Design and Evaluation of Thin-Walled Hollow-Core Wood-Strand Sandwich Panels

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ABSTRACT: Part of a long-term goal of developing a sustainable composite panel that meets both structural and energy performance requirements in building construction applications, this study discusses the development of a thin-walled wood-strand 3D core element that shows promise for a variety of panelized construction applications, such as in a building envelope. Sandwich panels take advantage of the lightweight corrugated core sandwiched between stress skin faces acting similar to an I-beam. Specific bending stiffness of sandwich panels fabricated with ponderosa pine strands was significantly higher than average values of commercially produced composite panels of equivalent thickness (141–156% and 120–133% stiffer than oriented strand board (OSB) and 5-ply plywood respectively). Compared to OSB of equivalent thickness, sandwich panels require 40% less wood strands by weight, which also means lower usage of resin. This basic concept creates tremendous flexibility in designing panelized wall, floor and roof elements for building envelope applications.

KEYWORDS: Sandwich panel, wood strand, OSB, corrugated core

1 INTRODUCTION

Lightweight sandwich panels consisting of a honeycomb core have been successfully utilized in aerospace and marine industries [1]. But, sandwich panels have only just started to be utilized in the construction industry. Structural insulated panels (SIPs) have had the most success penetrating the construction market, but they only account for 2% of the residential construction market in the United States [2].

The Forest Products Laboratory in Madison, Wisconsin, has developed a 3D fiberboard through a wet formed process that utilizes small-diameter timber and other cellulose-based raw materials [3–7]. The most significant advantage of re-pulping the recycled raw materials is that any virgin or recycled biofiber resource will be a viable raw material source for this product. However, because forming of 3D fiberboard is a wet process, significant effluence is discharged into the water system in a typical manufacturing facility. Additionally, wood-strand-based panels can provide structural performance that is not possible to achieve using wood in fiber form; but, wood strands as currently produced in a typical OSB plant are not well suited for manufacturing thin-walled 3D cores for further fabrication of lightweight sandwich panels.

Development of thin-strand ply using small diameter Ponderosa pine at Washington State University [8,9] was a natural progression towards developing thin-walled 3D strand core, lightweight laminates, and subsequently thick composite structural panels that can be used for constructing building envelopes of residential and commercial buildings to potentially meet our nation's goal of building net-zero energy structures. Thick sandwich panel construction with designed cavities in the core will lead to lighter prefabricated panels that have the potential to combine energy/hygrothermal performance with structural integrity for building construction. Thin-strand veneers or plies can yield strength and stiffness values that are 2–2.5 times greater than the parent material [8]. Research at the Composite Materials and Engineering Center at Washington State University has developed a thin wood-strand ply that utilizes small-diameter Ponderosa pine as its raw material; Ponderosa pine was chosen because it is one of the species in the mix of small diameter timber removed in a hazardous fuel treatment to mitigate forest fires and improve our nation's forest health in the western U.S. Strength and stiffness values of thin-strand composite plies were 2–2.5 times greater than the parent material [8,9]. Recommendations from studies

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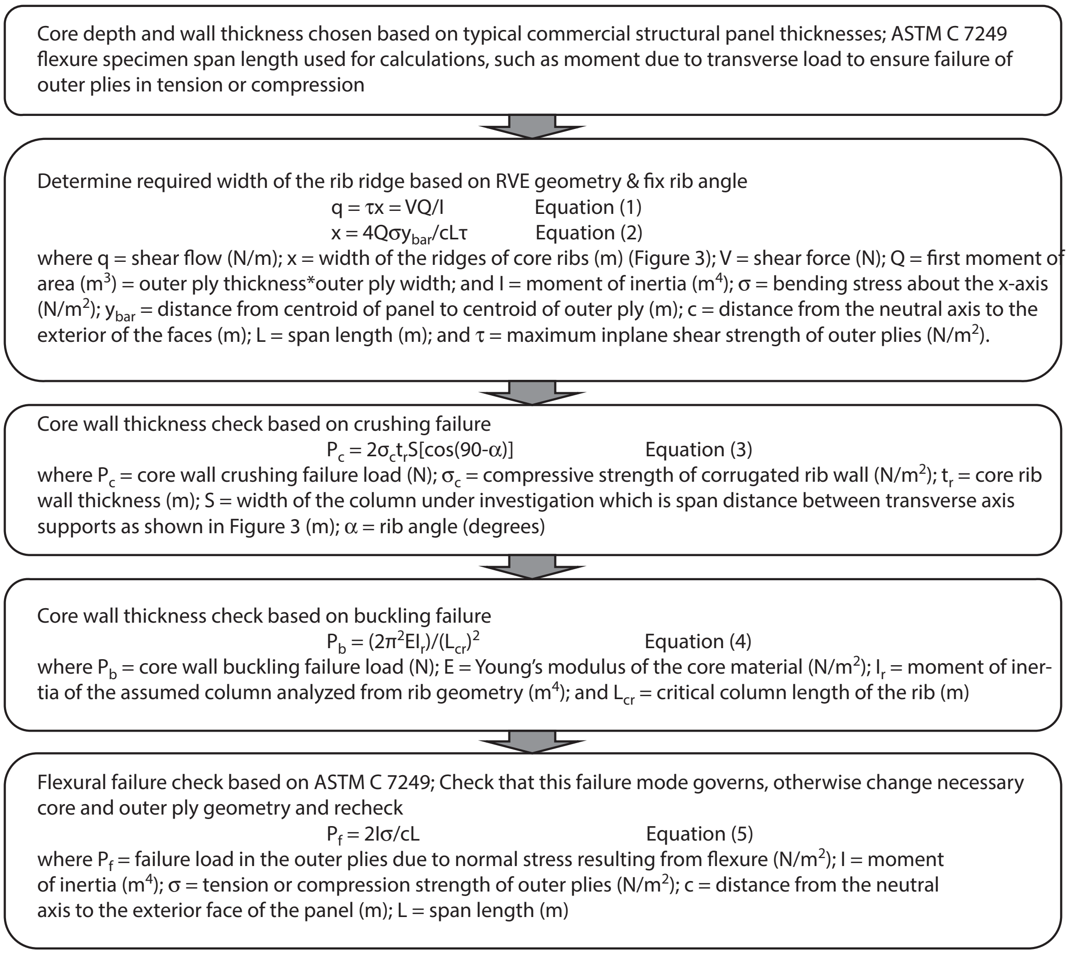
conducted by Weight and Yadama [8,9] along with extensive work on a 3D fiberboard utilizing small-diameter timber and other cellulose-based raw materials conducted by the Forest Products Laboratory [3–7] were the basis for the development of wood-strand sandwich panels presented in this research. Work presented in this article is a first step towards developing a panelized building envelope system to meet structural and energy performance requirements based on lightweight sandwich panels from wood strands.

