COMPOSITE HOLLOW CORE HIGH-END BIO-PANELS

S. Rao[1], V. Yadama[2] and D. Bhattacharyya[1*]
[1] Centre for Advanced Composite Materials, Department of Mechanical Engineering, The University of Auckland, Auckland Mail Centre 1142, New Zealand.
[2] Department of Civil and Environmental Engineering & Composites Materials and Engineering Center, Washington State University, Pullman, WA, U.S.A
[*] Corresponding author (d.bhattacharyya@auckland.ac.nz)

Keywords: *Sandwich Panels, Bio-Panels, Natural fibre composites, laminated strand veneer*

1 Introduction

Hollow cores are multifunctional in nature and have a wide range of applications in structural and non-structural areas. In structural applications, they are generally used as core material for sandwich construction, where they are bonded to thin rigid face sheets on either side of them, and in non structural applications they are used as acoustic panels or as air vents to change the air direction and as thermal insulators/conductors. Most of the conventional hollow core sandwich panels consist of metallic, paper or polymeric cores with polymeric or fibre reinforced faceplates, but due to the high cost involved in manufacturing, the application has been somewhat limited to high end products, such as those in aerospace industries. In the view of reducing its cost and the recent environmental concerns, hollow cores for sandwich panels have been produced from recyclable and natural materials.

The cores were fabricated from wood fibre/sisal fibre-polypropylene (PP) composites or laminated strand veneer (LSV). The specific mechanical properties of the hollow cores after fibre reinforcement increased to more than twice of those of the un-reinforced cores and the specific bending stiffness of the LSV sandwich panels increased by 88% compared to that of oriented strand boards (OSB) while utilising less than 50% of wood fibre and normally required resin amount. The characteristic functional properties of these panels, coupled with good mechanical properties, make them suitable for a wide range of applications, including those in automobile, aerospace, packaging and building/fabrication industries. Added value can be obtained by specifically achieving desirable properties with the incorporation of additives, such as fire retardant substances [1, 2].

2 Materials and Manufacturing

2.1 Materials and composite manufacturing

Wood-PP composites

Radiata Pine wood flour (length/diameter ~ 3) or sisal fibres (length/diameter ~ 30) were used as natural fibre reinforcement in as received conditions. The fibres were dry blended with polypropylene and a copolymer and lubricant (Licocene PP MA 6452 TP).

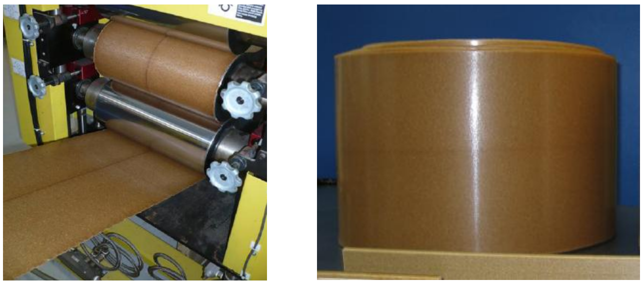


Fig.1 wood-PP composites (a) calendering to 0.7mm thickness (b) wood-PP composite roll

Sisal fibres (at 0.3 mass fraction) were dry blended with PP, lubricant and talc and the composite sheet was extruded using a 35mm conical twin screw extruder (Cincinnati Milacron TC35) through a die with a 300mm by 2.5mm rectangular cross-section, which was calendered to 1.5mm thickness, Fig 1 (a). For woodfibre composites, the woodfibres (at 0.3 mass fraction) was filtered and pre-blended with PP and lubricant in a twin screw co-rotating extruder with barrel temperatures varying between 140 and 200°C. The extruded material was pelletised and dried for 12 hours before extruding them in a 35mm conical twin screw extruder (Cincinnati Milacron TC35) through a die with a 300mm by 2.5mm rectangular cross section which was then calendered to 0.7mm thickness, Fig.1 (a).

