Properties of Commercial Kraft Paper Honeycomb Furniture Stock Panels Conditioned under 65 and 95 Percent Relative Humidity

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Abstract

Physical and mechanical properties of a range of commercially produced kraft paper honeycomb stock panels were assessed to provide technical information of interest to primary and secondary manufacturers and product end users. Five groups of four replicate panels each 44.45 mm in thickness were fabricated by Panolite Industries, Lac Megantic, Quebec, from unlaminated 6.3- and 9.5-mm-thick medium-density fiberboard (MDF) and particleboard (PB), and 3.2-mm-thick veneered hardboard (HB). At 65 percent relative humidity (RH) sandwiches made from MDF were superior in mechanical properties to those made from PB. Marked differences in flexural properties were found for 3.2-mm veneered HB; this type of facing and the sandwich structure made from it is significantly greater in flexure when the wood veneer runs parallel to the long axis of the panel. For PB and MDF facings, sandwiches were stronger and stiffer if made from thicker facing material (9.5 mm), and there was a small but significant effect of honeycomb ribbon orientation: an orientation parallel to the long axis of the panel/test specimen gives the sandwich greater resistance to deformation under load. Conditioning facing materials and sandwich specimens under 95 percent RH over 45 days caused loss of strength properties of up to 50 percent, especially for 6.3-mm MDF.

The manufacture and use of kraft paper honeycomb sandwich panels with wood-based composite facings for the furniture industry is well established in Europe (Egger 2013, Stosch 2008) and Asia and is steadily becoming more established in North America (Busch 2004, Anonymous 2009). The growth of the honeycomb furniture panel industry in North America is relatively recent and surprising given that the first wooden facing-paper honeycomb structural panels for furniture were produced by Lincoln Industries, Marion, Virginia, in the 1930s (Bitzer 1997). During and after World War II, the US Department of Agriculture (USDA) Forest Products Laboratory conducted much development work on resin-impregnated paper honeycomb and plywood stressed skin panels for mass production of postwar prefabricated housing (Seidl 1956, Wood 1958, Markwardt and Wood 1959, Palms and Sherwood 1979). Major honeycomb panel evolution took place in the aerospace industry primarily for weight reduction but also for the ability to fabricate deformation- and fatigue-resistant body components. Lined paper honeycomb is also widely used in the packaging industry as a vibration- and shock-resistant cushioning material for product shipping (Guo and Zhang 2004).

A resurgence in interest in hollow core panel manufacturing in North America came as late as 2006, when an Iowa company invested in custom fabrication of particleboard (PB)–framed honeycomb core stock panels for furniture (Anonymous 2006), and there are now at least five companies in the United States manufacturing kraft paper honeycomb and wood composite-faced stock panels for

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packaging and furniture. Canada has one expanding custom manufacturer of kraft paper honeycomb furniture stock panels—Panolite Industries, located in Lac Megantic, Quebec. Factors contributing to growth of the industry include trends in the furniture industry for thick-section but lightweight products, reduced component materials and manufacturing costs, automated panel production (e.g., Eurolite), technologies reducing labor requirements, lower shipping costs for flat-pack furniture, and increasing costs of wood used in conventional wood composites (Wisdom 2005, Stosch 2008, Anonymous 2011). The hollow panel industry has further benefitted from advances in process technologies such as ''woodwelding''—a form of edge banding allowing automated production of frameless panels, which can be subsequently cut to any dimension—and plastic edge bands applied without the need for internal solid edge rail substrates that add extra weight and constrict panel customization (Busch 2004). Other honeycomb panel-specific systems include ''Hettinject'': a bonding dowel fastener holder developed for placement anywhere within frameless panels of any size without requiring a solid substrate (Beins 2007, Hettich 2010). The separation of two thinner wood composite facings by the expanded honeycomb core increases the moment of inertia of the panel with very little increase in weight, producing an efficient, thick ''bulky-look'' structure for resisting bending and buckling loads (Petrus 1998).

While there are numerous industry magazine articles on the evolution of the hollow core wood panel industry (e.g., Busch 2004, Wisdom 2005, Anonymous 2006), and numerous studies on the properties of paper-lined honeycomb core packaging, there are far fewer studies on the fabrication and testing properties of sandwich panels made from wood composite facings and kraft paper honeycomb core. Previous published works on testing lignocellulosic honeycomb products have fabricated small sample panels by hand in the laboratory to quantify the effects of varying design parameters such as honeycomb cell wall height, cell diameter, and cell configurations. Barboutis and Vassiliu (2005) fabricated sandwiches with 8-mm PB facings and 35-mm-high expanded kraft paper honeycomb core with 30-mm-diameter cells and tested bending and impact bending strength of both the sandwiches and the PB in isolation. Sandwich modulus of rupture (MOR) and modulus of elasticity (MOE) values were extremely low relative to solid particleboard tested on its own; however, impact bending strength properties were significantly higher for the honeycomb sandwiches. Semple et al. (2007) and Sam-Brew et al. (2010, 2011) used different kinds of facing materials purchased from building suppliers, many of which (such as plywood) are not actually used to fabricate commercial honeycomb sandwich stock panels. These works studied the effects of honeycomb cell size (16- or 32-mm diameter), height (12.7, 25.4, or 38 mm), directional effects (loading along or across ribbon direction), and shelling ratio (3- or 6-mm-thick MDF facings) on sandwich compressive and flexural properties. Optimal conditions, particularly for longer spans, are small cells, greater cell height, thicker facing, and loading along the ribbon direction. There is little information about performance of wood-based honeycomb panels at high humidity; however, there are studies on paper honeycomb itself. Ping (2009) conditioned paper honeycomb to four different relative humidities (RHs), 30, 50, 70, and 90 percent, and found compression elastic modulus reduced with increasing RH.

In small-scale laboratory studies, considerable variation can come from the hand fabrication of small panels. Laboratory-made panels are also not an accurate facsimile of factory production in terms of both materials and fabrication techniques and equipment used. There is no published information on measured properties of commercial honeycomb core stock panels. For a company like Panolite, whom we collaborated with to sample stock panels, such information is of significant interest to both the company and their customers, especially those who undertake secondary manufacturing of custom end-products from the stock panels. The main objective of this work, therefore, was to test and present data on the physical and mechanical properties of a range of common honeycomb core stock panels produced by the same company and production line. Specific aims were to test for and assess variation in properties caused by sandwich type (a combination of facing material, facing thickness, and core thickness), honeycomb ribbon orientation, and the effects of exposing the panels to very high humidity. The different facing panels used were unlaminated so that we could measure the material properties of the facing substrate itself and determine how exposure to high humidity affects moisture uptake and strength properties of facings and the sandwiches made from them.

Materials and Methods

Panel materials and fabrication

A set of 25 honeycomb core panels was manufactured by Panolite Industries using their generic 12.7-mm cell diameter kraft paper expanded honeycomb core and five kinds of commonly used facing materials. Facings were 6.3-mm- and 9.5-mm-thick M2 grade particleboard (PB), manufactured by Tafisa, Lac Megantic, Quebec; 6.3-mm- and 9.5-mm-thick medium-density fiberboard (MDF), manufactured by Masonite Industries, Lac Megantic; and 3.2-mm-thick birch veneered-on-both-sides hardboard (HB). The honeycomb cores were supplied by Cascades, a Lac Megantic–based manufacturer of expandable kraft paper honeycomb. Three honeycomb cell wall heights were used to make panels, i.e., 25.4, 31.75, and 38.1 mm to match the 9.5-, 6.3-, and 3.2-mm facing thicknesses, respectively, to ensure all finished panels were the same final thickness of 44.5 mm. Table 1 provides a summary of the features common to all panels and differences, including type of facing material, facing thickness, height of honeycomb core, honeycomb ribbon orientation, and RH. For each of the five types of facing used, four stock panels, each measuring 120 by 240 by 4.44 cm in thickness, were fabricated on the Panolite production line. In all panels paper honeycomb ribbons were oriented perpendicular to the long axis of the facings. The cross-sectional appearance of the five kinds of honeycomb sandwich panels evaluated and the expanded honeycomb core is illustrated in Figure 1.

The glue used to attach the facings to the honeycomb core was a proprietary cold-setting polyurethane, which was applied by a roller-coater line to the top and bottom facing sheet surfaces at a spread rate of approximately 0.1 g/cm^2 surface area. The assembled sandwiches were stacked and lightly compressed in a hydraulic press for glue setting for half an hour. Completed sandwich panels were then shipped

Table 1.—Variable features of sandwich panels.[a]

Factor	Levels
Facing material	PB
	MDF
	Veneered HB
Facing thickness (mm)	9.5
	6.3
	3.2
Honeycomb height (mm)	25.4
	31.7
	38.1
Ribbon orientation	Along ribbons (x)
	Across ribbons (y)
RH condition (%)	65
	95

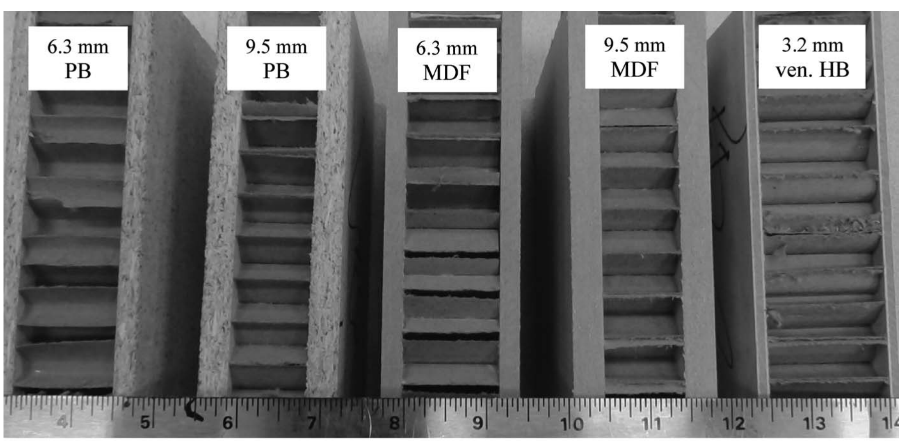
[a] Fixed features of sandwich panels are kraft paper honeycomb, cell diameter of 12.7 mm, and sandwich thickness of 45 mm. PB = particleboard; MDF = medium-density fiberboard; HB = hardboard; RH = relative humidity.

to FPInnovations in Quebec City along with two representative 120 by 240-cm sheets of each type of facing and each of the three thicknesses of honeycomb core.