This article discusses the design and fabrication process of thin-walled 3D wood-strand core and presents properties of lightweight panels constructed with these cores sandwiched between outer skins for building construction.

2 CORRUGATED CORE DESIGN

Designing the geometry of the core has no specific methodology, but there are guidelines based on the desired applications and knowledge about wood-strand conformance necessary for molding based on past experience [10]. The non-homogenous nature of the panel and the semi-hollow core requires one to consider different failure criterion than solid beams in designing these sandwich panels. The possible failure modes in sandwich panel under flexure are [1]: tensile failure of the outer plies, wrinkling failure of the faces due to compressive stress, interfacial shear failure at the bond between the core and outer plies, and core crushing/buckling due to localized loading at the supports. A design methodology (Figure 1), based on theoretical analysis as discussed in Hunt and Winandy [3], was developed to engineer the core geometry. The design maximized the benefits of sandwich construction by having a deep core, but limited the core depth to a thickness still suitable for structural panels. It is realized that linear elastic equations are being applied in designing the corrugated cored, but it is a reasonable first approximation to estimate required geometry. Furthermore, it is a conservative approach as strength values assumed in the calculations are lower than expected average values, especially where values of fiber-based composite materials were used instead



Core depth and wall thickness chosen based on typical commercial structural panel thicknesses; ASTM C 7249 flexure specimen span length used for calculations, such as moment due to transverse load to ensure failure of outer plies in tension or compression

Determine required width of the rib ridge based on RVE geometry & fix rib angle

$q = \tau x = VQ/I$ Equation (1)

$x = 4Q\sigma y_{bar}/cL\tau$ Equation (2)

where q = shear flow (N/m); x = width of the ridges of core ribs (m) (Figure 3); V = shear force (N); Q = first moment of area (m^3) = outer ply thickness*outer ply width; and I = moment of inertia (m^4); σ = bending stress about the x-axis (N/m^2); y_{bar} = distance from centroid of panel to centroid of outer ply (m); c = distance from the neutral axis to the exterior of the faces (m); L = span length (m); and τ = maximum inplane shear strength of outer plies (N/m^2).

Core wall thickness check based on crushing failure

$P_c = 2\sigma_c t_r S[\cos(90-\alpha)]$ Equation (3)

where P_c = core wall crushing failure load (N); σ_c = compressive strength of corrugated rib wall (N/m^2); t_r = core rib wall thickness (m); S = width of the column under investigation which is span distance between transverse axis supports as shown in Figure 3 (m); α = rib angle (degrees)

Core wall thickness check based on buckling failure

$P_b = (2\pi^2 EI_r)/(L_{cr})^2$ Equation (4)

where P_b = core wall buckling failure load (N); E = Young's modulus of the core material (N/m^2); I_r = moment of inertia of the assumed column analyzed from rib geometry (m^4); and L_{cr} = critical column length of the rib (m)

Flexural failure check based on ASTM C 7249; Check that this failure mode governs, otherwise change necessary core and outer ply geometry and recheck

$P_f = 2I\sigma/cL$ Equation (5)

where P_f = failure load in the outer plies due to normal stress resulting from flexure (N/m^2); I = moment of inertia (m^4); σ = tension or compression strength of outer plies (N/m^2); c = distance from the neutral axis to the exterior face of the panel (m); L = span length (m)

Figure 1 Overview of design methodology for corrugated core design and corresponding equations.

of strand-based composite materials. In addition, wood-strand composite plies fail in a brittle manner almost immediately after reaching the proportional limit when tested in tension.

To obtain critical material properties required for core design, thin wood-strand composite plies were manufactured and tested for tensile strength, Young's modulus, and internal bond (IB) (Table 1). IB, which reflects the bond quality between the strands, was used as a measure of quality of composite plies. Elastic and strength properties from ply testing provide the average material properties for modeling, especially as a first approximation. Manufacturing of the plies followed recommendations for weight [8,9,11]; Ponderosa pine strands (stranded from 100 to 180 mm diameter logs) were hot pressed using phenol formaldehyde (PF) resin (8% wt of wood) as a binder. Further details regarding manufacturing and material properties can be obtained from previous publications [11,12,13].

