Preliminary Experiments on the Manufacture of Hollow Core Composite Panels

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Abstract

Structural honeycomb panels consist of a lightweight, often paper, honeycomb column core between two thin, stiff face sheets, which results in a very light structure with high strength and stiffness. These panels have long been used in the shipping and aerospace industries and for furniture components in Europe. The wider adoption of honeycomb panels by Canadian furniture manufacturers is hampered by a lack of experience and technical data on their manufacture, properties, and performance. This study attempts to address this missing information with a series of experiments to test the influence of Kraft paper honeycomb type, orientation, cell wall height, and face sheet type on sandwich strength properties (flexural, shear rigidity, and panel deflection).

Failure of sandwich panels occurs by buckling of the honeycomb cell walls under the load point; panel load-bearing capacity is significantly improved by the use of stiff face sheets such as plywood. The strongest and stiffest panels are made with small honeycomb cells (16 mm). The extra cost and bulk associated with using paper-laminated pre-expanded honeycomb is not matched by increased bending strength and is therefore unnecessary. Bending strength is significantly enhanced by aligning the honeycomb so that the nodes and ribbon direction are perpendicular to the long axis (loading direction) of the panel due to the ability of the core to flex and conform to the curvature of the face sheets under load. The results from this study offer insights that furniture manufacturers may use to fabricate and potentially improve the properties of honeycomb sandwich panels.

Light-weight honeycomb sandwich technology has been in existence for decades in the aerospace, shipping, and transportation industries. The structure of honeycomb sandwich panels follows a basic pattern: two face sheets that are relatively thin yet strong enclose a thick and lightweight core. A number of studies have been conducted on the panel characteristics and strength properties of several honeycomb core materials in conjunction with different face materials (National Aeronautics and Space Administration 1969, Worrell and Wendler 1976, Chong et al. 1979, Desayi and El-Kholy 1991, Hassinen et al. 1997, Petras and Sutcliffe 1999, Vaidya et al. 2000, Côte et al. 2004, Murthy et al. 2006, Foo et al. 2008). Only a few of these studies have focused on using wood materials and/or composites for both the face and core materials (Wood 1958, Fahey et al. 1961, Pflug et al. 2002, Barboutis and Vassiliou 2005).

The manufacture and use of Kraft paper honeycomb panels for furniture and cabinetry is further advanced in Europe than in North America (Egger Eurolight 2007, Stosch 2008). However, there is increasing interest in North America to use this technology for the manufacture of commodity and specialty furniture (Busch 2004), which until recently was made from either solid wood or composite board. Consider, for example, ready-to-assemble furniture manufactures; they have a strong desire for lighter weight components to reduce materials input and transportation costs and to make handling and installation of the furniture easier. Honeycomb core panels can potentially provide the necessary strength and stiffness in a wide range of thicknesses for parts such as table tops and shelving at a fraction of the weight—as much as a 70 percent reduction (Wisdom 2005). This represents a significant savings on the wood and resin required to produce the parts from solid

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composite wood, with the additional benefit of lower formaldehyde emissions over the product's service life.

Hampering the wider adoption of honeycomb panels for furniture in Canada is the lack of domestic manufacturers of acceptable stock panels. This requires furniture manufacturers to custom fabricate their own panels on site, which reduces the time and resources available for their primary task of making furniture or components. Investment in domestic fabrication of hollow core stock panels is in turn hampered by a general lack of knowledge and data pertaining to the fabrication, properties, and performance of honeycomb panels made from locally available face and core materials.

This project aimed to fill this knowledge gap by constructing and testing Kraft paper honeycomb sandwich panels, using domestic face and core materials in several thicknesses, and identifying zones of weakness and significant problems (if any) that might hamper their adoption in the modular furniture industry. Two hypotheses were posed:

1. A combination of thick face sheets and Kraft paper honeycomb cores of small cell size will produce panels with high strength and stiffness values.
2. The orientation of the Kraft paper core in the sandwich panel will have no significant effect on the resulting panel properties since the core is made of a weak and low-density material.

Sandwich Structural Design

Four different kinds of honeycomb core material, (1) Verticel, (2) open cell expandable paper honeycomb, (3) paper-laminated small cell, and (4) paper-laminated large cell, were supplied by local North American manufacturers (Casewell and Pregis) and are shown in Figure 1. The small cell (sc) paper-laminated honeycomb had a cell size of 16 mm; the large cell (lc) paper-laminated, 32 mm; the open cell expanded honeycomb, 32 mm; and the Verticel, 13 mm. The density of the core materials and thickness of the paper base used in each core type are given in Table 1, and the standard structure of the hexagonal paper honeycomb cores (not Verticel) is shown schematically in Figure 2. The axis running along the continuous sheets of paper in the paper machine direction is termed the ribbon or x direction, while the axis running across the paper ribbons in which the core is expanded is the y direction.