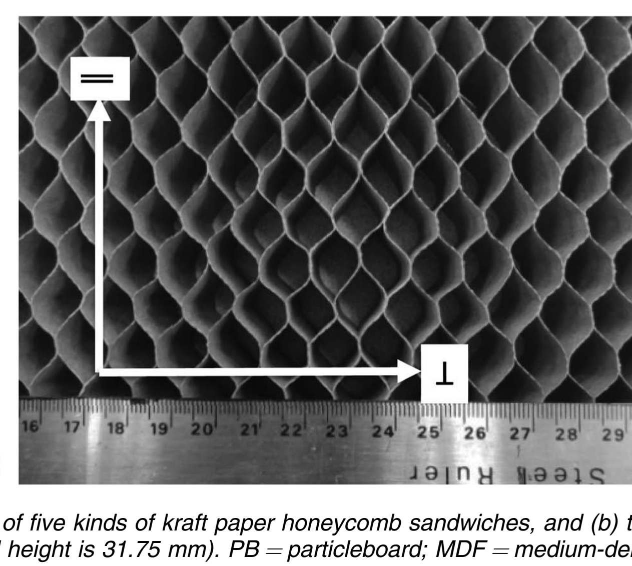
Material cutting and test specimen preparation

Facings.—Composite panels such as PB can have directional differences in strength properties depending on their orientation relative to the direction of the continuous pressing line (or in the case of the veneer-covered HB, the direction of the wood grain in the top and bottom veneers). The long axis of the panel was marked y direction, and the short axis marked x direction. From the two sheets of each facing type, short-term test specimens were marked out, labeled, and cut. The specimen dimensions, shapes, and locations for each type of test are given in Table 2 and Figure 2. Each face sheet was first divided into quarters each measuring 60 by 120 cm, labeled 1 to 4. From two diagonally opposite quarters (1 and 3) the test specimens were marked and cut (with their long axis parallel to the panel long axis), and from the remaining two quarters (2 and 4) the test specimens were marked and cut (so that their long axis was perpendicular to the panel long axis). This arrangement ensured that any directional effects (such as veneer orientation in the case of the veneered HB or machine direction in the case of PB and MDF) on flexural properties or linear expansion (LE) would be evenly distributed across the test specimen population.

Sandwich panels.—Each sandwich panel was marked up, labeled, and cut into test specimens according to the cutting pattern shown in Figure 3. The types of test specimens, their dimensions, and numbers of specimens per panel and panel type are given in Table 3. Each panel was first cut in half crosswise to give two squares measuring 120 by 120 cm. From one of the halves the long specimens (flex tests, shear, and LE) were marked out and cut such that the honeycomb ribbons



(a)



(b)

Figure 1.—(a) Internal appearance of five kinds of kraft paper honeycomb sandwiches, and (b) top view of expanded honeycomb core (cell diameter is 12.7 mm, cell height is 31.75 mm). PB = particleboard; MDF = medium-density fiberboard; HB = hardboard.

Table 2.—Test types, sample size, and properties for evaluation of facing materials.[a]

Test type and specimen dimensions (mm)	Responses	No.			Total no.
		Per panel	Per face type	Per RH condition	
Flexure, ASTM D1037-06, 254.0 × 76.4 or 50.8	Thickness (mm)	10	20	100	200
	Basic density (kg/m^3)	10	20	100	200
	MC (%)	10	20	100	200
	Peak load (kN)	10	20	100	200
	MOR (MPa)	10	20	100	200
	MOE (GPa)	10	20	100	200
Linear expansion, ASTM D1037-06, 304.8 × 76.2	Weight gain (%)	10	20	100	200
	Expansion (%)	10	20	100	200
	Final MC (%)	10	20	100	200
Interlaminar shear, ASTM D1037-06, 533.4 × 50.8	Maximum shear stress (MPa)	20	100	200	20
Vertical density profile	Density (kg/m^3)	24	48	NA	96

[a] RH = relative humidity; MC = moisture content; MOR = modulus of rupture; MOE = modulus of elasticity.

were oriented parallel to long axis, and specimens from the other half marked and cut with the ribbons oriented perpendicular to their long axis. Figure 4 shows the orientation of test specimens cut from the 3.2-mm veneered HB in relation to the direction of the honeycomb core ribbons.

Specimen types (shear and internal bond [IB]) that were required to be glued to solid wood backing boards were grouped together into long strips measuring 120 by 17.8 cm (denoted by the shaded areas in Fig. 3). The individual test specimens were only cut to size after the strips had been glued to planed backing boards. Defect-free strips of maple and birch timber measuring 240 cm, 15 to 20 cm wide, and 2 cm thick were selected from seasoned packs and then cross cut to 120-cm lengths. Boards were then planed to 19 mm thickness. Planing was done just prior to roller application of cold-setting polyurethane (Henkel Adhesives Macroplast UR-8346RD) at 0.3 g/cm^2 of wood surface area. The compiled sandwiches with backing boards were clamped for at least 2 hours to cure. Individual shear and IB test specimens were labeled and cut out and conditioned at either 65 or 95 percent RH prior to testing.

Specimen conditioning.—Specimens from each panel were divided into two groups: one to be conditioned to 65 percent RH and 20°C, the other to be conditioned to 95 percent RH and 20°C. The 95 percent conditioning zone was created within a wet lab using a custom-built system to spray a fine mist and plastic curtains to shield test specimens from liquid moisture. The temperature and humidity of this environment was recorded daily and was maintained at 90 to 95 percent RH and 18°C to 20°C. Test specimens were

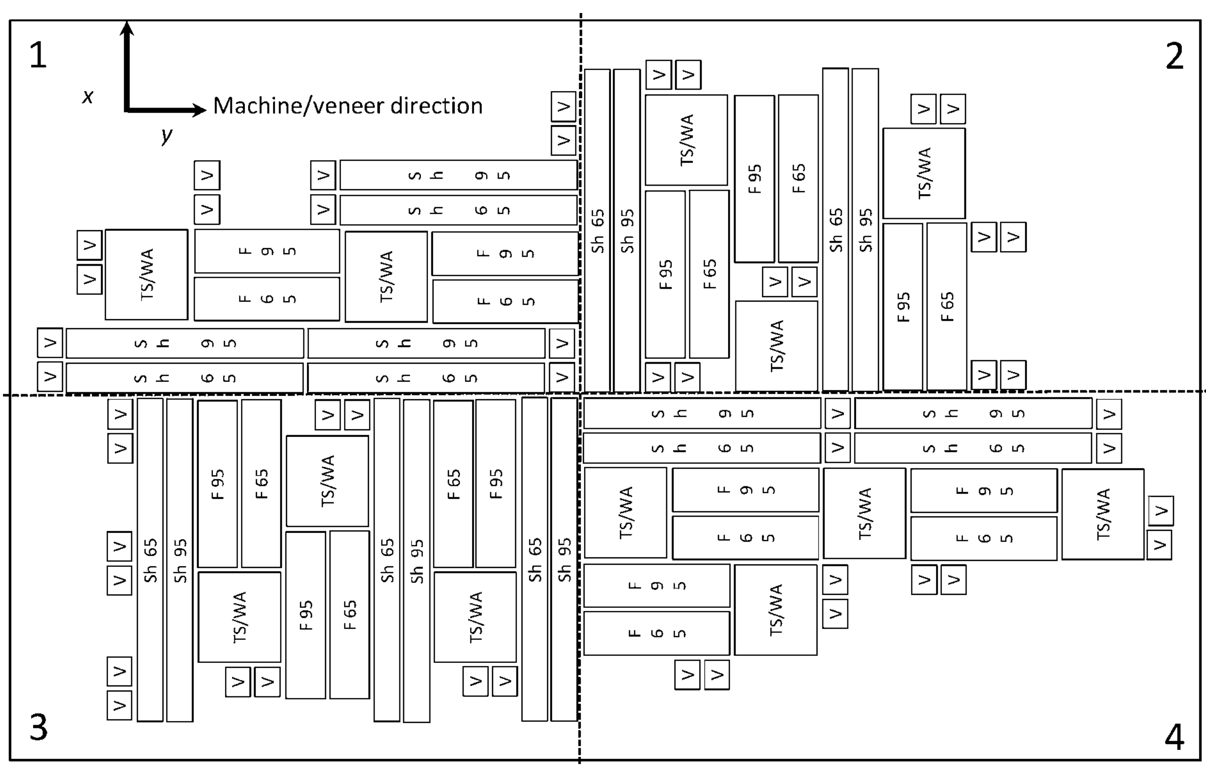


Figure 2.—Cutting pattern for 120 by 240-cm facing sheets. Whole sheets cut into four 60 by 120-cm subpanels labeled 1 through 4. 65 or 95 refers to relative humidity condition; v = vertical density profile and internal bond; TS/WA = thickness swell and water absorption; F = flexure in bending (modulus of rupture and modulus of elasticity); Sh = shear.

conditioned to constant weight (<0.05% change over 2 days) for at least 45 days prior to testing.

Materials characterization and mechanical properties

VDP (facings only).—The vertical density profile (VDP) through the thickness of a wood composite panel informs to a large extent its strength and stiffness under load and by extension the stiffness properties of any hollow core sandwich panels made from them. The VDP of 24 specimens from each of 10 face sheets (2 per type) was measured using a QMS X-ray density profiler model QDP-O1X (Quintek Measurement Systems Inc., Knoxville, Tennessee). Specimens were 51 by 51 mm by variable thickness (3.2, 6.3, or 9.5 mm). The specimen thickness was divided into three zones (upper surface, core, lower surface) to give the maximum density of the compacted surfaces and the average density in the lower density core region. A reading was taken every micrometer, and the wood composite materials tested had a mass absorption coefficient (μ) of 0.272 cm^2/g.

Mechanical properties.—Mechanical properties tests on facings and sandwiches, including the reference ASTM standard, specimen dimensions, and responses measured for or calculated from the test, are listed in Tables 2 and 3 for facings and sandwiches, respectively. All tests were carried out at FPInnovations except for shear tests, which were done at the University of Toronto.

Static bending (facings).—Prior to testing, specimens cut from the facings were each weighed, their width and thickness was measured at three points along the length, and the length was recorded to provide specimen width and thickness values for calculating modulus of rupture (MOR) and modulus of elasticity (MOE), and also piece density. Each specimen was reweighed after testing to failure then placed in an oven at 103°C for 24 hours and reweighed to provide specimen moisture content (MC) at the time of testing and its basic density. Flexural tests were done on a MTS Insight 820-010-EL load frame fitted with a 1-kN load cell and using a three-point center-span loading configuration in batches of 10 specimens per panel equally representing the two planar directions. For all batches, specimens were alternately tested top face up or face down. Flexural tests were conducted according to ASTM D1037 (ASTM International 2006a), which specifies different loading speeds and crosshead/bearer diameters in accordance with thickness, which are given in Table 4. Two different loading speeds were used: Segment 1 with a reduced loading speed whereby a linear variable differential transformer was used to measure the linear portion of the stress–strain curve, followed by Segment 2 with the loading speed corresponding to that recommended for the specimen thickness. For testing the facings, the loading nose and bearers were semicircular in shape as specified by ASTM D1037 (ASTM International 2006a). Response variables were peak load (kN), MOR (MPa), and MOE (GPa).