The design methodology started with choosing a core depth and wall thickness based on commonly used composite panel thicknesses for structural applications. As the panels are intended to carry flexure loads, certain dimensions of the core and the sandwich panel were based on flexure specimen specifications in ASTM C 7249 [14] (4-point loading configuration). In this study, a span length of 1220 mm, a core depth of 25.4 mm, and face ply thickness of 3.2 mm were assumed in design calculations. Although the core geometry was a biaxial corrugated shape with continuous ribs in the x-axis and segmented ribs in the y-axis, as shown in Figure 2, as a first approximation, the core geometry was designed assuming a corrugated ribbed contour in the x-axis only, as shown in the figure. This conservative assumption added to the safety factor as the final aluminum mold (although designed using the approach described in this paper) was fabricated with the wider segmented ribs in the transverse direction to provide local support in the transverse axis of the panel and additional bonding area between the outer plies and the core.

Table 1 Properties of thin wood-strand plies.

Property	Longitudinal Axis Mean	Longitudinal Axis Std. Dev	Longitudinal Axis % COV	Transverse Axis Mean	Transverse Axis Std. Dev	Transverse Axis % COV
Tensile Strength (MPa)	31.0	5.7	18.2	19.7	11.0	55.4
Young's Modulus, E (GPa)	6.37	0.46	7.3	5.85	1.12	19.1
Internal Bond Strength (MPa)	1.0	0.19	18.8	–	–	–

Then a basic shear flow theory (Equation 1 in Figure 1) was used to determine the width of the ridges on the corrugated shape to ensure no premature failure between the core and the outer plies when subjected to flexure due to transverse loads. Details of the dimensions considered for the shear area calculations for a representative volume element (RVE) are shown in Figure 3. The RVE and rib angle can be selected to appropriately design the required rib width for the core geometry; the goal is to ensure adequate bonding between the core and the outer plies to avoid premature failure.

Manipulation of basic shear flow theory produces Equation 2 (Figure 1), where Q is the first moment of the area above the bonding interface denoted by the cross-section area of the ply multiplied by the distance from the panel neutral axis to the centroid of the ply. Calculations in this study determined that the value of Q was 4.9×10^3 mm^3. The in-plane shear strength was assumed to be 3600 kPa based on structural wood-strand composite lumber shear strength because the composite strand plies are similar in strand orientation (unidirectional – along the longitudinal axis) and density variation (due to less variation in heat and mass transfer during the hot pressing process) to that of wood-strand composite lumber; a more accurate value would perhaps fall between 3600 kPa and 2070 kPa, shear strength of OSB [15]. Bending strength of 24 MPa was assumed based on average OSB strength. Based on these values, a required rib width was determined to be 18 mm. The mold designed included a fillet around all corners, thus rib width was selected to be 19 mm.

The next two design calculations were based on core wall crushing or buckling. Crushing should govern this failure criterion because buckling failures occur at far lower stresses than crushing failures. The failure load due to core wall crushing was calculated

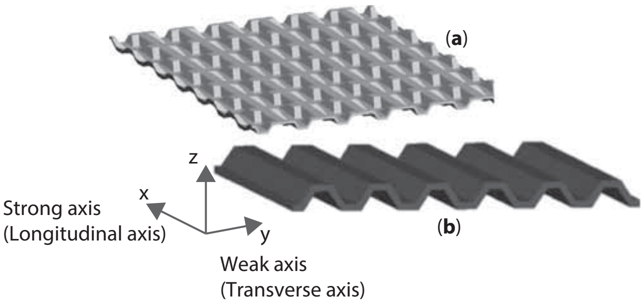


Figure 2 (**a**) Biaxial corrugation of actual core design, and (**b**) the assumed simplified unidirectional corrugated shape of the sandwich panel core for basic shear flow analysis calculations.

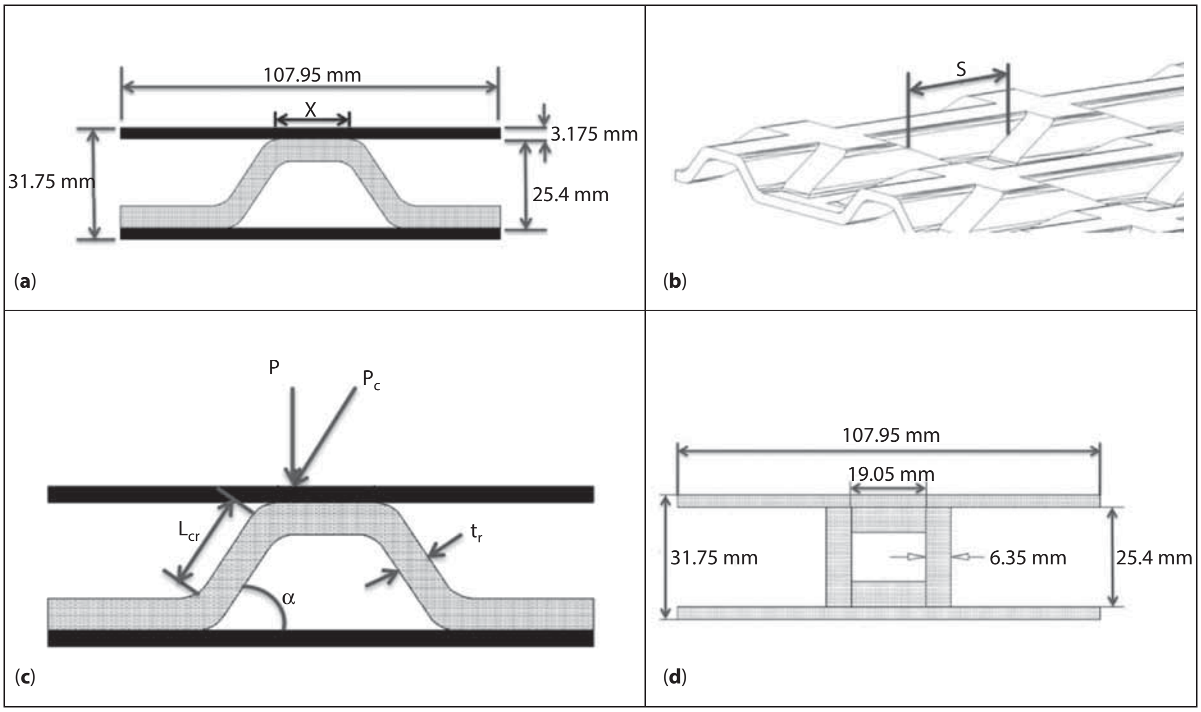


Figure 3 (a) RVE of sandwich panel; **(b)** definition of parameter S; **(c)** parameters related to RVE geometry, and; **(d)** simplified geometry of RVE for moment of inertia calculation.

using Equation 3, and the failure load due to core wall buckling was determined using Equation 4 [3].

