Development of Veneer-based Corrugated Composites, Part 1: Manufacture and Basic Material Properties

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Typically, wood-based composite materials have been developed through empirical studies. In these products, the constituent wood elements have broad spectrums regarding species, size, and anatomical orientation relative to their own dimensions. To define special strength and stiffness properties during a long-term study, two types of corrugated wood composite panels were developed for possible structural utilization. The constitutional elements of the newly developed products included Appalachian hardwood veneer residues (side clippings) and/or rejected low quality, sliced veneer sheets. The proposed primary usage of these veneer-based panels is in applications where the edgewise loading may cause buckling (*e.g.*, web elements of I-joists, shear-wall and composite beam core materials). This paper describes the development of flat and corrugated panels, including furnish preparations and laboratory-scale manufacturing processes as well as the determination of key mechanical properties. According to the results in parallel to grain direction bending, tension and compression strengths exceeded other structural panels' similar characteristics, while the rigidities were comparable. Based on the research findings, sliced veneer clipping waste can be transformed into structural panels or used as reinforcement elements in beams and sandwich-type products.

Keywords: Wood-based composites; Veneer; Hardwoods; Structural panels; Corrugated wood panels; Load bearing members; Mechanical properties

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INTRODUCTION

Since the last quarter of the 20th century, the global forest products industry has experienced significant shortages in raw material supply. The available timber resources have declined gradually both in quantity and quality, while the demand for construction materials has increased substantially. Responding to the market requirements, manufacturers of construction materials developed several wood-based, load supporting composites commonly referred to as structural composite lumbers (SCL). These include laminated veneer lumbers (LVL), parallel strand lumbers (PSL), and laminated strand lumbers (LSL), originally designed to utilize softwoods. With the advancement of technology, short-rotation trees and species previously neglected because of their unfavorable properties have been used in the manufacturing processes. The definite advantages of these composites are higher yield from forest resources, higher (engineered) mechanical properties, dimensions limited only by technological constraints, better moisture resistance, and dimensional stability (Smulski 1997).

Structural wood and wood-based composite productions are more energy-efficient and environmentally friendly than other construction material productions, such as steel, aluminum, and reinforced concrete. Structural composite lumbers do very well on a performance *versus* cost efficiency basis compared with other load-bearing elements.

Another important issue is carbon dioxide emissions to the environment. The bound carbon in woody tissues needs to be retained as long as possible to prevent the early CO_2 emissions by decay or incineration of wood or wood-based materials. Thus, it is expected that the demand for structural wood products will increase in the future (Winandy 2002). However, there is potential for better exploitation of natural wood resources, minimizing environmental impacts, and recycling wood residues for better CO_2 retention. Within the framework of the Wood Utilization Research at the West Virginia University and with the cooperation of the University of West Hungary, extensive research has been conducted to convert low-quality Appalachian and European hardwoods into value-added products. One of the segments of this project dealt with the use of veneer mill residues for furnish of structural composites.

By slicing or eccentric rotary peeling, decorative (face) veneer manufacturing processes transform high quality half or quarter logs, with an average length of 2 to 4 m, into thin (0.4 to 0.8 mm) veneer sheets, sometimes referred to as veneer "leafs". After drying and stacking, a clipping operation sets the final rectangular dimensions of the veneer bundles that contain 12 to 20 sheets. This process yields residual side-clipping wastes, with an average length of 1 to 4 m and width of 25 to 50 mm (Fig. 1). Moreover, full size veneer bundles are also rejected because of quality reasons including natural or processing defects and staining. Industrial experiences and analytical works have confirmed that there is a positive correlation between strand length in the grain direction and strength properties (Barnes 2000, 2002; Edgar 2003; Nishimura *et al.* 2004). Therefore, side clippings are particularly suitable as furnish materials for structural composite production. Additionally, the end clipping operation generates rectangular shaped cutoffs that can be easily converted into strand-type raw furnish for further composite panel manufacture.

