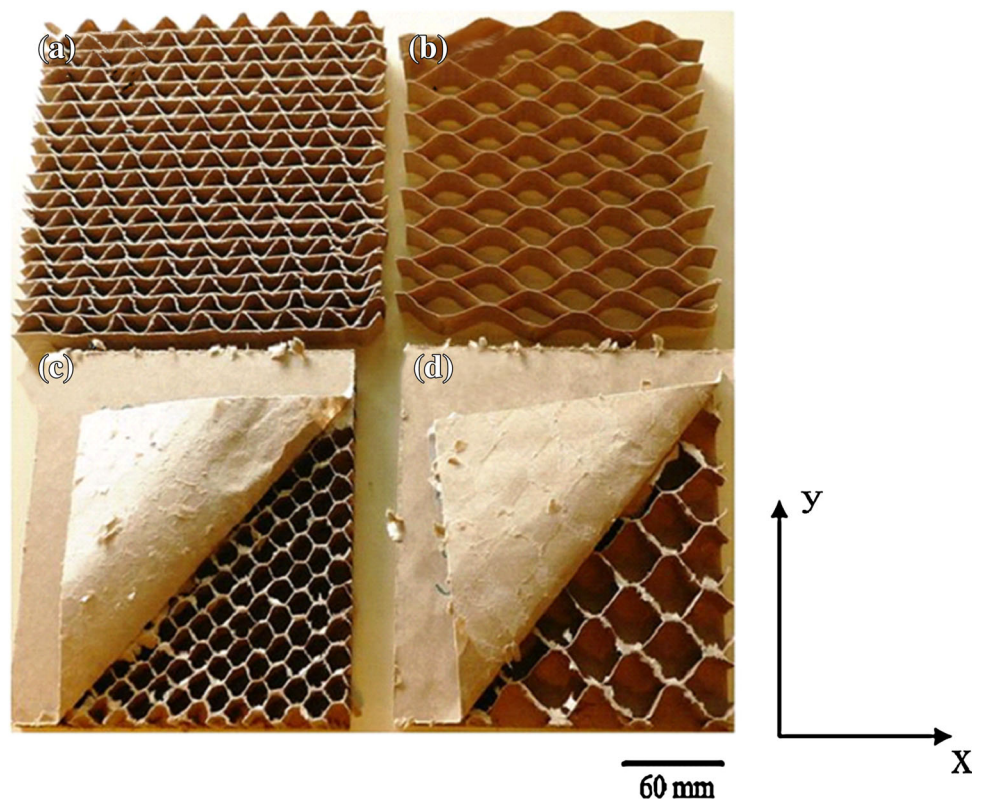
It has been shown previously that when a sandwich panel is subjected to loading, skin layers carry most of the bending and twisting moments as well as in-plane normal and shear forces. Meanwhile, the core layer bears the majority of the out-of-plane flatwise normal and interlaminar shear loads (Plantema 1966, Allen 1969, Lee and Tsotsis 2000, Chen and Yan 2012). Obviously, the core type and density, thicknesses of the core and skin, and their respective material properties will determine the panel's overall strength and stiffness. The fundamental relationships between the structural and material parameters of the panel and overall panel performance are important for development and improvement of sandwich structured products. In this study, a selected number of laboratory test panels were made to elucidate the relationships between the core and skin properties and panel performance. The core parameters to be studied included cell size, cell shape, web thickness, ribbon direction (the orientation of the ribbon sheet defined as x direction in Fig. 1), and core thickness (Sam-Brew et al. 2011). The mechanical properties of the

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**Fig. 1** Four types of Kraft paper honeycomb cores (These Kraft paper honeycomb cores were supplied by Casewell Products Co. in Vancouver, BC, Canada and Pregis Co. in Deerfield, IL USA) used in the test panels: **a** 19.1 mm cell size corrugated honeycomb, **b** 31.8 mm cell size expanded honeycomb, **c** 15.9 mm cell size laminated expanded honeycomb and **d** 31.8 mm cell size laminated expanded honeycomb (Sam-Brew et al. 2011)