LE (faces and sandwiches).—LE was measured according to ASTM D1037 (ASTM International 2006a) using the nail head distance method. Ten specimens of facing material or sandwich per panel were cut to measure 304.8 by 74.2 mm and preconditioned to 65 percent RH for approximately 6 weeks until specimen weight remained stable (<0.05% change over several days). After conditioning, the specimens were predrilled with two holes located a distance of

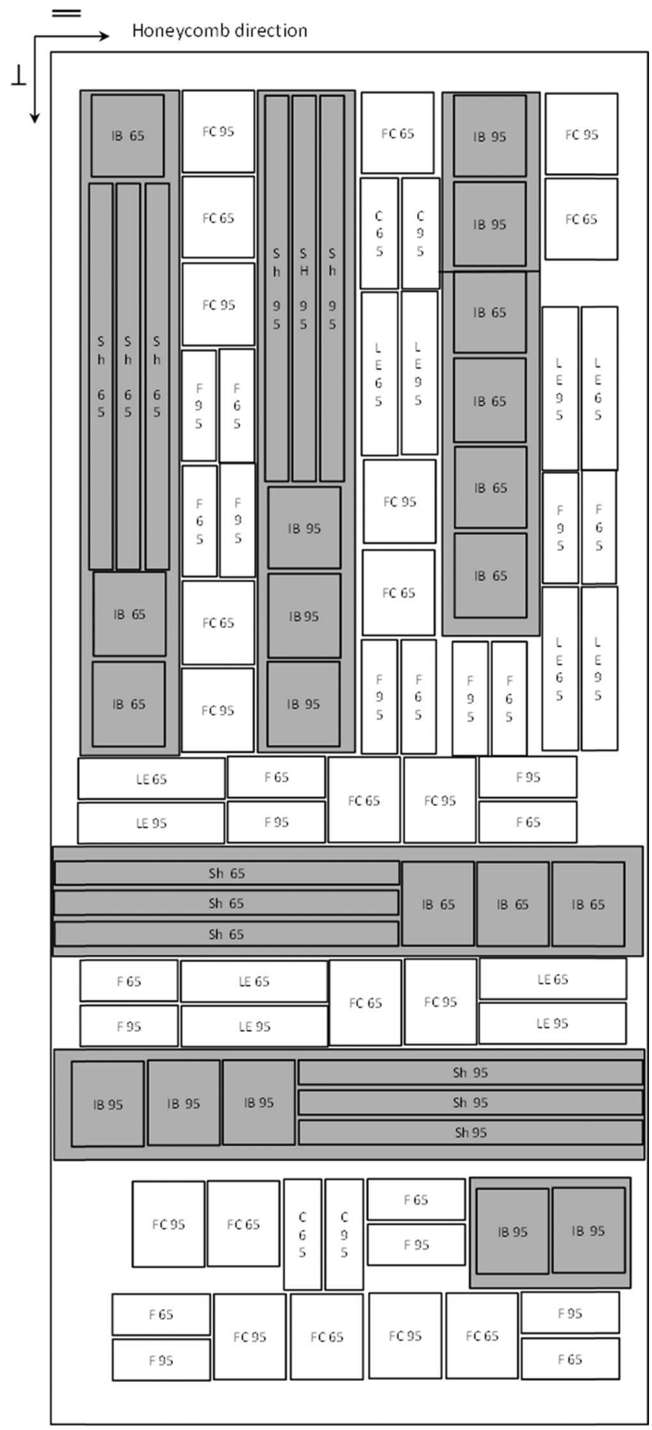


Figure 3.—Cutting pattern for 4 by 8-foot sandwich panels. 95 or 65 refers to relative humidity condition; IB = internal bond; F = flexure in bending (modulus of rupture and modulus of elasticity); C = creep; LE = linear expansion; FC = compression; Sh = shear.

25.4 mm in from the ends and 38 mm in from the sides of the specimen. Hole and aluminum nail specifications for the facing materials were 2.81-mm pilot hole, nail length of 31.75 mm, with a shank diameter of 3.11 mm and head diameter of 9.3 mm. For the sandwiches, pilot holes were 3.15 mm in diameter, and nails were 63.5 mm in length with

Table 3.—Test specimen type, dimensions, and sampling intensity for sandwich panels.[a]

Test type and specimen dimensions (mm)	Variables	No.			Total no.
		Per panel	Per sandwich type	Per RH condition	
Flexure, ASTM C393-06, 203.2 × 76.2 or 50.8[b]	Thickness (mm)	10	40	200	400
	Basic density (kg/m^3)	10	40	200	400
	MC (%)	10	40	200	400
	Peak load (kN)[c]	10	40	200	400
	Facing stress (kN)[c]	10	40	200	400
	Face shear ultimate stress (kPa)[c]	10	40	200	400
	Flexural stiffness (kN/mm^2)[c]	10	40	200	400
Flatwise compression, ASTM C365-11, 152.4 × 152.4	Thickness	10	40	200	400
	Basic density	10	40	200	400
	MC (%)	10	40	200	400
	Peak load (kN)	10	40	200	400
	Compressive modulus (MPa)	10	40	200	400
	Ultimate strength (MPa)	10	40	200	400
Delamination (internal bond), ASTM C297-10, 152.4 × 152.4	Peak load (kN)	10	40	200	400
	Peak stress (kPa)	10	40	200	400
Linear expansion, ASTM D1037-06, 304.8 × 76.2	Weight gain (%)	10	40	200	400
	Expansion (%)[c]	10	40	200	400
	Final MC (%)	10	40	200	400
Interlaminar shear, ASTM D1037-06, 533.8 × 50.8	Shear modulus (MPa)	6	24	120	240
	Maximum shear stress (MPa)	6	24	120	240

[a] RH = relative humidity; MC = moisture content; PB = particleboard; MDF = medium-density fiberboard; HB = hardboard.
[b] Width = 76.2 mm for 9.5-mm PB and MDF; 50.8 mm for 6.3-mm PB and MDF and 3.2-mm HB.
[c] Specimens from each panel evenly divided into parallel and perpendicular honeycomb ribbon orientation.

a shank diameter of 3.34 mm and head diameter of 9.15 mm. A shallow indent hole was drilled into the top of each nail head using a 1-mm-diameter jeweler's drill bit to provide anchorage for the tips of the linear displacement caliper used to measure the distance between the tops of the nails. Weight and nail distance were measured, and specimens relocated to the 95 percent conditioning chamber for 45 days prior to reweighing and remeasuring the distance between the nails. Responses were mass increase (%), LE (mm), percent change in dimension, and final specimen MC (%).

Flexural properties of sandwiches.—Flexural tests for sandwiches used ASTM C393 (ASTM International 2006b) and ASTM D7250/D7250M (ASTM International 2006c) using a 5-kN load cell. ASTM C393 specifies the loading nose, and the bearers are a flat thick strip of steel measuring 25.4 mm across and 5 mm deep. Span for sandwich specimens was 152 mm, crosshead width 16.7 mm, and loading rates of 1 and 6 mm/min for Segments 1 and 2, respectively. Response variables were peak load (kN), facing stress (MPa), core shear ultimate strength (kPa), and flexural stiffness (kN/mm^2), since these tests may be less familiar to readers they are summarized as follows:

$$\text{Facing stress} = P_{\max} S/2t(d+c)b \quad (1)$$

$$\text{Core shear ultimate strength} = P_{\max}/(d+c)b \quad (2)$$

$$\text{Flexural stiffness} = E(d^3 - c^3)b/12 \quad (3)$$

where

$P_{\max}$ = maximum load (kN) prior to failure,
S = span (mm),
t = nominal facing thickness (mm),
d = sandwich thickness (mm),
c = nominal core thickness or $d - 2t$ (mm),
b = sandwich width (mm), and
E = facing elastic modulus (MPa).

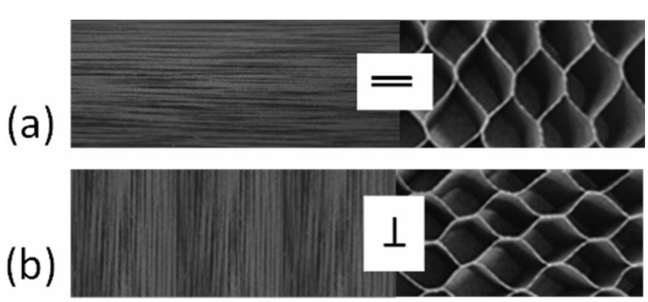


Figure 4.—Schematic representation of honeycomb orientation relative to surface veneer direction for the sandwiches fabricated from 3.2-mm hardboard: (a) veneer grain runs parallel (=) to specimen long axis and perpendicular to the honeycomb ribbons, (b) veneer grain runs perpendicular (⊥) to specimen long axis and the honeycomb ribbons.

Table 4.—Flexure test parameters for faces.

Panel type and thickness[a]	Span (mm)	Crosshead radius (mm)	Loading speed (mm/min)	
			Segment 1	Segment 2
9.5-mm PB	230	14.3	2.0	4.56
9.5-mm MDF	230	14.3	2.0	4.56
6.3-mm PB	158	9.5	2.0	3.17
6.3-mm MDF	158	9.5	2.0	3.17
3.2-mm HB	87	5.0	0.75	1.7

[a] PB = particleboard; MDF = medium-density fiberboard; HB = hardboard.

I-beam theory covering the flexural behavior of paper honeycomb sandwich panels is covered in Bitzer (1997) and Zenkert (1997) and was summarized in Sam-Brew et al. (2011) and so is not repeated here.

Interlaminar shear (sandwiches only).—Shear testing of solid wood–mounted sandwiches was carried out in accordance with ASTM D1037 (ASTM International 2006a) using a Zwick I Z100 test machine with a loading speed of 1 mm/min, i.e., specimen length by 0.002 mm. Each of the 10 groups of four specimens was conditioned in a climate chamber under 65 and 95 percent RH, respectively, to constant weight. Test specimen weight was recorded immediately before and after testing. After testing the specimens were oven-dried at 103°C ± 2°C to determine the MC of each specimen (including the solid wood) at the time of testing (ASTM D4442; ASTM International 2007). Maximum load, shear modulus (slope of stress–strain curve), and shear strength were recorded.