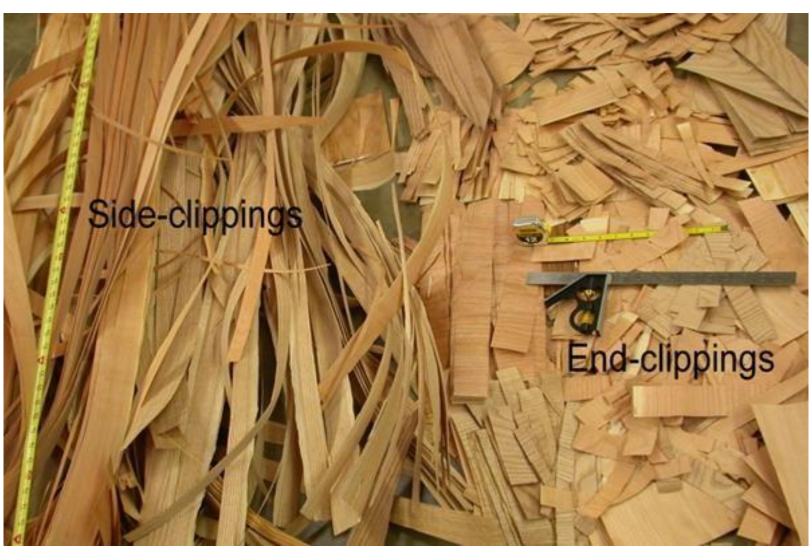

Fig. 1. Side- and end-clippings generated during decorative (face) veneer manufacture

Wastes from veneer processing are used routinely as fuel for energy production, albeit with low efficiency. Some colored species may be transformed into landscape mulch. However, only 10% of the clippings are recycled and utilized as wood fiber for composite manufacturing purposes. A survey revealed that in the central Appalachian region, 15 veneer mills generate approximately 60,000 metric tons of clipping residues annually (Hassler 2002). This volume corresponds to 92,000 m^3 wood based composite materials on a 650 kg/m^3 average density basis.

The experimental and development parts of the above-mentioned research resulted in several types of veneer based or veneer reinforced panels, tubes, and kitchen and interior panels (Fig 2). A mixture of polyurethane foam and veneer strips proved to be excellent core materials for structural insulated panels (Denes 2014).

Fig. 2. Variety of panels with PUR – side-clippings core materials and 3-D composites

Further research and development resulted in two characteristic structural composites designated as veneer strip panels (*VSP*) and veneer strip lumber (*VSL*). Figure 3 shows some of the products formulated from veneer wastes. Side- and end-clippings were reconstituted into discrete composite panels and load-supporting SCL slabs by traditional hot pressing consolidation processes. The resin application happened through roller coating and drum blending using conventional phenol-formaldehyde (PF) and polymeric diphenylmethane-diisocyanate (pMDI) resins common in structural panel and SCL manufacturing. Standard ASTM testing procedures (ASTM D-1037 1999 and ASTM D-143 1999) on limited sample sizes included apparent modulus of elasticity (MOE) and bending strength (MOR) determinations. Furthermore, internal bond (IB) tests demonstrated excellent strength values in the direction perpendicular to the principal plane of the materials (Denes *et al.* 2004, 2010). Besides the evaluations of mechanical and physical properties, response surface methodology (RSM) and robust parameter design (RPD) methods helped to identify the optimum parameters of orientation, resin coverage and furnish size (Montgomery 2005). The development of flat panels included the application of statistical quality control (Montgomery 1997). Results confirmed the superiority of unidirectional alignments (Denes *et al.* 2006).

Spruce veneer honeycomb elements using corrugated shapes for lightweight core sandwich panels has been proposed by Obataya *et al.* (2015) to increase the compressive strength of the structure, while Shibanuma *et al.* (2012) investigated bending strength and stiffness of the corrugated veneer-cored panels.