test panels were then evaluated according to the corresponding ASTM standards. Unfortunately, it is not possible to source cores that differ only by one structural parameter and access to facilities for making such customized cores is lacking. Finite element (FE) models can help overcome this limitation and make a more general prediction of the influence by the structural and material parameters of the panel components on overall panel performance. Although there are different numerical models used for simulating structural laminates, including sandwich constructions (Vinson 1999), FE method is one of the most cost-effective approaches for analyzing stress in sandwich constructions in terms of both large-scale structural simulations and detailed local deformation analysis. Due to the computational complexity and technical limitation of a detailed 3-D FE analysis, most published computational models on honeycomb sandwiches are either assuming honeycomb cores as a homogeneous continuum model (Noor et al. 1996) or focusing only on the honeycomb core structure itself (Foo et al. 2006, Goswami 2006, Xu and Qiao 2002, Van Vuure et al. 2000). In addition, only a limited number of FE models dealt with complex wood based materials (Gamstedt et al. 2013; Mackenzie-Helnwein et al. 2003).

FE models developed in this study intend to simulate mechanical response of wood based sandwich panels with more detailed considerations of their honeycomb core and skin components. The core and skin in these models can be

either isotropic or orthotropic. Compared to most published FE models in the literature, the FE models developed here contain considerations that are closer to real situations.

## 2 Materials and methods

### 2.1 Panels for specimen preparation

For determining the effects of the shelling ratio (defined as the ratio of the core thickness to skin thickness,  $h_c/t_f$ ) (Chen and Yan 2012) on the sandwich panel properties, six types of laboratory panels with different shelling ratio were made and denoted as Set 1. These test panels were made with skins of 3 or 6 mm thick medium density fiberboards (MDF) and expanded honeycomb core made of Kraft paper with a cell size of 31.8 mm and thicknesses of 12.7, 25.4 or 38 mm. The shelling ratios of these panels were 2.2, 4.3, 6.3, 8.7 and 12.7, respectively. The overall length of each panel was 1,219 mm. The width of each panel was 457 mm and the test span was perpendicular to the ribbon direction of the core. The density and web thickness of the panels were  $9.99 \text{ kg/m}^3$  and 0.13 mm, respectively. Two replicates were made for each combination of skin and core thicknesses for a total of 12 panels.

A second set of panels (eight types), designed as Set 2, for evaluating the influence of core type, cell size, skin

**Table 1** Specimen number, panel structure and component parameter for test panel Set 2

Specimen no. <sup>a</sup>	Panel structure	Core density (kg/m <sup>3</sup> )	Core cell size (mm)	Web thickness (mm)	Skin thickness (mm)
EX3HBX	Expanded core, HB skins	9.99	31.8	0.13	3
EX3HBY					6
EX6HBY					6
LAL3HBX	Laminated core, HB skins	11.53	31.8	0.15	3
LAL3HBY					3
LAS3HBX					3
LAS3HBY	Corrugated core, HB skins	22.01	19.1	0.13	3
CO3HBX					3
CO3HBY					3
EX6PLY	Expanded core, plywood skins	9.99	31.8	0.13	6

<sup>a</sup> The letter X at the end of the specimen name indicates that the ribbon direction of the core was parallel to the long edge of the sample and Y indicates that the ribbon direction was perpendicular to it

materials and ribbon orientation of the honeycomb core on the mechanical properties of the sandwich panel, were made. The construction of Set 2 is indicated in Table 1 and Fig. 1. The overall length and width of Set 2 panels was the same as that of Set 1 panels. The thickness of the core for all panels in this set was kept constant at 25.4 mm. Four panels were made for each core type: two with the ribbon direction in parallel to the length of the panel; and another two with the ribbon direction in perpendicular to the length of the panel. A total of 20 panels were made for this set. The temperature and relative humidity (RH) of the test environment were kept at  $21 \pm 1$  °C and  $70 \pm 2$  %, respectively.

The specimens for compression and shear test were cut from these two Set panels. Each specimen size was described as below.

## 2.2 Flatwise compression test

Sandwich panels measuring  $200 \times 200$  mm<sup>2</sup> were tested for compressive properties according to ASTM C365/C365M-05 (American Society for Testing and Materials (ASTM) 2005) on a Sintech 30/D Universal Testing machine. The samples were placed on an aluminium block as specified by the standard. A standard initial load of 45 N was then applied via a circular loading head and zeroed. A compressive force at a loading speed of 0.5 mm/min was applied and the maximum load borne by the sample was recorded. The panels containing 3 mm thick hardboard

(HB) skins and four types of 25.4 mm thick honeycomb cores as shown in Fig. 1 were tested. Four replicate samples of each type of panel were analyzed.

