Three-Dimensional Engineered Fiberboard: Opportunities for the Use of Low Valued Timber and Recycled Material


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Abstract

Fiberboard sandwich panels constructed of a structural core with exterior skins can be produced with high strength and stiffness values that compare to other wood-based panels. At the same time, as much as two-thirds less material is used in the process compared to commercial wood composite products. This offers large savings in raw material and weight. The panel technology is promising in construction, furniture, and packaging applications. The manufacturing process is compatible with a wide range of fiber types and qualities. The three-dimensional fiberboard is manufactured from no- or low-value material acquired from forest thinnings and recycled corrugated containers. This paper presents the initial investigations into the properties of sandwich panels produced from recycled and residual wood material.

Introduction

The United States Forest Service's National Fire Plan has mandated the reduction of forest fire hazards. Much of the fire hazard is created by high stand density of small-diameter trees and woody material left on the forest floor from wind, snowfall, and logging. Currently, this biological material has little to no commercial value, which discourages its removal from the ecosystem. Many federal, state, and private foresters are advocating prescribed burning. Burning is at present the most cost effective method for removing this material, but at the cost of pollution and potential risk of catastrophic fires. Combustion of these materials releases a substantial amount of carbon into the atmosphere.

An alternative, mechanical thinning, is costly, since there are few commercial outlets for this material to offset the cost of the manual work. In the western United States, dry conditions extenuate the problem of thinned material being left on the forest floor and not decomposing significantly, thereby adding to the forest fuel load thus presenting an increased fire hazard. To try to reduce this hazard, especially in fire-prone areas, value-added products need to be developed to offset the cost of removal and transportation out of the forest (Hunt and Winandy 2002b). An important consideration when using this material is the need to minimize processing cost.

One way of accomplishing this is to use as much of the thinning biomass material as possible, including the bark and limbs thus minimizing the cost to remove and separate these components. These extra materials are traditionally unwanted components for most product applications, however, with careful processing, the authors believe it is possible to include these materials in the mix without significant reduction in properties. The authors also believe that in combination with these processing methods and engineering three-dimensional (3D) composites products can then begin to use this undervalued material to produce value-added products. Numerous applications for these new composites are in 3D structural and semi-structural panel applications in the furniture and packaging industries. Initial engineering analyses (Hunt and Winandy 2002a) showed that with a modest increase of the modulus of elasticity (MOE) above traditional composite materials and redistribution of the materials similar into an I-beam corrugated shape, significant improvements of performance could be obtained with even up to two-thirds removal of the core material. The authors regard this as 3D engineered fiberboard.

Three-dimensional forming of fibers is not new. Pulp molding companies are currently using recycled paper to produce products such as egg cartons and cushioning packaging (Gale et al. 2004). Also, in the patent literature, there are processes and products described that use 3D fiber forming for structural applications (Lynch et al. 2004, Owens 2004). The authors, however, have not seen any literature describing analytical methods to optimize the strength properties of wet-formed fiberboard having complex geometries.

Research efforts to recycle paperboard fibers into hardboard-like products are not new either. Steinmetz (1974) investigated fibers from wax-coated corrugated containers as a partial or total replacement for virgin hardboard fibers in wet-process hardboards. He found that adding increasing amounts of fibers from wax-coated corrugated containers up to 100 percent increased bending strength 10 percent and stiffness 4 percent but decreased drainage rates 110 percent. Kruse (1995) reported equivalent hardboard properties from a commercial trial where 20 percent recycled old corrugated container (OCC) fibers were added to virgin hardboard fibers. Adding OCC fibers reduced drainage rates and caused fractures in the mat during wet pressing due to high press closing speeds. Kruse concluded that OCC fibers could be added to the manufacturing system with minor adjustments to the process equipment. Yao (1978) explored the properties of hardboards made from 100 percent municipal solid wastepaper fibers and investigated the effects of binder type, heat treatment, wax treatment, and one versus two screens during press-drying. Yao found that hardboards met or exceeded the commercial requirements for tensile strength, modulus of rupture (MOR), internal bond (IB), and thickness swell (TS). He also found that properties improved if two screens were used rather than one- sided screen panel drying.