Several SCL products are already on the market that have well-developed manufacturing technologies. Therefore, this research was focused on specialty products, including buckling resistant panels, pallet parts, tubes, and shear wall components. The general objective of this segment of the work was to develop corrugated, veneer-based composite panels with improved edgewise load supporting capacity. The targeted specific objectives were: 1) to demonstrate the viability of structural panel corrugation using veneer wastes; 2) to identify basic technological parameters of the process; and 3) to establish the basic mechanical properties of the product.

Fig. 3. Variety of structural composites made from veneer clippings: (a) single-layer beams and panels from shredded side-clippings; (b) structural panels from side-clippings; (c) three-layer structural composite with end-clippings in the core

EXPERIMENTAL

Materials

Raw materials for furnish preparation were Appalachian hardwood veneer sideclippings and rejected full size veneer leafs with varying widths. The mixture of species included red maple (*Acer rubrum*), American white ash (*Fraxinus americana)*, black cherry (*Prunus serotina*), white oak (*Quercus alba*), and yellow poplar (*Liriodendron tulipifera*). The raw materials came from different veneer mills in the Appalachian region in dry conditions. For flat panels production a mix black cherry (85%) and white oak (15%) was used. Besides preconditioning and length adjustments, there was no additional manipulation of the veneers or clippings.

Adhesion was achieved by application of liquid phenol-formaldehyde (PF) resin with 50% dry material content typically used for LVL production. During mat forming for corrugated panels, the face layers of the mat were covered with melamine-base films to minimize future in-service moisture uptake.

Methods

During the first step, flat panels were manufactured to evaluate physical and mechanical properties. The furnish preparation included the cutting of the mixed hardwood side-clippings to uniform length (0.8 m). The widths of the veneer strips were not adjusted; this dimension was governed by side clipping operation, resulting in random widths between 30 and 120 mm. The average thickness was 0.5 mm. Preconditioning to 6% moisture content (MC) took place in a walk-in climate chamber set to 21 °C temperature (*T*) and 25% relative humidity (RH). The 700 kg/m^3 target density on a 9.5 mm average thickness required 3.8 kg strand materials for each panel.

Resin was applied with a laboratory roller-coater to both sides of the strands with a spread of 15 g/m^2. This agreed with the recommended furnish/resin mass ratio of 5% (Barnes 2000). The resin coated strands were manually aligned unidirectional on a screen-caul plate forming a rectangular mat with approximately 19 to 20 layers. The mat was covered with the top screen-caul plate.

Panels were pressed with a 200-ton capacity single day light, laboratory press with ~1 m × 1 m heated top and bottom platens. The pressing operation was under displacement control. Per the resin manufacturer's recommendations, a minimum 100 °C core temperature was maintained for 60 s to cure the liquid PF adhesive. Therefore, press plates were preheated to 180 °C. The pressing schedule was as follows: close the press rapidly to the maximum compaction (~ 8 mm), hold for 60 s, and gradually release the pressure applying three venting phases. Figure 4 shows a complete pressing cycle with the indication of pressure, platen displacement (*i.e.*, thickness) and the mat core temperature. The total pressing operation for a panel took 5.5 min.