## 2.3 Edgewise compression test and interlaminar shear test

Edgewise compression and interlaminar shear tests were conducted at FPIInnovations laboratory in Quebec City, Quebec, Canada. The size of the samples was 203.2 mm long by 50 mm wide. The samples were tested in edgewise compression in accordance with ASTM C364 standard (American Society for Testing and Materials (ASTM) 2007). Interlaminar shear samples, 150 mm long by 50 mm wide, were tested in accordance with ASTM D1037 standard method (American Society for Testing and Materials (ASTM) 2006). Four replicates were made for each panel type.

## 3 FE model development

The FE models for the Kraft paper honeycomb core sandwich panels with wood composite skins were developed using the commercial COSMOS WORKS Advanced Professional software (COSMOS Work 2008). In order to evaluate the influence of the sandwich panel's skin and core configurations, FE models for the panels were assembled using two skins and one honeycomb core. In FE models, x represents the ribbon direction of the honeycomb core, i.e. the direction of the continuous honeycomb sheets, y is the direction in which the honeycomb core is expanded (i.e. perpendicular direction to the ribbon direction), and z is the direction parallel to the cell openings in the honeycomb core, i.e. direction along the thickness of the sandwich panel. Four different honeycomb core types (shown in Fig. 1) were simulated by using their corresponding FE models separately. The corrugated honeycomb core samples used for the experiments had reinforced ribbon staggered as mentioned by Bitzer (1997). In order to simplify the calculation, the following assumptions were made for the assembled FE models:

1. The bond between the core and skin is perfect and does not contribute to any additional stiffening or softening of the sandwich panel.
2. The effect of the finite radius of the cell corners is negligible.

The parameters for FE models were determined as follows: (1) The Kraft paper properties reported by Karademir et al. (2004) were used as Modulus of Elasticity (MOE) of the paper for the honeycomb core in the x direction  $E_{cx}$  and MOE of the core materials in the y direction as well as  $E_{cy}$

for the FE models for Kraft paper expanded honeycomb core. MOE of the paper for the honeycomb core in the z direction  $E_{cz}$ , and shear moduli of the core materials under the interlaminar shear force in the x and y directions,  $G_{cxz}$  and  $G_{cyz}$ , were determined by changing these parameters in the FE models independently until the respective MOE and shear moduli of paper honeycomb core layer simulated by the FE model had a satisfactory fit with the flatwise compression and interlaminar shear test results of paper honeycomb core layer obtained from Advanced Honeycomb Technologies Inc. (2007). (2) Material properties of HB, MDF, and plywood, such as MOE of skin material along x, y, and z directions, i.e.  $E_{fx}$ ,  $E_{fy}$ , and  $E_{fz}$ , shear moduli of the skin materials under interlaminar shear force in the x direction,  $G_{fxz}$  and  $G_{fyz}$ , and shear moduli of the skin materials under the edgewise shear force,  $G_{fxy}$ , were taken from references by Youngquist (1999), Chow et al. (1996) and Bodig and Jayne (1982).  $E_{cx}$  and  $E_{cy}$  of the Kraft paper for corrugated honeycomb core and laminated honeycomb core were taken from Karademir et al. (2004).  $E_{cz}$ ,  $G_{cxz}$  and  $G_{cyz}$  of these two types of cores were deduced by varying these parameters individually until  $E_{cz}$ ,  $G_{cxz}$  and  $G_{cyz}$  of the FE model predictions fit with the test results for edgewise compression and interlaminar shear of the panels containing the same type of cores and hardboard skins. The type of materials and their material properties used by the FE models are summarized in Tables 2 and 3.

$G_{cxy}$  in Table 2 is shear modulus of the core materials under the edgewise shear force. Poisson's ratio for Kraft paper in this study was assumed to be 0.4 according to the literature (Chen and Yan 2012, Schulgasser 1981). Poisson's ratio of the MDF skins was assumed to be 0.2 based on literature values (Youngquist 1999, Noboru and Taeko 2004, Ganey et al. 2005). The cell size, paper thickness, and thickness of the core and skin were set in accordance with the dimensions of the tested specimens during the FE