For the mold design in this research, core wall crushing strength was assumed to be 13.8 MPa based on recommendations by Hunt [5] for wood fiber-based composites because the primary failure in compression is localized microbuckling of fibers or strands. The core wall thickness, t_r, was designed to be 6.35 mm, and S, width of the column (clear distance between ribs in the y-axis) was set at 57 mm (Figure 3). Based on results of finite element analysis conducted by Hunt [5], as well as geometry restrictions to achieve the maximum number of ribs in the mold while maintaining adequate shear area for the outer faces, the rib angle, α, was chosen to be 56°. A failure load due to core wall crushing was calculated to be 8300 N.

Core wall buckling analysis used a Young's modulus of 5.85 GPa based on the transverse ply properties. The moment of inertia of the rib was determined to be 950 mm^4 by using the basic moment of inertia formula for rectangles. The critical column length was determined to be 22 mm. Then, a core buckling failure load was determined to be 5000 kN. Since core wall crushing and core wall buckling failure loads are relatively high, redesign of the core wall thickness could be evaluated. However, for manufacturing wood strand composites, it is not practical to reduce the wall thickness [12], therefore the core wall geometry was left as shown.

Using the core depth and face ply thickness, normal stresses due to flexure in outer plies is then checked to ensure that failure of the outer plies will occur prior to crushing or buckling of the core [3]. A face ply ultimate tensile stress of 31 MPa was assumed for these calculations (Table 1). The moment of inertia, I, was computed to be 22.9×10^4 mm^4 based off simplified geometry (Figure 3). Calculated flexural failure load, P_f, was 1960 N, which is significantly lower than wall crushing or critical buckling loads calculated above, indicating the panel will fail in flexure and not core wall crushing or buckling. Using the dimensions and rib angle assumed and required rib width determined an aluminum mold was designed for pressing a thin-walled core of wood strands (Figure 4).

3 SENSITIVITY ANALYSIS

After fabrication of the mold, to understand the influence of core and panel parameters on desired failure modes and required shear area at the interfaces between core and outer plies to avoid premature failure (observed when testing sandwich panels in flexure), a sensitivity analysis was conducted. Sensitivity analysis was also conducted to gain an insight into geometry effects, as a more robust and refined analytical model is being developed as a follow up to this study. For this analysis, Young's modulus of 6.37 GPa, bending strength of 31 MPa, and shear strength of

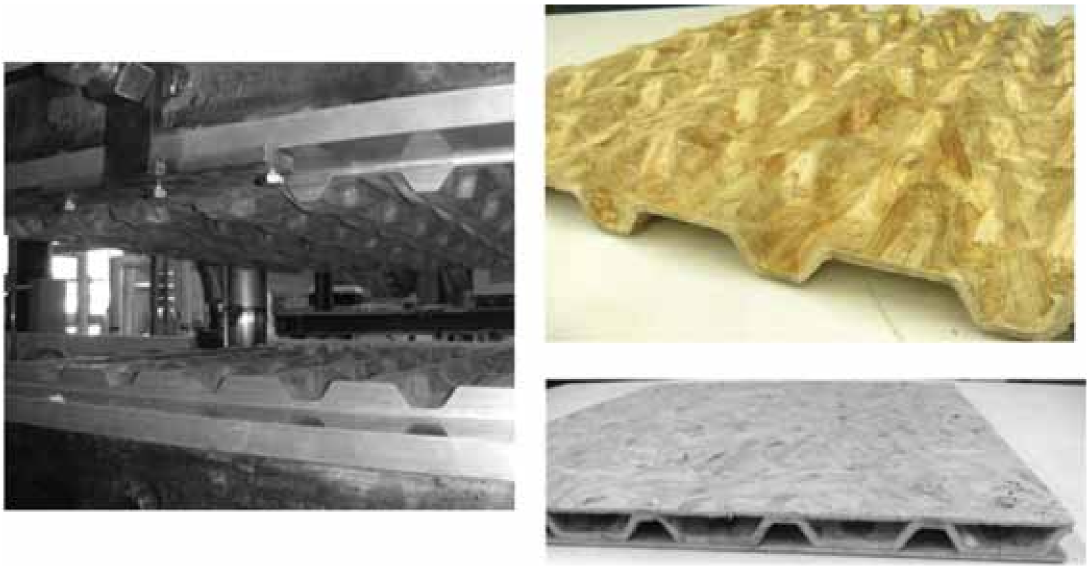


Figure 4 Small hot press with 3D mold installed, hot-pressed wood-strand core, and wood-strand sandwich panel.