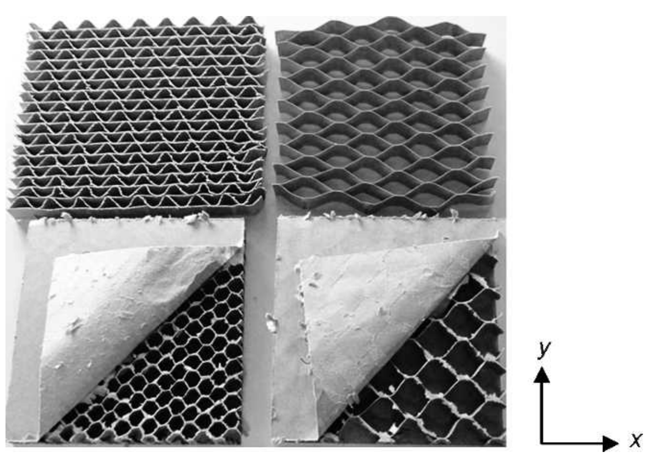

Figure 1.—The appearance of the four honeycomb core types: (top left) 13-mm Verticel, (top right) 32-mm open cell expanded honeycomb, (bottom left) 16-mm paper-laminated honeycomb, and (bottom right) 32-mm paper-laminated honeycomb. All cores have the ribbon direction oriented horizontally (left to right).

Table 1.—Physical properties of the honeycomb core materials used.

Honeycomb core type	Honeycomb density (kg/m^3)	Cell size (mm)	Base paper thickness (mm)[a]
Open cell expanded	10.03	32	0.13
Paper-laminated large cell	24.00	32	0.15, 0.15
Paper-laminated small cell	47.41	16	0.15, 0.30
Verticel	24.88	13	0.13

[a] The paper-laminated core materials have two paper thicknesses—the paper laminate and the base paper thickness.

To make the sandwich panels, seven face sheet materials that are commonly used in the furniture industry were selected based on a survey of the Canadian market (Semple et al. 2007) and purchased from local building supply stores. The panel types were 3-mm hardboard, 6-mm hardboard, 3-mm Masonite, 3-mm medium-density fiberboard (MDF), 6-mm MDF, 4.5-mm Meranti plywood, and 6-mm Douglas-fir plywood. The plywood materials were both 3 ply, the Douglas-fir plywood was made with phenol formaldehyde resin, and the Meranti with urea formaldehyde resin. Sandwich panels were fabricated using DURO-LOK 422150 (a cross-linked polyvinyl acetate containing phenolic resins and no catalyst—none is required for interior purposes), an adhesive used for gluing solid and hollow core doors.

The physical properties of the face sheets (in the machine direction) and honeycomb cores were measured in a three-point bending test on an Instron Universal testing machine to determine modulus of rupture (MOR) and modulus of elasticity (MOE) for both the core and face materials. These tests were conducted in accordance with the American Society for Testing and Materials (ASTM) Standards D1037-99 (ASTM 1999), C393-00 (ASTM 2000), and C365/C365M-05 (ASTM International 2005). Four replicates were prepared for the core materials and 12 for the face sheet materials. It was not possible to obtain MOR and MOE values for the open cell honeycomb types (Verticel and open cell expanded) because they had no continuous top or bottom surface. These samples deformed easily by hand with essentially no resistance to bending; therefore, the physical properties of only the paper-laminated honeycomb cores were measured.

Before expansion, the top and bottom edges of the unexpanded Kraft paper honeycomb were roughened with a sand block using 80-grit sandpaper to increase the surface area exposed to the adhesive. Shallow incisions (about 2 mm deep) at spaced intervals along the length of the honeycomb strip were made using a band saw to create pathways for air flow and moisture migration during and after pressing. The core material was then evenly expanded by hooking (lengthwise) the cells on each end to nails spaced at intervals of 44.5 mm on a 1,219.2 by 2,438.4-mm (4 by 8-ft) oriented strand board. To set the honeycomb in its expanded form, the boards were placed in a walk-in oven (8 by 6 by 4.5 ft) for 3 hours at 80°C. The core materials were allowed to cool overnight before removal from the boards because they tend to return to an under-expanded state as they reabsorb moisture if removed immediately.