simulation. Since the structural features of the sandwich panels included in this study were comprised of closed honeycomb cell structures with thin cell walls and skins, as well as the fact that MOE and shear modulus of the panel in three orientations (under both in-plane and out-of-plane loadings) were the target properties to be modeled, only solid elements instead of shell elements were used to mesh the FE model using the COSMOS software (Aydingak and Kayran 2009). Because the effect of local warping on panel's mechanical properties, such as  $G_{xz}$  and  $G_{yz}$ , would be different for cells located in different parts of the panel, the FE models developed in this study all have two cells located away from the edge to cover all possibility. The length and width of the models were set to be between 73 and 162 mm, and between 46 and 96 mm, respectively, so that each FE model contained 15 honeycomb cells as shown in Fig. 1. Ten node parabolic tetrahedral solid elements of COSMOS software were used to ensure sufficient calculation accuracy in the FE models. The core and skin of the panel model were meshed together as one entity. The Voronoi-Delaunay meshing scheme was used for subsequent meshing operations. The FFE Plus solver with an advanced matrix reordering technique was used in the simulation (COSMOS Work 2008). By increasing the mesh density and re-analyzing the model until the results converge satisfactorily, the number of elements for each model was set to be between 19,459 and 66,505; the number of nodes was limited to between 36,343 and 131,970. The element size of each FE model was between 1.6 and 3 mm with a tolerance between 0.08 and 0.15 mm. The contact points or edges of the skin and core were considered to be coincidental because the skin and the core were assumed to be perfectly bonded. During the simulation of the panel's response under flatwise compression or edgewise shear, the surface of one skin was considered as a fixed face, while the surface of the opposite skin was allowed to move along

**Table 2** Mechanical properties of different types of honeycomb core used for the FE models

Honeycomb core type	$E_{cx}$ (MPa)	$E_{cy}$ (MPa)	$E_{cz}$ (MPa)	$G_{cxy}$ (MPa)	$G_{cyz}$ (MPa)	$G_{cxz}$ (MPa)	Web density (kg/m <sup>3</sup> )
Expanded	1,700	1,700	576	110	646	2,500	915
Laminated	1,700	1,700	169	110	161	593	915
Corrugated	1,700	1,700	169	110	161	593	915

**Table 3** Mechanical properties of different types of wood composite skins used for the FE model

Skin type	$E_{fx}$ (MPa)	$E_{fy}$ (MPa)	$E_{fz}$ (MPa)	$G_{fxy}$ (MPa)	$G_{fyz}$ (MPa)	$G_{fxz}$ (MPa)	Density (kg/m <sup>3</sup> )
HB	3,410	3,410	3,410	341	341	341	900
MDF	2,064	2,064	2,064	206	206	206	700
Plywood	1,251	100	63	89	84	8.4	600

MOE and shear modulus data were taken from Youngquist (1999), Chow et al. (1996) and Bodig and Jayne (1982)



a particular direction in accordance with the loading direction. During the simulation of the panel’s response under edgewise compression or inter-laminar shear, one end of the panel was fixed, while the opposite end of the panel was allowed to move along the loading direction. In each simulation, the translation value for the loaded face of the sandwich panel was set at 0.5 mm. The movement in any other direction other than the loading direction was set to be zero.

### 4 Results and discussion

#### 4.1 Comparison of the FE predicted panel stiffness with the experimental measurements

The experimental data and FE model predicted results for the sandwich panels are shown in Figs. 2, 3, 4, 5. Error bars in all figures represent  $\pm 1$  standard deviation. Overall there

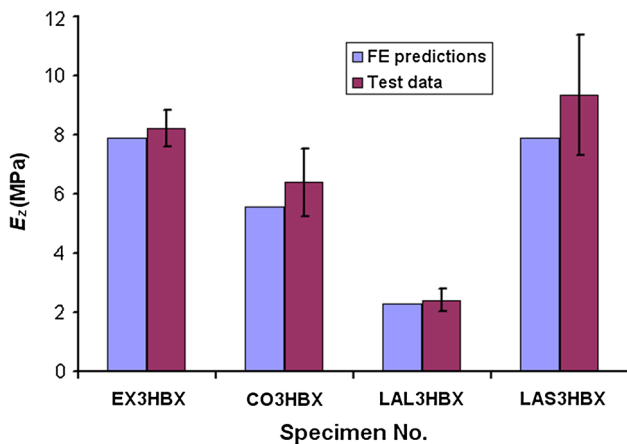


Fig. 2 Comparison of FE predictions with the measured  $E_z$  of test panels containing different core structures