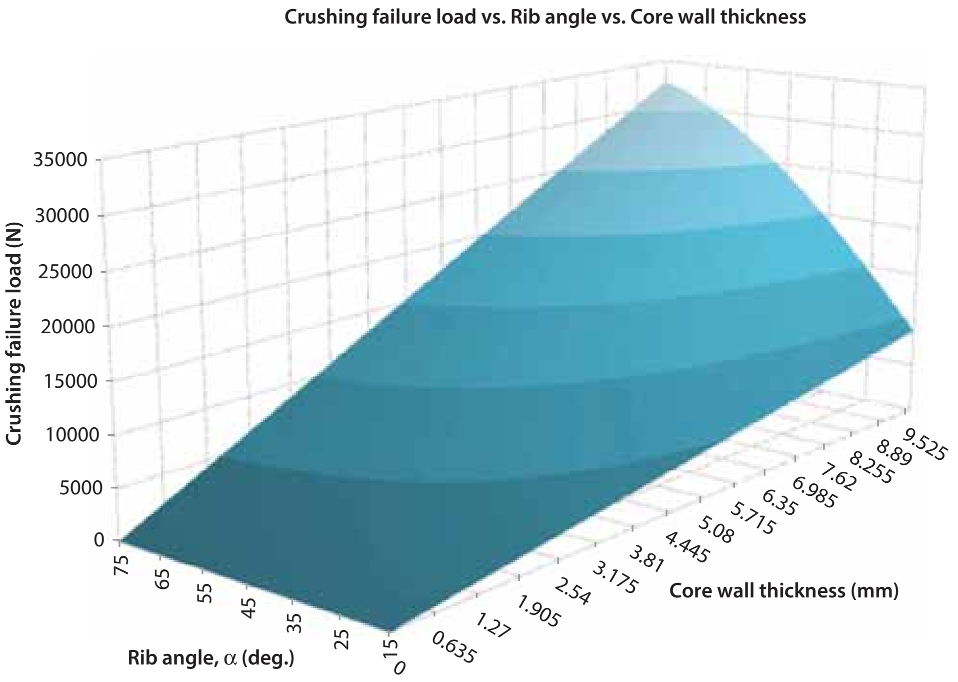


Figure 5 Core crushing analysis.

2070 kPa were assumed for the wood-strand composite material for plies as well as the core (Table 1).

The core crushing failure analysis (Figure 5) based on Equation 3, as expected, showed an increasing trend in crushing failure with increasing core wall thickness, t_r, and became more pronounced with a combination of increasing rib angle, α, and core wall thickness. The column width, S, was assumed to be 57 mm, consistent with the mold used in this study.

Core buckling failure analysis (Equation 4) indicates that rib angle does not play a significant role in causing a buckling failure, unlike core wall thickness, but once the rib angle exceeds 45° failure mode will be governed by core crushing (Figure 6). These calculations assumed a constant core depth of 25.4 mm. The rib angle plays a crucial role in ensuring that fracture of the wood-strand composite material does not occur over a sharp change in the slope of the core geometry.

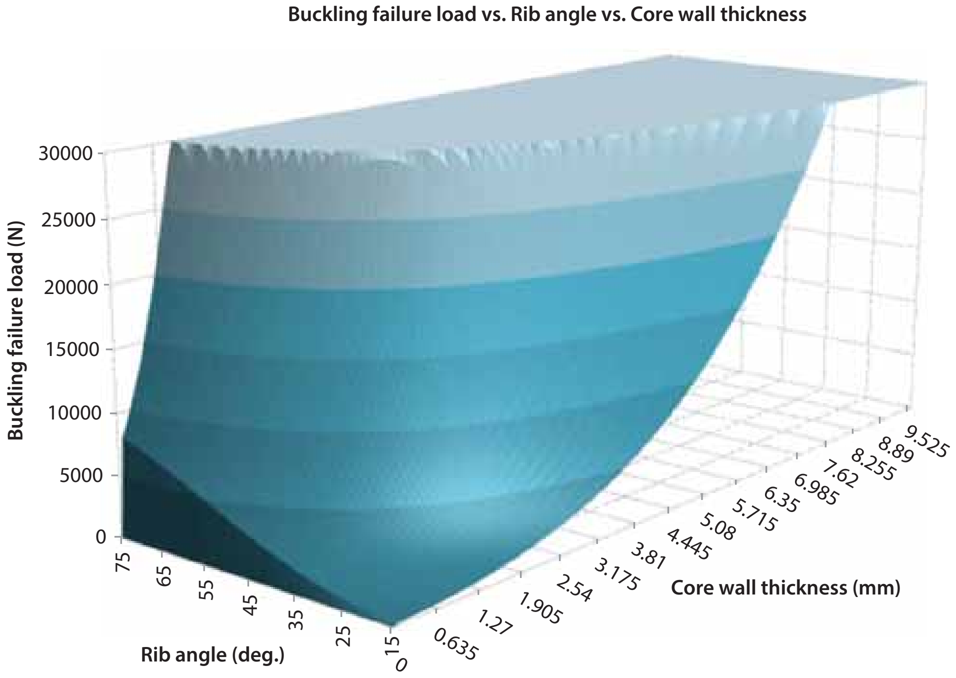


Figure 6 Core buckling analysis.

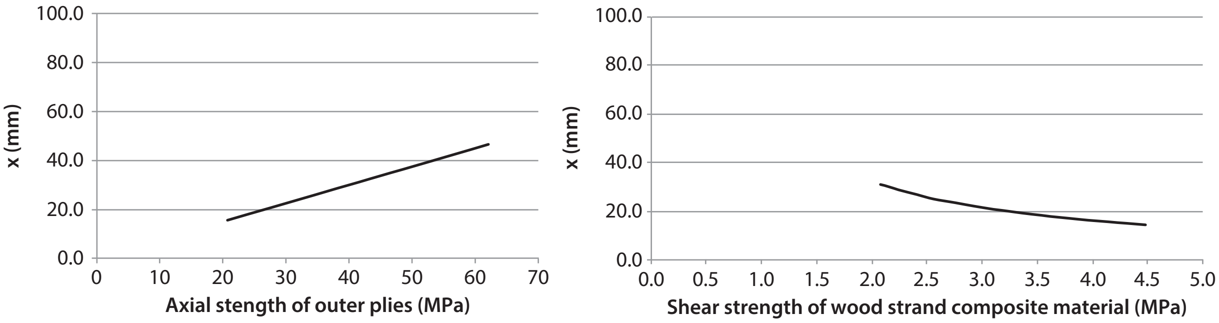


Figure 7 Influence of axial and shear strength of wood-strand composite material on required rib width, x.