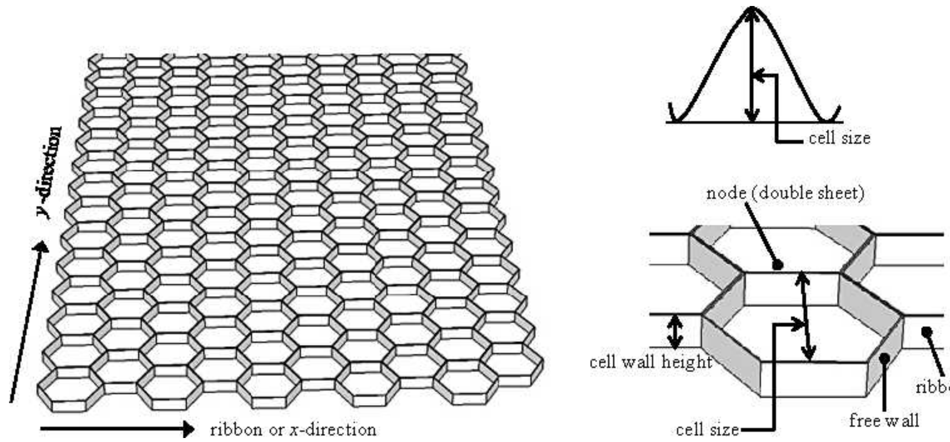

Figure 2.—(Left) The different honeycomb orientations. (Top right) Cell size for the corrugated Verticel material and (bottom right) cell size for the open cell honeycomb material.

The face and core materials were cut to dimensions of 457.2 by 1219.2 mm (1.5 by 4 ft) and weighed prior to gluing. After glue application using a carpet-coated roller, each sheet was reweighed before assembly to check the consistency of the glue mass applied to all panels. An average of 133 g of glue was applied to each face material. Panels were assembled and weighed down with a 26-mm-thick medium-density board evenly loaded with 50 kg of weights (89.7 kg/m^2). The stacks were left to cure for 2 days before removing the weights.

Design of Experiments

Experiment 1: Effect of different face and core thickness ratios

Open cell expanded honeycomb of three different cell wall heights—12.7 mm (0.5 in.), 25.4 mm (1 in.), and 38 mm (1.5 in.)—was used in conjunction with smooth-surfaced MDF face sheets, 3 and 6 mm in thickness. This created six different face sheet–to–core thickness ratios (shelling ratios), where the factors of interest were the thickness of the face sheet and the honeycomb cell wall height. All panels were made with the ribbon direction of the honeycomb core oriented parallel to the long axis of the sandwich panel. For each shelling ratio two replicate panels were fabricated for a total of 12 panels.

Experiment 2: Effect of different types of honeycomb cores and orientation

A set of sandwich panels consisting of 3-mm hardboard faces and four different types of honeycomb core materials with a constant cell wall height of 25.4 mm were fabricated. The core materials were oriented in both the ribbon and y directions with reference to the long edge of the panel. The fixed factors for this experiment were core type and core orientation. The sandwich panel dimensions were the same as in Experiment 1. For each orientation and honeycomb type combination, two replicate panels were fabricated for a total of 16 panels.

Experiment 3: Effect of different types of face sheets

Sandwich panels were fabricated using seven different types of face materials and the 25.4-mm open cell expanded honeycomb for the core. The ribbon direction of the core was parallel to the long edge of the sample, and two replicates were made for each face material type for a total of 14 panels.

Sandwich properties measured

Because of the limited quantity of stock on hand, honeycomb sandwich panels were fabricated to a standard size of 457.2 by 1219.2 mm. Note that the main properties of interest for this experiment were the behavior of the honeycomb panels under bending and shear loads. In accordance with the ASTM standards, the span length of the test samples for the six shelling ratios (six different panel thicknesses) were of different spans. To ensure the consistency of test samples, cutting patterns were designed to help obtain the maximum number of samples from each panel with consideration for the main properties of interest. The specified span length for the sandwich panels with the 38-mm core height limited the total number of flexure samples from the two panel replicates to three test specimens.

For each experiment, the panel's shear modulus (G), flatwise compressive strength (FC), flexure strength, and internal bond strength (IB) were measured in accordance with the appropriate ASTM standards. The maximum bending moment (M), bending stiffness (D), shear rigidity (U), and panel deflection (y) properties for each panel were then computed. The relevant standard testing procedures were ASTM C393-00 for the flexure samples, ASTM C297/C297M-04 (ASTM International 2004) for the IB sample, ASTM C365/C365M-05 for the FC sample, and ASTM C393/C393M-06 (ASTM International 2006a) and D7250/D7250M-06 (ASTM International 2006b) for the shear samples.

A statistical software package (SAS version 9.1) was used in the analysis of the experimental data obtained using a 5 percent significance level. All three experiments were designed using a Completely Randomized Design fixed effects model. Experiments 1 and 2 were analyzed using a two-way analysis of variance (ANOVA) and Experiment 3, a one-way ANOVA. Tukey-Kramer's honestly significant difference multiple comparison method was used to identify significant differences between means.