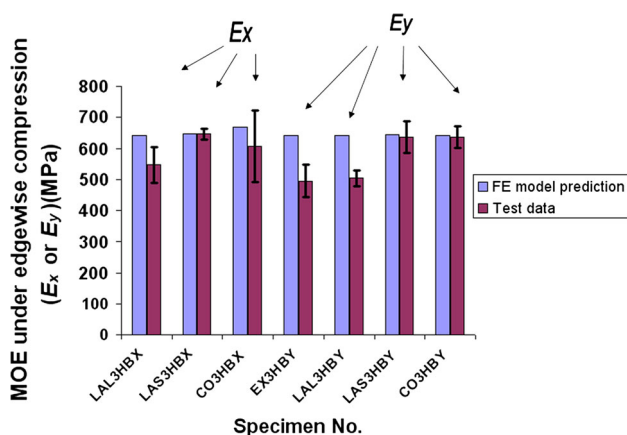


Fig. 3 Comparison of the FE predictions with the measured MOE of panels with different core structures under edgewise compression

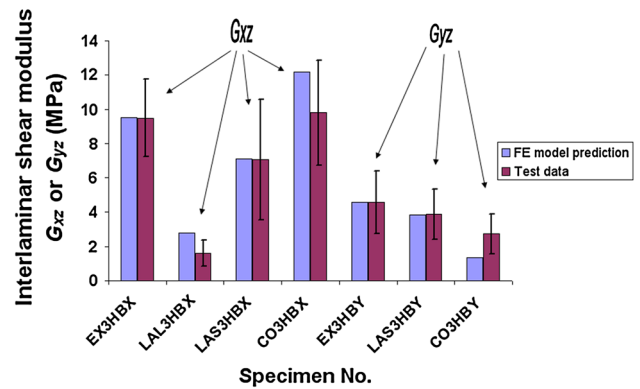


Fig. 4 Comparison of the FE predictions with the test data of interlaminar shear modulus of panels with different core structures

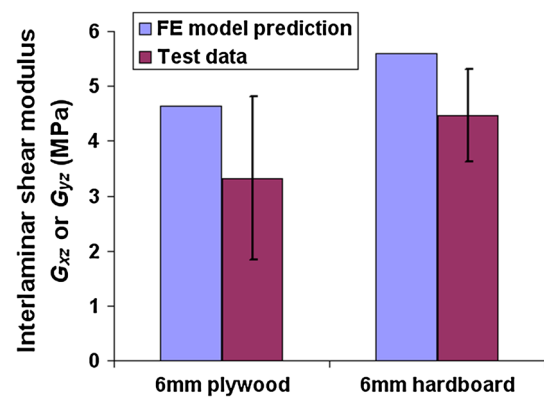


Fig. 5 Comparison of the FE predictions with the measured  $G_{xz}$  or  $G_{yz}$  of panels with different skin materials

were good agreements between the measured results and the model predictions even though some discrepancies were observed. For example, differences were noted between the predicted and measured MOE of the sandwich panel perpendicular to ribbon direction under the edgewise compression  $E_y$  for the panel containing 31.8 mm cell size expanded honeycomb core and 3 mm thick HB skins (Specimen EX3HBY in Fig. 3). The difference may be due to the inaccuracies in the measurement of the cell size of the expanded honeycomb core, or skin properties or defects in bonding between the core and skin.

The experimental results for the sandwich panel containing MDF skins and 31.8 mm cell size Kraft paper expanded honeycomb core of various thickness values agreed reasonably well with the FE model predictions (Figs. 6, 7). The regression analysis suggested that  $E_y$  was a power function of  $h_c/t_f$ . For panels with the 31.8 mm cell size expanded honeycomb core, the relative difference between the measured and the model predicted data for  $G_{yz}$  was larger than that for  $E_y$ . Since interlaminar shear load is carried more by the core,  $G_{yz}$  is much more sensitive to the properties of the core. Any change in core shape, size or

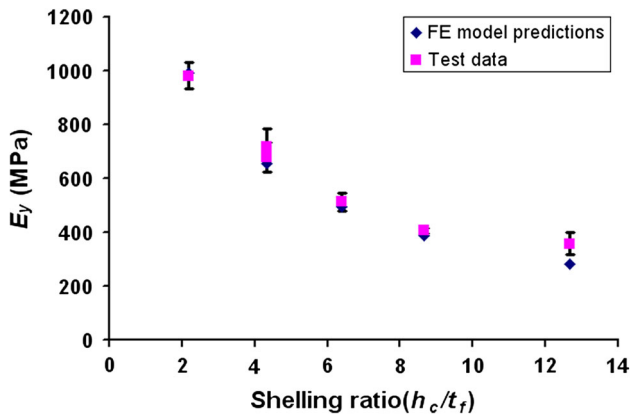


Fig. 6 Comparison of the FE predictions with the measured  $E_y$  of panels with different shelling ratios