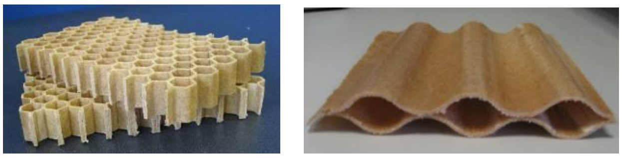
Several settings were trialled to maximise the throughput while maintaining a uniform flow output from the die [3], and a torque of 18 percent (of the total available screw torque of 1,740Nm) and screw speed of 45rpm were finally used. A flat temperature profile of 200°C was maintained along the barrel and the die. The extruded sheet was passed through calendering rolls to reduce the thickness to 0.7mm.

Woodstrand-PF resin composites

Ponderosa pine (*Pinus ponderosa*) obtained from northwest Washington, USA, was used for stranding. To obtain consistent strand width, green logs were ripped into boards 13mm thick using a band saw and fed into a strander operating at a rotation speed of 500 rpm. The projection of the strander blades was adjusted manually to obtain consistent thicknesses. A constant strand width and length of 13mm and 150mm respectively were targeted. The strands were then dried to 6% moisture content and screened before being hot-pressed. Phenol Formaldehyde (PF) resin with 57% solids content that was used in OSB faces was utilised for hot-pressing all the strand veneers. All plies were pressed using a hydraulic 914 mm square oil-heated press in conjunction with the Pressman™ (Alberta Research Council 2006) control system. PF resin was applied to the strands using an air atomised resin sprayer in a rotating drum mixer. Strands were distributed by hand into a forming box placed on an aluminium caul sheet. Orientation was accomplished by vanes with staggered heights and a spacing of 38 mm on centre. The forming box was set on an oscillating table to provide a uniform distribution of flakes passing through the vanes. Once the ply was formed, it was placed in the hot press and pressed with a holding time of 210s at target thickness.

2.2 Manufacturing cores with natural fibre reinforcement

The sheets were thermoformed into half hexagonal and sinusoidal profiles using matched-die thermoforming technique with a forming rate of 500mm/min and a die temperature of ~165°C was used.



(a) (b)

Fig.2 Honeycomb cores assembled from the formed sisal-PP composites (a) hexagonal cores (b) sinusoidal cores

The thermoformed corrugations were cooled to room temperature in the die before extraction. These corrugated sheets were cut to required heights and bonded using ultrasonic welder, MP 2022 with a generator, SL20, 20 kHz to form hollow cores, Fig. 2.

The cores can be used in sandwich panels between any facing materials; in this research work, 3-ply and 6-ply wood veneers were used as facings, Fig. 3. The wood veneer facings were bonded using methacrylate glue Loctite 401 but thermoplastic matrix based composite facings were ultrasonically bonded to the cores.

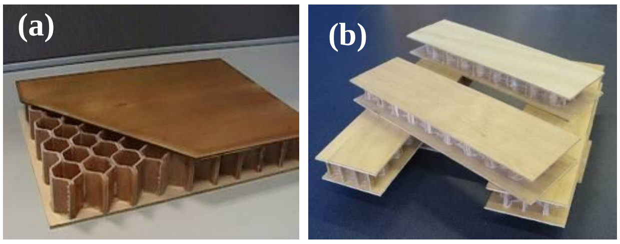


Fig.3 Bio panels (a) woodfibre-PP core (b) sisal fibre-PP core

An Aluminium mould was designed for pressing a thin-walled core composed of small-diameter timber strands. The core geometry is a biaxial corrugated shape with continuous ribs in the *x*-axis and segmented ribs in the *y*-axis. 3-D wood-strand cores were then manufactured using ponderosa pine strands bonded with 8% PF resin in that 3-D mould. The Sandwich panels were fabricated with thin plies of wood strands board as facings and 3-D strand cores for determination of their mechanical properties, Fig. 4. The cores and face plies were bonded using a modified diisocyanate (MDI) adhesive.