IB strength (sandwiches only).—IB strength was tested according to ASTM C297 (ASTM International 2010) and is a measure of the core-to-facing bond integrity necessary to maintain face stability and allow load transfer between the face and the core. Specimen dimensions were 152 by 152 mm by specimen thickness (not including the thickness of the wood backing blocks). The specimens had been precut to size from the larger glued backing block assemblies described earlier and consisted of the sandwich specimen glued between two solid maple backing bocks each measuring 152 by 152 by 19 mm. Prior to conducting the tests, a set of 10 specimens was premeasured for width and breadth, the center of the top and bottom backing blocks was located with diagonal lines, and a hole measuring 6.3 mm in diameter and 10 mm deep was drilled where the lines intersect. A pointed wood screw with a hooked end measuring 115 mm in length and 9.4 mm in diameter was inserted into the drilled hole to provide the grip point for the load frame (MTS Renew Upgrade Package system 8249). Tensile loading speed was 0.5 mm/min so as to produce failure within 3 to 6 minutes. Response variables were peak load (kN) and peak stress (ultimate strength) in MPa.

Flatwise compression (sandwiches only).—Flatwise compression tests of the sandwich panels were carried out according to ASTM C365-11 (ASTM International 2011) for stabilized cores using the same load frame as for IB. The loading head was fitted with a swiveling ball and socket to allow the load to distribute uniformly over the specimen. Specimen dimensions were 152 by 152 mm by specimen thickness. Standard initial load placed on the specimen was 45 N, and loading speed was 0.5 mm/min so as to produce failure within 3 to 6 minutes. Response variables were peak load (kN), compressive chord modulus (MPa), and ultimate strength (MPa).

Experimental design and data analysis

The common and variable features of the panels are given in Table 1. Data sets were analyzed by RH grouping separately, since there were very large differences in properties of specimens conditioned to 65 or 95 percent RH. For IB at 95 percent RH, there were insufficient data for analysis due to specimen deterioration and invalid test results. Statistical analysis of all valid data sets was carried out using JMP 9 (SAS Institute Inc. 2010).

Data sets were first assessed for any significant differences in properties between the individual panels of each type. Any directional effects in the facing materials or from honeycomb direction (i.e., statistically significant differences in mechanical properties in specimens cut along or across the long axis of the facing or sandwich panel) were identified, and, where there was either no statistically significant difference or a significant difference between panels or panel directions that was very small, then data were pooled for practical purposes to give averages for the panel type. Means comparisons for panel types were undertaken using the Tukey-Kramer honestly significant difference method at a significance level of 5 percent. Significant differences between means on the graphs are assessed using the 95 percent confidence interval. For comparing panel types, the flexural and LE samples of HB 3.2 mm had to be separated into two groups because of the large differences in veneer direction. Since the objective was to compare the performance properties of different panel types, no interactive effects were examined.

Results

VDPs of face materials

VDPs for the five different kinds of wood composite facing materials used are shown in Figure 5. MDF (Figs. 5a and 5b) is characterized by highest density at the surfaces sharply decreasing over the first 1 mm of thickness to consistent density across the core. Note the consistently higher surface and core density of the 6.3-mm MDF product compared with the 9.5-mm product. In contrast, the PB (Figs. 5c and 5d) was characterized by a shallow U-shaped profile, with minimum density in the center of the core. The VDP for the 9.5-mm and 6.3-mm PB types were different, i.e., the highest density was at the very surface of the 9.5-mm product, whereas density tapered off at the very uppermost surfaces of the 6.3-mm product. The VDP of the veneered HB (Fig. 5e) was characterized by a high-density HB sheet (around 1000 kg/m^3) sandwiched between two lower density surface veneers of birch that had experienced some surface densification during the hot press veneer application process.

Effects of material and conditioning factors on mechanical properties of facings and sandwiches.—A summary of the factors (material and RH conditioning level) and their significance on the mechanical properties for facings and sandwiches is given in Table 5. Results for mechanical properties are described below, and significant effects are shown graphically.

Static bending facings (peak load, MOR, and MOE) at 65 and 95 percent RH.—MOR and MOE for the two representative sheets of each facing type were for the most part not significantly different from each other. Exceptions to this included a very small but statistically significant ($P < 0.001$) difference in MOR between the two sheets of 3.2-mm HB, and a very small but significant machine direction effect in MOE in the 6.3-mm PB sheets. Machine direction has been shown to significantly influence MOR and MOE in some PB (Semple et al. 2005a, 2005b). However, since the effect in the products sampled here was very small in magnitude and confined to MOE of the 6.3-mm PB, we pooled the MOR and MOE data for machine direction in the PB and MDF for the purpose of making a comparison of average flexural properties for each facing type and thickness.

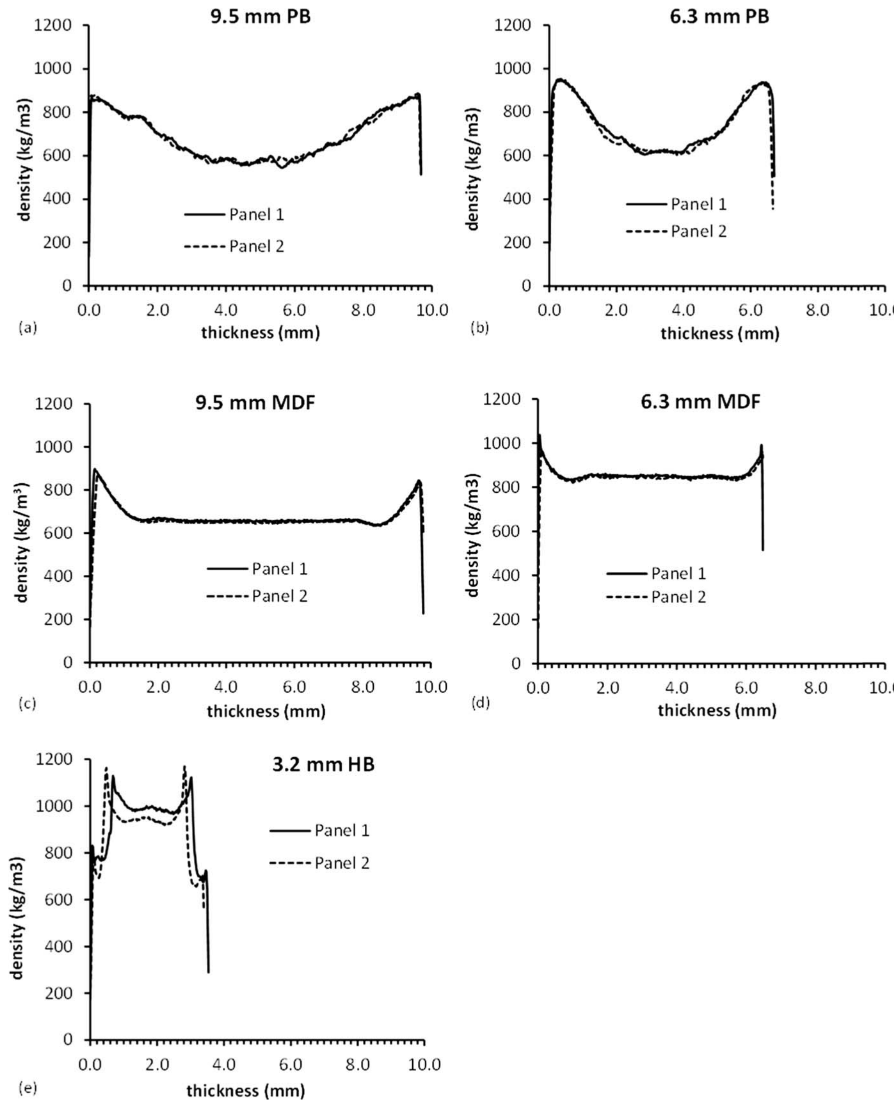


Figure 5.—Vertical density profiles of facing materials: (a) 9.5-mm particleboard (PB), (b) 6.3-mm PB, (c) 9.5-mm medium-density fiberboard (MDF), (d) 6.3-mm MDF, and (e) 3.2-mm veneered hardboard (HB).

The effect of veneer direction on the flexural properties of the veneered HB was highly significant ($P < 0.001$). Average MOR and MOE values for facings conditioned to 65 or 95 percent RH are given in Table 6, and shown graphically in Figure 6. For facings conditioned to 65 percent RH, MOR was highest in 3.2-mm HB, with wood veneer running along the long axis of the panel and testing specimen (MOR = 99.41 MPa, MOE = 8.44 GPa), followed by 6.3-mm MDF and 9.5-mm MDF. Average MOE for 3.2-mm HB perpendicular to veneer direction was 0.73 GPa. MDF was higher in flexural properties than PB (18 to 30 MPa in MOR and 2.4 to 3.3 GPa in MOE) compared with 10 to 12.5 MPa in MOR and 2.3 to 2.4 GPa in MOE for PB.

After conditioning to 95 percent RH, the facings lost up to 50 percent of their original strength, and the differences between facing types became less apparent. Strength and stiffness loss was highest in 6.3-mm MDF (55%). The increase in MC and thickness was also highest for this facing type (136% of the conditioned EMC at 65% RH), and were on average 10.7 percent greater than the thickness at 65 percent RH. The other facings underwent MC increases of between 80 and 107 percent and thickness increases of between 6 and 9 percent. The 3.2-mm HB parallel veneer retained the highest proportion of original stiffness after conditioning under 95 percent RH. PB suffered significant surface mold growth; their average MC increased to 17.5 percent after conditioning to 95 percent.

LE facings and sandwiches.—Average values for LE and associated weight gain and MC are given for facings and sandwiches in Table 7, and dimensional LE is shown graphically in Figure 7a for facings and Figure 7b for sandwiches. The relationship between different facing types remained consistent. Lowest LE was for 3.2-mm HB parallel to veneer grain (0.05% facing, 0.11% sandwich panel) while 6.3-mm PB were highest for both faces and sandwiches (0.42% facing, 0.50% sandwich). LE was almost 10 times greater for 3.2-mm HB perpendicular to veneer grain than 3.2-mm HB parallel to grain. The thinner facings underwent a greater percentage change in length (0.42% for 6.3-mm PB, 0.39% for 3.2-mm HB across veneer grain, and 0.30% for 6.3-mm MDF), compared with 0.25 and 0.21 percent for 9.5-mm PB and MDF, respectively.

