Development of Veneer-based Corrugated Composites, Part 2: Evaluation of Structural Joints and Applications

Levente Denes,[a,]* Elemer M. Lang,[a] Joseph F. McNeel,[b] and Brad McGraw [b]

This publication introduces and describes the mechanical properties of a newly developed structural composite using corrugated veneer panels as core material. Prior to this study, rejected hardwood veneers and veneer residues (side-clippings) were converted into three-dimensional panels, and the basic physical and mechanical properties were investigated through the testing of similar, but non-corrugated products. This study focuses on the application of I-joist web elements, although other application possibilities are also mentioned. Different web to web and web to flanges joints were configured and tested for their tension and shear strength resistance. The load-bearing capacity was evaluated using standard structural size prefabricated members. The I-joists that had corrugated web panels showed an improved load carrying capacity under concentrated loads. Buckling failure, which is common in deep straight web panels of oriented strand board (OSB), or plywood, under concentrated loads could not be observed.

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

Contact information: a: Institute of Wood and Paper Technology, University of West Hungary, H-9400 Bajcsy-Zsilinszky u. 4 Sopron, Hungary; b: Division of Forestry and Natural Resources, West Virginia University PO Box 6125, Morgantown, VW 260506-6125, USA;
** Corresponding author: levente.denes@skk.nyme.hu*

INTRODUCTION

Prefabricated wood I-joists consist of solid-sawn or structural composite lumber flange members that are connected with structural panel webs, which are traditionally made of plywood or OSB (oriented strand board). The flanges are fixed to the web using moisture-resistant, cold-setting adhesives. They are well suited for long-span beam applications such as roof and flooring systems in both residential and commercial constructions (Wood Handbook 1999). These joists are an aesthetically attractive and economical alternative to traditional beam products. Engineered wood I-joist composites are highly efficient and lightweight structural elements with a shape that maximizes the bending stiffness while minimizing the material used (Nelson 1997; Adair 2003). However, the buckling characteristics of these composite panels discourage the use of I-joists under heavy concentrated loads. For increased spans, if the joist is not supported in the lateral direction (*i.e.*, perpendicular to the plane of bending) and the flexural load increases to a critical limit, the joist will fail due to lateral buckling of the compression flange. Furthermore, the slender web elements that have relatively large depth-to-thickness ratios are also particularly susceptible to local buckling. To enhance the load-carrying capacity of the wooden I-joists, some additional reinforcements are necessary. For instance, providing horizontal support at the top flanges can prevent lateral instability. Local buckling of the web is usually eliminated by using filler blocks at the locations of heavily concentrated loads that are acting on the beam (Zhu *et al*. 2005). Currently, the I-joist manufacturing companies use several wood species and wood-based composite materials. The vast variety of available sizes, including length and depth, can practically fulfill all costumer needs. A previous paper described the transformation of veneer wastes into corrugated, structural wood composites (Denes *et al.* 2017). The article discussed the mechanical and physical properties of both flat and corrugated structural panels. These works resulted in circular- and sine-wave corrugations with varying thicknesses. I-joist web elements were the apparent future utilization of these products (Fig. 1). With holes in the corrugated web, the performance I-joists were comparable to the performance of similar products (Afzal *et al.* 2006). This further encouraged the extension of the work, which resulted in the present study.

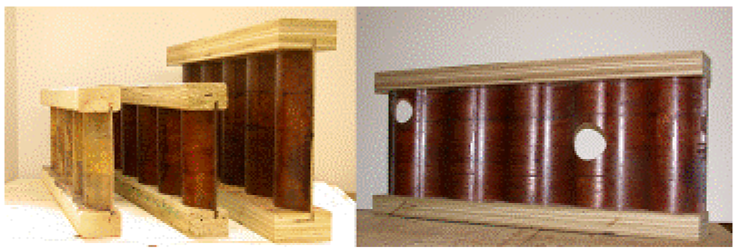

Fig. 1. Wood-based I-joists with 5 mm, corrugated, veneer-waste web elements

Profiling the web generally increases the stability of the I-joists and avoids the buckling failure of the beam (Hindman *et al.* 2005a,b; Zou *et al.* 2005; Chen *et al.* 2013) Different profiles were developed over the years, and the most common profiles are the corrugated and trapezoidal. The long, flexible veneer strips are particularly suitable for corrugation. Additionally, three-dimensional elements, such as molded panels, tubes, *etc*., may be produced. The corrugated circular, or sinusoidal, shapes have the advantage over trapezoidal profiling because they alleviate the local buckling of the flat portions in edgewise loading situations (McGraw 2009; Chen 2013). Furthermore, the deep dimensions of web elements may be avoided, resulting in more economical load-supporting beams and better resource utilizations *via* recycling (Denes *et al.* 2004; Lang *et al.* 2008; Denes *et al*. 2010). To demonstrate the viability of corrugation and to check the performance of the corrugated panels in structural wood composites, this study pursued a number of goals.