Beam theory for sandwich panels

The basic beam theory and nomenclature used in the analysis of the Kraft paper sandwich panels are outlined below:

$b =$ width of sandwich panel (mm),
$c =$ honeycomb core thickness (mm),
$d =$ sandwich panel thickness (mm),
$E_f =$ MOE of the face sheet (N/mm^2),
$E_c =$ MOE of the honeycomb core (N/mm^2),
$G =$ core shear modulus (N/mm^2),
$P =$ load (N),
$L =$ span length (mm),
$M =$ moment (N·mm^2),
$k_b =$ bending deflection constant dependent on the loading condition, and
$k_s =$ shear deflection constant dependent on the loading condition.

The bending stiffness of a sandwich panel is defined as the ability of the panel to resist applied forces or loads that create rotation. Generally the calculations for the bending stiffness of sandwich panels neglects the contribution of the core because of its low bending modulus (it does not resist bending); hence, $E_c = 0$ and the stresses in the face sheet are uniformly distributed (Zenkert 1997). The calculations, however, include the sandwich cross-section properties also known as the second moment of area ($I = bd^3/12$), which helps predict the panel's ability to resist bending and deflection. Therefore the bending stiffness, D (N·mm^2), of a sandwich panel having faces of equal thickness and the same material is given as

$$D = \frac{E_f(d^3 - c^3)b}{12} \tag{1}$$

In most cases, the panel shear rigidity also assumes a constant shear stress throughout the honeycomb core (Moody et al. 2007). Thus the panel shear rigidity, U (N), of a sandwich panel is given by the following:

$$U = \frac{G(d + c)^2 b}{4c} \tag{2}$$

For four-point loading, the total panel deflection for a sandwich panel is the sum of the panel bending deflection and the shear deflection. The bending stiffness of the sandwich panel influences the bending deflection, while the core shear modulus influences the shear deflection (Bitzer 1997). The total deflection of a sandwich panel, y (mm), is given as

$$y = \frac{k_b PL^3}{D} + \frac{k_s PL}{U} \tag{3}$$

Results and Discussion

Constituent material properties

The physical properties of the paper-laminated honeycomb of different cell sizes and honeycomb orientation are shown in Figure 3. The mode of failure for the paper-laminated honeycomb core was the crushing of the tops of the honeycomb cell walls due to deformation of the paper sheet directly below the loading nose.

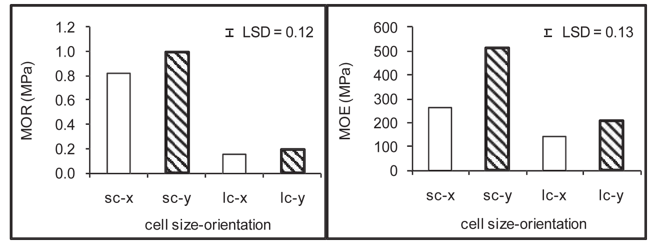

Figure 3.—Modulus of rupture (MOR) and modulus of elasticity (MOE) of small cell (sc) and large cell (lc) paper-laminated honeycomb oriented in the x *direction and* y *direction.* n = *4 for each mean. Error bars represent the least significant difference (LSD) between means.*

The most significant factor affecting the MOR and MOE of paper-laminated honeycomb was the cell size. The smaller 16-mm cell size (sc) core material was much stronger and stiffer than the larger 32-mm cell size (lc), consistent with the smaller cell size honeycomb having more cell wall material over which the load was dispersed. The MOE was significantly higher for those samples with the ribbon direction of the core oriented perpendicular to the long edge of the sample. This was consistent with the experience of manually bending a piece of expanded honeycomb parallel to the plane of the nodes (i.e., bending in the ribbon direction).

The average density, MOR, and MOE of the different face sheets are given in Table 2. From the table, though the plywood face sheets (4.5-mm Meranti and 6-mm Douglas-fir) recorded the lowest density values in comparison with the hardboard materials, the 6-mm Douglas-fir plywood had the highest bending strength (MOR) and elastic modulus (MOE). The lowest values for both MOR and MOE were observed in the 6-mm MDF. For both the hardboard and MDF materials, the 3-mm sheets had consistently higher MOR and MOE compared with the 6-mm sheets, which was attributed to its higher density.

For Experiments 1 through 3, sandwich panels made of the different face and core materials were tested for their internal bond and flatwise compressive strength properties. The results for these tests were from a very limited number of samples, i.e., a single 200 by 200-mm IB or FC sample per panel, and as such do not permit statistical inferences to be drawn. However, these results have been included to serve as comparison values for future researchers (Table 3).

For the paper-laminated core materials, failure during the IB test was mainly between the paper laminate and the

Table 2.—The physical properties of the candidate face sheets.[a]

Face sheet material	Mean density (kg/m^3) (n = 8)	Mean MOR (MPa) (n = 12)	Mean MOE (GPa) (n = 12)
6-mm hardboard	974.6	37.99	3.77
3-mm hardboard	972.7	45.80	4.56
3-mm Masonite	926.0	32.29	3.07
3-mm MDF	845.9	31.26	3.40
6-mm MDF	749.3	24.14	2.86
6-mm plywood	463.0	70.55	9.28
4.5-mm plywood	357.2	39.65	5.43

[a] MOR = modulus of rupture; MOE = modulus of elasticity; MDF = medium-density fiberboard.