Table 5.—P values for significance of relevant effects on the properties of facings and sandwiches.[a]

Test	Responses	Facings: Facing type 65%	Facings: Facing type 95%	Facings: Panel axis 65%	Facings: Panel axis 95%	Facings: RH
Thickness	Thickness	<0.0001	<0.0001	NA	NA	NA
Basic density	Basic density	<0.0001	<0.0001	NA	NA	NA
MC	MC	NS	<0.0001	NA	NA	NA
Flexure	Peak load	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
	MOR	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
	MOE	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Linear expansion	Weight gain	<0.0001	<0.0001	NS		NA
	Expansion	<0.0001	<0.0001	NS		NA
	Final MC	<0.0001	<0.0001	NS		NA
		Sandwiches				
		Sandwich type[b]		Ribbon direction[c]		
		65%	95%	65%	95%	RH
Thickness	Thickness	<0.0001	<0.0001	NA	NA	NA
Basic density	Basic density	<0.0001	<0.0001	NS	NS	NA
MC	MC	NS	<0.0001	NA	NA	<0.0001
Flexure	Peak load	<0.0001	<0.0001	0.0002	<0.0001	<0.0001
	Facing stress	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
	Core shear ultimate stress	<0.0001	<0.0001	0.0006	<0.0001	<0.0001
	Flexural stiffness	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Flatwise compression	Compressive modulus	<0.0001	<0.0001	NA	NA	<0.0001
	Ultimate strength	<0.0001	NS	NA	NA	<0.0001
IB	Ultimate strength	<0.0001	NA	NA	NA	<0.0001
Linear expansion	Weight gain	<0.0001		NS		NA
	Expansion	<0.0001		NS		NA
	Final MC	<0.0001		NS		NA
Interlaminar shear	Shear modulus	<0.0001	0.0002	0.0024		<0.0001
	Maximum shear strength	0.0023	0.0054	0.0136		<0.0001

[a] RH = relative humidity; NA = not applicable; MC = moisture content; NS = not significant; MOR = modulus of rupture; MOE = modulus of elasticity; IB = internal bond; PB = particleboard; MDF = medium-density fiberboard.

[b] Encompasses facing type, thickness, and honeycomb height.

[c] Contrast made for PB and MDF sandwiches only.

Sandwich static bending (peak load, facing bending stress, core shear ultimate stress, flexural stiffness) at 65 and 95 percent RH.—The average values for flexural properties of sandwich panel types at 65 and 95 percent RH separated by honeycomb orientation are given in Table 8. For comparative purposes, ultimate load at failure and flexural stiffness of the sandwich structure are shown in Figure 8, and an example of the flexure test is shown in Figures 9a and 9b. Ultimate load is the first failure load of the facing–honeycomb interface (see Figs. 9a and 9c), after

Table 6.—Average values for flexural properties of facing materials used in sandwich construction ($n = 20$ per mean).[a]

Facing material	Conditioning chamber (%)	Basic density (kg/m^3)	Thickness (mm)	MC (%)	MOR (MPa)	MOE (GPa)
9.5-mm PB	65	674.02	9.66	8.6	12.66	2.30
	95	668.16	10.37	16.47	7.91	1.36
9.5-mm MDF	65	695.64	9.76	7.28	17.99	2.39
	95	695.44	10.35	14.45	12.39	1.44
6.3-mm PB	65	729.0	6.64	8.45	10.76	2.39
	95	715.33	7.25	17.48	6.45	1.28
6.3-mm MDF	65	856.76	6.53	7.09	27.91	3.31
	95	837.92	7.23	16.73	10.59	1.36
3.2-mm HB[b]	65 =	899.88	3.55	8.82	99.41	8.44
	65 ⊥	899.88	3.55	8.82	30.94	1.31
	95 =	900.53	3.77	16.05	60.53	6.11
	95 ⊥	900.53	3.77	16.05	17.68	0.73

[a] MC = moisture content; MOR = modulus of rupture; MOE = modulus of elasticity; PB = particleboard; MDF = medium-density fiberboard; HB = hardboard.

[b] For 3.2-mm HB, "=" denotes veneer grain parallel to specimen long axis, and "⊥" denotes veneer grain perpendicular to specimen long axis.

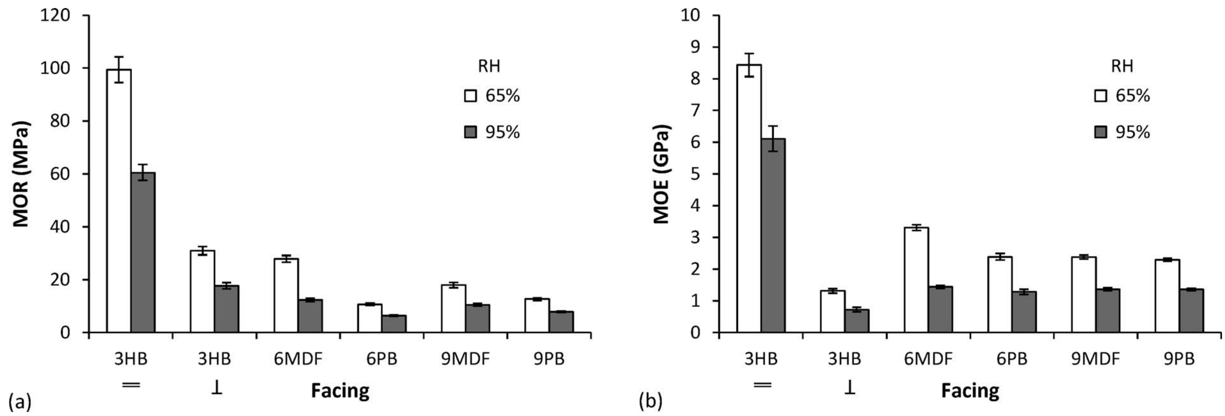


Figure 6.—(a) Modulus of rupture (MOR) and (b) modulus of elasticity (MOE) for facing materials after conditioning under 65 and 95 percent relative humidity. Error bars represent 95 percent confidence intervals—means that do not overlap are significantly different at $P \leq 0.05$.

which the structure continues to take load until facing failure (Figs. 9b and 9c). At 65 and at 95 percent RH the differences in flexural properties between sandwich types were statistically significant ($P < 0.0001$); see Table 5. Ultimate load was highest for 9.6-mm MDF sandwiches and lowest for 3.2-mm HB perpendicular grain. The flexural stiffness of the sandwiches followed the same trend as MOE of the facings tested in isolation (see Fig. 6b). Accordingly, the 3.2-mm HB sandwich loaded parallel to grain was highest in flexural stiffness (2.98×10^6 kN/mm^2) of all sandwich types, but at much lighter weight (170 kg/m^3) for same sandwich thickness as the panels made with MDF or PB.

All flexural properties (peak load, facing stress, core shear ultimate stress, sandwich flexural stiffness) decreased significantly ($P < 0.0001$) after exposure to 95 percent RH. Average peak load was reduced from a range of 0.8 to 1.8 kN at 65 percent RH to between 0.58 and 1.1 kN at 95 percent RH (Table 7; Fig. 8a). From Table 7 and Figure 8b flexural stiffness of sandwich panels was mostly between 0.8 and 1.3×10^6 kN/mm^2 at 65 percent RH, but decreased to below 0.7×10^6 kN/mm^2 after conditioning at 95 percent RH, a reduction of around 40 percent. The facings that experienced higher moisture uptake and loss of strength and stiffness after exposure to 95 percent RH, i.e., 6.3-mm MDF, produced sandwiches that were also susceptible to greater loss of stiffness when conditioned to high humidity, losing around 50 percent of original stiffness. In contrast, the reduction in stiffness was not as great for the 3.2-mm HB sandwiches. The specimens with the honeycomb ribbons running parallel to the long axis were significantly higher in load-bearing capacity than those with the honeycomb running perpendicular to the long axis. In the 3.2-mm HB the honeycomb orientation was masked by the much stronger effect on sandwich flexural properties of veneer direction, which was perpendicular to the honeycomb ribbon direction.

Sandwich interlaminar shear (shear modulus, shear strength) at 65 and 95 percent RH.—Average values for shear modulus and shear strength for core material and sandwiches conditioned under 65 and 95 percent are given in Table 9 and for general comparison across panel types in Figure 10. From Table 9, shear properties were higher when tested parallel to ribbon direction. Average shear modulus for the core only (parallel, 65% RH) was 1.91 MPa, which decreased to 0.76 MPa after conditioning to 95 percent RH. At 65 percent RH, shear strength of 3.2-mm HB and 9.5-mm MDF sandwiches was significantly higher than 9.5-mm PB. Maximum shear strength was 0.108 MPa for 3.2-mm HB parallel to ribbons.

Sandwich IB strength at 65 and 95 percent RH.—Average peak load and stress at delamination for sandwich panels conditioned to either 65 or 95 percent RH are given in Table 10, and peak stress for 65 percent RH is shown graphically in Figure 11 for comparison. Specimens conditioned to 65 percent RH were mostly between 60 and 70 kPa in peak stress at delamination, except for the panels made using the 9.5-mm PB, which were significantly lower ($P < 0.001$) in average face–core bonding strength (35.5 kPa). The averages

Table 7.—Moisture uptake and linear expansion for facing materials and kraft paper honeycomb sandwiches conditioned under 65 percent RH, measured and then conditioned under 95 percent RH for 45 days and remeasured ($n = 20$ per mean).[a]

	Face materials				Sandwiches			
Facing material[b]	% weight gain	Expansion (mm)	% change	MC at 95% RH (%)	% weight gain	Expansion (mm)	% change	MC at 95% RH (%)
9.5-mm PB	7.44	0.63	0.25	17.25	6.06	0.54	0.21	15.92
9.5-mm MDF	8.23	0.53	0.21	16.57	7.05	0.46	0.18	15.34
6.3-mm PB	9.33	1.08	0.42	19.83	10.38	1.26	0.50	20.99
6.3-mm MDF	10.27	0.76	0.30	18.97	9.55	0.7	0.28	18.34
3.2-mm HB =	9.09	0.11	0.05	19.22	11.65	0.28	0.11	22.30
3.2-mm HB ⊥	9.09	0.97	0.39	19.22	11.65	1.27	0.50	22.30

[a] RH = relative humidity; MC = moisture content; PB = particleboard; MDF = medium-density fiberboard; HB = hardboard.

[b] For 3.2-mm HB, "=" denotes veneer grain parallel to specimen long axis, and "⊥" denotes veneer grain perpendicular to specimen long axis.