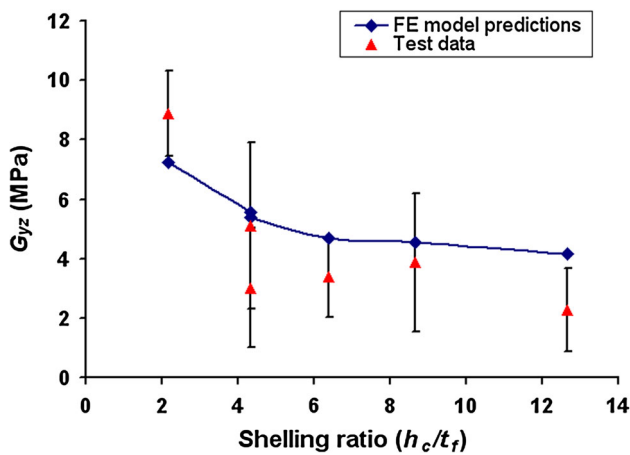


Fig. 7 Comparison of the FE predictions with the measured  $G_{yz}$  of panels with different shelling ratios

web thickness will change the core density and affect the computed  $G_{yz}$ . For example, differences in the position of the cell walls with respect to the loading points in testing caused noticeable variability in the measured  $G_{yz}$  values, indicated by the large standard deviations in the test data. However, the predicted  $G_{yz}$  values still lay within the range of the standard deviation of the test data (Fig. 7).

Experimental results indicated that the panels made with either a small cell size (15.9 mm) or a corrugated honeycomb core had the higher MOE, shear modulus, compressive and shear strengths (see  $E_z$  and  $G_{yz}$  of specimen LAL3HBX, LAS3HBX and CO3HBX in Figs. 2, 4). However these higher stiffness and strength are not necessarily due to the smaller cell size in the core because honeycomb core density is not only determined by the cell size and shape, but also by the web thickness. For example, a honeycomb core with a smaller cell size may also have a lower core density than a honeycomb core with a larger cell size if the smaller cell size core has a thinner web thickness.

## 4.2 Analysis of results by FE modeling

### 4.2.1 Influence of the core density

Four FE models for panels with different web thicknesses were established to investigate two scenarios. The core and skin materials for these models were 26 mm thick Kraft paper expanded honeycomb and 3 mm thick HB, respectively. In one scenario, two of these models had different core cell size, but the core density of these two panels was the same at  $44.03 \text{ kg/m}^3$ . Their MOE and shear moduli values under in-plane and out-of-plane loadings of the panels were simulated and were found to be the same (Table 4). In another scenario, core density was different while the core cell size was the same at 31.8 mm in the FE models. Simulation results showed that an increase in the core density increased the panels' interlaminar shear moduli and MOE under flatwise compression. Changing the core density did not affect the MOE and shear modulus under the in-plane loading, i.e. MOE of the sandwich panel in ribbon direction under the edgewise compression  $E_x$  and Shear modulus of the sandwich panel under the edgewise shear load  $G_{xy}$  shown in Table 5. These two scenarios illustrated that core density and not cell size had a major impact on the stiffness of the sandwich panel under out-of-plane loading conditions when the core had the same shape.

### 4.2.2 Influence of an orthotropic core

In this study, it was found that by experimental testing and FE simulation sandwich panels had isotropic response under the in-plane loading conditions and became

Table 4 Comparison of stiffness of two panels that have different core cell sizes and web thicknesses with the same core density as predicted by the FE models

Core cell size (mm)	Web thickness (mm)	$E_z$ (MPa)	$E_y$ (MPa)	$G_{yz}$ (MPa)	$G_{xy}$ (MPa)
15.9	0.29	10.06	644.76	4.72	228.55
20.3	0.37	10.07	645.08	4.86	228.64

Both panels were made from the expanded core and HB skins

Table 5 Comparison of stiffness of two panels that have different core densities and web thicknesses with the 31.8 mm cell size as predicted by the FE models