(a)


(b)

Fig.4 Bio panels (a) woodstrand-PF core (b) woodstrand-PF core sandwich panel

Sandwich panels were also manufactured from NZ radiate pine veneers with corrugated and honeycomb (sinusoidal) cores. The plywood consisted of three 0.6 mm thick veneers bonded with two part polyvinyl acetate (PVA) glue to form a [0/90/0] laminate. These sheets were sourced from a local plywood manufacturer and measured on average 1.8 mm thick, with a variation within ±0.05 mm. Sections to fit in the matched die were soaked in a hot water bath for three minutes to become pliable and were then pressed for 40 seconds at 160 °C. The resulting corrugated sheets were used to manufacture the two types of core mentioned earlier. The average density of the corrugations was calculated as 118 kgm^{-3}; roughly five times lower than the original plywood density of 530 kgm^{-3}.

3 Testing

3.1 Mechanical testing of composite cores

Flat-wise stabilised compression tests of the cores were conducted as per standard ASTM C 365[4] on universal testing machine. Four-point bending with two point loads equidistant from the supports was used and the flexural test on flat sandwich construction was conducted according to ASTM C 393 [5] to determine the flexural and shear stiffness of the construction, and shear modulus and shear strength of the core.

The specific compressive strengths (σ^*/ρ^*) and moduli (E^*/ρ^*) of PP honeycomb and sisal-PP honeycombs, manufactured from composite sheets (compression moulded or extruded) are shown in Table 1. The average compressive strength of the core was 8.7 (±0.9) MPa and the average compressive modulus was 269.0 (±24.6) MPa. The failure of the core was initiated due to the buckling of the cell walls and finally failing due to the fracture.

Table 1 Specific properties of honeycomb cores subjected to *out-of-plane* compressive loading

Density (kg/m^3)	Material	E^*/ρ^* (Nm/kg)	σ^*/ρ^* (Nm/kg)
49 (±12.0)	PP core	0.80×10^6	0.02×10^6
151 (±7.6)	Sisal-PP hexagonal	1.73×10^6	0.05×10^6
145 (±3.2)	Sisal-PP sinusoidal	1.82×10^6	0.05×10^6
115 (±1.2)	Wood-PP hexagonal	1.80×10^6	0.03×10^6

The sandwich panels with sinusoidal cores exhibited higher core shear strength of ~2.0 MPa, sustaining flexural loads up to 6.5 kN as compared to 5.2 kN of that of the hexagonal cores. The failure in this case was initiated due to the de-bonding at the core-facing interface.

The failure in the panel during flexural testing was initiated due to debonding at the core-to-facing interface followed by core shear. The core shear strength was estimated to be 0.7 ±0.2MPa compared to the unreinforced PP honeycombs (0.5MPa) and sisal-PP honeycombs of ~1.5MPa.

The specific shear strength of the sisal-PP and wood-PP core along with other standard cores is listed in Table. 2. The values of the wood-PP cores were similar to those of the unreinforced ones, but these values were achieved at much lower cell densities and *t/l* values of 0.07, compared to that of the PP cores, which was 0.08 (*t* and *l* are the thickness and length of the cell wall, respectively). The sisal-PP cores exhibit an increase in shear strength, ~25% higher than that of the PP cores at *t/l* ratio of 0.1. Therefore, with an increase of the *t/l* vaues of the cores, the cell density would increase and shear strength of the core is expected to increase accordingly. Specific mechanical properties of some wood veneer cores along with commercially available cores for the purpose of comparison are listed in Table.3.

Table.2 Specific shear strengths of various honeycomb cores

Material, cell size (mm)	Density (kg/m^3)	τ^*/ρ^*(Nm/kg)
PP core, ~6	49 ±12.0	8×10^3
Aluminium (5056), ~10	37 ±3.0	32×10^3
Nomex (Phenolic), ~10	48 ±3.0	27×10^3
Sisal-PP hexagonal core, ~12	151 ±7.6	10×10^3
Sisal-PP sinusoidal core, ~12	145 ±3.2	12×10^3
Wood-PP hexagonal core, ~12	115±7.0	8×10^3

Table 3 Specific mechanical properties (compressive) of cores compared with commercially available cores

	Density (kg/m^3)	E_c (MPa)	$\sigma_{c\,max}$ (MPa)	Sp E_c	Sp $\sigma_{c\,max}$
Corrugated core	118	10.1	0.53	85.6	4.5
Honeycomb core	118	222	3.9	1880	33
Commercially Available Cores:					
PP-HC	110	50	2.4	450	21
Nomex	128	255	5.3	3200	66

(Sp-Specific; PP- Polypropylene; HC-Honeycomb)

3.2 Mechanical testing of LSV cores

Specimens were cut and evaluated in flexure and compression for bending stiffness, panel shear rigidity, core shear modulus, and compression strength and modulus following ASTM standards for sandwich panel constructions. Specimen configurations with length oriented with strong axis (*x*-axis) and weak axis (*y*-axis) were evaluated for their properties.