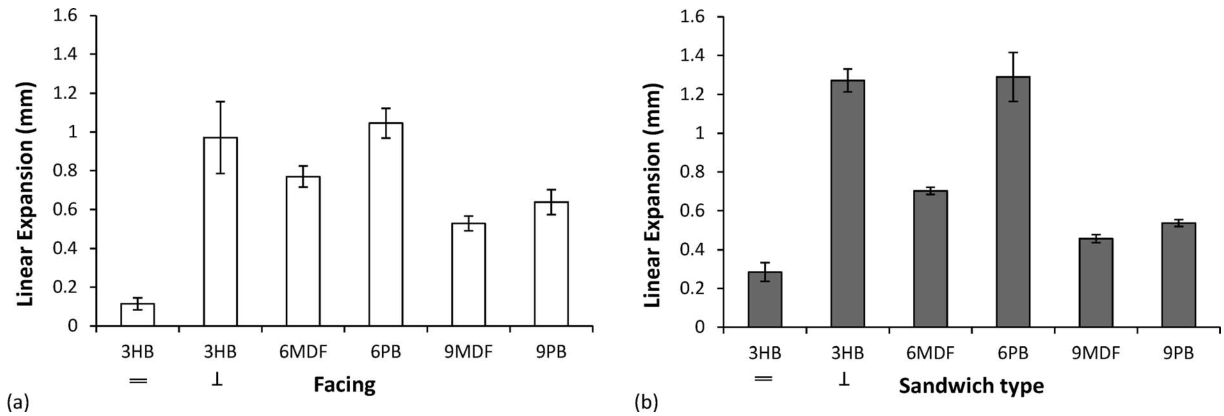


Figure 7.—Average linear expansion of (a) facings and (b) sandwiches. Error bars represent 95 percent confidence intervals—means that do not overlap are significantly different at $P \leq 0.05$.

given in Table 9 for specimens conditioned to 95 percent RH were very low because of a combination of distortion and the wood backing blocks causing premature delamination. The very high proportion of damaged specimens from the 95 percent conditioned group meant that no statistical analysis and inference could be made.

Sandwich flatwise compression at 65 and 95 percent RH.—Average values for sandwich flatwise compression (peak load, compression modulus, ultimate strength) are given in Table 11. For comparison purposes the compression modulus for different types of sandwiches conditioned under 65 or 95 percent is shown in Figure 12. There was high within- and between-panel variability in flatwise compression. There was a small but statistically significant between-panel variation in the case of the sandwich panels made from MDF facings of both thicknesses. Average compressive strength and modulus was higher in the 3.2-mm HB sandwiches with the 38-mm-high honeycomb cells. Note that in Figure 12b, there is less variation among sandwich types in compressive strength and after conditioning at 95 percent RH, and any differences between sandwich types disappear.

Discussion

Facings

The 3.2-mm HB parallel to veneer direction stood out as being the most appropriate facing material for honeycomb sandwich construction, for its high strength and most light weight thick sandwich panels. However, the very large differences in properties of this facing and its sandwiches with the veneer grain direction could have implications for

Table 8.—Static bending properties for kraft paper honeycomb core sandwich panels conditioned under 65 or 95 percent RH, by honeycomb direction ($n = 20$ *per mean).*[a]

Facing material	Conditioning chamber (%)	Basic density (kg/m^3)	Thickness (mm)	MC (%)	Honeycomb direction[b]	Peak load (kN)	Facing stress (kN)	Core shear ultimate stress (kPa)	Flexural stiffness (kN/mm^2)
9.5-mm PB	65	310.8	44.93	9.05	*x*	1.56	2.31	291.34	1.08×10^6
					y	1.42	2.11	265.38	1.08×10^6
	95	318.23	46.67	16.87	*x*	1.07	1.54	194.53	7.38×10^5
					y	0.97	1.40	176.38	1.7×10^6
9.5-mm MDF	65	318.34	45.02	7.78	*x*	1.76	2.61	329.27	1.13×10^6
					y	1.59	2.37	298.16	1.13×10^6
	95	328.85	46.38	15.02	*x*	1.10	1.59	200.81	7.11×10^5
					y	0.99	1.43	180.56	7.15×10^5
6.3-mm PB	65	240.37	45.06	8.78	*x*	1.12	2.22	192.61	8.93×10^5
					y	0.92	1.82	157.67	9.03×10^5
	95	252.68	46.48	17.19	*x*	0.78	1.53	132.67	5.49×10^5
					y	0.63	1.22	105.66	5.51×10^5
6.3-mm MDF	65	277.41	44.94	7.75	*x*	1.41	2.80	242.22	1.23×10^6
					y	1.24	2.46	212.78	1.23×10^6
	95	288.49	46.23	15.66	*x*	0.91	1.77	153.28	6.06×10^5
					y	0.75	1.46	126.51	6.11×10^5
3.2-mm HB[c]	65	168.4	45.03	9.0	*x*	0.81	2.80	128.53	2.98×10^6
					y	1.11	3.82	175.33	1.94×10^6
	95	179.58	45.50	15.82	*x*	0.58	2.19	100.38	1.75×10^6
					y	0.75	2.78	127.84	1.51×10^6

[a] RH = relative humidity; MC = moisture content; PB = particleboard; MDF = medium-density fiberboard; HB = hardboard.
[b] Honeycomb *x* direction, the ribbons run parallel to specimen long axis; *y* direction, the ribbons run perpendicular to specimen long axis.
[c] For 3.2-mm hardboard, the *x* honeycomb direction specimens have the wood veneer perpendicular to the long axis, and *y* specimens have parallel wood veneer.

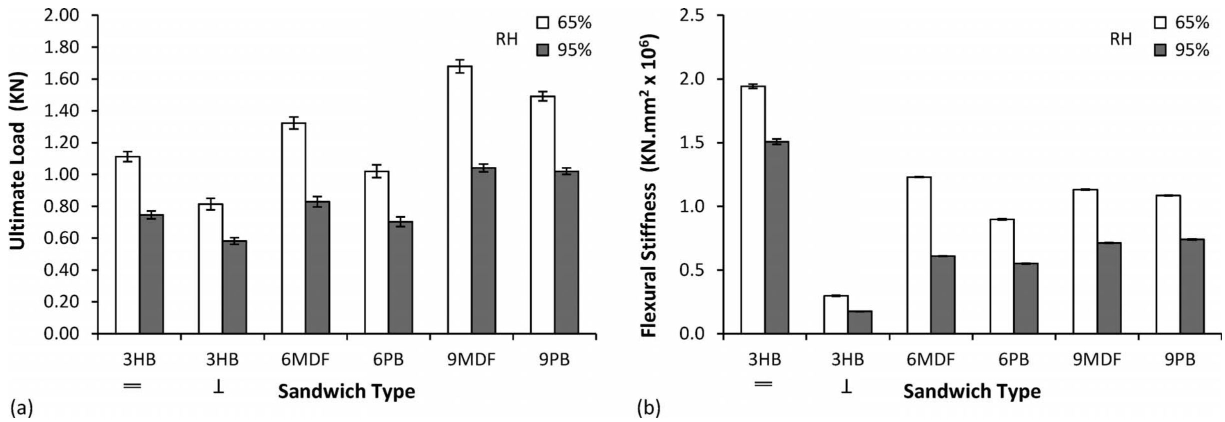


Figure 8.—(a) Peak load and (b) flexural stiffness of kraft paper honeycomb sandwiches conditioned under 65 or 95 percent relative humidity (RH). Error bars represent 95 percent confidence intervals—means that do not overlap are significantly different at $P \leq 0.05$.

sandwich performance depending on how the stock panel is cut and converted to shelving or a table top. The higher observed variation in the density and density profile of different veneered HB sheets (see Fig. 5e) could be expected to lead to the observed variability in sandwich panel strength. Different sheets of wood veneer can vary considerably in their grain characteristics and tensile strength, meaning that greater variability in the properties between sandwiches made from this facing type is inevitable.

The degree to which the material in the facings expands in the lateral plane or flexes in response to prolonged exposure to high humidity can affect the durability and service life of the sandwich and potentially stress the glueline between the facing and the honeycomb (Palms and Sherwood 1979). It was observed that LE of the 3-mm HB was almost 10 times higher perpendicular to veneer grain than parallel, which is consistent with the swelling of solid wood, which is several times greater in the transverse direction than along the grain. The PB facings underwent

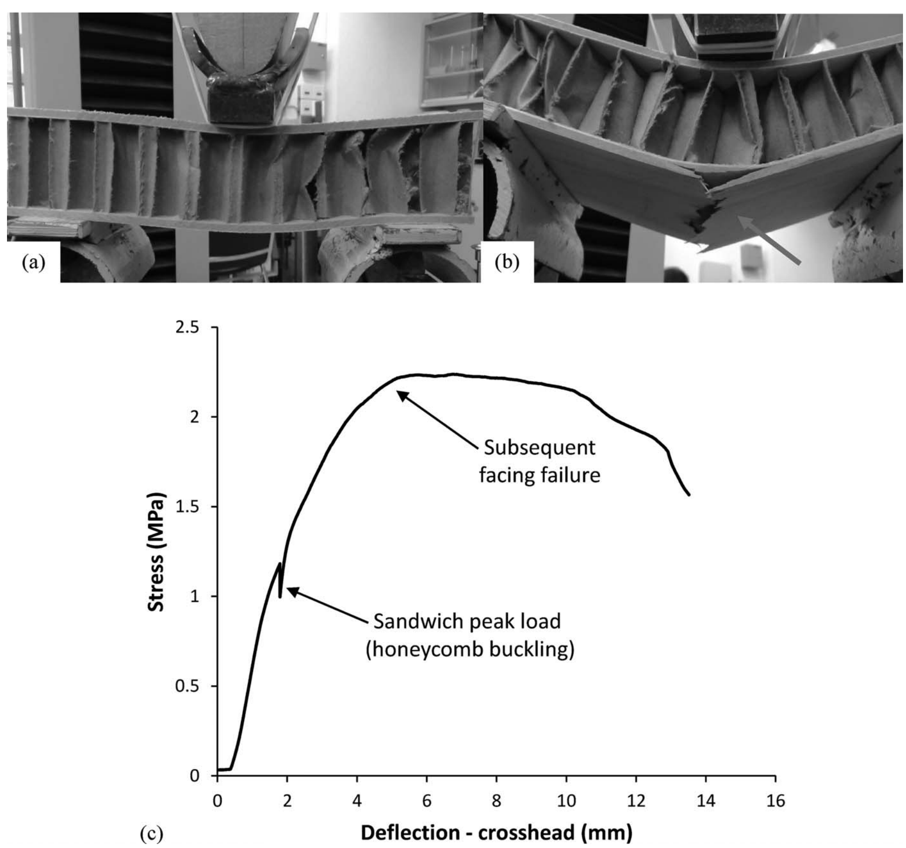


Figure 9.—Flexure test of 3.2-mm hardboard with veneer running (a) across specimen long axis, and (b) along specimen long axis; and (c) typical stress–strain curve for sandwiches (6.3-mm medium-density fiberboard shown). Arrow in (b) indicates facing failure after continued flexing beyond the initial failure at face–core interface.