The objective of this project is to produce an engineered, commercially viable structural panel out of no- or low-value residual material that currently is fuel for forest fires and/or recycled waste material. The goal of this paper is to describe the initial results obtained from structural panels made from fiberized treetop residual material and recycled OCC. Comparisons are made between actual flexural and flatwise compression tests with predicted analytical values. The structural panels consist of a corrugated core sandwiched between flat sheets. These panels will be produced in a manner that minimizes the use of additives and energy in order to reduce processing costs and environmental impact.

Experimental Procedures

Fiber Processing

Lodgepole pine (*Pinus contorta*) (LP) treetops (from logging residues) harvested from the Bighorn National Forest and Wyoming State Forest were used as raw material for this study. The material was chipped (with the bark) and further reduced to pin-chips of approximately 0.5 to 1.0 mm in diameter by 10 to 15 mm long using a Bolton-Emerson Tornado machine. The pin-chip material was pretreated for 1 hour with 4 percent NaOH at 90°C in a rotating digester. It was then refined three times using a Sprout-Waldron atmospheric wet-refiner using plate gaps of 0.43, 0.25, and 0.25 mm, respectively. These processing conditions were determined from a previous study and reported in a separate article (Hunt and Supan 2004). The goal in fiberizing was to provide a fibrous material that had improved fiber-to-fiber bonding with minimal processing. Average length-weighted fiber length for the lodgepole pine was 1.1 mm.

Corrugated paper box blanks were hydropulped to obtain recycled corrugated fiber furnish for this study and referred to as OCC. For this study, OCC with its longer fiber length, 1.5 mm, was added to the 1.1 mm pine fiber (50% by weight) to improve the fiber mat's flexibility during panel forming over the corrugated mold.

Forming and Panel Manufacture

Three-dimensional cores for this study were made by first forming flat fiber mats. The still wet, flat mats were then post formed over a 3D pressing mold. Flat-formed mats rather than 3D formed mats were used because flat forming provides a method for obtaining a very uniform mat with a known fiber distribution that can be used to form corrugated cores. For this initial study, a uniform fiber distribution was important for predicting and evaluating the panel properties. The flat mats are made using a conventional wet-forming 610 by 610 mm deckle box. Then, they were vacuum pressed to 70 kPa, which dewatered them to approximately 78 percent moisture content (MC).

Vacuum pressure dewatering was done for two reasons. The first reason is to reduce the total amount of water going into the hot-press. Too much water in a sheet during pressing can cause hydraulic tears in the sheet. Also, too much water in a sheet during hot-pressing wastes energy. Mechanical dewatering prior to hot-pressing always increases the energy efficiency of the hot-pressing process. The second reason is to reduce the thickness of the fiber sheet to facilitate forming the flat mat into the corrugated shape prior to hot-pressing. A thinner sheet more easily conforms to the corrugated shape and is less prone to fiber shearing in the angled sections as the matched molds consolidate the mat during hot-pressing. This dewatering step has not been optimized. Additional work to understand the interaction of mat thickness, fiber length, MC, and mold angle needs to be undertaken.

The dewatered flat mats were formed into position using V-shaped machined blocks to press and hold the mat into the corrugated shape over the corrugated mold. The mat was post-formed starting from one side of the mold and working to the other side. The post-formed mat was placed in the corrugated mold, which had double screens on the top and bottom. It was designed to produce an overall finished corrugated core height of l_0 = 28.5 mm with a rib thickness of t = 1.27 mm and having an angle of a = 50" (Fig. 1). After the mat was positioned in the bottom mold section, the top mold section was positioned on top of the mat and then hot-pressed for approximately 15 minutes at constant mat pressure of 1,400 kPa. The pressure was increased from 345 kPa to 1,379 kPa over 120 seconds. The pressure remained constant throughout the drying process. Optimum pressing schedules were not considered but longer

