LIGHTWEIGHT SANDWICH PANELS USING SMALL-DIAMETER TIMBER WOOD-STRANDS AND RECYCLED NEWSPRINT CORES

By

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To the Faculty of Washington State University:

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Abstract

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As the natural resources of this planet are being stretched to the limit, it is necessary to look towards effective utilization of undervalued raw materials for production of structural building materials with reduced impact on the Earth's environment. Small-diameter timber is often used for production of structural panels for building construction, but new value-added products using this timber need to be developed to pay for fuel reduction treatments in our national forests for their removal. A lightweight sandwich panel construction with a thin-walled core provides a system to use these undervalued lignocellulosic based materials for production of structural and non-structural panels.

Analysis of the core design was investigated to determine a process that can be utilized for engineering design of future sandwich panel cores. The most crucial design parameter for the core is to ensure sufficient width of the corrugated ribs so that flexural failure of the sandwich panel occurs in the face plies as opposed to failure at the interfaces between the core and faces due to shear or crushing/buckling of the walls.

Small-diameter Ponderosa Pine wood-strands were utilized in fabrication of a lightweight sandwich panel that has a specific bending stiffness (D, lb-in^2/in) 88% stiffer than commercial OSB. The sandwich panels designed within this study utilize 60% less wood-strands and resin by weight compared to OSB panels of equivalent thickness. A case study was performed on the wood-strand sandwich panels to determine their potential in structural flooring as an alternative

for OSB. The sandwich panel can support a 40 psf live load and a 20 psf dead load without exceeding IBC (2006) deflection limits.

Sandwich panels consisting of old newsprint (ONP) cores were designed for non-structural applications such as shelving units, doors, furniture, etc. The newspapers were shredded into strips and hot-pressed using a powdered phenol formaldehyde resin. ONP strips were oriented to take advantage of the 4:1 ratio in strength and 7:1 ratio in Young’s Modulus due to their directional dependent properties. The ONP sandwich panels have a bending stiffness (D, lb-in^2/in) 83% stiffer than particle board and over 125% stiffer than a medium density fiberboard.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

DEDICATION

This thesis is dedicated to my loving fiancé. Without her love and support throughout the entire process, this thesis would not be the thesis it has become. Thank you Lena for being there when it means the most.

Chapter 1: Introduction of an Innovative Lightweight Sandwich Panel Using Environmentally Conscious Substrates

1.1 Introduction:

In the world today, there is a seemingly endless search to be more environmentally conscious when it comes to the utilization of our planet's raw materials. Following the push of sustainable building materials and environmentally conscious design, this research is a contribution to the science of sustainable building construction materials. The concept of lightweight sandwich panels has been around for a long time. Most sandwich panels today consist of two dense outer faces and a foam core. The largest market for sandwich panels is the aerospace industry with the use of high-performance aluminum and honeycomb cores, but sandwich panels are also widely used for structural parts in the marine, wind energy, and transportation industries (Black 2003). However, lightweight sandwich panels have not become a major component of the building and infrastructure construction industry. Structural Insulated Panels (SIPs) have had the most success penetrating the residential construction market. However, SIPs account for only 2% of the residential construction market (Miller 2006).

Researchers at the Forest Products Laboratory (FPL) have been developing an innovative new type of core for lightweight sandwich panels suited more for non-structural applications, such as furniture. This new type of sandwich panel consists of a hollow 3D fiberboard core (Hunt 3D Engineered Fiberboard, 2004). This innovative core has significant benefits in the light framed construction industry. The hollow cavities of the core allow for electrical and plumbing conduit, as well as heating and ventilation, or just filled with foam insulation (Winandy et al. 2004). The biggest disadvantage of this process is the use of massive amounts of water for wet forming of the three dimensional core, which results in dealing with release of effluents, an environmental hurdle with stricter regulations being implemented. A dry forming process for manufacturing three dimensional medium density fiber cores has also been developed at WSU in collaboration with a private entrepreneur (Yadama et al. 2008). These 3-D fiber-based panels are well suited for non-structural applications. There is a need for a lightweight sandwich panel that can replace structural panels, such as oriented strand board (OSB), and also be utilized to develop hybrid structural panelized elements. This type of sandwich panel has possible applications in the field as floor, wall, or roofing panels, doors, crates, industrial shelving, furniture, and building systems that provide both structural and insulation performance.

This study will investigate the feasibility of using two different environmentally conscious materials, recycled old newsprint (ONP) and small diameter timber strands, as substrate for a lightweight sandwich panel core. Over 72 percent of newsprint is recycled and nearly one-third of that recycled newsprint is exported to other countries (2007 Recovered Paper Annual Statistics). According to Forest Products Laboratory (FPL), for healthy forests to grow, small diameter trees are cleared and left felled or burned because there is no commercially viable alternative (Hunt and Winandy 3D engineered Fiberboard 2003). A value-added opportunity is necessary to economically thin overcrowded national forests for removal of small-diameter trees in fuel-reduction treatments. These resources could be utilized as raw materials for a three dimensionally contoured, thin-wall core for sandwich panel construction.

1.2 Incentive:

Logging operations in the U.S. require thinning of low value timber which is felled and left on the ground, chipped, or burned because most mills are not equipped to handle it, and it is an increasing fire hazard as it dries (Levan-Green and Livingston 2001). The forest fire season of

2000 was the most costly on record for the U.S. which cost the government over $1.36 billion (Hunt and Winandy Lam I-Joist 2003). Most fire-prone small-diameter timbers are generally not economically valuable enough to cover the costs of removal, therefore a viable commercial process will encourage the private sector to remove these fuels and minimize federal costs for forest mitigation (Levan-Green and Livingston 2001). Developing a value-added manufacturing process for this material provides an environmentally conscious building material, reduces the danger of forest fires, and reduces the amount of tax payers' dollars going towards forest mitigation.

Many sawmills in Western North America are operating substantially below their optimum levels due to saw timber shortages (Wagner 1998). The average diameter of timber felled in the Pacific Northwest of the U.S. declined from 14 inches in the mid-1970's to 7 inches a decade later and is continuing to decline (Douglas 2009). Because of the decline of raw timber available to sawmills, innovations are necessary to allow for previously undesirable materials to become economically viable. Sandwich panels would require less material to produce a similar structural panel to OSB.

Structural sandwich panels have not become a main component of the construction industry. The potential uses in fields as a replacement for solid panels would greatly reduce the demand on resources that could be allocated elsewhere. According to a 1996 statistic published by the Annual Survey of Manufacturers, the pallet industry has annual sales in the U.S. of over $3 billion, wood office furniture is a $2.4 billion dollar market, wood partitions and fixtures are a

$3.7 billion market, and wood doors account for $2.2 billion of the total door market (US Census Bureau 1996). Sandwich panels will have a significant demand in these markets.

Utilization of small-diameter timber from hazardous fuel treatments in national forests and intensively managed short rotation plantations, unsuitable for lumber or veneer production, for manufacturing value-added composites as suggested in this study, will reduce wastage of biomass. Products utilizing net shape cores will reduce the material requirement by over 60 percent compared to similar products of solid cross sections. Due to thin-walls of the three dimensional cores, the heat required during hot-pressing using molds would also be considerably lower. Moreover, as less fiber content will be used per unit volume, the amount of resin will also be lowered further, adding to the energy savings. Resin production can consume a large amount of energy for both feedstock and production (approximately 20% during composite processing) (Kline 2005, Puettmann and Wilson 2005).