Objectives

The primary objectives of the research were to examine the global and local buckling behavior of engineered wood I-joists with corrugated web panels made of hardwood veneer clippings or rejected full-size veneer leafs. This part of the study investigated the effects of the construction parameters, such as the depth of joists, web-to-web, web-to-flange joint strengths, and the bending performance of the joists. The specific objectives of this study were to discover the tensile strength determination of various web-to-web joints. The shear force resistance was analyzed in the different web-to-flange joint types. The bending strength and stiffness determination of I-joists with corrugated web panels were also observed, along with the exploration of further application possibilities of veneer-based corrugated panels.

EXPERIMENTAL

Materials

The two types of corrugated panels had average thicknesses of 9.5 mm and 5.0 mm. The panel sizes were 750 mm × 550 mm and 750 mm × 400 mm for circular- and sine-wave panels, respectively (Fig. 2). The geometry of corrugations is given in the first part of this paper (Denes *et al.* 2017). Theoretical analyses indicated that the better edgewise load resistance was with the use of sine-wave corrugation (McGraw *et al.* 2010a,b; 2012, Jiao *et al.* 2012), and the same system was incorporated into the present research.

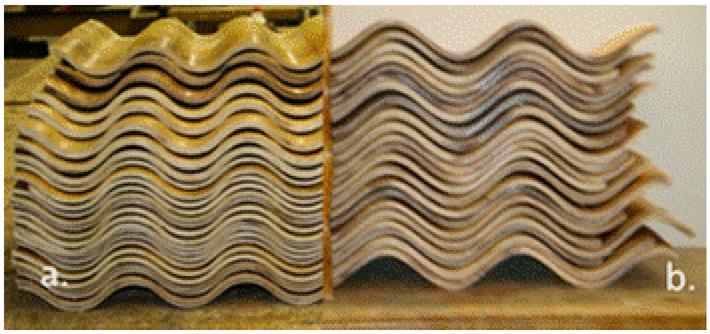

Fig. 2. Trimmed, 9.5 mm, thick corrugated panels with (a) circular- or (b) sine-wave corrugations

The examined flange materials included aspen laminated strand lumber (LSL), parallel strand lumber (PSL), and laminated veneer lumber (LVL). In order to examine the size effect of the flanges, the width was varied between 42.8 and 85.7 mm and the thickness ranged from 33.3 mm to 44.5 mm. Some of the flanges were finger jointed in length using the same profile with the flange and web joint. The connections between the flanges and the web had two configurations, namely 6-mm long finger joints and 9-mm grooved connections. The joining of the connections was achieved by manual application of the Dynea Prefere 4050M type two-component cold-setting phenol resorcinol resin mixed with the Dynea Prefere 5750 liquid hardener in a 1:1 ratio. For parts compression, pipe clamps were used at every 0.3 m along the flanges and the pressing force was applied by hand. The clamped I-joist were conditioned for 24 h while the complete cure of the resin took place. Figure 3 shows the various combinations of web-flanges joints and materials.

Fig. 3. Assembled I-joists with different flanges and joint configurations. (a) Spruce-pine-fir (SPF), finger jointed; (b) PSL, finger jointed; (c) LSL, grooved; (d) LVL, grooved

Note that only I-joists with structural composite flange materials were tested. The web elements were 9.5-mm thick sine- and circular-wave corrugated panels. The two 5-mm thick circularly corrugated web elements were included for comparison purposes. Table 3 specifies the dimensions, sectional properties, and materials of the tested I-joists with the bending strength and modulus of elasticity values.

Methods

The methods of corrugations were described in a separate publication (Denes *et al.* 2017). Therefore, only I-joists configurations and their structural performance tests are discussed in this paper. After several trials, two types of reliable web-to-flanges connections were formed.