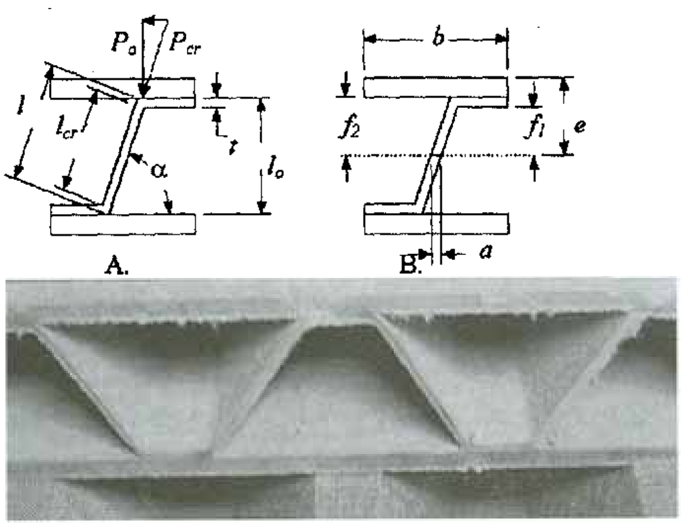

Figure 1. – Geometry of the sandwich panels and an actual cross section of one of the panels.

press times were used to ensure dry boards when the pressure was released.

The face panels were formed from the same material as the cores, placed between two screens and two cauls, and hot-pressed until dry. The target thickness for the face panels was 4.7 mm. They were hot pressed with an adjusted press schedule for the thicker mat and for 15 minutes at a constant pressure of 1,400 kPa.

The face and core panels were brought to equilibrium moisture content (EMC) and then bonded together at the core flat sections using a common commercial polyvinyl acetate water-based adhesive, After the glue dried, the test specimens were cut from the boards and conditioned at 50 percent RH for a week before testing.

Panel Testing

Three tests (ASTM C393 (flat-wise bending), ASTM C364 (edge-wise compression), and ASTM C365 (flat-wise compression)) were used to assess the performance of the 3D structure with respect to possible target applications in packaging and furniture applications. The edge-wise compression test, ASTM C364 (1999), was modified to use a rigid test head rather than a swivel head. The modification to the test method was made because the core rib thickness was only 1.27 mm, which may have resulted in localized core buckling of the ribs rather than total panel compression/buckling.

To estimate the number of specimens needed for testing, the coefficient of variation is estimated at 0.02. This estimate was made from preliminary tensile tests of flat panels. The probability of a Type-I error is taken to be 0.05. Thus, six test specimens are estimated for each of the three tests. Six corrugated panels and twelve flat panels are needed for each type of material to manufacture the sandwich panels. A bending specimen of 432 by 229 mm, a 152 by 152 mm flat-wise compression specimen, and two 152 by 152 mm edge-wise compression specimens were cut from each of the manufactured panels, paying attention to the alignment of the corrugated core. The specimens were cut along lines of symmetry of the corrugated length.

Material Property Predictions

To analytically predict the performance of a non-homogeneous structural panel, it is necessary to use input material properties for each of the individual components. There are several options for non-destructively evaluating (NDE) material properties available for composite wood panels. Most are based on having a uniform geometrical form of relatively uniform density. Because the structure in this study is both geometrically variant with potential variations in density in the core rib structure, we chose to use spectra correlation method from Fourier Transform Near-Infrared (FT-NIR) spectroscopy. The FT-NIR evaluation method has been shown to provide good correlation with material properties from the localized scanned areas. Correlations have been greater than R^2 = 0.95 for spectral to mechanical relationships. For this FT-NIR evaluation, previously scanned spectra correlated with test data was used to obtain the material properties of core and face panels. The data was obtained from panels made from either lodgepole pine or OCC fibers. Scanned panels were then mechanically tested and property values were assigned to each spectrum. Chemometric regression software was used to optimize the data for the best correlations. A complete description of the process will be described in a later publication (Hunt, unpublished). For this study, both the faces and several ribs of untested sections were scanned and the FT-NIR method used to predict the modulus of elasticity (MOE) and compressive strength of the components.

Results and Discussion

Fiber Processing

Since a part of the National Fire Plan focuses on revitalizing rural economies, the fiber processing equipment and methods were chosen with small business capabilities in mind. The authors used standard equipment suitable for processing small batches of material such as chipping, pin-chip processing (Tornado), refining (low-freeness, atmospheric refiner), fiber digesting (8-ft.-long, rotating), hydropulping, and dewatering. All this equipment could be used in a small industrial operation. The chips and pin chips were processed at 90°C in order to eliminate the use of pressurized steam, which may increase costs for small-scale manufacturers. The fibers were refined three times after pre-treatment with 4 percent NaOH because those processing conditions were found to maximize strength properties while keeping chemical usage low (Hunt and Supan 2004). The OCC fiber was used for several reasons. First, in previous studies at the Forest Products Laboratory, panels made from OCC fibers have shown to have very good strength properties (Hunt and Vick 1999). Second, OCC is readily available and easy to prepare by hydropulping. Third, the longer fiber length in the OCC pulp was used to assist in stretching of the fiber mat as it was post formed over the corrugated molds. Preliminary post-forming of 100 percent lodgepole pine fiber mats over a 50" angle caused some mat tearing. The authors found that the tearing was eliminated when 50 percent OCC fibers were added to the mixture.