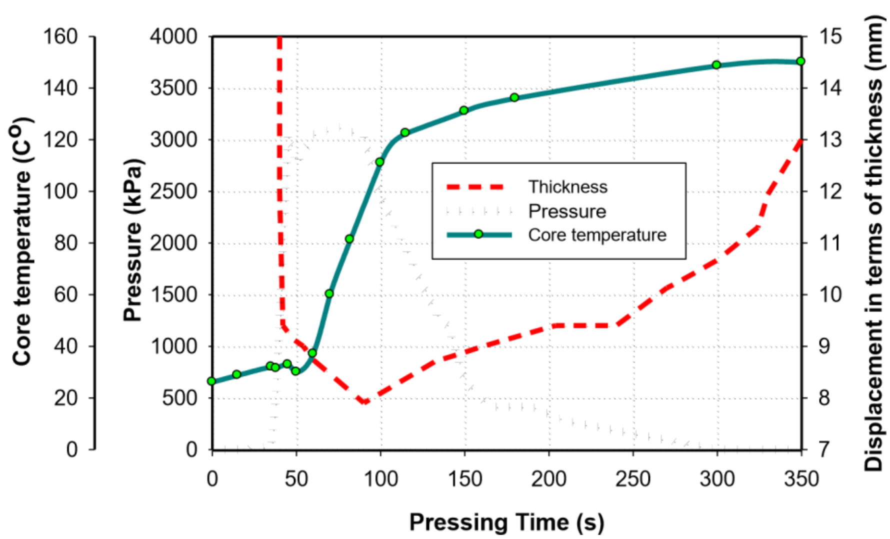

Fig. 4. Press cycle for panel consolidation

After pressing, flat panels were stacked under weights to prevent warping during cooling and acclimatization. Panels were trimmed, and standard ASTM test specimens were machined from randomly selected panels and areas. Tests and measurements included density, thickness swell, tension, compression, and flexural property evaluations. All assessments of physical and mechanical properties followed the specification of relevant standards (ASTM D 143-94 and D 1037-96) except specimens for tension strength and MOE determination. Because of the machine grip constrain, these specimens were cut to a 25 mm width instead of the standard 50 mm. Mechanical tests were performed parallel and perpendicular to the veneer strands in both flatwise and edgewise directions of the specimens.

Results of numerical analyses demonstrated that the highest buckling resistant is achieved by sine wave-shaped corrugation (McGraw *et al.* 2010a,b). Initially, the aluminum templet was designed with circular segments. An additional pair of sine-wave templates was machined to a width of 450 mm, but full in length (800 mm). For both the circular- and sign-wave forms, the wavelengths were milled to 150 mm, with ± 20 mm maximum vertical dimensions at the apexes (Fig. 5).

Figure 6 shows the schematics of these templates. Note that the even thickness of circular-wave panels could be ensured with alternating radii. However, because of milling constraints, the profiles of the top and bottom of sine-wave templates were identical. This resulted in under and over pressed regions at locations A and B, respectively (Fig. 6).

Fig. 5. Sine-wave corrugated panel during the pressing operation

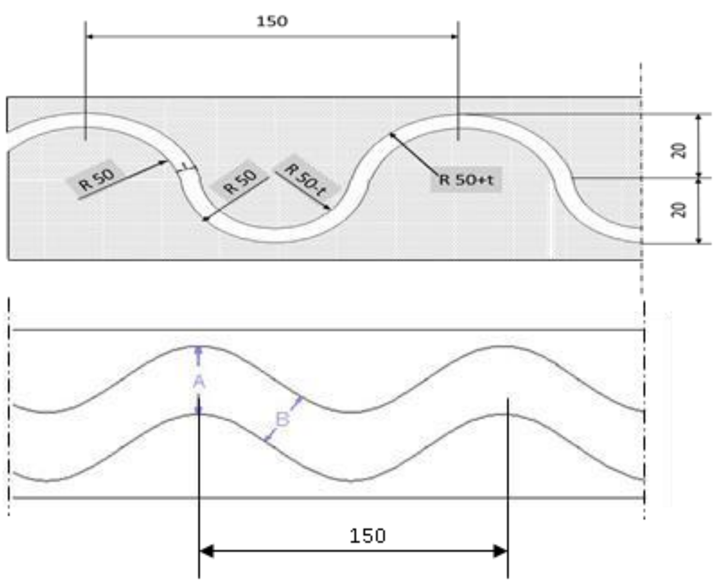

Fig. 6. Schematics of the aluminum templates (not to scale). Dimensions are in mm.

Mat preparation was the same as for flat panels, except that the length of furnish was adjusted to the calculated length of the wave form. A similar pressure cycle as depicted on Fig. 4 assured the consolidation and resin cure. The pressed and corrugated panels were stacked for acclimatization, trimmed, and stored until further conversions into structural elements of load bearing composites.