1.3 Background:

Research on recycled ONP as a structural building material dates back to the early 1970's. A U.S. patent was filed in 1976 for producing recycled composition paper flake board (Balatinecz 1976). This patent describes a dry process to press composite panels using recycled newspaper strips known as "paper flakes." These paper flakes were combined with wood flour or finely fragmented cellulosic matter and bonded with a thermosetting resin like urea-formaldehyde (UF) or phenol-formaldehyde (PF) either in liquid or powdered form. The paper flakes were conditioned somewhere between 6% and 12% moisture content (MC) for optimum pressing conditions for the resins to cure completely. Pressed panels varied in thickness from ¼ inch to

1½ inches. Despite pressing successful boards with densities ranging from 30 pcf to 60 pcf, research on this project appears to have been abandoned.

The most prominent work done on structural sandwich panels using small-diameter timbers has been done at the Forest Products Laboratory (FPL). John Hunt and his team (Hunt 2004, Three-Dimensional Fiberboard 2007) have developed a wet processed 3D fiberboard known as Spaceboard that utilizes small-diameter timber as well as other cellulose base raw materials. The raw material is ground into pulp and refined physically and chemically, formed in a rubber mold, and hot pressed to release the moisture and bond the fibers together. 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. This allows uniform structural sandwich panels to be made from multiple non-uniform resources. The FPL has gone as far as to design emergency housing where this 3D fiberboard is the primary building component. It is light weight and does not require the use of additional framing components (Winandy et al. 2004).

Despite the extensive positive benefits provided by the FPL's 3D fiberboard, there are significant disadvantages that need to be overcome before a viable product can be produced. A risk and feasibility study was conducted for the use of small diameter timber in the Western U.S. for both pulp mills and OSB mills. The study concluded that a bleached chemi-thermomechanical pulp (BCTMP) mill produced a negative net present value (NPV) with a low rate of return ($r = 0.10$) (Stewart 2004). This study suggests that turning small diameter timber into pulp for processing is not economically feasible while the OSB mill has a positive NPV on a rate of return up to approximately r = 0.15 (Stewart 2004). The main difference between the two plants is that the OSB mill will process four times the material as the pulp mill (Stewart 2004). Another disadvantage is the amount of refining necessary to produce fibers with sufficiently strong enough bonds to produce quality structural material. A study (Hunt and Supan 2006) conducted to determine the viability of old corrugated containers (OCC) fibers and virgin fibers from small-diameter timber in a binderless fiberboard concluded that panel properties increase as chemical processing and refining of the higher-yield pulp increases. With additional chemical and physical refining, a significant amount of chemical additives and excess water inherently required in re-pulping operations would cause significant impact on the environment and a further need to search for more environmentally safe alternatives (Balatinecz 1976). A dry processing method does not carry as many environmental impacts as a wet process (Balatinecz 1976).

Two different studies (Nourbakhsh 2008, Suchsland 1998) evaluated the potential of ONP as a raw material for use in medium and high density fiberboard (MDF and HDF respectively). Both studies concluded that ONP decreased the bending strength and internal bond of the MDF significantly so that it is not a viable product. It is suggested that the cause of this reduction in strength is due to the ONP fibers being shorter than virgin timber as well as the possibility that the chemical additives in ONP decrease the bonding abilities of the fibers in conventional adhesive bonding. Suchsland (1998) determined that ONP could have potential in HDF or hardboards; a wet or dry pulping process of ONP produced hard boards with respectable mechanical properties.

Canadian researchers have successfully developed a dry manufacturing process for pressing shredded paper strips from recycled phone books (Ellis 1993). This study investigated the use of plastic grocery bags as the source for the adhesive and compared it to both a liquid and powdered PF resin. The study concluded that a powdered PF resin content of 10% produced bending properties comparable to commercially available wood-based panels.

Research at the Composite Materials and Engineering Center (CMEC) at Washington State University has developed a thin wood-strand ply which uses small-diameter Ponderosa Pine as its raw material. The stranded composite has strength and stiffness values that were 2 to 2.5 times greater than the parent material (Weight 2007, Weight and Yadama 2008). Optimum values for processing variables examined for their study were determined to be a resin content of 5.5%, platen temperature of 152^{o} C, and aspect ratio (length/thickness) of 430 (Weight 2007). Recommendations from Weight's (2007) study will be used as a basis for development of sandwich panel construction in this study.

1.4 Objectives:

Previous research has indicated a great potential for lightweight sandwich panels in the construction industry as an alternative to bulky OSB panels. This study investigates the potential of sandwich panels, constructed by laminating thin strand plies on thin-walled strand core, as a substitute for structural OSB panels. ONP thin-walled cores are intended to be a substitute for solid composite panels (particleboard or MDF) in non-structural applications such as furniture, shelving units, and doors. Sandwich panel construction using a wood-strand based hollow 3D contoured core has the potential to provide a successful implementation of these undervalued raw materials for structural panels such as OSB in building construction. Further investigation into the physical and mechanical properties of these materials and sandwich panel design is required for successful production and implementation in applications requiring structural performance. The specific objectives of the research presented herein are to:

- Determine ply properties of outer skins of sandwich panels necessary for designing core geometry of the panel.
- Design the core geometry of a sandwich panel capable of supporting structural loads and having the desired failure criterion.
- Produce a lightweight sandwich panel with a hollow 3D core out of ONP and wood strands from small-diameter timber that have comparable mechanical properties to composite panels currently used for corresponding end uses.
- Develop preliminary tables based on average properties to determine structural efficiency in certain structural systems, such as flooring.

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Chapter 2: Characterization of Old Newsprint and Wood-Strand Plies

2.1 Introduction:

With increasing emphasis on sustainable practices, there is a need to find value-added opportunities for recycled and undervalued materials. Without a value adding proposition, it is difficult to promote an industry that utilizes these raw materials. Two such materials are old newsprint (ONP) and small-diameter timber from hazardous fuel removals in our national forests. The following study is part of a larger scope of utilizing these two materials for manufacturing lightweight sandwich panels serving as structural and non-structural elements in applications such as furniture, shelving, transportation, decorative paneling, and building construction.

Characterization of ONP strip properties need to be analyzed for identifying potential weaknesses and determine challenges inherent to the material that could possibly be overcome through the manufacturing process of thin plies. This chapter discusses the material properties of the ONP under investigation. This analysis includes understanding of directional properties of ONP in paper form, which is lacking in the past studies on ONP. Once knowledge of the constituent material is obtained, a manufacturing process can be developed to form ONP mats that will be hot-pressed into ONP plies.

Analysis of the small-diameter timber wood-strands for this study does not include testing of individual wood-strands. As a starting point, recommendations in the manufacturing process for wood-strands were taken from Weight (2007, Weight and Yadama 2008). Wood-strand mats were hot-pressed into plies. These plies were tested for tensile strength and internal bond (IB) to establish their properties. Properties obtained from these tests are crucial for the design of the aluminum mold to hot-press the thin-walled sandwich panel core. Ponderosa Pine wood-strands plies were analyzed to corroborate Weight's (2007) study conducted using the same small-diameter timber.

2.2 Objectives:

The goal of this study was to establish elastic and strength properties of ONP strips and thin plies fabricated using ONP and wood-strands from small-diameter timber; these properties are critical in designing molds to manufacture three dimensional cores of sandwich panels, as well as evaluating properties of sandwich panels that are manufactured using thin face plies from these constituents. In a follow up study, sandwich panels will be evaluated for their properties. Specific objectives formulated to attain the main goal of this study are to:

- Determine the basic properties of ONP strips used for this study to characterize the potential for application in a sandwich panel construction.
- Determine a manufacturing process for ONP plies and confirm a suitable manufacturing process for wood-strands from small diameter timbers based on Weight's (2007) recommendations in which a structurally suitable ply can be fabricated.
- Determine the mechanical properties of an ONP and wood-strand plies for use in mold design calculations.