The length-weighted fiber length for the lodgepole pine used in this study was 1.1 mm. The fiber length for the OCC was 1.5 mm. The lower fiber length for the lodgepole pine may in part be due to the small diameter treetop material used as the starting material, which contains more juvenile and bark fibers. It may also be in part due to the lower amounts of chemical used in processing and the additional refining done to the fibers in order to increase fiber bonding. Only 4 percent NaOH was used to help soften the pin-chips whereas paper processing uses up to 20 percent which aids in significantly softening the fibers and helps to maintain maximum fiber length during the fiberization process and applications.

Forming and Panel Manufacturing

The forming process used in this study to achieve the corrugated core geometry was not optimized. Post forming the fiber mats by hand into the corrugated shapes proved to be adequate, but improved automated methods will be developed for future studies.

The overall dimensions for the finished structural panels are described in **Table 1.** It is interesting to note that the core and panel density are significantly less than a comparable wood (450 to 800 kg/m^3) or commercial particleboard (600 to 1,000 kg/m^3). If performance could be made to be similar to these other monolithic structures, then there would be potential strength/weight advantages for a number of applications.

Resin was not used to aid in fiber-to-fiber bonding in the panels. The authors were trying to optimize fiber processing to enhance fiber-to-fiber bonding

Table 1. –Component and panel physical properties for the corrugated panels. Standard deviations are in parentheses.

	Core			Panel	
Fiber furnish	Rib thickness	Height	Density	Height	Density
	(mm)	(cm)	(kg/m^3)	(cm)	(kg/m^3)
OCC[a]	1.37(0.15)	2.74(0.028)	42.4(0.94)	3.39(0.057)	234(12.86)
LP/OCC[b]	1.65(0.17)	2.73(0.05)	39.6(1.11)	3.46(0.067)	249(4.35)

[a] OCC is recycled old corrugated container fiber furnish.
[b] LP/OCC is a 50%/50% mixture of lodgepole pine and recycled old corrugated container fibers.

without the complexities of resin addition. In some packaging applications as well as some office furniture it may be more advantageous to make panels without resin either for recyclability or to eliminate off gassing of unwanted chemicals. Future work will include resin addition and other techniques to further improve panel durability where performance requires it.

Since most commercial composite products use dry forming to form flat panels, the decision to use wet forming for this project may seem unusual. The authors have found that forming complex structural geometries is easier with a wet process than a dry process. The wet-forming process is used in the pulp molding packaging industry for forming complex low-density pulp-molded products, as mentioned above. The panels made for this study are significantly higher density and stronger. It helps advance pulp-molded fiberboard from niche-market materials to engineered structural materials.

Panel Properties

Flexure

The sandwich panels were tested in flexure aligned with the length of the corrugated core. Localized crushing was observed under the crosshead during testing. The values obtained for bending MOE were compared with three common wood composites that are used in furniture manufacturing: medium density fiberboard (MDF), hardboard, and particleboard (Falk et al. 1999). These composites have wood constituents that range from fibers in MDF and hardboard to particulate for particleboard. They were manufactured using a dry-forming method and are bonded with an adhesive. The densities range between 0.50 to 0.90 g/cm^3 (*Wood Handbook* 1999). The bending values for these materials were obtained from ASTM method D1037 for testing wood-based composites (Fig. 2). This presents some discrepancy in the comparison with the sandwich-constructed panels tested using ASTM's test method for sandwich panels, but the data allows far a benchmark for typical panel performance values for targeting specific applications. The MOE for OCC composites compared favorably within the range seen for MDF panels