Average flexure strength and stiffness of thin strand plies were 100 MPa and 12.1 GPa; whereas, average OSB properties range between 20.7 to 34.5 MPa for flexure strength and 3.5 GPa to 7.0 GPa for stiffness. As for laminated strand lumber, a substitute for structural lumber, average properties range between 34.5 MPa to 44.8 MPa for strength and 9.0 GPa to 10.3 GPa for stiffness.

Range of possible wood-strand ply tensile properties possible are shown in Table 4. Range is based on testing of veneers in studies conducted by Weight [6] and Voth [7]. Average internal bond (IB) of these plies was approximately 1.0 MPa (COV =19%). These ply properties were used as needed in determining lightweight sandwich panel properties.

Table.4 Typical tensile properties of thin wood-strand plies bonded with PF resin

Properties	Longitudinal Axis		Transverse Axis	
	Average	COV (%)	Average	COV (%)
σ (MPa)	31	18.2	19.7	55.4
E (GPa)	7.0 – 11.7	7.3	3.4 – 6.0	19.1

Published [8] modulus of elasticity values for 5-ply plywood and OSB panels with a density of 640 kg.m^{-3} were used for comparison, and the sandwich panel densities were calculated to be 310kg.m^{-3} based on the densities determined from the flexural specimens. The panels' specific bending stiffness was 71 % greater than the plywood and 88 % greater than the OSB [9]. These results indicate that material usage (wood and resin) can be more efficient with use of lightweight sandwich panels constructed with thin-wall strand core and thin strand-based plies. The sandwich panel utilizes only 40 % of the wood-strand furnish and 40 % of the resin when compared to the quantities utilized in a typical OSB panel of the same dimensions. These percentages are calculated based on the weight of the materials.

3.3 Functional properties of fibre reinforced cores

Sound absorption

The sound absorption coefficient of the sandwich panels were tested in a Brüel & Kjaer standing wave apparatus. Two impedance tubes of 150mm diameter, 2.0m length and 30mm diameter, 500mm length were used to determine the absorption coefficients in the frequency range of 200Hz - 1.6 kHz and 1.6 kHz – 4 kHz, respectively, Fig. 5 and 6.

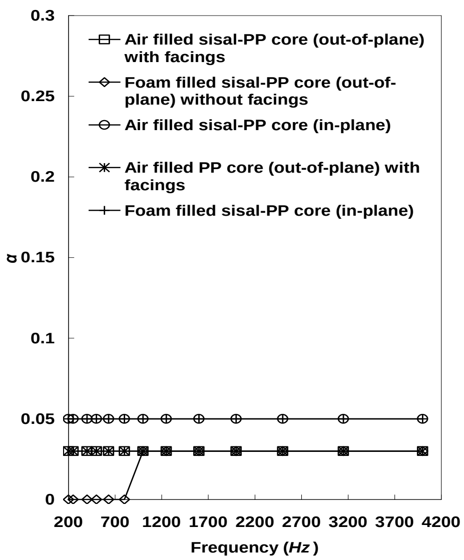


Fig. 5 Sound absorption coefficient of the panels with air and foam filled cavities at frequencies between 200Hz and 4kHz at intervals of 1/3 octaves [10]

An interesting property to be noted in Fig. 6 is that the sandwich panels exhibit sharp absorbance peaks at a certain frequency when the sound waves are incident on the faceplate and surface of the woodfibre filled cores. It is a characteristic of a resonant panel, which vibrates at a certain frequency and transmits the sound wave to the cavity behind it, which in this case is the core, filled with woodfibres, allowing the sound waves to be absorbed by the porous medium. The resonance in this study occurred at 1kHz for the sound waves incident on the in-plane direction of the core and at 1.25kHz for the sound waves incident on the face plate in the out-of-plane direction of the core. Well-designed resonant panels can absorb and control sound, and the efficiency in sound absorption can be achieved by having thicker absorbing media behind the resonating panel [11]. An optimum sound absorption in the panel can be obtained by the balancing the fibre density, porosity, fineness and bulk elasticity, and the core thickness.