2.3 Methods and Materials

2.3.1 Newsprint Strips:

The newspaper chosen for this study was Washington State University's (WSU) campus newspaper, *The Daily Evergreen*, as it is readily available in excess. Newspapers were acquired from recycling bins located on the WSU campus. Knowing that all fiber-based material has directional characteristics based on fiber orientation; it is important to classify such differences to optimize the material usage. Within newsprint, the two principal directions are denoted by the machine direction (MD) and the cross direction (CD). It is critical to determine if material orientation has a significant influence on its properties to help take advantage of the differences in engineering a composite ply.

Initially, to determine the material properties of the newspaper, tension coupons were cut into strips of 1 inch thickness and 10 inches long in accordance with ASTM D 828-97 (2002). Specimens were taken from both principal directions in order to determine the MD and the CD as well as the differences between the directional properties of ONP. Tensile strength of newsprint is generally measured according to TAPPI 541 for paper applications, which reports its value as lb/in width of newsprint. ASTM D 828-97 (2002) reports tensile strength as a stress, which produces inherent errors within the data due to insufficient accuracy during measurements of the ONP thickness. The test procedure for this experiment follows ASTM D 828-97 (2002), however results will be presented in both forms for comparison purposes.

The ONP strips were tested in a 2 kip Instron testing machine with a 112 lb load cell. A laser extensometer was used in the setup shown in Figure 2.3.1 to determine the strain due to the extreme inelastic behavior of ONP in accordance with ASTM D 828-97 (2002). The laser extensometer measures the distance between two reflective pieces of tape set at a gage spacing of 4 inches. It was setup at a distance of 12 inches from the specimens. Spacer plates were placed between the tension grips to prevent the newsprint from sliding within the grips. Applied load and percent strain were recorded for data manipulation and determination of tensile strength and Young's Modulus for the ONP.

Figure 2.3.1: Depicts the setup for the tensile tests for ONP in accordance with ASTM D 828-97 (2002). Note the reflector tape on the strip of ONP set at a gage length of 4".

2.3.2 Manufacturing and Testing of Thin Plies

2.3.2.1 Newsprint:

Initial trials to form and press ONP panels shed light on several fundamental challenges to overcome based on the characteristics of ONP. Narrow ONP strands (¼-inch wide) posed significant difficulties in forming the furnish mat for pressing. There was a high degree of variability in densities due to the shape of the ONP strips (specimen densities varied from 27 pcf to 48 pcf). Visible voids and weak spots were easily detected. Combined with extreme difficulty in the forming process and results of a past study (Balatinecz 1976) suggesting that ONP strips have a width of ¼ inch to 2 inches and a length of 1 inch to 6 inches, ONP strips of ¾ inch by 5 inches were selected for use in this study. The shorter length reduced strips from spanning across the vanes on the forming box, therefore increasing the ease of the forming process. The lightweight and flexible nature of ONP also proved difficult in the forming process as well as resin selection. Wood-strands' rigid nature allow them to fall uniformly through the vanes on the forming table, while ONP's flexible nature produces oriented plies with far less uniformity.

2.3.2.2 Wood-strands:

Wood strands were produced from small diameter Ponderosa pine logs as described by Weight (Weight 2007, Weight and Yadama 2008). Forty Ponderosa Pine logs 4-7 inches in diameter and 8 ft long from Northwest Washington were used for stranding. These logs were ripped on a band saw into boards of ½ inch thick and then debarked. These boards were fed into a CAE strander operating at 500 rpm in stacks of ten. The strands were dried and stored in large plastic bags to reduce moisture absorption. For use in this study, the strands were dried to a MC of 2-5%. During the drying process, a significant amount of fines were produced and therefore were sorted out using a shake table with a 1.0 inch by 1.0 inch square holed screen.

2.3.2.3 Resin and Application:

A phenol formaldehyde (PF) resin was selected for hot pressing the ONP mats based on several recommendations (Balatinecz 1976, Ellis 1993, Hunt, O'Dell, and Turk 2008, etc.). Initial trials with a liquid PF resin resulted in ONP strips adhering to one another prior to the mat forming process preventing uniform forming of the mat and any ability to orient the ONP strips. Oriented strips in the direction parallel with the principal corrugated ribs allows for improved performance capabilities opposed to random orientation (Hunt 2004). To allow for the orienting of ONP strips, a dry powdered PF resin was selected, which allowed for the ONP strips to be oriented.

Based on recommendations from Balatinecz (1976), ONP strips were conditioned to a moisture content (MC) of approximately 12%. The increase of MC is important for an equal dispersion of the powder PF resin over the surface of the ONP strips. The target resin content for the ONP strips was 10%; however, due to the powder form of the resin, not all of the resin adhered to the ONP strips. Initial calculations concluded that the actual resin content was on average 8% just prior to pressing. PF resin is a thermosetting resin and therefore was investigated to determine its peak cure rate temperature. A differential scanning calorimeter (DSC) test of the powder PF resin indicates that the peak curing rate occurred at 149 ^{o}C. This requires adjustment to the platen temperature and pressing schedule to insure the core of the plies reaches this temperature. See Appendix A for the graphs from the DSC tests.

The ONP strips and powdered PF were sealed in a plastic bag and mixed within a rotating drum for 5 minutes. See Figure 2.3.2 a and b for clarity on the amount of free air space provided for the ONP strips to mix within the plastic bag. Actual calculations for ONP furnish for mats as well as resin content were calculated based on oven dry weight and having a desired density of approximately 40 pcf. See calculations in Appendix B. Note that in those calculations there is a 20% waste factor to compensate for loss in the mixing and forming process.

Figure 2.3.2: A) Depicts the plastic bag used to mix the ONP strips and the powder PF resin. B) Depicts the rotating drum the plastic bag was placed in for 5 minutes to allow the powder PF resin to be distributed equally throughout the ONP strips.

The Ponderosa Pine wood-strands were bonded using a more conventional liquid PF resin. The resin consisted of 55.71% solids. Calculations were made for each batch based on oven dry weight of the wood furnish and having a target resin content of 8%. Similar to ONP, calculations included a 20% waste factor. The PF resin was atomized and applied with a pneumatic sprayer within a rotating mixing drum. The PF resin and wood-strand furnish were mixed for 5 minutes after all the resin had been dispensed through the pneumatic sprayers.

2.3.2.4 Manufacturing of ONP and Wood-Strand Plies:

It was determined early that the manufacturing process for the ONP must be a dry process. Repulping processes of ONP requires large quantities of water as well as limitations on wet strength resins. It should also be noted that additives to the ONP (printing ink, sizing agents, fillers, etc.) can pollute the water supply and therefore contains certain risk towards polluting the environment (Balatinecz 1976). In an attempt to take advantage of the directional properties of

ONP discussed in previous sections, it was determined to shred the ONP into strips and orient them accordingly.

ONP mats were formed on a forming table with dimensions of 13 inch by 13 inch by 1/8 inch seen in Figure 2.3.3. Due to the significant height of these mats, pre-pressing was performed using the self weight of a caul sheet. Pre-pressing is done in an attempt to create a more uniform density profile within the ONP plies after pressing by reducing the amount of densification of the exterior layers. Pre-pressing reduced the initial thickness of the ONP mats from approximately 8 inches to 4 inches. The hot press was set at a temperature of 160 ^{o}C. The pressing schedule for these test mats are in Appendix C. It was determined that the closing rate of the press needed to be significantly fast in order to produce a smooth finish on the ONP mats. A smooth finish is necessary for proper adhesion in the manufacturing process of the lightweight sandwich panels.