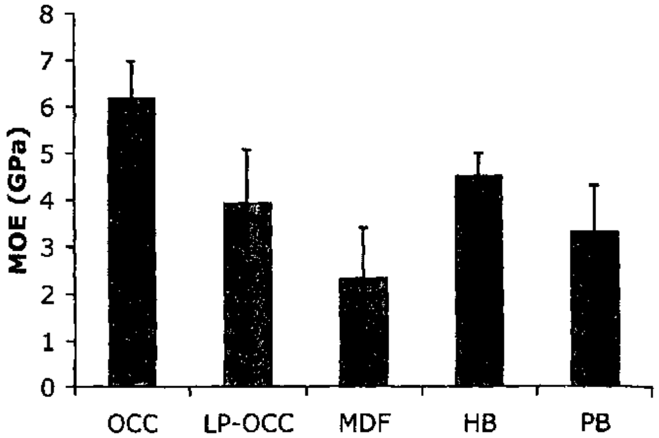

Figure 2.–Comparison of bending MOE for the sandwich panels with a range of values compiled from the wood composites literature for MDF, hardboard (HB), and particleboard (PB) (Falk et al. 1999).

(Fig. 2). The MOE for the composite structures of both fiber types compared favorably with the standard values seen for MDF panels, which range from 1.2 GPa to 3.4 GPa (2.4 GPa Standard (*Wood Handbook* 1999)). The LP-OCC composite produced lower MOE values than that of the OCC panels. The MOE values of panels made from both fiber types are sufficient to be potentially incorporated into structural packaging material or furniture applications. The material properties can be further optimized for a target application by manipulating the geometry, density, and thickness of the sandwich panel core (Hunt 2004).

The flexure results did not yield high strength values in the faces. The test values obtained for maximum bending load and deflection at maximum load are listed in **Table 2.** MOR was not calculated because panel failure was due to localized core crushing under the mid-point load and not caused by either tensile or compressive failure in the panel faces. Localized crushing could pose a problem in some applications especially those that do not have uniformly distributed loads. The flexural results presented are promising for applications such as furniture where MDF and particleboard are frequently used. In future studies, increasing the core weight should increase panel properties and minimize buckling failures from localized loads. There is significant room for improvement in optimizing the product for flexural strength.

Table 2. – Flexure properties of OCC and LP/OCC sandwich panels. Standard deviations are in parentheses. MOE is calculated using shear plus bending. Predicted extensions are calculated using basic material properties from FT-NIR analysis.

	Actual			Predicted
Fiber furnish	Maximum load Der rib	Deflection	Panel MOE	Deflection
	(kN)	(mm)	(MPa)	(mm)
OCC [a]	15.8 (2.6)	2.282 (0.224)	3,587 (246)	0.889 (0.112)
LP/OCC [b]	14.3 (1.0)	2.938 (1.105)	2,786 (302)	0.726 (0.085)

[a] OCC is recycled old corrugated container fiber furnish.
[b] LP/OCC is a 50%/50% mixture of lodgepole pine and recycled old corrugated container fibers.

Table 3. – Flatwise compression values predicted versus actual loads and deformation for corrugated fiberboard. Standard deviations are in parentheses.

	Predicted		Actual			
Fiber furnish	Load	Deformation	Load	Deformation	Maximum stress	Maximum stress/core density
	(kN)	(mm)	(kN)	(mm)	(kPa)	(kN-m/kg)
OCC [a]	7.27 (2.65)	0.0387 (0.0094)	2.14 (0.662)	0.736 (0.440)	91.5 (28.3)	2.15 (0.630)
LP/OCC [b]	12.5 (3.97)	0.0578 (0.013)	2.31 (0.660)	0.431 (0.185)	98.4 (28.3)	2.48 (0.671)

[a] OCC is recycled old corrugated container fiber furnish.
[b] LP/OCC is a 50%/50% mixture of lodgepole pine and recycled old corrugated container fibers.

This will be accomplished by optimizing the geometry, density, and thickness of the sandwich panel core for targeted applications (Hunt 2004). This is currently part of another study.

The observed failure modes of the boards displayed a considerable amount of localized buckling and deflection before the boards completely failed. Material property predictions obtained from FT-NIR spectra were used to try to analyze the behavior through analytical methods.