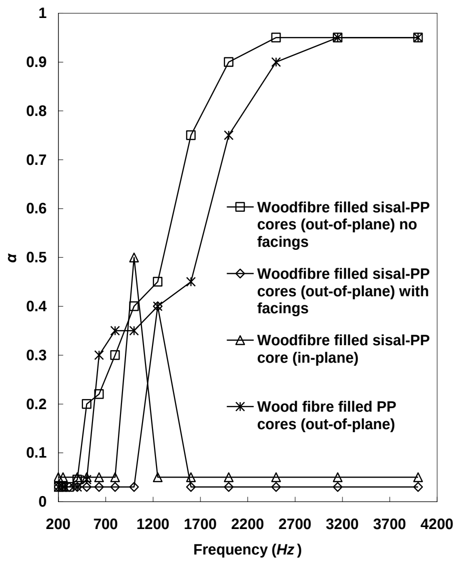


Fig. 6 Sound absorption coefficient of the panels with woodfibre filled cavities at frequencies between 200Hz and 4kHz at intervals of 1/3 octaves [10]

Energy absorption

Flat-wise bare compression testing of all the honeycomb cores were conducted as per standard [4], on a universal testing machine (Instron 5567). Specimens of cross-sectional area of 3600mm^2 and height of 50mm was subjected to compressive loading by setting the cross-head speed to 30mm/min until densification. The energy absorption curves were obtained by plotting the load against the deformation, Fig. 7.

Two different specimens were tried: commercially available un-reinforced PP honeycombs and sisal fibre reinforced PP honeycombs. The energy absorbed in each tested specimen has been estimated as the area under the respective stress-strain curve. Two different specimens, commercially available unreinforced PP honeycombs and sisal fibre reinforced PP honeycombs were compared to determine any change in the absorption after reinforcement. The energy absorbed in all the tested specimens has been estimated as the area under the respective load-displacement curve, Fig.7. An increase in energy absorption is exhibited by the reinforced cores as seen in Table. 5.

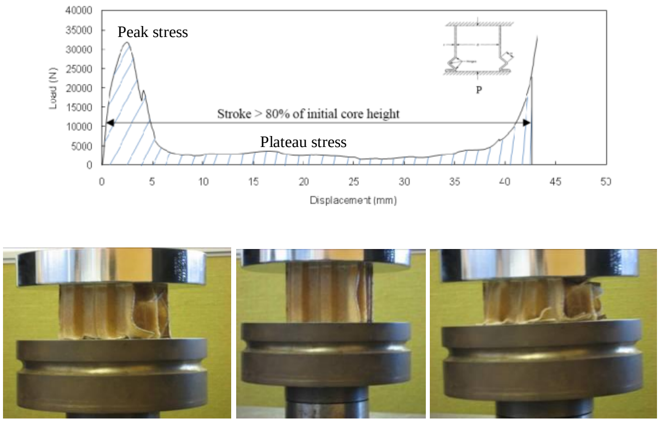


Fig. 7 Images taken during compaction of sisal-PP honeycomb core, and a corresponding load vs. displacement plot [10]

Table.5 Energy absorbed in the PP cores and sisal-PP cores

Honeycomb (core height in mm)	Density (Kg/m^3)	Volume (m^3)	Energy absorbed per unit volume (MJ/m^3)
PP (25mm)	49 (±12.0)	76 x 10^3	0.44
Sisal-PP (25mm)	151 (±7.6)	76 x 10^3	1.9
Sisal-PP (50mm)	151 (±7.6)	180 x 10^3	1.5

The basic concept of energy absorption is the conversion of kinetic energy of the moving object into internal work. In the case of a honeycomb core, the kinetic energy is used in the yielding or deformation of the cell walls of the core. In Fig.7 the peak stress is the compressive strength of the honeycomb core and the plateau is the average crush stress and the final rise in the strain is due to densification of the core. If the cores were applied in packaging, the distance it takes to stop the load from colliding with the ground is the stroke length (plateau region) and this is a function of the load and height of the core.