The wood-strand plies were formed similarly. The main difference between the wood-strands and the ONP was the type of resin used. The liquid PF resin presented no difficulties in orienting the rigid wood-strands. For initial tensile specimens, a 20 inch by 20 inch by 1/8 inch mat was formed. This was to insure a significant amount of wood-strands in the rotary mixing drum to apply an even amount of resin. These specimens were tested to confirm Weight's (2007) results, rather than to reproduce his work in its entirety.

Figure 2.3.3: Depicts the shake table used to form the mats of ONP furnish prior to hot pressing. Note that the vanes seen don't move, but the table beneath them that the ONP is formed on moves back and forth.

2.3.2.5 Hot-Pressing:

The press used was a 38 inch by 28 inch rectangular oil heated press controlled by Pressman ™ (2006). Pressman ™ (2006) worked in conjunction with a thermocouple to determine core temperature of the panels during pressing. Based on initial trials, the press was set at a temperature of 160 ^{o}C. Figures 2.3.4 and 2.3.5 are typical graphs of the data recorded by Pressman ™ (2006) for and ONP and wood-strand panel respectively. The mat pressure required to press the wood-strand panels is approximately 100 psi more than that required to press the ONP panels. This has to do with the material properties of the furnish being pressed. The pressing schedule for the 1/8-inch mats is in Appendix C. The mat pressure peaked under initial loading and the drop is due to material relaxation. The pressing schedules are designed so that the press will hold at the design thickness for approximately one minute after peak cure rate temperature is achieved in the core. Panels are allowed to de-gas prior to opening the press to insure no delaminations within the material. Panels are allowed to cool prior to being cut into final dimensions.

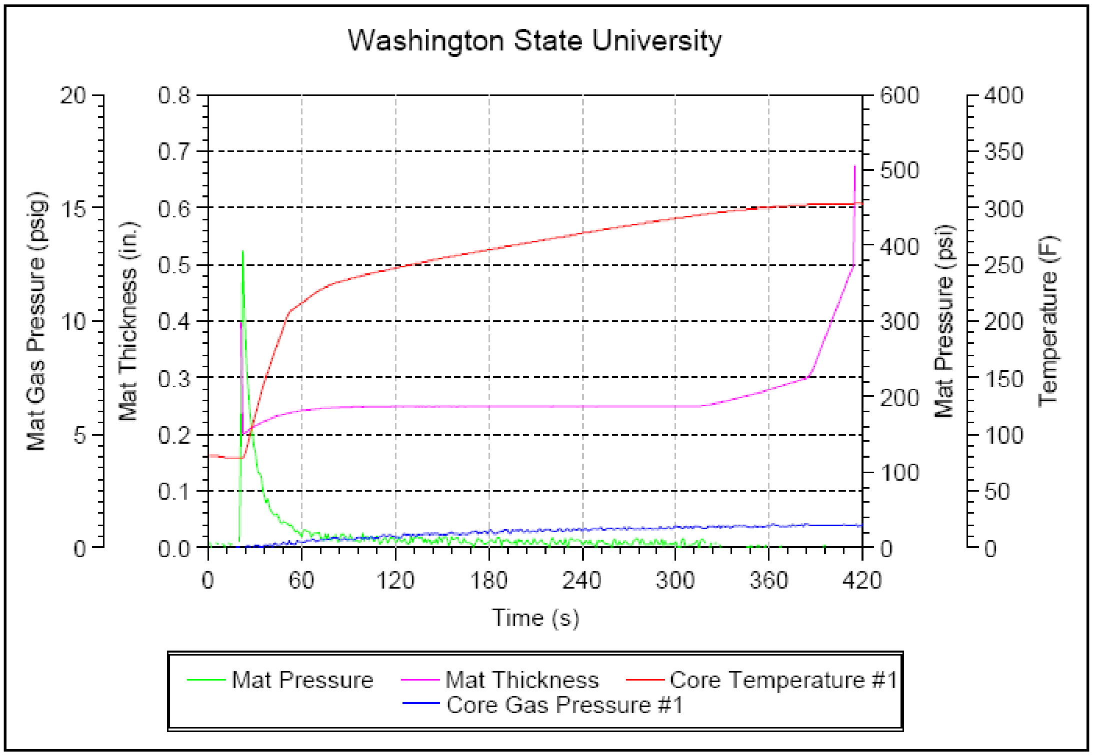

Figure 2.3.4: The above plot shows the data recorded when pressing an ONP Panel. This data was taken from a panel with ¼ in thickness.

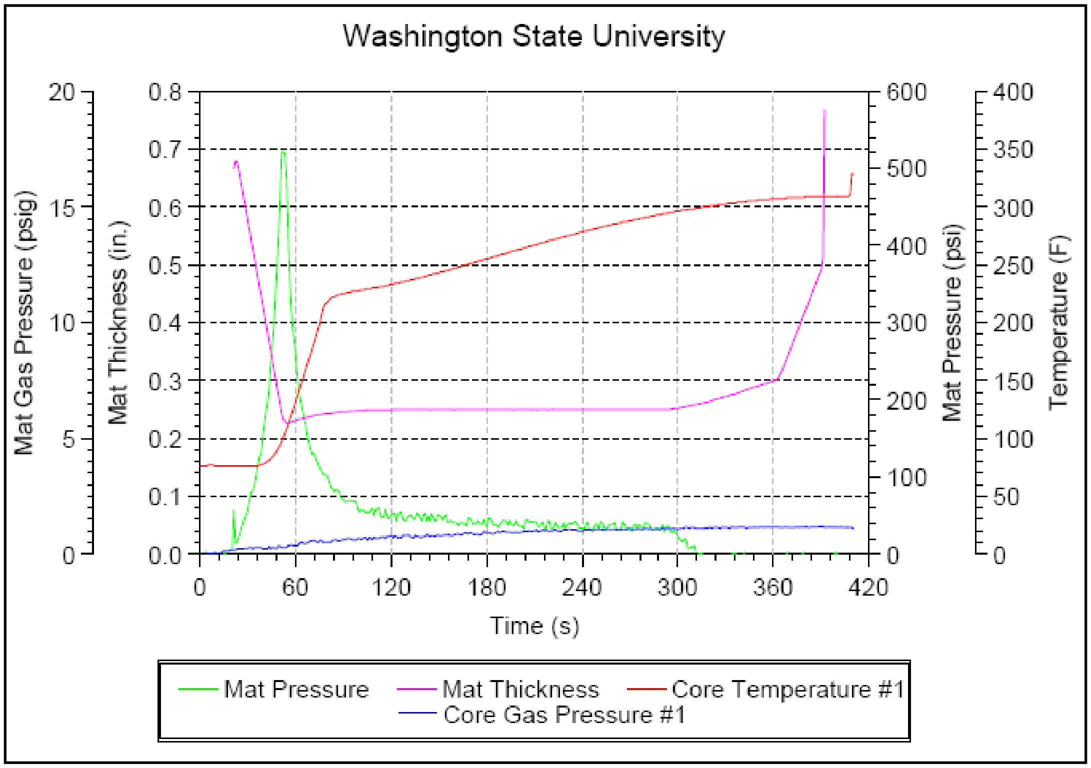

Figure 2.3.5: The above plot shows the data recorded when pressing a wood-strand panel. The data is taken from a panel with a ¼ in thickness.