Specimen assembly and preparation

In the first configuration, 9-mm deep and 5-mm or 9.5-mm wide grooves housed the web elements. With the help of a template, a handheld router machined the grooves. The advantage of this joint type is that there is no edge preparation necessary of the web, except for straight trimming. However, the assembly requires precision machining and some flexibility of the web panels. The second solution included finger jointing both the flanges and the web elements; thus the assembly became easier. The resin was manually applied with a brush for both joint configurations, covering the joining surfaces. Figure 4 shows the two solutions without the bonding agent.

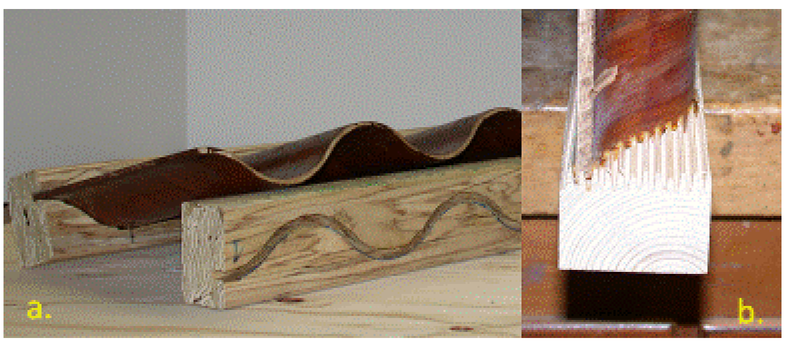

Fig. 4. Joint configurations of web-to-flanges connections. (a) Tongue and groove for 5-mm web thickness; (b) 9.5-mm thick web finger-jointed to the flanges

At every 0.3 m, pipe clamps secured the parts together, providing pressure and positions until the resin cured. After 24 h minimum of clamped time, the I-joists were further processed lengthwise to prepare the specimens for various standard (ASTM) and non-traditional testing procedures.

The 750-mm length of the corrugated web elements did not allow a structural size joist to be manufactured. Thus, the 9-mm end finger-jointing and 15-mm long, dove-tail joints were applied to the length-wise joining of the web elements. To obtain a precise finger geometry the hot pressing aluminum template was used together with a Rockler type dovetail jig for dove-tail jointing. Finger joints were positioned horizontally if it was necessary, which elongated the flanges. Note that the tension tests of these joints and the control value determination happened by using previously manufactured structural size flat panels, as shown in Fig. 5. Tensile tests were performed in accordance with ASTM D3500-05, Method B, except for the specimens' length, which ranged between 12 and 16 inches instead of 48 in. prescribed by the standard. A fixture apparatus was designed and built with striated plates and fixing bolts at both ends of the specimens.

The preparation of the specimens for the web-to-flanges shear tests included the lateral supports of the webs. Profiled blocks of solid wood were glued and bolted to the corrugated web panels. The length of the specimens was determined on a full wave basis, resulting in a length of 152.4 mm; 3-mm gaps at both sides between the flanges and the web ensured the undisturbed shear force applications (Fig. 6). For the flange and web connection strength, determination the effective area of the web was taken into account.

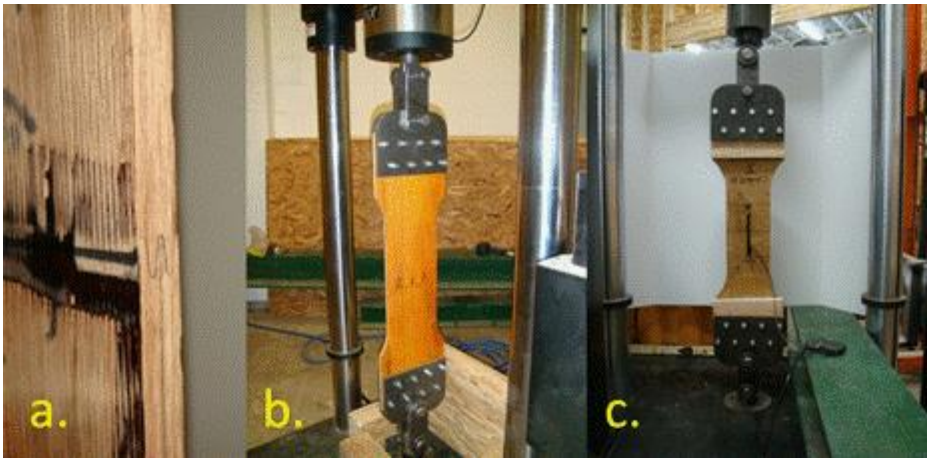

Fig. 5. (a) Finger-jointed tension specimen and (b,c) the actual test setup

Fig. 6. (a) Preparation of specimens for web-to-flanges shear tests and (b) testing