Table 9.—Average values for shear modulus and shear strength of kraft paper honeycomb sandwiches conditioned under 65 or 95 percent RH (n = 12 per mean).[a]

Sandwich type	Conditioning chamber (%)	Basic density (kg/m^3)	Moisture content (%)	Honeycomb direction	Shear modulus (MPa)	Shear strength (MPa)
Core only	65	34.1	9.3	*x*	1.91	0.080
				y	1.04	0.043
	95	37.2	18.0	*x*	0.76	0.040
				y	0.51	0.027
9.50-mm PB	65	310.8	10.9	*x*	1.24	0.024
				y	0.86	0.027
	95	318.23	20.2	*x*	0.72	0.017
				y	0.56	0.033
9.5-mm MDF	65	318.34	9.3	*x*	1.94	0.062
				y	1.63	0.066
	95	328.85	18.0	*x*	0.71	0.022
				y	0.65	0.025
6.3-mm PB	65	240.37	8.4	*x*	1.72	0.071
				y	0.94	0.034
	95	252.68	19.5	*x*	0.51	0.023
				y	0.53	0.014
6.3-mm MDF	65	277.41	7.6	*x*	1.86	0.061
				y	1.62	0.061
	95	288.49	23.0	*x*	0.90	0.037
				y	0.61	0.022
3.2-mm HB	65	168.4	8.2	*x*	2.01	0.108
				y	1.29	0.061
	95	179.58	21.3	*x*	1.30	0.053
				y	0.97	0.034

[a] RH = relative humidity; MC = moisture content; PB = particleboard; MDF = medium-density fiberboard; HB = hardboard.

higher LE than the MDF, likely due to the presence of larger solid wood particles that undergo hygroscopic swelling with water uptake. Swelling is more restricted in MDF products as a result of its different manufacturing process, whereby the wood fibers undergo a form of heat stabilization during the defibration and resination process as well as wax addition. Different density among facings is also likely to have affected the extent of water uptake and LE. The 6.3-mm panels of PB and MDF were higher in basic density than their 9.5-mm counterparts and therefore tended to absorb more water and undergo greater dimensional change.

In addition to structure and density profile, the overall density of the facing material also influenced their flexural properties; 6.3-mm MDF was 19 percent more dense than the 9.5-mm thickness, and its MOR and MOE were 36 and 28 percent higher, respectively. However, for some reason the higher density of the 6.3-mm PB did not translate into markedly higher flexural properties. One possible reason for this observation was that the two thicknesses of PB were quite different in the shape of their VDP (Figs. 5a and 5b); in the 9.5-mm panels, density was highest at the very outer layer, whereas in the 6.3-mm panels, the density profiles had distinctly rounded shoulders with lower density material on the very outermost surfaces, where bending stress is most concentrated. For the facing materials alone, MDF of a particular thickness was stronger and stiffer than PB of the same thickness. Therefore the use of MDF facing might be preferable to PB for sandwich strength, but at the same time

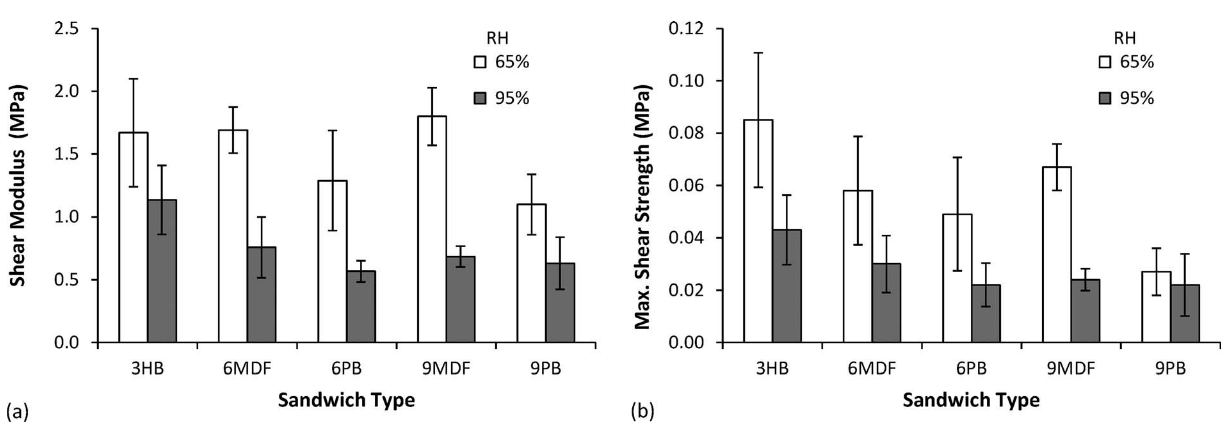


Figure 10.—(a) Shear modulus and (b) maximum shear strength for sandwiches conditioned under 65 or 95 percent relative humidity (RH). Error bars represent 95 percent confidence intervals—means that do not overlap are significantly different at $P \leq 0.05$.

Table 10.—Average values for internal bond strength of kraft paper honeycomb sandwiches conditioned under 65 or 95 percent RH (n = 40 per mean).[a]

Facing material	Conditioning chamber (%)	Peak load (kN)	Peak stress (kPa)
9.5-mm PB	65	0.84	35.5
	95	0.184	7.9
9.5-mm MDF	65	1.47	61.84
	95	0.694	29.5
6.3-mm PB	65	1.60	67.47
	95	0.444	19.77
6.3-mm MDF	65	1.35	57.01
	95	0.576	24.71
3.2-mm HB	65	1.59	67.26
	95	0.501	21.13

[a] RH = relative humidity; PB = particleboard; MDF = medium-density fiberboard; HB = hardboard.

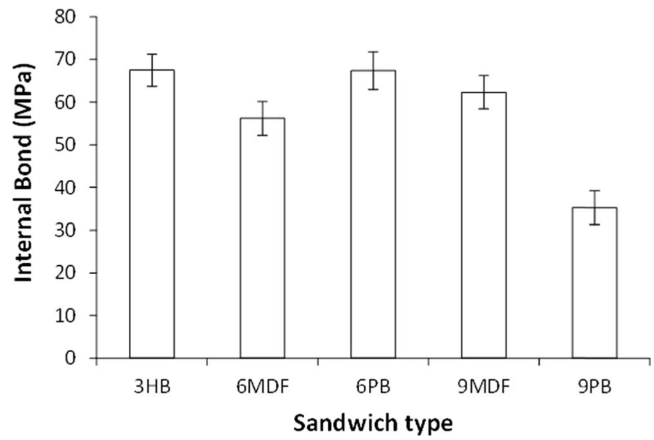


Figure 11.—(a) Compressive modulus and (b) compressive strength for sandwiches conditioned under 65 or 95 percent relative humidity. Error bars represent 95 percent confidence intervals—means that do not overlap are significantly different at P $\leq$ 0.05.HB = hardboard; MDF = medium-density fiberboard; PB = particleboard.

it can lead to a heavier product due to its higher material density.

Sandwich panel properties—flexural

Despite the facings tested in isolation having high peak load values, loads at first failure for the honeycomb sandwiches were a small fraction of the facings (see Table 6). In a sandwich structure the interface between the core and the facing critically affects the failure load and mode of the structure under static loading (Bitzer 1997). According to Bitzer (1997), honeycomb sandwiches are very effective as lightweight fatigue-resistant structures because the core can be continuously bonded to the surface skin, which eliminates stress concentration. During loading, stress is transferred through the face to the much weaker facing–core interface. This causes buckling of the core (Fig. 9a). Once the sandwich has reached its ultimate load due to honeycomb failure, it is able to continue flexing under further loading until the facing itself eventually fails. In the case of the veneered HB, the sandwich structure was able to undergo large deflection (up to 50 mm) before failure of the facing itself (Fig. 9b). Classical sandwich theory assumes the core carries the entire shear load, facings carry the entire bending load, and core compression is negligible provided the facings and core undergo elastic deformation with low facing–core thickness ratio (Zenkert 1997). Contrary to this theory, the load-carrying capacity of certain kinds of sandwich structures continues to increase after initial failure of the core (Mercado and Sikarskie 1999), and in our sandwiches the load decreased temporarily at honeycomb failure but subsequently increased, with the facings and the damaged honeycomb taking further strain to failure of the facings. Since sandwich theory assumes load-carrying capacity of the sandwich does not exceed the honeycomb failure load, there is therefore some transfer of the additional shear load to the facings in these cases (Akhour and Maaitah 2012).

There was a trend for the thicker facings to translate into higher first failure load for sandwiches (Fig. 8a). However, it was noted that the high MOR for 3.2-mm HB parallel grain facings tested in isolation (see Fig. 6a) did not translate into higher ultimate load–bearing capacity of the sandwiches. Thicker honeycomb of the same cell size is more rigid than thin sections and therefore more resistant to elastic deformation to conform to facing flexure, which places greater stress on the bond lines. For a honeycomb sandwich structure to remain intact with curvature, the core must have high flexibility and low resistance shearing deformation (Fulton and Skyes 1966). Flexing of the facing induces shearing forces along the surface–core bonding interface, producing localized buckling of the honeycomb cell walls under the loading point nose, accumulated glue line failures, as well as localized buckling of the tops of the honeycomb cells beneath the loading head. The stronger the glueline bond strength and the less resistant the core is to shear deformation, the longer it takes for bond line failure, so as flexing continues, buckling at the cell wall tops becomes the predominant mode of failure. The failure mode is independent of the diameter of the loading head (Petras 1998).