Table 3.—Internal bond (IB) and flatwise compressive (FC) strength properties for sandwich panels with different face-to-core material combinations.[a]

Sandwich panel type	IB (MPa)	FC (N/mm^2)
Experiment 1		
3-mm MDF/12.7 mm	0.126	0.090
3-mm MDF/25.4 mm	0.089	0.073
3-mm MDF/38.1 mm	0.064	0.076
6-mm MDF/12.7 mm	0.105	0.091
6-mm MDF/25.4 mm	0.109	0.082
6-mm MDF/38.1 mm	0.094	0.081
Experiment 2		
Open cell-*x* (32 mm)	0.127	0.072
Open cell-*y* (32 mm)	0.081	0.082
Large cell-*x* (32 mm)	0.027	0.062
Large cell-*y* (32 mm)	0.025	0.072
Small cell-*x* (16 mm)	0.061	0.241
Small cell-*y* (16 mm)	0.023	0.239
Verticel-*x* (13 mm)	0.143	0.119
Verticel-*y* (13 mm)	0.054	0.120
Experiment 3		
3-mm Masonite	0.066	0.069
4.5-mm plywood	0.125	0.075
6-mm plywood	0.073	0.077
6-mm hardboard	0.065	0.079

[a] $n = 1$ for each sandwich panel type.

honeycomb cells, a feature that material users have no control over. Contrary to expectations, there were no major differences in IB strength of sandwich panels made from different face materials. The under surface of each type of face sheet was different and this was expected to affect the contact between the honeycomb and the face sheet. The hardboard had a wire imprint underside, which may have created some weak links in glue bond lines; the MDF products were smooth and bonded easily to the honeycomb material.

Experiment 1: Shelling ratios

The average maximum bending moment (*M*) and panel deflection (*y*) for each shelling ratio are shown in Figure 4. An ANOVA analysis on the bending moment results grouped by core thickness revealed significant differences ($P < 0.001$); the mean moment for panels with the 12.7-mm cores was 22.5 kN·m and for the 25.4-mm cores was 22.8 kN·m. The value for panels with the 38-mm core was just over 20 percent higher at 28.2 kN·m, making it significantly different from both the 12.7- and 25.4-mm core heights. Grouping the bending moment results by face thickness produced significantly different means ($P < 0.001$) with a mean maximum moment for the panels made with the 6-mm faces of 29.7 kN·m compared with only 19.2 kN·m for panels with the 3-mm-thick faces. Furthermore, there was no significant interaction between these parameters, and the effect of each factor is merely additive. Examination of the deflection results showed only the 12.7-mm core was significantly different from the 25.4- and 38.1-mm core heights for both face sheets. The overall trend in Figure 4 is an increasing moment with increasing core height and face thickness, and a decreasing panel deflection with increasing core height.

The panel shear modulus and rigidity values are given in Table 4. From the table it is observed that the core shear modulus values for the sandwich panels increases as the panel becomes thicker and the corresponding panel deflection smaller (Fig. 4). Generally, the honeycomb sandwich panels failed by crushing and deformation of the honeycomb core (Figs. 5 and 6) directly under the loading noses. The better performance by panels with the 6-mm face material is not surprising because it should remain flat and relatively undeformed compared with the 3-mm material for the same load since it distributes the load over a larger area. Once the core began to crush, the panel immediately (and loudly) delaminated from the face sheet. This mode of failure was attributed to the low resistance offered by the Kraft paper core to bending loads and the high shear stress in the glue line between the face and core—a mode of failure that has been reported by Bryan (1957), Hassinen et al. (1997), Thomsen (1998), Petras and Sutcliffe (1999), and Zok et al. (2003), for a wide variety of different core and face materials such as Nomex, aluminum honeycomb cores, textile cores, and metallic and fiber-reinforced plastic face sheets.

Equation 1 suggests that any increases in sandwich panel thickness either due to an increase in face sheet thickness and/or core height will invariably increase the panel bending stiffness. Figure 7 confirms this, with increasing panel bending stiffness as core height increases for both the 3- and 6-mm MDF sandwich panels; the increase is more pronounced in the 6-mm sandwich panels. The trend observed with increasing core heights are in agreement with those of Lingaiah and Suryanarayana (1991) who worked with polyurethane foam cores sandwiched between fiber-glass-reinforced plastic and aluminum alloy face materials.