The standard means of analyzing beam deflection for conditions without shear uses Equation [1]:

$$y = \frac{P_0 L^3}{48EI} \qquad [1]$$

However, because the beam's span-to-depth ratio was 15, which was less than the test standard of 24, and the beam had a thin rib section, shear deflection was included in the analysis. The form factor, F (Equation [2]), was used to calculate shear deflection (Equation [3]) for beams (Young 1989).

$$F = \left[1 + \frac{3(e^2 - f^2)f}{2e^3}\left(\frac{w}{a} - 1\right)\right]\frac{4e^2}{10r^2} \qquad [2]$$

$$y_s = \frac{1}{4} F \frac{P_0 L}{AG} \qquad [3]$$

where:

a = horizontal thickness of the web (a = t/sina: **Fig. 1**), FIX
e = distance from the neutral axis to the extreme fiber (**Fig. 1**),
f = distance from the neutral axis to the nearest surface of the flange (($f = (f_1 + f_2)/2$: **Fig. 1**),
w = width of the flange (**Fig. 1**),
r = radius of gyration of the beam's cross section with respect to the neutral axis,
P_0 = beam load (**Fig. 1**),
L = span length,
A = cross-sectional area, and
G = modulus of rigidity (shear modulus) and is determined by the relationship $G = E/(2(1+v))$ which assumes isotropic material behavior.

The values obtained for the predicted versus the actual beam deflection display a discrepancy in beam deflection (Table 3). The predicted values assume an infinitely stiff core properties with no localized buckling, thus predicting minimal deflection before estimated maximum face stress values would have been reached. This, however, is not consistent with the observed localized buckling behavior that occurred during testing. If the localized buckling issues are improved through increase core material, this then should result in a stiffer panel.

Flatwise Compression

A flatwise compression test of the structure should be a result of either compression or buckling failure of the core ribs. Classical equations to predict these critical compression or buckling loads are shown in Equations [4] and [5], respectively. These critical loads, P_{cr}, act parallel with the angle of the ribs (**Fig. 1**). Equation [6] was used to transform the critical rib loads into maximum panel loads, P_0, acting normal to the faces. Total thickness deformation for a structural load with a composite core can be determined from Equation [7]. The load value used for this Equation is shown as the maximum critical load. The panel load, P_0, could also be substituted into the Equation using the relationship shown in Equation [6]. Both buckling and compression failure loads were calculated with failure estimated to occur whenever the lowest of the two failure criteria was met. To determine these failure loads two input values were needed. First, the maximum compressive stress for the ribs was needed in order to determine the critical compressive load (Equation [4]) for the panel. Second, the modulus of elasticity, E, of the ribs was needed to determine the buckling load (Equation
fix [5]). Physical dimensions (t, l_{cr},, l_0, a) and radius of gyration (I_r) for the rib were obtained and determined from the actual the test samples.

$$P_{cr-c} = \sigma_{cr}(tl) \qquad [4]$$

$$P_{cr-b} = \frac{n\pi^2 EI_r}{l_{cr}^{\,2}} \qquad [5]$$

$$P_0 = P_{cr}\cos(90-\alpha) \qquad [6]$$

$$\Delta l_o = \frac{l_o \dfrac{P_{cr}}{tl}}{E} \qquad [7]$$

where:

P_{cr-c} = critical failure load for compression,
P_{cr-b} = critical failure load for buckling,
s_{cr} = critical Compressive stress, X
t = rib thickness,
l = unit the depth,
n = an end effect constant for Euler's Buckling Formula,
E = modulus of elasticity,
I_r = radius of gyration,
l_{cr} = rib length,
a = angle of the core with respect to the faces, X
l_0 = core height,
Dl_0 = change of core height. X

FT-NIR spectra were obtained from the core material and were used in a chemometric regression computer model to predict both maximum compressive and E values. These were then used in the above equations to help predict values. More information on using FT-NIR to predict properties will be published later.

From Equations [4] and [5] we find the predicted buckling failure for all the samples. This was confirmed in testing. All flatwise compression tests failed due to buckling failure in the ribs. Table 3 shows the actual load and deformation values. The actual test loads where much lower and actual deformations were much higher than what the Equations predicted. The authors believe this was primarily due to geometrical differences (Fig. 1) and assumptions in the Equations that lead to the differences. Preliminary finite element analysis by Hunt (2004) also showed significant differences between the predicted results and the finite element analysis of the 3D engineered fiberboard panels. In the finite element analysis, the reason was due to the structural response of the curved rib geometry to the load. Further analysis and comparisons are being examined to help understand loading and geometrical effects on performance of the 3D structural engineered fiberboard.