The final sensitivity analyses were performed to determine the variables that influence the required rib width, x, to resist interfacial shear failure between the core and face plies. While holding all other variables constant, increasing outer ply axial strength linearly increases the required rib width; whereas, increasing shear strength of wood-strand composite material gradually decreases the required rib width (Figure 7). Thickness of core has little influence on the required rib width (Figure 8). Increasing outer ply thickness, however, significantly increases the required rib width. As flexure span increases, reduction in contribution of shear is reflected in decreasing value of required rib width to resist the interfacial shear stresses at the intersection between core and the outer plies (Figure 8).

4 SANDWICH PANEL TESTS AND RESULTS

The outer 3.2 mm thick plies were bonded to the 3D core with a modified polyisocyanate (MDI) adhesive to fabricate sandwich panels. Finished panels measured approximately 800 mm by 660 mm by 32 mm thick (Figure 4). Sandwich panel specimens were then prepared and tested to determine flexure [14], core shear [16], and flatwise compression [17] properties. Specimens were conditioned (20°C and 65% relative humidity) to equilibrate prior to testing. To determine specimen density, length, width, thickness, and weight were recorded prior to testing; density was used to normalize evaluated properties for comparing with typical sheathing materials (OSB and plywood). Tests were conducted on two sets of sandwich panels that were fabricated and prepared independently for two

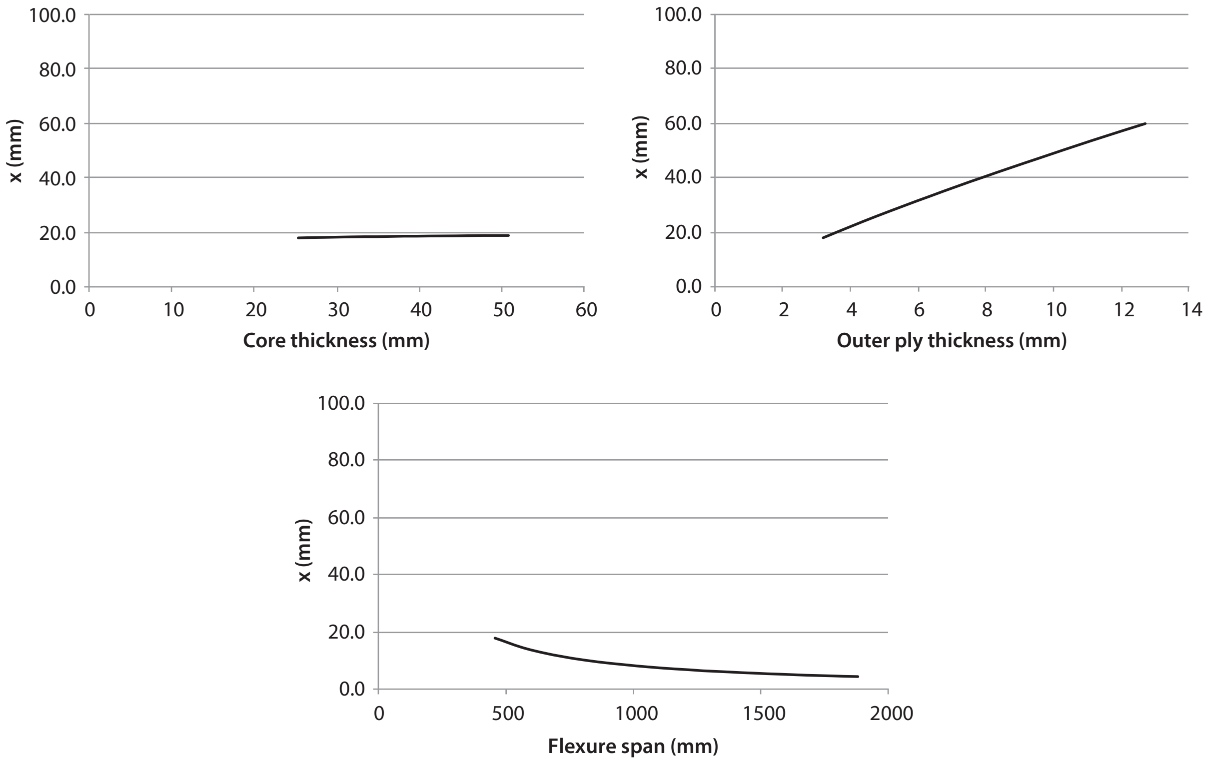


Figure 8 Rib width analysis with respect to core and outer ply thickness and span length.

Table 2 Summary of sandwich panel properties from two separate studies.

Study	Axis	Beam Flexure, P_{max} (N)	Max Flexural Defl. (mm)	Bending Stiffness (N-m^2/m)	Core Shear Rigidity (N)	Core Shear Modulus (MPa)	Flatwise Comp. Strength (kPa)	Comp. Modulus (MPa)	Density (kg/m^3)
Voth	Long.	2709	12.8	18078	41306	11.6	421	8.55	312
	Trans.	698	10.1	4768	18530	5.14	–	–	308
White	Long.	3848	7.70	18757	89250	25.4	806	9.71	306
	Trans.	1126	8.27	4435	17055	4.86	–	–	303

different studies [12,13]. Both studies used the same base materials and resin content.