From the results presented in Figures 4 and 7, one can see that the use of a stiffer and thicker 6-mm MDF face sheet

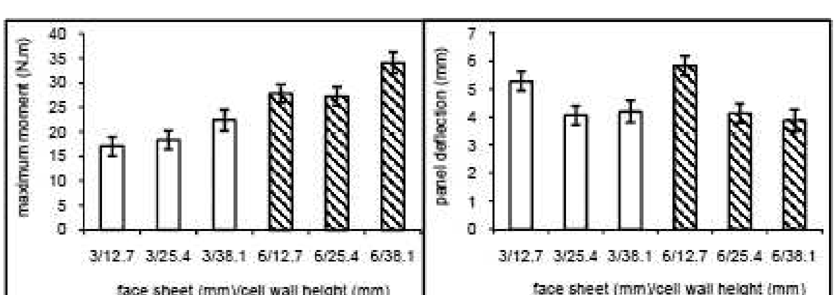

Figure 4.—The different face-to-core height ratios in terms of the maximum bending moment and deflection values for panels with honeycomb oriented in the ribbon direction. n = 4 *for each mean except for the 38-mm core height where* n = 3*. Error bars represent ±95 percent confidence intervals for each mean.*

Table 4.—Face-to-core height sandwich properties.[a]

Face/core height (mm)	Peak load (N)	Shear modulus (N/mm^2)	Shear rigidity (kN)	Bending stiffness ($N{\cdot}m^2$)
3/12.7	272.6	9.75 (1.7)	14.5 (2.5)	99.23
3/25.4	352.9	6.75 (1.1)	16.5 (2.7)	334.0
3/38	338.8	8.84 (1.8)	30.0 (6.0)	682.9
6/12.7	412.9	10.1 (1.8)	20.9 (3.6)	213.9
6/25.4	429.6	10.2 (1.0)	29.4 (3.0)	652.5
6/38	395.3	8.93 (0.8)	33.9 (3.1)	1,239

[a] Values are means (standard deviations). $n = 6$ for each mean.

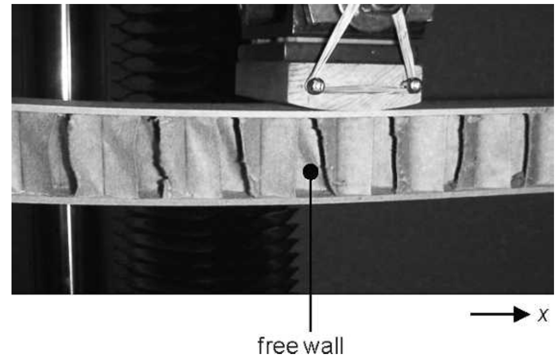

Figure 6.—Shear in the honeycomb cells (oriented in the x *direction) of the 3-mm medium-density fiberboard sandwich panel under one loading nose in a four-point bending test; note the shear deformation in the free wall of the honeycomb.*

with a 38-mm honeycomb core height in the manufacture of sandwich panels results in panels that have a 30 percent higher maximum moment and 45 percent higher bending stiffness compared with the 3-mm face sheet sandwich panels.

Experiment 2: Different types of honeycomb cores and orientation

Figure 8 shows the average maximum bending moment (*M*) and total panel deflections (*y*) for sandwich panels with different types of core material grouped by ribbon orientation. Other panel properties are given in Table 5.

The results show that both honeycomb core type and cell orientation significantly ($P < 0.001$) affected sandwich bending moments, with panels containing the small cell size core materials (the 16-mm small cell paper-laminated and 13-mm Verticel honeycombs) recording significantly higher loads. This observation could be related to the smaller cell core materials being more stable and possessing more cell walls over which to distribute the applied load from the point of application. Generally, sandwich panels with the honeycomb core oriented in the ribbon direction failed at significantly lower loads compared with panels in which the core was oriented in the *y* direction. These results were also consistent with the observations from the flexure tests on paper-laminated cores themselves.

Our results for the directional effect (*y* direction) of the core material on the load-bearing ability of sandwich panels with different core types also confirmed those of Petras and Sutcliffe (1999) for Nomex honeycomb sandwich panels with13-mm cell size. According to Petras and Sutcliffe, sandwich panels (made of glass fiber–reinforced plastic laminate faces and Nomex honeycomb core) with 3-mm core cell size and oriented with the ribbon direction parallel to the long axis of the panel failed at significantly higher loads compared with those oriented in the *y* direction. However, the opposite result was reported for a core material with 13-mm cell size; this difference was attributed to intracell buckling, which at higher loads resulted in the crushing of the honeycomb core. This mechanism may be occurring in our study since the cell sizes of the honeycomb used in this work (13, 16, and 32 mm) were all bigger than the 13 mm used by Petras and Sutcliffe (1999). That said, our sample number was small and more research is necessary to determine the effect of other core properties such as base paper type, thickness, and density.