Another reason for the difference in predicted versus actual test results may be due to how the panels used in this study were the made using the corrugated molds. The results show a wide variation for the compressive maximum load for both the predicted and calculated values (Table 3). Variations may be due to variations in thickness and quality of the cores. The

Table 4.–Edgewise compression comparison of material types and orientations. Standard deviations are in parentheses. Parallel and perpendicular refer to the orientation of the strong axis of the. corrugated structure with respect to the vertical axis.

Rib alignment to load	Material	Total panel stress	Total material stress
Perpendicular	OCC[a]	2.34 (0.42)	9.49 (1.67)
	LP/OCC[b]	3.05 (0.63)	11.2 (2.46)
Parallel	OCC[a]	4.55 (1.03)	18.5 (3.91)
	LP/OCC[b]	5.29 (0.67)	19.4 (2.32)

[a] OCC is recycled old corrugated container fiber furnish.
[b] LP/OCC is a 50%/50% mixture of lodgepole pine and recycled old corrugated container fibers.

panels had several forming and process control problems that need to be improved to reduce the high variance in sample preparation. This processing variation affects the resulting test values. For future evaluations and testing, specific care will be taken to minimize variations in the processing. Also, the thickness of the core ribs will be increased (increased core weight) to decrease the potential of rib buckling and thus move toward rib compression failure.

Edgewise Compression

From each panel, edgewise compression tests were conducted with the ribs aligned parallel and perpendicular to the loading conditions. The authors observed that the failure mode was different for the two rib alignments. With the ribs parallel to the load, material compression failure occurred. With the ribs oriented perpendicular to the load, the panel faces buckled before the material reached the material compressive stress. The specimens were cut having four evenly spaced ribs, similar to **Figure 1.** Buckling generally occurred at the mid-point of the panel face that was between ribs. For the panels with the ribs parallel with the load, the ribs supported the faces better, thus preventing buckling. These results were expected. The compressive stress for both conditions is presented in **Table 4.** The results are presented for the stress over the entire panel cross-sectional area and also the compressive stress for the material only cross-sectional area. Depending on the needed application either stress calculation may be used to help determine needed performance characteristics.

The authors believe significantly improved flatwise compression properties are possible with thicker ribs that fail in compression rather than buckling. However, there may be applications where buckling would be the preferred method of failure, such as in cushioning applications. In cases where buckling was the desired failure mode maximum stress and stress per core material are give in **Table 3.**

While these resin-free corrugated boards cannot be substituted in compression for particleboard on a thickness to thickness basis, they could be used where a combination of light weight and bending strength are desired. Greater uniformity of the forming process and pressing schedule will decrease the variation in the strength of the cores and result in improved properties.

Conclusions

These initial results from 3D engineered fiberboard panels made with thin rib core sections showed that even with buckling core failures it is possible to make corrugated structures for moderate-strength applications out of small-diameter and recycled fibrous material.

Bending MOE values were equal or slightly better than commercial wood composite materials. To improve bending properties thicker ribs would be necessary to prevent premature rib buckling under concentrated loads.

Flatwise compression also showed buckling was the primary mode of failure. Similarly, as above, thicker rib sections will significantly reduce buckling, moving failure mechanism toward compression. If, however, buckling failure was the preferred method of failure for cushioning products then, it is feasible to develop engineering information to predict performance for protective packaging applications.

Edgewise compression results showed, with this configuration, there are significant differences in failure mechanism. Ribs aligned with the load significantly stiffen the faces forcing compression failure to occur in the faces. It is important to know the loading conditions to adequately design the alignment of the rib structure.

Current analytical methods do not adequately predict mechanical properties of the 3D engineered fiberboard panels. Additional work is necessary to develop analysis techniques that take into consideration the various wood fiber forming characteristics, geometrical considerations, and final fiber properties. Finite element analysis may be the necessary method combined with true orthogonal property relationships that can truly design and predict final performance properties whether for cushioning or structural applications. There is no known literature for engineering specific strength properties into a panel of this type. Future research will investigate the use of finite element analysis to help predict the various modes of failures for complex 3D fiberboard geometries and to further develop means to engineer performance from fibrous materials.

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