4.0 Summary and Conclusions

With growing environmental concerns and increasing competition, any future development of product and process should strive to reduce material consumption, minimise emissions, and consume less energy. The structural sandwich panels discussed in this study are an attempt to develop products that can achieve those requirements.

The reinforced cores manufactured in this study were mechanically superior to unreinforced PP cores, providing an improvement in specific strengths and moduli greater than two fold. Moreover, with the fibre alignment during extrusion, it was possible to align the principal direction of the fibres in the loading direction, increasing stiffness in the cell walls and hence the load carrying capacity of the cores. Additionally, based on the principle of resonance, by varying the core and face sheet thicknesses, sound absorbance at desired frequency could be anticipated. The energy absorption experiments revealed that the cores could be compressed to over 80% of their initial heights exhibiting long plateau with more or less steady stress, thus making them applicable as energy absorbers if they were to be considered for packaging applications.

The production of wood-strand sandwich panels using the matched-die mould design in this study could manufacture panels with 40% of the materials required to produce a solid panel of same thickness. This would also significantly reduce the petroleum-based resin consumption accounting to over 25% of the production costs. These panels exhibited significantly greater stiffness values than solid OSB panels using the same amount of constituent materials due to the 88% increase in specific bending stiffness.

References

[1] Genovese, A. and R.A. Shanks "Fire performance of poly(dimethyl siloxane) composites evaluated by cone calorimetry", *Composites Part A: Applied Science and Manufacturing*, vol 39, No. 2, pp. 398-405, 2008.

[2] Mouritz, A.P., Z. Mathys, and A.G. Gibson "Heat release of polymer composites in fire: *Composites Part A: Applied Science and Manufacturing*, vol 37, No.7, pp 1040-1054, 2006.

[3] Rao, S, D. Bhattacharyya, K. Jayaraman, A. Fernyhough "Manufacturing and Recycling of Sisal-Polypropylene Composites". *Polymers and Polymer Composites*. Vol 17, pp 467-479, 2009.

[4] ASTM C 365 Standard Test Method for Flatwise Compressive Properties of Sandwich Cores, 2000.

[5] ASTM C 393 Standard Test Method for Flexural Properties of Sandwich Constructions, 2000.

[6] S. Weight and V. Yadama "Manufacture of laminated strand veneer (LSV). Part 1: Optimization and characterization of thin strand veneers" *Holzforschung*, Vol 62, pp 725-6, 2008.

[7] C. Voth, "Lightweight sandwich panels using small-diameter timber wood-strands and recycled newsprint cores", M.S. Thesis, Washington State University, 2009.

[8] APA The Engineered Wood Association. *Mechanical Properties of APA Structural Panels Form No. TT-044A.* Tacoma, WA: APA The Engineered Wood Association, 2005.

[9] V. Yadama, S Weight and Chris Voth "Development of Wood-Strand Composites for Structural Applications" *Proceedings of PFAM* xix, Auckland, New Zealand, Vol. 1, Paper number 7.7, pp 1042-51, 2011.

[10] S. Rao, K Jayaraman and D. Bhattacharyya "Short fibre reinforced cores and their sandwich panels: processing and evaluation", *Composites Part A: Applied Science and Manufacturing*, doi:10.1016/j.compositesa.2011.05.006, 2011.

[11] Smith, W. R., Buschow, K.J.H., Robert, W.C, Merton, C.F, Bernard, I, Edward, J.K, Subhash, M. and Patrick, V "Wood: Acoustic Properties in Encyclopedia of Materials: Science and Technology" Oxford, Elsevier, pp 9578-9583, 2001.