2.4 Results and Discussion

2.4.1 Newsprint Properties:

Table 2.4.1 details the summary values of average tensile strength and Young's Modulus for the ONP strips. It's important to note that the ratio of average tensile strength in the MD direction compared to the CD direction is 4:1. There is also a 7:1 ratio in Young's Modulus from MD direction to CD direction. Due to the significant difference in possible tensile strength and Young's Modulus based on directionality of the ONP, it is important to utilize this advantage in construction. This difference in maximum tensile strength further confirms the need to orient the ONP in manufacturing of ONP mats prior to hot pressing. The tensile strength of newsprint reported from Inland Empire Paper Company in the MD direction is 10.2 lb/in. and 5.1 lb/in. in the CD direction (Averyt 2009). These values can vary based on fiber density and other manufacturing parameters. The above tensile strength values were reported to confirm the accuracy of the experimental values listed in Table 2.4.1.

Table 2.4.1: Summary of ONP Strip Properties

	Tensile Strength				E	
	MD		CD		MD	CD
	(psi)	(lb/in)	(psi)	(lb/in)	(psi)	(psi)
Average	5370	14.84	1330	3.47	721200	106900
Std. Dev.	748	1.88	145	0.21	61550	16650
%COV	13.9	12.67	10.9	5.95	8.5	15.6

2.4.2 ONP and Wood-Strand Ply Tensile Specimens:

Twenty-four ONP ply specimens were tested for tensile strength and E, twelve in the longitudinal direction and twelve in the transverse direction. Tensile tests were performed according to ASTM D 1037. Table 2.4.2 displays tensile strength, E, and specimen density for ONP panels. The data for tensile strength and E was normalized to a density of 40 pcf assuming a linear relationship between both tensile strength and E with density (Kellogg and Ifju 1962). The normalized tensile strength in the strong direction of 3876 psi, exceeds Ellis' study with recycled phonebook paper achieved its best product with a tensile stress of 3045 psi at a density of 50 pcf (Ellis 1993). Future studies might investigate a higher density panel; however, panels that get beyond 50 pcf have a significant tendency to delaminate in the degassing stage of the pressing process. From observations, it is suggested that 50 pcf be an upper limit for pressing unless the MC is reduced from the current 12-13% MC.

Table 2.4.2: ONP Ply Tensile Specimen Summary

	Longitudinal Axis			Transverse Axis		
	Avg.	Std. Dev.	%COV	Avg.	Std. Dev.	%COV
Tensile Strength (psi)	4450	1239	27.86	2400	1282	53.05
Normalized Tensile Strength (psi)	3880	1180	30.43	2030	1012	49.75
E (psi)	729500	152362	20.89	420500	158891	37.79
Normalized E (psi)	634400	139527	21.99	355000	121807	34.31
Density (pcf)	46.2	3.52	7.61	46.7	4.85	10.39

The wood-strand ply (WSP) tensile specimen data is shown in Table 2.4.3. In comparison with ONP, the WSP specimens have a slightly higher ultimate tensile strength, but the main difference is in the Young's Modulus (924 ksi), which was approximately 1.5 times greater than that of ONP ply specimens. The data collected herein coincides with results obtained by Weight (2007). Weight determined an ultimate tensile strength in the longitudinal axis of 4470 psi, which differed by less than 1% from that measured in this study. Weight determined the tensile modulus to be 1579 ksi, which is approximately 70% greater than that measured in this study. This difference could be due to variations in the orientation of the individual strands. In thin specimens, small variations in orientation can have a significant effect on properties. In light of the fact that the actual cause of this discrepancy is unknown, future calculations and analyses using the E values of the wood-strands shall be completed using these mean values as opposed to those determined in Weight (Weight 2007).

Table 2.4.3: Wood-Strand Ply Tensile Specimen Summary

	Longitudinal Axis			Transverse Axis		
	Avg.	Std. Dev.	%COV	Avg.	Std. Dev.	%COV
Tensile Strength (psi)	4500	820	18.2	2860	1590	55.4
E (psi)	924000	67600	7.3	847600	161700	19.1

2.4.3 Density Profiles and Internal Bond:

Specimens with dimensions 2 inch by 2 inch were taken from the panels for use in Internal Bond (IB) testing according to ASTM D 1037 and to determine their density profiles. The mean IB strength of the ONP panels is 9.93 psi with a %COV of 31.7. This value is extremely low and could present significant problems in application of a sandwich panel using an ONP core. A study conducted on MDF using ONP as a fiber reinforcement produced IB strengths of 79 psi as its weakest specimen (Suchsland 1998). Failure tends to occur several layers below the adhesion surface between the specimen and the testing fixtures. Chemical modification to ONP fibers for printing purposes reduces the bonding potential of the ONP fibers (Nourbakhsh 2008). These additives could prove to be an inherent weakness within ONP that could limit the applications of this product.

Density profiles were obtained using a QMS Density Profile System. Figure 2.4.1 is a typical graph produced by the density profiles for ONP. The intent is to analyze the pressing schedule in its ability to produce a uniform density through the thickness of a panel. Figure 2.4.1 has a good density profile due to the lack of low density locations within the specimen and that the surfaces are not significantly denser than the interior of the specimen. The mean density of the specimens was 41.7 pcf. These specimens are within 4.2% of the design target density of 40 pcf and therefore are deemed acceptable.

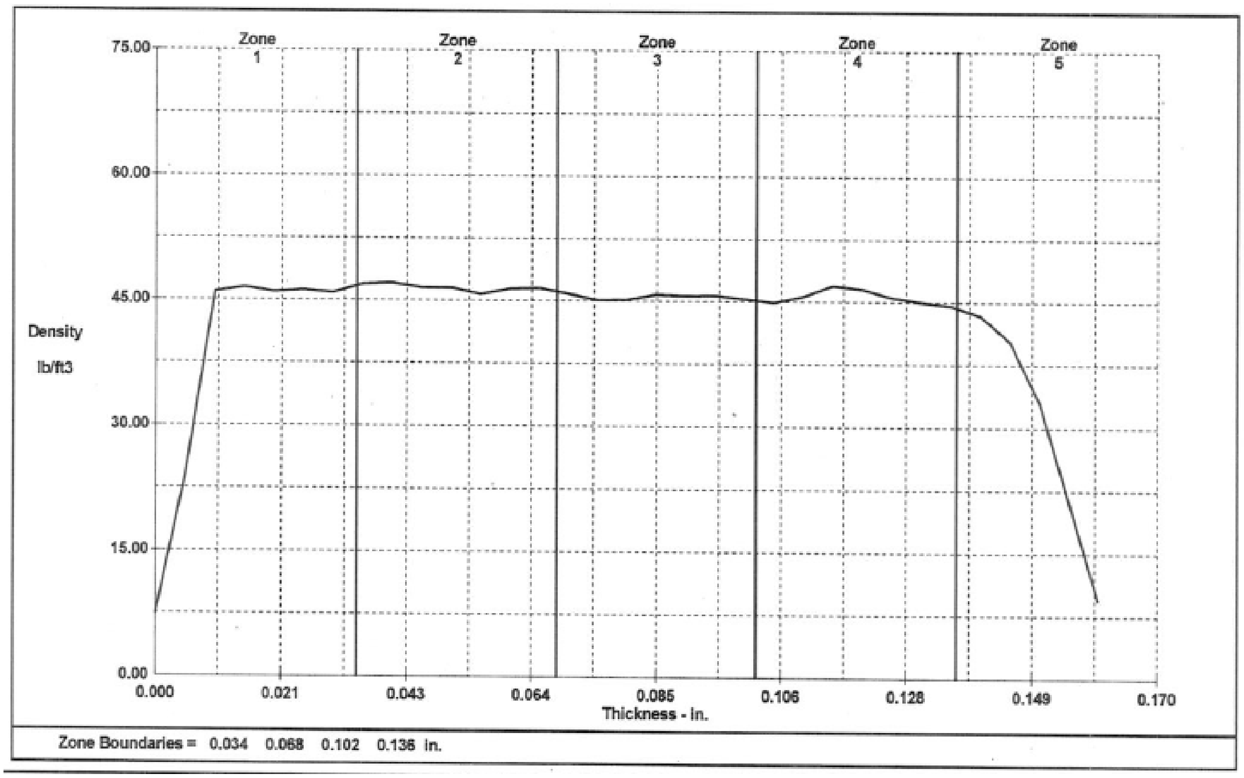

Figure 2.4.1: Density profile for ONP specimen. This specimen has an extremely uniform profile since its density does not vary much.