RESULTS AND DISCUSSION

Flat Panel Characteristics

The assessed physical attributes of flat panels included density and moisture uptake, thickness, and volumetric swelling (Table 1). On average, the target density was exceeded by about 6%, and the overall coefficient of variation (COV) was 12.7%. This may be attributed to the low density hardwoods higher densification at elevated temperature. The moisture related properties were very comparable to the swelling of structural panels currently on the market.

Table 1. Physical Properties of Flat Panels

Treatments	Properties			
	Density (k/m^3)	Weight Increase (%)	Thickness Swell (%)	Volumetric Swell (%)
Target	700	------	------	------
Actual	740 *(94)*	------	------	------
2 hour soak	------	19.2 *(6.4)*	5.5 *(1.9)*	11.7 *(4.5)*
24 our soak	------	41.1 *(9.2)*	14.6 *(2.9)*	19.3 *(6.8)*

Standard deviations are in parenthesis; an average of 15 to 20 measurements were included for each property.

Standard testing procedures revealed that strength and stiffness properties of the new composites met or exceeded the similar characteristics of competing oriented strand boards (OSB) and plywood. Table 2 compiles the average values with standard deviations. In fact, the strength values were even better than that of similar properties of commercial solid wood (Forest Products Laboratory 1999). This fact can be explained by the origin of furnish materials. The defect free veneers came from high quality solid wood prisms, prepared for slicing or eccentric peeling. Furthermore, densification during the pressing process remarkably improved the mechanical properties. This confirms the finding that the correct pressing time, temperature, and pressure have utmost importance in quality wood composite manufacture.

The mean modulus of rupture value also exceeded the similar values of other structural panel type products (OSB, plywood, LVL) when specimens were tested flatwise in parallel to strand direction, while the rigidity of the specimens were comparable. In the case of perpendicular grain directions, a significant drop of the mechanical properties can be observed.

Table 2. Average Mechanical Properties of Flat Panels

Load Orientation		Sample Size	MOR (MPa)	MOE_t (GPa)	σt (MPa)	σc (MPa)	MOE_c (GPa)	Shear (MPa)	IB (MPa)
Parallel with strands	Flat	20	132.5 *(23.3)*	15.5 *(1.9)*	99.6 *(29.7)*	73.7 *(10.4)*	11.45 *(2.75)*	5.76 *(1.08)*	1.05 (0.38)
	Edge	20	110.5 *(10.8)*	13.4 *(1.0)*					
Perpendicular to strands	Flat	20	86.9 *(2.69)*	8.9 *(2.7)*	4.03 *(1.60)*	15.9 *(4.9)*	1.10 *(0.041*	3.56 *(1.15)*	
	Edge	20	7.24 *(1.65)*	7.2 *(1.7)*					

Mean values with standard deviations are in parenthesis; σ_t and σ_c are tension and compression strengths, respectively.

Visual assessments of failure modes showed splintering and brush tension failures in bending (MOR). Specimens in tension failed in splintering manner almost one hundred percent. Under compression, the re-glued panels failed because of buckling after delamination. Figure 7 shows some characteristic failure modes. The internal bound (IB) tests resulted in more than 50% wood failure. However, the variability of data was unexpectedly wide (1.9 to 0.45 MPa). This may be explained by the different densification of diverse species. Therefore, this phenomenon should be investigated further.