The equipment used was an Instron universal testing machine (Norwood, MA, USA) with a 60 kN ± 5 N load cell (Figs. 6b and 7a). The loads were applied continuously under displacement control according to the relevant ASTM standards (ASTM D-108 (2006) and D-1037 (2006)). In the case of bending tests the deflections were measured with a linear voltage-displacement transducer (LVDT) with ± 0.01-mm accuracy (Fig. 7b). The load and displacement data were recorded in real time by the BlueHill computerized data acquisition and analysis system.

For the section modulus (S) and for the second order of the moment of inertia (I), the actual thickness of the corrugated web panels was adjusted as follows. The actual lengths of the waves were measured with a flexible measuring tape. Next, these values were multiplied by the average thicknesses and heights of the web element. From the obtained volume the adjusted thickness could be calculated by dividing it with the projected web area of the specimen.

The obtained data were analyzed by standard statistical procedures including the computation of descriptive statistics. Additionally, a one way ANOVA analysis with pair-wise comparisons (Tukey and Dunnet's tests) was also performed.

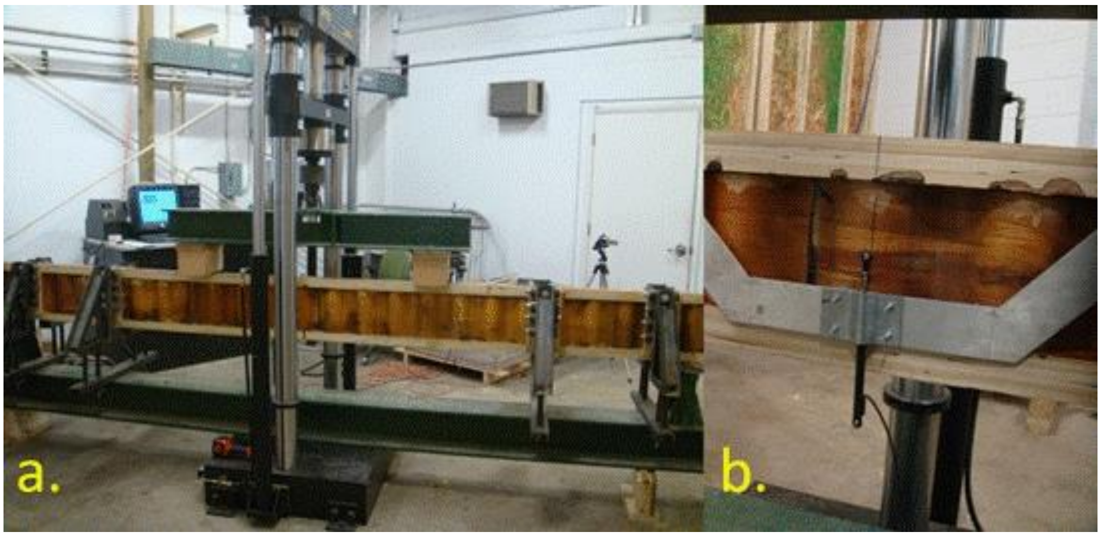

Fig. 7. (a) Four-point test setup on the INSTRON machine; (b) deflection measurement of the I-joist with an LVDT

RESULTS AND DISCUSSION

Tension Strength of Web-to-Web Connections

An ANOVA analysis and pair-wise comparisons revealed that there were significant differences between the tension performances of web-to-web joint types (Table 1). The dovetail joints could only provide 14% of the unjointed strength control value. The finger jointing method appeared to be substantially better with almost 40% strength retention. The control tension strength of the structural size tests was about 30% lower than that of the tension strength that was measured on the small clear specimens (σ_{tMAX}: 99.6 MPa *vs.* 66.5 MPa). The sample variation of small specimens was higher (co-efficient of variation (COV): 30% *vs* 18%). The higher strength but even higher variation of the previously measured tension strength on the small specimens (Denes *et al.* 2015) highlights the importance of structural size testing. The weak and strong localities within a panel could significantly influence the strength values. The results illustrated the superiority of finger joints for the longitudinal joining of corrugated panels. Based on this outcome and argument, only the finger jointing is proposed to elongate the web elements. However, other than with laboratory conditions, corrugation might be performed with an increased length of the panels, and the need for longitudinal joining is essentially eliminated.