Cross-section dimensions of ten flexural specimens were 108 mm by 610 mm (width of the RVE) and another ten, to determine the effects of additional rib, were 215 mm by 610 mm. Five of each were tested about the strong axis (x-axis) and weak axis (y-axis) under a 4-point loading configuration with load bars at third points. As per ASTM D7250 [18], span length is recommended to be such that length/panel thickness is greater than 20. However, due to trimming of panels and required overhang, span length was chosen to be 610 mm (resulting in a length/panel thickness ratio of 19). Deflection was measured and bending stiffness, D, was calculated using results within the linear elastic region following ASTM D7250 [18].

Twenty core specimens (108 mm by 254 mm) were tested in flexure (ten strong and ten weak) to determine core shear properties as per ASTM D7250 [18]. Specimens were centrally loaded and spanned 203 mm to ensure shear failure within the specimen. Core shear rigidity, U, was calculated by rearranging the deflection equation that considers both flexure and shear [18]; after obtaining core shear rigidity, core shear modulus, G, was calculated.

Five specimens with cross-section dimensions of 108 mm by 108 mm and five measuring 215 mm by 215 mm were tested under flatwise compression. Larger specimens were tested to determine the effects of additional bonding surface at the interface between ply and core. Flatwise compressive strength and compression modulus were calculated. Table 2 summarizes all mechanical results of sandwich panel specimens. Test results are presented by the two independent studies conducted [12,13]. When bending stiffness of the panels was normalized by width, the results indicated no significant advantage of an additional rib. Higher core shear rigidity and core shear modulus results obtained by White [13] could be due to denser outer plies compared to those tested by Voth [12].

To determine if the wood-strand sandwich panels are a feasible replacement for typical building envelope materials, results were compared to bending stiffness of OSB and 5-ply plywood panels of equivalent thickness. The OSB stiffness was calculated using longitudinal and transverse moduli of elasticity (MOE) of 5.8 GPa and 2.1 GPa respectively [19]. Similarly, 5-ply plywood panel bending stiffness was calculated using longitudinal and transverse MOEs of 6.34 GPa and 2.1 GPa respectively [19]. Both these materials were assumed to have a density of 640 kg/m^3. Comparison shows that the sandwich panels have 17–21% and 7–11% greater bending stiffness than OSB and 5-ply plywood (Figure 9).

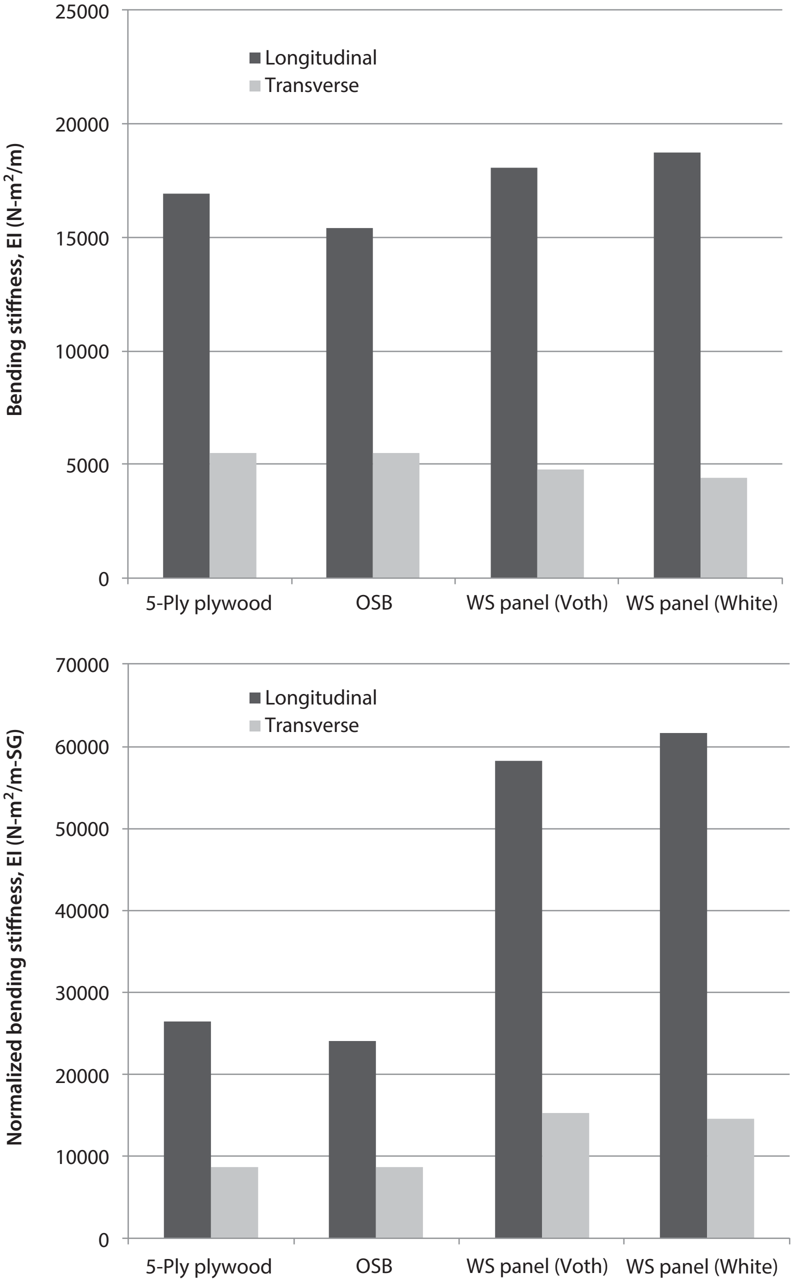


Figure 9 Bending stiffness comparison between plywood, OSB, and wood-strand sandwich panels; bottom figure compares density normalized values.