Core density ( $\text{kg/m}^3$ )	Web thickness (mm)	$E_z$ (MPa)	$E_x$ (MPa)	$G_{xz}$ (MPa)	$G_{xy}$ (MPa)
11.53	0.15	2.68	642.85	2.81	218.77
22.01	0.29	5.05	644.74	5.31	218.61

Both panels were made from the expanded core and HB skins

orthotropic when subjected to the out-of-plane loading conditions. In practice, a sandwich panel might be loaded either under bending or under torsion with the skin of the panels carrying most of the load. Therefore, the properties of the skin materials played a key role in determining the products performance. The orthotropic nature of a panel's core could be neglected under these loading conditions. However, in some cases, such as in flooring applications, both in-plane loading and out-of-plane loading could be present to cause some localized deformation and damage in the panels, e.g. the local deformation and damage of the floor caused by bending or interlaminar shear due to a concentrated static load (Tsotsis and Lee 1996, Chen et al. 2008). Orthotropic property of the core should therefore be considered in those types of applications.

#### 4.2.3 Influence of the core structure

Table 6 summarizes the FE model predicted MOE and shear modulus of the panels with four different core structures as predicted by the FE models. For illustrating the influence of the core structure, simulated results of LAL3HB2X and LAL3HB2Y were added to Table 6 to compare with the results of LAL3HBX and LAL3HBY, respectively. The samples had the same cell size but different core densities. The results indicated that MOE under edgewise compression and edgewise shear modulus of these four types of sandwich panels were similar. However, MOE under flatwise compression and interlaminar shear modulus of these panels were affected by the core type. Panels with the corrugated honeycomb core had a lower  $G_{yz}$  and a higher  $E_z$  and  $G_{xz}$  than the panels with 31.8 mm cell size laminated expanded honeycomb core, even though both cores had the same core density. This showed that the shape of the core instead of the core density affected mainly  $E_z$ ,  $G_{xz}$  and  $G_{yz}$  (see  $G_{xz}$ ,  $G_{yz}$  and  $E_z$  of specimen

LAL3HB2X, LAL3HB2Y, CO3HBX, and CO3HBY in Table 6).

Some earlier work (Bitzer 1997, Allen 1969) indicated that corrugated honeycomb core panels had not only higher flatwise compression strength and interlaminar shear strength, but also higher MOE and shear modulus under the out-of-plane loading conditions than the expanded honeycomb core panels. Similarly, in this study,  $E_z$  of the corrugated honeycomb core panels was higher than that of the laminated expanded honeycomb panels when their core densities were similar. However, this research also showed that the corrugated core would not necessarily result in higher panel stiffness than the expanded core because panels with the corrugated core were more orthotropic than the panel with the expanded core (Fig. 4). Both the model predicted and experimentally measured interlaminar shear modulus data showed that the  $G_{xz}$  of the panels with the corrugated core was much larger than the expanded core panels of the same core density.  $G_{yz}$  of the corrugated core panel was smaller than some of the expanded core panels even when the density of the panel was higher (e.g. comparison of  $G_{yz}$  of specimen CO3HBY with that of specimen EX3HBY in Fig. 4 and Table 6).

#### 4.2.4 Influence of skin materials

It was mentioned earlier that the material properties of the skin could significantly affect the stiffness of the panels under in-plane loading conditions. The FE model predictions for panels with different skin materials showed that an increase in the stiffness of the skin only resulted in a higher  $E_x$ ,  $E_y$  and  $G_{xy}$  of the panel when the skin material was isotropic (e.g. HB and MDF).  $E_z$ ,  $G_{xz}$  and  $G_{yz}$  of the panel did not change significantly. For example, comparing the Kraft paper expanded honeycomb core sandwich panel made of a 3 mm thick MDF skin with the panel that had a

**Table 6** Stiffness of the panels with different honeycomb core structures

Specimen no. <sup>a</sup>	Core density (kg/m <sup>3</sup> )	Web thickness (mm)	$E_z$ (MPa)	$E_x$ or $E_y$ (MPa)	$G_{xz}$ or $G_{yz}$ (MPa)	$G_{xy}$ (MPa)
EX3HBX	9.99	0.13	7.91	643.16	9.51	218.84
EX3HBY			8.05	641.78	4.58	227.46
LAS3HBX	34.59	0.23	7.86	645.73	7.09	218.39
LAS3HBY			8.02	644.54	3.83	228.33
LAL3HBX	11.53	0.15	2.68	642.85	2.81	218.77
LAL3HBY			2.72	641.82	1.33	227.45
LAL3HB2X <sup>a</sup>	22.01	0.29	5.05	644.74	5.31	218.61
LAL3HB2Y <sup>a</sup>			5.14	642.98	2.52	227.89
CO3HBX		0.13	6.67	669.24	12.19	217.92
CO3HBY			6.52	641.61	1.37	229.50