Table 1. Summary of Preliminary Web-to-Web Joint Tensile Strength Tests with Panels made from Ash

Joint Types	Sample Size (n)	σ_{tMAX}	
		Mean (MPa)	CV (%)
Finger Joint	13	25.32	0.25
Dovetail Joint	10	9.19	0.20
Without Joint	9	66.47	0.18

Shear Resistance of Web-to-Flanges Connections

The shear force resistances of the different web-to-flanges connections are compiled in Table 2. There were no significant differences between the resistance of finger joints and the tongue and groove joints. However, both joint types had significantly lower shear force resistances compared to the commercial I-joists, by having a 9.5-mm thick OSB web, and connected to the spruce-pine-fir (SPF) flange members. This phenomenon may be explained by the better adhesion between the OSB and the softwoods. Furthermore, the corrugated edges after finger jointing showed fiber tear-offs, where the length of the panel was not parallel with the direction of the feed. These loose fibers, after a resin application and assembly, created weak points along the glue line. The elimination of fiber tear-offs and improvements in the adhesion will need further investigation.

Table 2. Summary Statistics of Web-to-Flanges Shear Force Resistance Measurements

Joint Types	Sample Size(n)	Shear Force Resistance	
		Mean (kN/m)	COV (%)
Finger Joint	6	54.91	0.21
Tongue and Groove Joint	6	58.33	0.29
Commercial Joist*	8	82.00	0.25
*Commercial I-joist with 3/8" thick OSB web and tongue and groove joint			

Table 3. Specifications and Results of Bending Performance Evaluation of I-Joists

Spec #	Length (m)	Depth (mm)	Nominal Web Thickness (mm)	S (cm^3)	I (cm^4)	M_{max} (Nm)	Bending Strength (MPa)	MOE_b (GPa)	Flange Material	Joint Type
Sine-wave corrugation										
1	3.66	232	5.0	254	2862	3856	15.2	12.6	PSL	FJ
2	3.66	273	9.5	422	5856	4823	11.4	8.7	LVL	FJ
3	3.66	302	9.5	542	8085	10369	19.1	13.2	PSL	TG
4	3.66	287	9.5	447	6382	3843	8.6	12.8	LVL	FJ
5	3.66	291	9.5	479	6920	4823	10.1	12.0	PSL	FJ
6	3.66	306	5.0	608	9356	5190	8.5	12.92	LVL	TG
Circular-wave corrugation										
7	2.44	237	9.5	432	5075	10134	23.5	---	LVL	TG
8	2.44	267	9.5	451	4958	8776	27.5	---	PSL	TG
9	2.44	418	9.5	1230	10008	156792	75.1	---	LSL	TG
FJ, finger jointed connections; TG, tongue and groove connections										

Bending Performance of the I-Joist under Concentrated Loads

Table 3 compiles the bending test results under the standard 4-point loading conditions (ASTM D-198 (2006)). Due to the short specimens length and different joist depths, the span-to-depth ratio for the 3.66 m long joists was 12-15:1, for the 2.44 m long joists 6-10:1 as compared to the recommended 17-21:l ratio. Samples were laterally supported to minimize off-axis buckling. The shorter joists were supported at the mid distance between supports and load application points, the longer joists at the same places and closed to the supports additionally. The limited number of structural-size specimens and the multiple manufacturing parameters, including the factors of size and material, did not allow strong, statistically supported conclusions to be established. However, some inferences were made. The I-joists with tongue and groove web-flange connections proved to have a higher load bearing capacity than the finger joints. As discussed earlier, the weak shear resistance between the flanges and the web elements was manifested in a lower load-bearing capacity. The approximate 12 GPa average bending modulus of elasticity may ensure the fulfillment of the maximum deflection criteria. The thickness of the corrugated web element had no significant effect on the load supporting capacity. Some analytical works (McGraw *et al.* 2010a,b) predicted a better performance of the sine-waved web elements. However, the results indicated otherwise. Some circularly corrugated web panels had significantly higher load bearing capacities with similar sectional properties than the sinus-shaped counterparts (specimens 7 and 8 *vs.* specimens 3 and 6).

Failure Mode Analysis

The failure mode analyses followed the specifications of the ASTM D 5055-95a (2006) standard. Figure 8 illustrates the observed failure modes. A combined tension failure of the bottom flanges and the web elements was usually observed. The web elements failed in tension exclusively at the panel joints, as was expected.