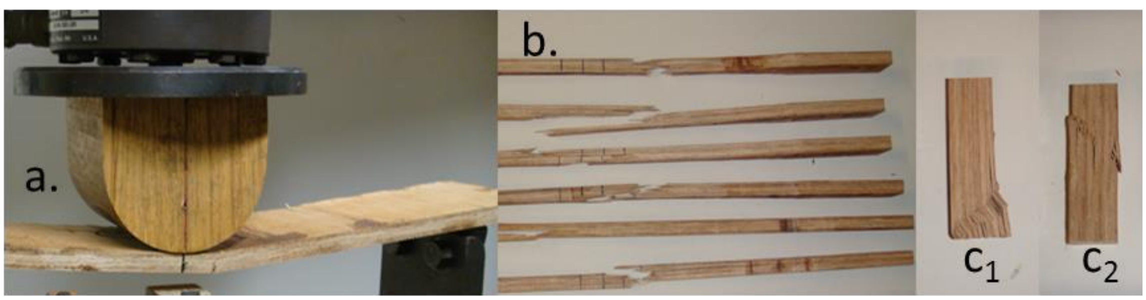

Fig. 7. Typical failure modes of flat panels: (a) brush failure at the tension side of a cross grained specimen; (b) splintering tension failures; (c_1, c2) failure modes of compression specimens with parallel and perpendicular strand alignments, respectively

Results of Corrugation

The segmented circular corrugation yielded 750 × 550 mm trimmed panels with four full and two half wavelengths in the longitudinal direction (Fig. 8). The average density was 725 kg/m^3 with a comparatively low COV (12.5%). This could be achieved by the alternating radii of the top template. Thus, more even panel thickness was created at every point of the templet surfaces; the normal distance between the two templates over the entire surface was constant.

It should be noted, however, that for the full contact of the strands and because of the spring back effect, the templates were close to ~8 mm at the apexes. This created some higher densifications at the oblique surfaces, although no statistically significant differences could be measured in thicknesses of the relevant areas of the panel.

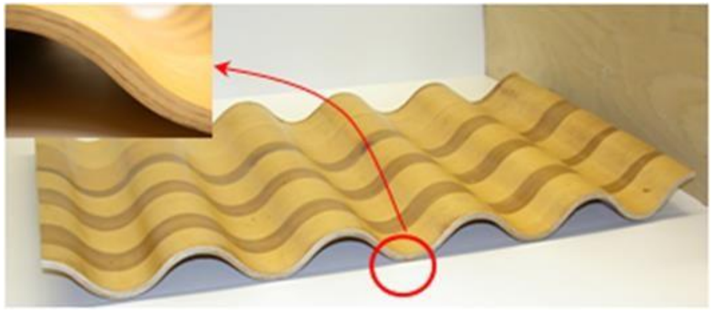

Fig. 8. Circularly segmented, 9.5 mm thick corrugated panel made of ash veneer side clippings

The trimmed panel size for both sine-wave and circular wave corrugations was 750 mm × 400 mm, which include four full and two half waves along the length of the panel (Figs. 8 and 9). The average density was 738 kg/m^3. This agreed with the flat panel actual density, although the spread of data increased significantly (COV = 16.1%). As already mentioned, the top and bottom templates had identical sine-wave millings. For the 9.5 mm target thickness, the differences between the normal distances of apexes and the inflexion points of the sine-wave was 2 mm (Fig. 6 A and B). Thus, over and under densifications were manifested in the high variation of density data for this type of panel. This discrepancy was accepted because the panel mechanical properties are considerably better than that of wood based panel materials currently on the market. Despite the density variations, during long term storage, the corrugated panels remained warp and twist free, though thin flat panels of full size (750 × 650 mm) tend to warp in conditions having high relative humidity fluctuations.

Both types of corrugated panels were further processed and tested in engineered structural composites. Part 2 of this paper provides further information about these products and performances.

Fig. 9. 9.5 mm thick, sine-wave corrugated panels made of mixed hardwood side-clippings

CONCLUSIONS

1. Veneer mill residues, including side clippings and rejected veneer bundles, can be successfully converted into value-added, composite panels.

2. The long, thin, and flexible veneer strips are particularly appropriate to create structural, 3-dimensional elements.
3. Circular- and sine-wave corrugations can be achieved by traditional hot pressing operation with appropriate heat transferring templates.
4. The physical and mechanical properties of the new products are very comparable to the properties of similar products already on the market.
5. The devised corrugation process results in dimensionally stable panels without warping even in changing environmental conditions.
6. The utilization possibilities of corrugated, veneer based panels, especially in load bearing structural composites, are very broad.

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