The wood-strand IB specimens failed as desired with complete breaks within the core of the specimen rather than failure near the surface of the specimens as occurred with the ONP plies. The IB strength of the wood-strands was determined to be 145 psi. This is a 60% increase in capacity compared to Weight's (2007) results, which yielded an IB of 89 psi. Wood-strand specimens followed a similar density profile as that of Figure 2.4.1. There were more variations within the core of the wood-strand specimens. However, this is likely due to the nature of the wood-strands because they are thicker. A single wood-strand within a thin ply has a more significant effect than that of an ONP strip because there are fewer wood-strands relative to the thickness of the ply than there are in ONP plies. The average density for the batch of five specimens tested was 34.5 pcf. This is a little low compared to the target density. The waste factor for wood-strands was bumped from 10% up to 20%, similar to the ONP calculations.

2.5 Summary and Conclusion:

Initial newsprint tensile tests further support the benefits of orienting the ONP strips because of the 4:1 ratio of tensile strength in the MD. Because of the utilization of the strength in the MD of newsprint, ONP plies could produce strength properties comparable to wood-strands from small diameter timbers. However, they differ significantly in their respective stiffness properties. The wood-strands are significantly stiffer and therefore are more likely to be able to produce sandwich panels of strong enough properties for structural applications. ONP's weakness appears to be its inability to bond to itself. Despite this inherent weakness in the ONP, application in a non-structural system is still feasible. An analysis of MC and its effect on structural properties of ONP should be conducted. It might be possible to increase IB strength by reducing the moisture within the material. Additives added to newsprint to improve the printing process have significant detrimental effects in the fibers bonding ability (Nourbakhsh 2008). Wood-strand panels have sufficient strength and stiffness properties to be utilized in sandwich panel construction.

2.6 References

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Chapter 3: The Mold Design

3.1 Introduction

The mold design was conducted to produce a finished lightweight sandwich panel. Therefore, some of the mold design is governed by the core geometry alone and at other times the mold geometry is based on calculations for finished lightweight sandwich panels. A 3D engineered sandwich panel cannot be designed using basic beam theory, as in Equation 3.1.1. The non-homogeneous nature of the panel and the semi-hollow core allows for different failure criteria than those for solid beams. The possible failure criteria for a lightweight sandwich panel are (Davies 2001):

- Tensile failure of the faces
- Wrinkling failure of the faces (due to compressive stress)
- Shear failure of the core or the adhesion between the core and face
- Crushing failure of the face and core at support
- Tensile or shear failure of fasteners

$$\sigma = \frac{M \cdot y}{I} \qquad \text{(Equation 3.1.1)}$$

σ = Bending stress (psi)

M = Bending moment (lb-in)

y = Distance from the neutral axis to the fiber in the beam (in)

I = Moment of Inertia (in^4)

This study does not focus on connections or fasteners; therefore, the fifth failure criterion will be ignored. The desired failure criterion is a flexural failure in the faces of the panel. In order to achieve a flexural failure, shear resistance of the core or the adhesion between the core and faces as well as crushing or buckling resistance of the core need to be designed to resist the maximum design loads.

The core geometry will be designed assuming a corrugated ribbed contour as shown in Figure 3.1.1, although the actual core geometry is a modified two directional corrugated shape detailed in Figure 3.1.2. This conservative assumption will only add to the safety factor. The panel's longitudinal axis has the continuous ribs while the transverse axis has slightly wider segmented ribs. The transverse axis ribs were added to provide local support in the transverse axis of the panel. The benefits of having the semi-hollow core allows for electrical, plumbing, or heating conduit to run through the structural panel itself.

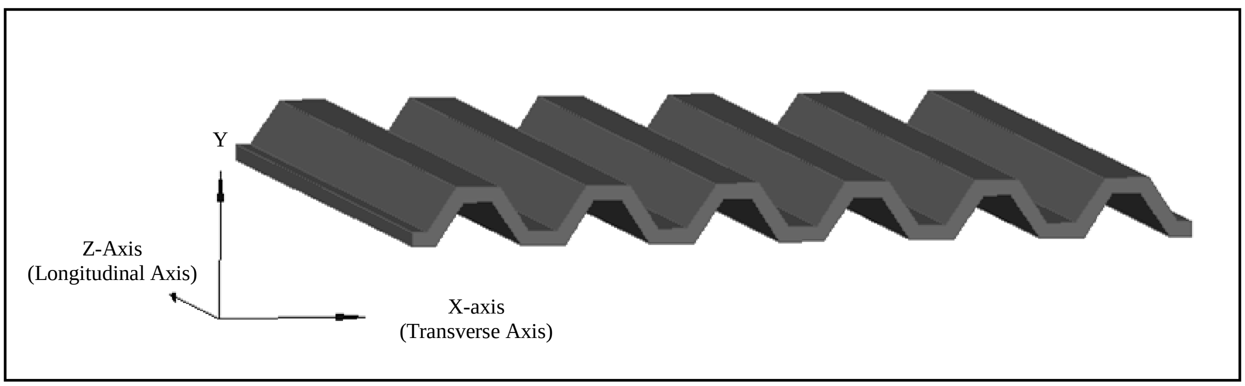

Figure 3.1.1: The assumed simplified unidirectional corrugated shape for the sandwich panel core so that basic shear flow analysis could be calculated.

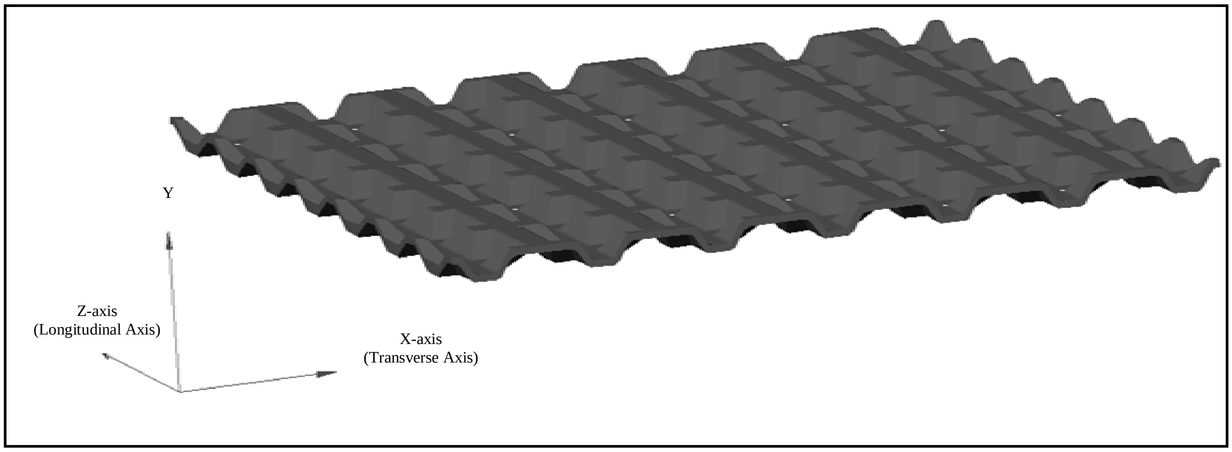

Figure 3.1.2: The actual designed core geometry without geometry simplifications for calculation purposes.