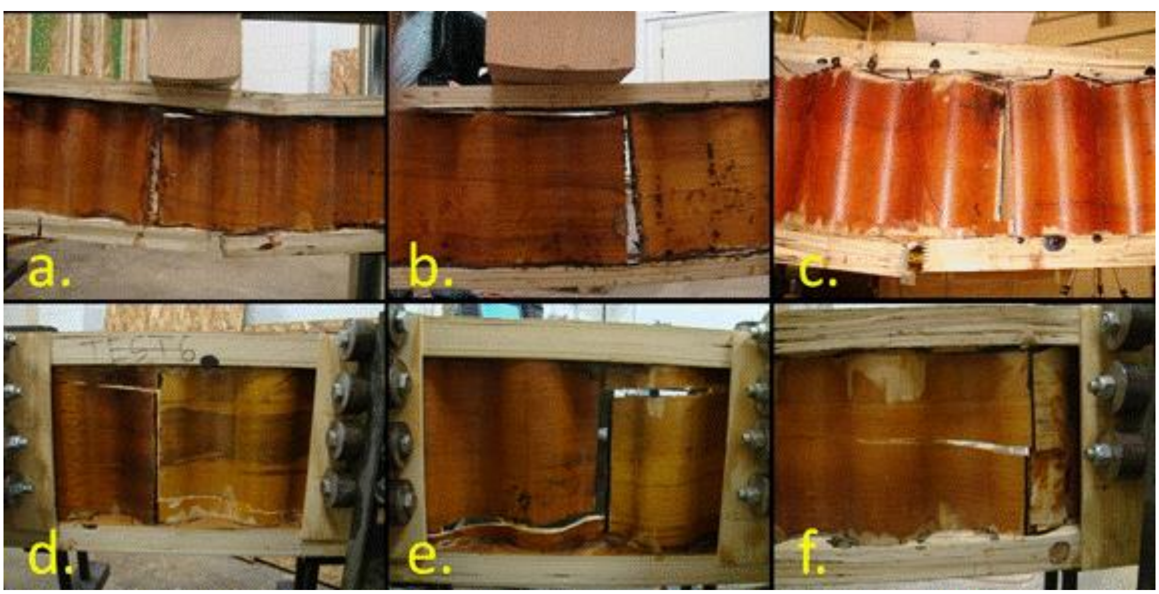

Fig. 8. Typical failure modes of I-joist under four-point loading. (a, b, and c) Tension failure of web and bottom flanges; (d) tension and horizontal shear of the web; tension and “Z” type failure of the web; (e) pure horizontal shear of the web (f)

I-joists with finger joint connection between flanges and web failed in finger's rolling shear at the top or bottom flanges followed by the web-web joint shear failure. (Fig. 8a,b,c). This can be explained by the chipping outs the finger jointing cutter head made on corrugated panel portions with perpendicular grain orientation. Joist 7 with the highest web thickness failed in crushing of both bottom flange and web panel at end reaction. The corrugated panel had a loose part in that region contributing significantly to the failure. The top flanges of Joist 9 crushed locally at one of the load application points and the skewed load caused lateral buckling. The adequacy of the finger jointed web-to-web connections was confirmed by the pure horizontal shear failure at the finger jointed web element (Fig. 8f). None of the specimens demonstrated a buckling of the web elements under concentrated loads. However, the corrugated thin webbed I-joists might twist when the loading approaches ultimate capacity (Fig. 8c).

Other Structural Applications

Corrugated veneer panels may be used to reinforce shear walls having OSB or plywood face layers (Fig. 9a). The polyurethane matrix material provides both heat and sound insulations, and adhesion ensures the structural integrity as well. Another possible utilization is to cut the panels into appropriate strips in width and use them as headers for doors and windows (Fig. 9b, c). The preliminary calculations showed that these beam elements might compete successfully with the structural composite lumbers (SCL) that are used in light frame residential and commercial constructions. Furthermore, with a 90° rotation of this polyurethane (PUR) composite core, box beams with different cross sections may be formed (Fig. 9).