The method of construction for hexagonal honeycomb cores results in some cell walls having double layers of paper, i.e., a node in Figure 2, compared with a free wall that has only a single wall, making the honeycomb highly anisotropic and producing major differences in its shear properties. The shear properties (Table 5) for sandwich panels containing different core materials indicated panels with the core oriented in the ribbon direction had higher shear moduli and rigidity values. This directional effect was consistent with the shear properties reported by Kollman et al. (1975) and Bitzer (1997) for a hexagonal cell honeycomb

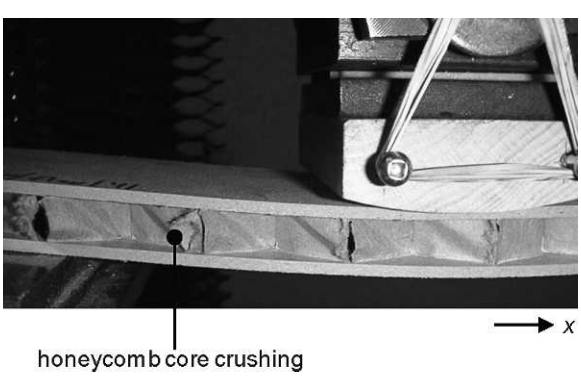

Figure 5.—Failure mode of Kraft paper honeycomb panel indicating core shear and crushing (6-mm medium-density fiberboard sandwich panel under one loading nose in a four-point bending test).

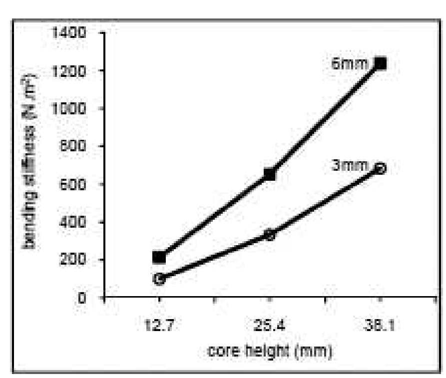

Figure 7.—Bending stiffness values for sandwich panels with three open cell expanded honeycomb core heights. n = 4 *for each mean except for the 38-mm core height where* n = 3.

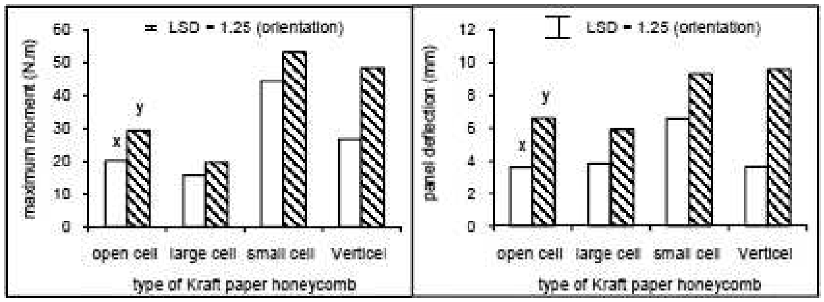

Figure 8.—The maximum bending moment and deflection of panels with different honeycomb types oriented in the x *and* y *directions, respectively.* n = 4 *for each mean. Error bars represent the least significant difference (LSD) between means.*

core. The differences in value between the honeycomb core types were, however, the result of the different core densities (Table 1).

Similar to the maximum bending moment results, panel deflection was significantly influenced by the type of core material and honeycomb core orientation. The highest deflection values were recorded for sandwich panels with the small cell paper-laminated and Verticel honeycombs oriented in the y direction. For each core type, the panel deflection differences recorded for the x and y core orientations may be attributed to the core shear moduli because honeycomb cores with relatively higher shear rigidity values had correspondingly lower deflection values. There are, however, other parameters such as variations in core density and/or sample assembly that may have also contributed to this directional effect on deformation.

Based on these findings, it is recommended that in the choice of a honeycomb type for furniture applications, the nonlaminated small cell and Verticel honeycomb materials oriented in the y direction be used. This recommendation is based on the fact that the measured maximum moment (Fig. 8) supported by the sandwich panels with the small cell paper-laminated and Verticel cores were significantly higher than the other cores. However, given that the bond strength between the face paper and the honeycomb cells of the paper-laminated core was low (Table 3), we conclude the small cell size without any face paper would be the strongest of the cores considered.

Experiment 3: Different types of face sheet

Statistical analysis of the results from this experiment revealed significant differences ($P < 0.0001$ and $P = 0.0024$) in the load-bearing capacity and deflection values for sandwich panels with different face materials. From the average maximum bending moment and panel deflection values shown in Figure 9, the lowest deflection values were recorded for sandwich panels made with the 6-mm hardboard and 6-mm plywood face materials. Panels with the 6-mm Douglas-fir plywood face sheet in bending carried the highest load. For the 3-mm face sheet types—hardboard, Masonite, and MDF—there were no significant differences in their maximum bending moment. The differences can be explained in terms of the MOE of the face material and the panel cross-sectional properties (Eq. 1); sandwich panels having a thicker face material with a high elastic modulus (with reference to the long axis of the panel) turn to have significantly higher bending properties (Table 6).