The specimens with the honeycomb ribbons running parallel to the long axis were significantly higher in load-bearing capacity than those with perpendicular ribbons (notwithstanding the masking effect of veneer direction in the 3.2-mm HB). This is likely due to the core being more rigid along the ribbon direction than across. This suggests that paper honeycomb core and its rigidity contribute to some extent to the load-bearing capacity of this class of wood composite and paper-based honeycomb sandwiches. Nevertheless, elastic modulus (E) of the core is considered in ASTM D7250/D7250M (ASTM International 2006b) to have a negligible effect on bending stiffness of the sandwich and is not used for calculating sandwich flexural stiffness. It is the E of the facings, and the facing and core dimensions, that determine the calculated flexural stiffness of a paper honeycomb sandwich. There is also no account made for core rigidity or how resistant the honeycomb cells are to buckling, and paper honeycomb has comparatively low resistance to buckling compared with polymer, metal, or carbon fiber cores. If the core has high out-of-plane stiffness then damage does not propagate through the core, and the facings will fail eventually by compressive macrobuckling (Petras 1998). Enhancing both the bond durability and the buckling resistance of the honeycomb core would contribute greatly to enhanced sandwich strength. The buckling load of

Table 11.—Average values for compressive strength of kraft paper honeycomb sandwiches conditioned under 65 or 95 percent RH ($n = 40$ per mean).[a]

Facing material	Conditioning chamber (%)	Basic density (kg/m^3)	Thickness (mm)	Moisture content (%)	Peak load (kN)	Compression modulus (MPa)	Ultimate strength (MPa)
9.5-mm PB	65	312.17	44.95	9.16	5.06	7.01	0.22
	95	318.61	46.14	15.08	3.34	4.74	0.14
9.5-mm MDF	65	318.08	44.98	7.67	5.33	9.28	0.23
	95	327.13	46.29	14.37	3.29	5.71	0.14
6.3-mm PB	65	342.25	45.11	8.95	5.09	9.62	0.22
	95	265.02	46.25	15.82	3.23	5.99	0.14
6.3-mm MDF	65	277.78	44.96	7.62	5.28	9.21	0.23
	95	287.97	46.27	15.63	3.2	5.24	0.14
3.2-mm HB	65	169.77	45.07	8.82	5.87	14.36	0.25
	95	178.15	45.57	17.1	2.1	10.07	0.14

[a] RH = relative humidity; PB = particleboard; MDF = medium-density fiberboard; HB = hardboard.

honeycomb sandwiches, which is especially important in curved forms, can be significantly increased by combining a face sheet with high flexural stiffness and a core material that is weak in shear (Fulton and Skyes 1966).

According to Kollmann et al. (1975), Bitzer (1997), and results for similar kinds of laboratory-fabricated wood-based honeycomb panels (Sam-Brew et al. 2011), the shear properties (shear modulus and rigidity) of hexagonal cell, flexible wall (Nomex or plain kraft paper) honeycomb are also greater parallel to ribbons. Small cell (3 mm diameter) Nomex honeycomb sandwiches are significantly stronger parallel to ribbons (Petras 1998, Petras and Sutcliffe 1999). However, as the cell diameter increases to above 13 mm, the honeycomb directional effect on sandwich flexural properties has been shown in previous studies (Petras and Sutcliffe 1999, Sam-Brew et al. 2011) to be reversed, i.e., sandwiches are stronger if the long axis runs perpendicular to ribbon direction. This is thought to be due to the greater propensity of larger cells to buckle early, causing sandwich failure, since there is less cell wall area per unit surface area.

The maximum flexural rigidity theory governing ultra-light honeycomb sandwiches used in the aerospace industry states that core weight should be two thirds of the total sandwich weight (Murthy et al. 2006). The theory refers to sandwiches with nonmetallic Nomex (i.e., resin-impregnated paper honeycomb) and very thin unidirectional or woven glass or carbon fiber skins. For thin mild-steel structures the core should be 50 to 66.7 percent of total weight (He and Hu 2008). In the wood- and paper-based sandwiches this is reversed, since the facings are much thicker, and several times the weight of the core. Facing-to-core weight ratios were 20:1 for 9.5-mm facings, around 12:1 for 6.3-mm facings, and 6:1 for the HB facing. The 3.2-mm HB produced by far the most efficient sandwich structure in terms of core-to-facing weight ratio and maximizing the effect of honeycomb cell height. Here the core contributes significantly (via the positive effect of cell height on sandwich stiffness) to the strength-to-weight ratio of a thick sandwich panel.

Sandwich panel properties—shear, IB, and compressive strength

Shear properties were lower for 9.5-mm PB sandwiches, which is consistent with the lower facing-to-core bond strength for 9.5-mm PB sandwiches. The PB material itself does not appear to have adversely affected glue bond strength, since the highest bond line strength was found for the 6.3-mm PB sandwiches, and it is likely that this difference was caused by differences in surface characteristics between the 6.3- and 9.5-mm PB types. Some evidence for this can be seen in the different density profiles at the surfaces of the boards. The topmost surface density being maximum at the very top layers of the 9.5-mm PB (Fig. 5c) but having a rounded profile in the 6.3-mm PB

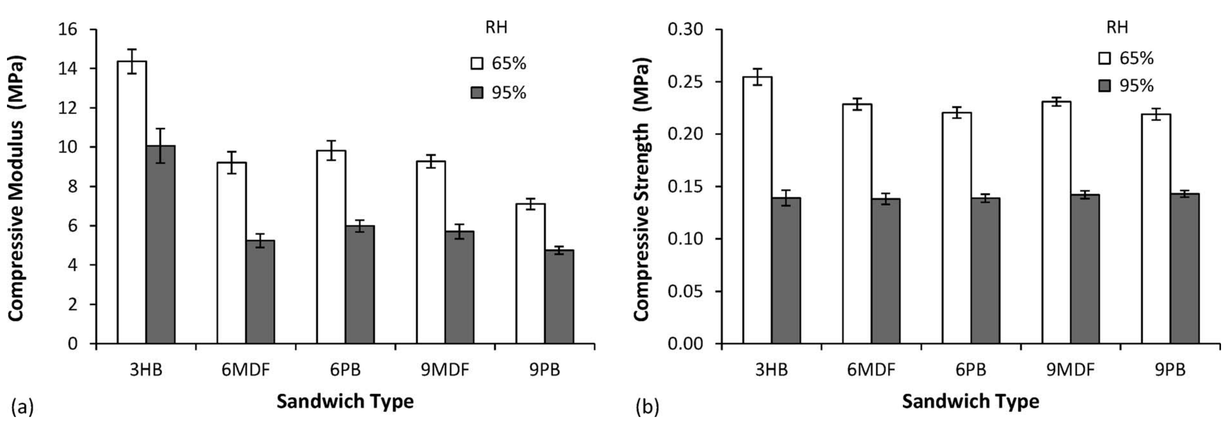


Figure 12.—Average internal bond strength of sandwich panels conditioned under 65 percent relative humidity. Error bars represent 95 percent confidence intervals—means that do not overlap are significantly different at $P \leq 0.05$. HB = hardboard; MDF = medium-density fiberboard; PB = particleboard.

suggests the 9.5-mm boards were sanded to remove any low density ‘‘precured’’ layers that can occur after hot pressing (Maloney 1993). Other unknown factors, such as surface energy, ageing history or differences in sandwich compaction pressure between the two board types, may have also affected adhesive bond strength.

Owing to the method used to test IB strength, few valid data points were obtained for 95 percent RH because of distortion of the solid wood backing causing partial delamination in most of the test specimens. Cured polyurethane adhesive is resistant to moisture at ambient temperatures, and evidence of this comes from the one or two specimens in each group of 40 specimens of each sandwich type conditioned to 95 percent RH that did not delaminate. Peak stress values for undamaged 95 percent specimens were 27 MPa for 9.5-mm PB, 61 MPa for 9.5-mm MDF, 46 MPa for 6.3-mm PB, 55 MPa for 6.3-mm MDF, and 56 MPa for 3.2-mm HB; not very different from values for specimens at 65 percent.

The sandwich type with the thickest honeycomb, i.e., the 3.2-mm HB, was highest in average compressive modulus and strength but showed little difference between the other two honeycomb heights (25.4 mm and 31.75 mm) made from PB and MDF. The exception was that compressive modulus of 9.5-mm PB sandwiches was significantly lower than the others (Fig. 12a). This was consistent with the low shear and IB strength for this sandwich type. The sandwich structure fails at the topmost facing–core interface via flattening of the tops of the honeycomb cells. As the wall deviates from the vertical, it exerts localized stress on the glue bonds between the cell tops and the facing, which were already significantly weaker for the 9.5-mm PB. Since the surface area of all specimens was constant, the ultimate failure load was consistent regardless of honeycomb cell height, which is largely a function of the rigidity of the honeycomb cell wall. According Khan (2006) the compressive strength of honeycomb sandwiches (in this case aluminum and glass fiber facing) is largely dependent on the facing material, and there is little effect of core thickness. Bitzer (1997) also states there is little difference between honeycomb height and compressive behavior. Nevertheless for paper honeycomb and wood composite sandwiches, an increase in compressive strength with honeycomb cell height was observed in laboratory-fabricated sandwiches of the same thickness made with 3- or 6-mm-thick MDF (Semple et al. 2007, Sam-Brew et al. 2011).

After conditioning to 95 percent RH, the sandwiches lost up to 44 percent (in the case of the 3.2-mm HB) of their compressive strength at 65 percent RH. Depending on manufacture and surface treatment for water resistance, paper honeycomb can be highly sensitive to moisture; compressive strength in humid environments can be as low as 25 percent of its strength in dry environments (Palms and Sherwood 1979, Pohl 2009). Another contribution to the variation in compressive strength was variability observed in the extent of honeycomb cell expansion both within panels and also across panels, affecting cell numbers and shapes in each test specimen.

Conclusions

1. The strongest facing material used for sandwiches was the 3.2-mm HB with wood veneer grain running parallel to the long axis of the specimen, followed by the 6.3-mm MDF and the 9.5-mm MDF. In contrast, the 3.2-mm HB with veneer running perpendicular to the long axis of the panel was low in flexural strength.
2. Thinner facing materials (3.2 and 6.3-mm) were denser and attained a higher MC after exposure to high humidity, associated with greater LE and thickness swelling. The direction of the veneer grain of the thin HB facing strongly affected its dimensional stability—LE is significantly higher if the veneer grain runs perpendicular to the long axis of the specimen.
3. Sandwich panels made with thicker facings were stronger than those made with thinner facings for PB and MDF. Sandwiches made from PB and MDF had a higher loading tolerance prior to failure if the honeycomb ribbons were parallel to the length of the sandwich panel.
4. For a given thickness, panels made from MDF were stronger than those made from PB; however, if a lightweight structure is required, thin-veneered HB performs well *provided* the veneer grain runs parallel to the long axis of the sandwich structure. The facing and sandwich structure is much weaker if the wood veneer grain runs perpendicular to the long axis.
5. After exposure to 95 percent RH, facings and sandwiches lost up to half their original strength properties. The effect was particularly apparent in the 6.3-mm MDF, which was denser and had a greater increase in MC.
6. PB sandwiches were lower in shear strength and modulus, and sandwiches with 3.2-mm HB or 9.5-mm MDF backing were higher.
7. Face–core bond strength values (assessed for 65% RH only) were similar for sandwich types except those made with the 9.5-mm PB, which were significantly lower in bond strength.
8. Compressive modulus was highest for the 3.2-mm HB and lowest for the 6.3-mm PB sandwiches.

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