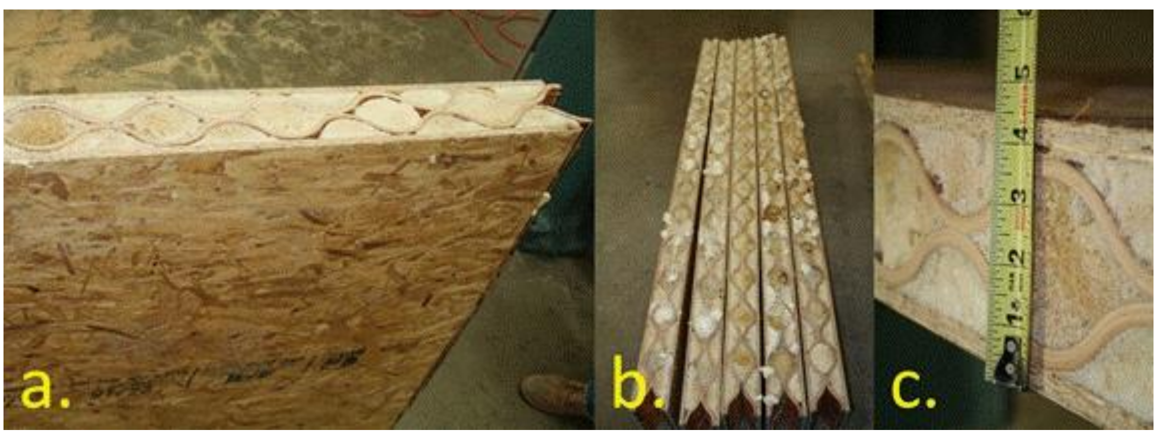

Fig. 9. Further use of corrugated panels. (a) SIP shear wall with PUR and corrugated panel core; (b) insulated beams for headers of building constructions; (c) one possible cross sectional configuration

Fig. 10. Utilization of side clippings: 90-mm diameter tube for lightweight, pallet blocks

The pallet industry is also a potential end user of panels and tubes that are manufactured from veneer residues. Tubes can be formed on a cylinder with veneer strip layers alternating as right and left handed helixes, and have an excellent axial load supporting capacity (Fig. 10).

Thus, with cutting to the appropriate lengths, strong pallet blocks can be formed. With either fixed or releasable connections to the top- and bottom deck-boards, lightweight and durable pallets can be produced. Due to the entire pallet being made of engineered wood composites, the phytosanitary requirements do not apply (ISPM No. 15 standard). The preliminary calculations revealed that these pallet constructions would be lighter by 15% to 20% compared with similar sized, solid hardwood pallets that are currently in use for storage and transportation.

CONCLUSIONS

1. This pilot investigation explored the application possibilities of corrugated panels made from sliced veneer wastes. The research focused on the development of web-to-web and web-to-flange joint solutions and on the determination of bending strength and stiffness of full size I-joists. Due to the technical constraints and the variability of the joining and functional parameters, only a limited number of test specimens could be manufactured. Therefore, no strong, statistically backed inferences could be made. However, some general conclusions are as follows:
2. Both the sinusoidal and circularly corrugated veneer panels are suitable for I-joist manufacture as web elements. Both the thin (5 mm) and the thicker (9.5 mm) corrugated panels showed excellent buckling resistance within the range of 230-mm to 430-mm beam depth.
3. Finger jointing the web elements in the longitudinal direction may provide approximately 30% of the tension strength of the panels, compared to the unjointed strength values.
4. Regarding the shear force resistance between flanges and the web element, the new I-joist demonstrated about 70% of the strength values of commercial products. There is a potential to improve this attribute with better joint configurations and machining, which may improve the ultimate load supporting capacity.
5. The observed bending properties are very comparable to the strength and stiffness values of commercially available I-joists.
6. Further combinations of the corrugated veneer panels with different matrix and skin materials may result in several new types of load-bearing composites. Besides the engineered properties, the advantages of these new products lie in the utilization of wood wastes and carbon dioxide retention.

ACKNOWLEDGEMENTS

This research was partially financed by the Hungarian National Science Foundation (OTKA) project number: T-25985, and the Research Challenge Grant Program of West Virginia at West Virginia University during the academic year of 2003-2004. The continuation at WVU in 2010 had been made possible through the Wood Utilization Research Program Task #21. All of the financial supports are gratefully acknowledged. This manuscript was published with the approval of the Director of West Virginia Agricultural and Forestry Experimental Station as Scientific Article No. 3300.

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Article submitted: August 25, 2016; Peer review completed: October 29, 2016; Revised version received and accepted: March 7, 2017; Published: March 23, 2017.
DOI: 10.15376/biores.12.2.3478-3489