Once normalized by specific gravity (Figure 9), differences in specific bending stiffness values among the three panel types became even more significant (sandwich panels were 141–156% and 120–133% stiffer than OSB and 5-ply plywood). The much lower density of sandwich panels equates to using 40% of the wood strands compared to that of an OSB panel of equal thickness. Therefore, material usage (wood and resin) can be more efficient by substituting thicker sandwich panels for currently used OSB in sheathing applications. Considering estimated average flexure strength of OSB (of 0.6 specific gravity) based on published values in the Wood Handbook [20], the calculated maximum load (P_{max}) in flexure is determined to be 4730 N; whereas, average P_{max} of sandwich panels ranged from 2709 N (based on batch fabricated and tested by Voth [12]) and 3848 N (based on batch fabricated and tested by White [13]). During flexure testing of sandwich panels, it was observed that failure was initiated at the intersection between core and the bottom ply due to interfacial shear stresses, which could be one explanation for the lower P_{max} values of sandwich panels compared to average OSB values.

5 CONCLUSION

A mold was designed to manufacture complex corrugated cores to fabricate lightweight wood-strand sandwich panels. Based on their mechanical performance, sandwich panels show high potential for structural replacement for OSB in residential sheathing applications. Compared to OSB of equivalent thickness, sandwich panels require 40% less wood strands by weight, which also means reduced resin consumption. These panels take advantage of the lightweight corrugated core sandwiched between stress skin faces, acting similar to an I-beam (faces act as flanges and core acts as web) to allow for increases of 17–21% in bending stiffness. Normalized bending stiffness of sandwich panels was 141–156% stiffer than OSB of equal thickness. Potential advantages of lighter panels are reduced transportation costs and increased efficiency of material usage. Incorporating several cores to form a thicker panel offers advantages of selectively filling some of the cavities with insulation foam and leaving some for utilities. Cavities filled with foam offer improved mechanical and thermal properties [13]. Engineered wood composites, coupled with multiple 3D wood-strand core elements have the potential to increase the functionality and energy efficiency of building envelopes. Achieving desirable mechanical and thermal performance will allow for this material to be utilized in designing and prefabricating panelized wall, floor, and roof elements for building envelope systems.

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REFERENCES

1. J. Davies. *Lightweight Sandwich Construction*, Blackwell Science, Oxford, UK/Malden, MA (2001).
2. S.L. Miller, Construction products review: Structural insulated panels. *Building Products Magazine* (2006).
3. J.F. Hunt and J.E. Winandy, 3D engineered fiberboard: Engineering analysis of a new building product, Eco-Comp (2003).
4. J.F. Hunt, D.P. Harper and K.A. Friedrich, Three-dimensional engineered fiberboard: Opportunities for the use of low valued timer and recycled material, in: Proceedings of the 38th International Wood Composites Symposium, Seattle, WA (2004).
5. J.F. Hunt, 3D engineered fiberboard: Finite element analysis of a new building product, in: Proceedings of the 2004 ANSYS Conference (2004).
6. J.F. Hunt and K. Supan, Binderless fiberboard: Comparison of fiber from recycled corrugated containers and refined small-diameter whole treetops. *Forest Prod. J.* **56** (7/8), (2006).
7. J.F. Hunt, J. O'Dell, and C. Turk, Fiberboard bending properties as a function of density, thickness, resin, and moisture content, *Holzforschung*, **62**, 569–576, (2008).
8. S. Weight and V. Yadama, Manufacture of laminated strand veneer (LSV) composite. Part 1: Optimization and characterization of thin strand veneers. *Holzforschung*, **62(**6), 718–724, (2008).
9. S. Weight and V. Yadama, Manufacture of laminated strand veneer (LSV) composite. Part 2: Elastic and strength properties of laminate of thin strand veneers, *Holzforschung*, **62**(6), 725–730, (2008).
10. Y. Wang, V. Yadama and D. Bhattacharyya, Profile forming of pre-pressed wood-strand preforms. *Compos Part A*, **46**, 131–139, (2013).
11. S. Weight, A novel wood-strand composite laminate using small-diameter timber. MS Thesis, Department of Civil and Environmental Engineering, Washington State University, Pullman, WA (2007).
12. C.R. Voth, Lightweight sandwich panels using small-diameter timber wood-strands and recycled newsprint cores. MS Thesis, Department of Civil and Environmental Engineering, Washington State University (2009).
13. N.B. White, Strategies to improve thermal and mechanical properties of wood composites. MS Thesis, Department of Civil and Environmental Engineering, Washington State University (2011).

14. Standard Test Method for Face Properties of Sandwich Constructions by Long Beam Flexure, ASTM D7249-06 (2006).
15. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. *Wood Handbook—Wood as an Engineering Material*. Gen. Tech. Rep. FPL-GTR-113 (1999).
16. Standard Test Method for Core Shear Properties of Sandwich Constructions by Beam Flexure, ASTM C393-06, (2006).
17. Standard Test Method for Flatwise Compressive Properties of Sandwich Cores, ASTM C365-05, (2005).
18. Standard Practice for Determining Sandwich Beam Flexural and Shear Stiffness, ASTM D7250-06, (2006).
19. APA The Engineered Wood Association. *Mechanical Properties of APA Structural Panels Form No. TT-044A*. Tacoma, WA (2005).
20. Forest Products Laboratory. *Wood Handbook – Wood as an Engineering Material*. Gen. Tech. Rep. Madison, WI (2010).