These results imply that depending on the specific application, a thick face material with a high elastic modulus, e.g., the 6-mm Douglas-fir plywood, would best suit ready-to-assemble furniture applications.

The adoption of paper honeycomb sandwich technology in the furniture industry is extensively dependent on the costs of the constituent materials—the face sheets and honeycomb core relative to conventional composite board (i.e., particleboard). Based on square foot price of a standard 25.4-mm expanded core (Can$0.6) there is a significant cost increase of 65 to 75 percent for the small cell core (13 mm) compared with the large cell core (32 mm). This is due to the smaller cell honeycomb containing twice as much paper and glue per unit area compared with the large cell form. The price differences between different types of composite board face sheets of the same thickness were found to be minimal. Major price differences only exist between the

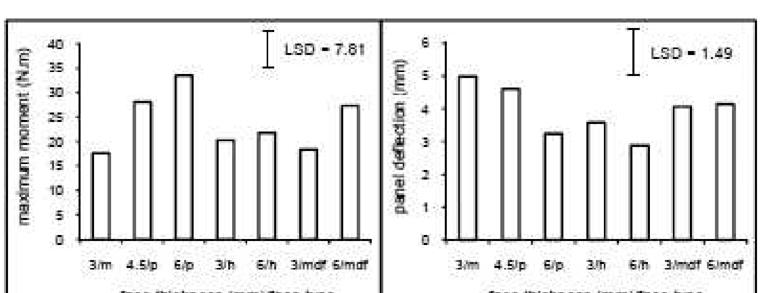

Figure 9.—Maximum moment and deflection values for sandwich panels with different face materials. m = Masonite; p = plywood; h = hardboard; mdf = medium-density fiberboard. n = 4 *for each mean. Error bars represent the least significant difference (LSD) between means.*

Table 5.—Shear modulus and rigidity values for the different honeycomb sandwich panels.[a]

Honeycomb type	Peak load (N)	Shear modulus (N/mm^2)	Shear rigidity (kN)
Open cell-*x*	302.8	6.36 (1.1)	15.7 (2.6)
Open cell-*y*	225.9	3.67 (0.2)	9.02 (0.5)
Large cell-*x*	312.3	3.76 (0.6)	9.04 (1.4)
Large cell-*y*	340.2	2.44 (0.5)	5.88 (1.2)
Small cell-*x*	709.0	11.9 (1.0)	29.3 (2.4)
Small cell-*y*	662.8	6.64 (0.9)	16.4 (2.1)
Verticel-*x*	591.9	15.3 (1.6)	37.9 (4.6)
Verticel-*y*	417.8	4.68 (0.5)	11.6 (1.3)

[a] Values are means (standard deviations). $n = 6$ for each mean.

Table 6.—Panel properties for sandwich panels with different face materials.[a]

Face material	Peak load (N)	Shear modulus (N/mm^2)	Shear rigidity (kN)	Bending stiffness (N·m^2)
3-mm Masonite	278.9	6.13 (1.1)	14.6 (2.7)	250.1
4.5-mm plywood	351.7	4.45 (1.3)	11.9 (3.4)	814.2
6-mm plywood	746.6	5.45 (1.6)	16.1 (4.6)	2,117
3-mm hardboard	302.8	6.36 (1.1)	15.7 (2.6)	474.3
6-mm hardboard	363.9	8.53 (0.9)	24.6 (2.7)	752.8
3-mm MDF	352.9	6.75 (1.1)	16.5 (2.7)	334.0
6-mm MDF	429.6	10.2 (1.0)	29.4 (3.0)	652.5

[a] Values are means (standard deviations). $n = 6$ for each mean.

different face sheet thicknesses: a 1,219.2 by 2,438.4-mm (4 by 8-ft)-long 6-mm MDF ($13.25) is approximately twice as expensive as the 3-mm MDF ($7.82). Therefore a relatively expensive face sheet could be combined with a less expensive (in comparison with the face material) core material to produce a sandwich panel whose weight would be well below that of solid wood components of similar size.

Conclusions

This preliminary study has shown the factors that require consideration in the manufacture of Kraft paper sandwich panels are the core properties (cell size, core height, core density, and orientation) and face stiffness along the long axis of the sandwich panel.

To minimize the deflection in a paper sandwich panel and obtain a maximum panel stiffness, the honeycomb cell size should be as small possible and the core height as large as practical. This core material can then be oriented with its paper strips perpendicular to the long axis of a thick face material, which has a high elastic modulus. A combination of such a core and face material will result in a lighter product compared with solid wood composite boards.

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