3.2 Core Geometric Design

The geometry of the core has no specific design methodologies, but there are guidelines based on the desired applications and knowledge about wood-strand conformance necessary for molding based on past experience. The aluminum mold was restricted to the size of the small press in the Composite Materials and Engineering Center’s (CMEC) lab, which measures 38 inches x 28 inches. The core depth was designed to be 1.0 inch thick with ¼ inch thick walls. Budget constraints and commonly used composite panel thicknesses for structural applications further played a role in deciding the core depth. The dimensions of the aluminum block used for the mold were 38 inches by 26 inches by 2.0 inches. The design attempted to maximized the benefits of sandwich construction by having a deep core, but limited the core depth to a thickness still suitable for structural panels. Due to the connection apparatus used to attach the mold to the press and the machining capabilities of the machine shop that built the mold, the contoured surface of the mold was limited to 31.5 inches by 26 inches. The mold is designed to make old newsprint (ONP) cores with medium density fiberboard (MDF) face plies for applications such as doors or shelving units; however, it will be used to make wood-strand cores for applications such as structural floor and roof sheathing in light framed wood structures.

Hot-pressing processes for manufacturing composite wood materials are highly sensitive to moisture content (MC) due to delaminations or “blows.” Upper limits for MC are limited to approximately 10-12% after liquid adhesive application. ONP requires higher MC (approximately 12%) to allow the dry powder phenol formaldehyde (PF) resin adhere to the ONP strips prior to hot pressing. Holes that are 1/16-inch in diameter were drilled through the contoured surface of the mold at the mid-depth to allow vapor pressure to dissipate during the hot-pressing process. These holes are connected to channels that allow the steam to vent out of the side of the press to enable hot-pressing of strand mats with higher than usual moisture content (generally furnish is dried to a MC of less than 3 to 5 percent). See Figure 3.2.1 a and b for the detailed pattern of these venting holes and channels.

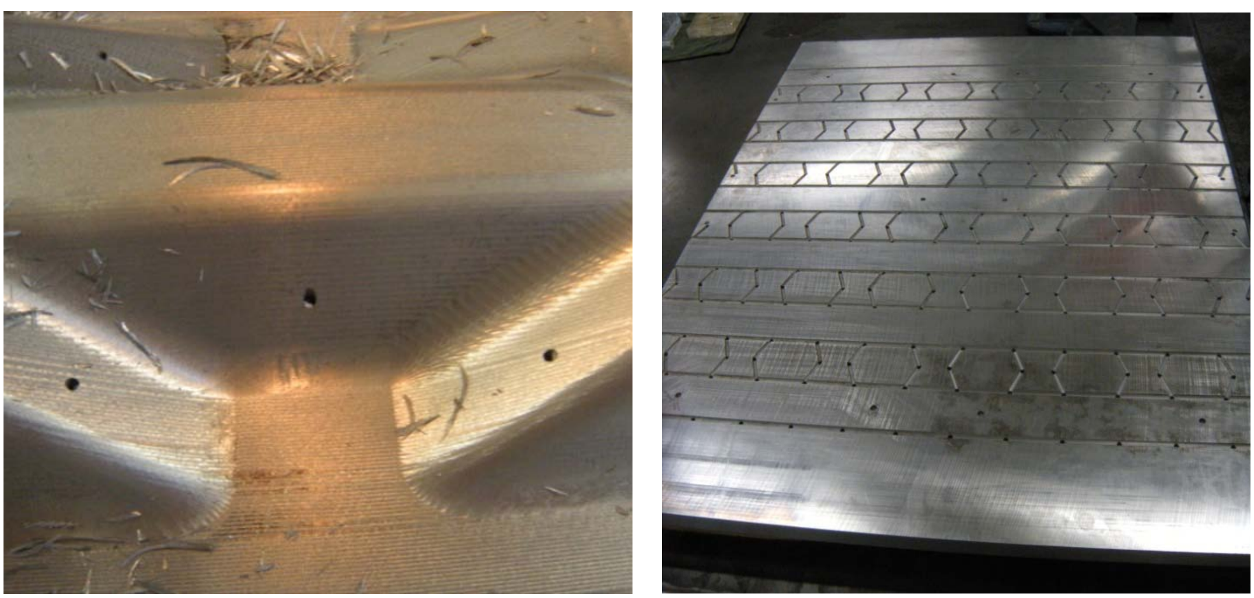

Figure 3.2.1 a and b: Details of the ventilation holes and channels to allow for gas pressure to dissipate prior to opening the press. This should allow for higher quality panels to be pressed using MC in excess of 12-15%.

3.3 Sandwich Panel Shear Design

Analysis for the shear capacity of the sandwich panels was governed by the shear area at the adhesion interface between the core and the face plies. Basic shear flow theory (Equation 3.3.1) was used to determine the width of the ribs, denoted by the variable x in Figure 3.3.1.

$$q = \frac{V \cdot Q}{I} \qquad \text{(Equation 3.3.1)}$$

q = Shear flow (lb/in)

V = Shear Force (lb)

Q = First moment of the area (in^3)

I = Moment of Inertia (in^4)

For these calculations, the core geometry was assumed to be a simple corrugated shape and a representative volume element (Figure 3.3.1) was considered. Any shear area provided by the ribs in the transverse axis was neglected and therefore could be considered as an added safety factor to this design.

The panel dimensions were assumed to be 18 inches long for these calculations; this was to ensure flexural failure using the minimum span length for flexural testing of the sandwich panels set forth in ASTM D 7249 (2006). Figure 3.3.1 details the dimensions analyzed for the shear area calculations for a repetitious geometry element. The outer faces were assumed to be a medium density fiberboard (MDF). An ultimate tensile stress of the MDF faces was assumed to be 3480 psi (U.S. Department of Agriculture, Forest Service 1999). Equation 3.3.1 was manipulated using Equation 3.3.2 to provide a required thickness of the rib shown in Figure 3.3.1.

$$q = x \cdot \tau \qquad \text{(Equation 3.3.2)}$$

τ = Shear stress of the faces (psi)

x = Rib width (in)

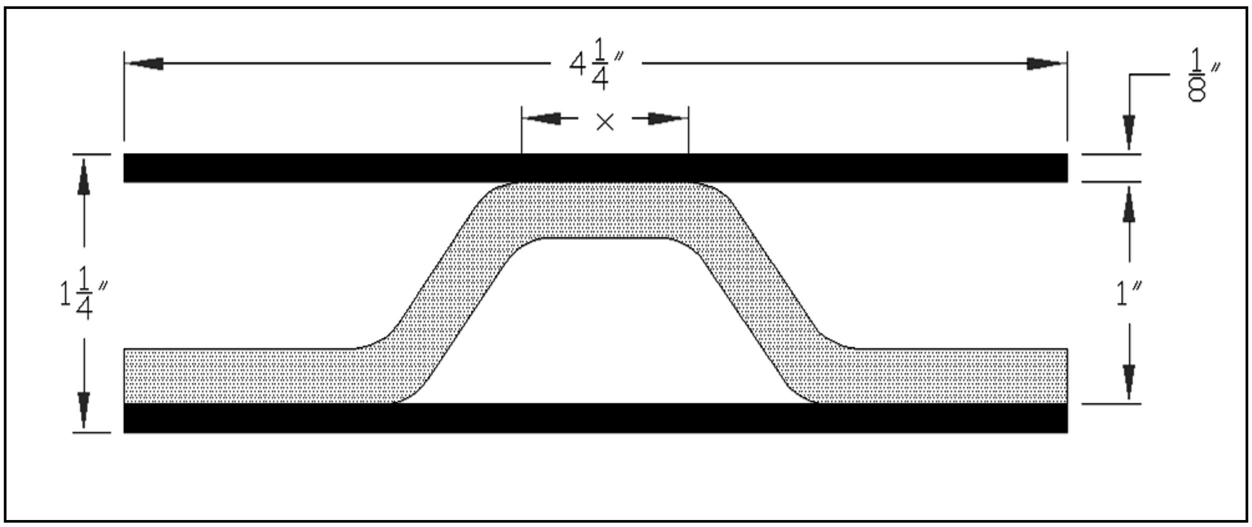

Figure 3.3.1: Schematic drawing of sandwich panel analyzed for shear area required to prevent failure at the interface between the core and face materials.