<sup>a</sup> The cell size of core, thickness of core and skin of LAL3HB2X and LAL3HB2Y are the same as that of LAL3HBX and LAL3HBY

**Table 7** Comparison of the stiffness of two honeycomb panels with different skin materials

Skin material	$E_z$ (MPa)	$E_x$ (MPa)	$E_y$ (MPa)	$G_{xz}$ (MPa)	$G_{yz}$ (MPa)	$G_{xy}$ (MPa)
3 mm thick MDF	8.03	–	388.88	–	4.56	137.78
3 mm thick HB	8.05	–	641.78	–	4.58	227.46
6 mm thick Plywood	7.80	396.42	396.00	2.88	4.63	19.70
6 mm thick MDF	9.51	654.49	654.00	9.10	5.40	231.85

3 mm thick higher stiffness HB skin (both panels had 25.4 mm thick core, 0.13 mm thick core web and 31.8 mm in core cell size), the panel's stiffness under the out-of-plane loading ( $E_z$  and  $G_{yz}$ ) was quite similar. However, the stiffness under the in-plane loading ( $E_y$  and  $G_{xy}$ ) was very different (Table 7). If the skin materials were orthotropic (such as the case for plywood), the material properties of the skin affected the stiffness of the panel under both in-plane and out-of-plane loadings. For example, the expanded honeycomb core sandwich panel with a 6 mm thick plywood skin had a lower  $E_x$ ,  $E_y$ ,  $G_{xy}$ ,  $E_z$  and  $G_{xz}$  than the panel with a 6 mm thick MDF skin when the core cell size, core thickness and core web thicknesses were the same at 31.8, 25.4, and 0.13 mm, respectively (Table 7).

It has been known that the skin of a sandwich panel supports mostly in-plane loading while the core bears mostly out-of-plane loading (Lee and Tsotsis 2000). According to the classic sandwich theory (Allen 1969), skins were supposed to affect the stiffness of the sandwich panel under the in-plane loading only. In their study, the skin was isotropic. However, it was shown in this study that if the skin material was orthotropic, skin properties could also influence the stiffness of the sandwich panel under both in-plane and out-of-plane loadings (Table 7). A possible explanation might be that when the shelling ratio is below or equal to a certain value (4.33 in this particular study), skin deformation would start to affect the whole panel deformation due to the unbalance.

#### 4.2.5 Influence of the panel thickness

Bitzer (1997) mentioned that core thickness affected neither compressive strength and modulus nor shear modulus of aluminum honeycomb core sandwich panels. He also noted that thicker panels had lower shear strengths. Zhang and Ashby (1992) work showed that out-of-plane strength (compression and shear) was independent of the thickness of the honeycomb core and only depended on the core density. However in this study, the effect of the panel

thickness on the panel stiffness or strength was not apparent, rather it was shown that only  $h_c/t_f$  affected the stiffness of the panel.

## 5 Conclusion

In this study, the influence of structural and material parameters of the core and skin components on the mechanical properties of sandwich panels was investigated experimentally and numerically. It was shown that honeycomb core density affected mainly the stiffness of the panels under the out-of-plane loading conditions (e.g.  $E_z$ ,  $G_{xz}$  and  $G_{yz}$ ) for the core shapes that were the same. However, a higher core density did not always increase the panel stiffness when the cell shape was different in the core. Kraft paper corrugated honeycomb core panel had a higher  $G_{xz}$  than the panels with other types of Kraft paper honeycomb cores even if the core density of these panels was equal to or higher than that of the corrugated core. However, perpendicular to the ribbon direction,  $G_{yz}$  of the corrugated honeycomb core panels was lower than that of the expanded honeycomb core panels even if the density of the corrugated core was equal to or higher than that of the expanded core.

For isotropic skin materials, material properties of the skin mainly influenced the stiffness of the sandwich panel under in-plane loadings. However if the skin material was orthotropic, material properties of the skin affected the stiffness of the panel under both in-plane and out-of-plane loadings when the skin thickness relative to the core thickness was equal to or greater than a threshold value.

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