A uniform load was assumed on the panel resulting in a shear and moment that can be calculated using Equations 3.3.3 and 3.3.4.

$$V = \frac{w \cdot l}{2} \qquad \text{(Equation 3.3.3)}$$

$$M = \frac{w \cdot l^2}{8} \qquad \text{(Equation 3.3.4)}$$

w = Uniform load (lb/in)

l = Span length (in)

M = Maximum moment at mid-span (lb-in)

Substituting Equation 3.3.4 into Equation 3.1.1, we can solve for the uniform load, w, as shown in Equation 3.3.5. The depth, y, in Equation 3.1.1 was replaced with the variable, c, the maximum distance from the neutral axis to the exterior of the sandwich panel face.

$$w = \frac{8 \cdot I \cdot \sigma_x}{c \cdot l^2} \qquad \text{(Equation 3.3.5)}$$

σ_x = Bending stress about the x-axis (psi)

c = Distance from the neutral axis to exterior of the faces (in)

Equation 3.3.5 was inserted into Equation 3.3.3 to determine Equation 3.3.6. Finally, Equations 3.3.2, 3.3.6, and 3.3.7 were inserted into Equation 3.3.1 and rearranged to solve for the rib width, x, shown in Equation 3.3.8.

$$V = \frac{4 \cdot I \cdot \sigma_x}{c \cdot l} \qquad \text{(Equation 3.3.6)}$$

$$Q = A_{ply} \cdot y \qquad \text{(Equation 3.3.7)}$$

$$x_{reqd} = \frac{4 \cdot Q \cdot \sigma_x}{c \cdot l \cdot \tau} \qquad \text{(Equation 3.3.8)}$$

A_{ply} = Cross-sectional area of the face ply (in^2)

y = Distance to the centroids of the face ply from the neutral axis (in)

MathCAD worksheet showing the actual calculations is presented in Appendix D. The MathCAD worksheet shows an easier to follow progression of the manipulations done to the equations discussed above. A shear stress of 522 psi was assumed based on the in-plane shear strength of OSB from an unconfirmed source. However, when this value was being confirmed after the manufacturing process, it was determined that this is not a conservative value. A more accurate shear stress that should have been assumed was 300 psi (U.S. Department of Agriculture, Forest Service 1999). The required width of the shear area was determined to be 0.71 inches using Equation 3.3.8. The final design has built in safety factors to ensure failure at this interface will not occur from the neglected shear area from the transverse ribs. The mold was designed to have a shear area width of 0.75 inches for the longitudinal core ribs. However, using the more correct value of shear stress for OSB of 300 psi (U.S. Department of Agriculture, Forest Service 1999), the required width of the shear area is 1.24 inches.

Analysis of the interface between core and the face plies was conducted for ONP and MDF face plies. After fabrication of the mold, an analysis was conducted to determine the effect of using wood-strand face plies and cores instead of the assumed MDF face plies and ONP core. The assumed bending stress was changed to 4500 psi, which is the tensile strength of the wood-strand plies. A correct value for shear strength of OSB (300 psi as mentioned previously) was assumed as well to perform an accurate analysis of the mold. Based on the same procedure described above, a required rib width for the current geometry was determined to be 1.6 inches. The safety factor placed on the design by not including the transverse rib areas will not be sufficient to withstand the shear demand placed on the interface between the core and face plies. Flexural specimens are expected to fail due to transverse shear at the interface between the core and face plies. Therefore, for future manufacturing of sandwich cores, it is recommended that the mold design be changed to ensure a rib width of over 1.6 inch.

3.4 Core Failure Design

3.4.1 Core Crushing Design:

The following analysis is for designing the failure method of the core geometry through application of a load perpendicular to the sandwich panel. This analysis of the core geometry was conducted using theoretical analysis techniques suggested by Hunt and Winandy (2003) to determine expected failure of the core. A point load is applied at the center line of a single cross section of the core's 3-dimensional shape. Figure 3.4.1(Hunt, Harper, and Friedrich 2004) details half of a single cross section. Equation 3.4.1 (Hunt and Winandy 2003) is used to determine the crushing load, P_{crc}.

$$P_{crc} = \sigma_{crc} \cdot t_r \cdot S \qquad \text{(Equation 3.4.1)}$$

P_{crc} = Critical crushing load applied parallel to core wall (lb)

σ_{crc} = Critical crushing stress (psi)

t_r = Rib wall thickness (in)

S = Span distance between transverse axis supports (in)

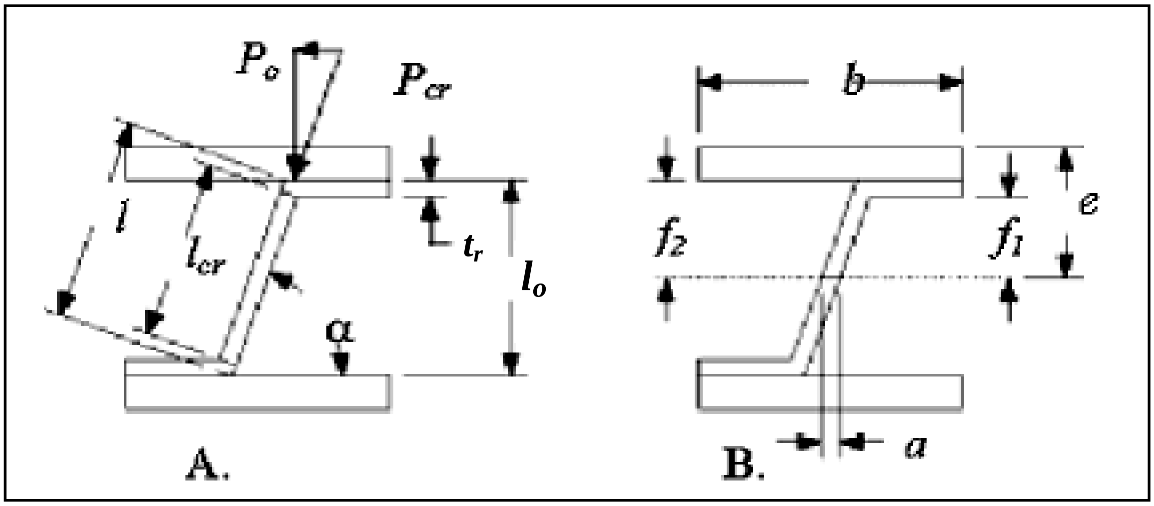

Figure 3.4.1: A) Geometry considerations for determining normal load, Po, per rib unit Depth for both compression and buckling failure mechanisms; B) variables used to describe geometry, for shear stress (Hunt and Winandy 2003).

The component in the vertical direction of P_{crc} is determined from Equation 3.4.2, P_o. The ultimate load per rib for crushing, P_{ultc}, is determined by Equation 3.4.3.

$$P_o = P_{crc} \cdot \cos(90\deg - \alpha) \qquad \text{(Equation 3.4.2)}$$

$$P_{ultc} = 2 \cdot P_o \qquad \text{(Equation 3.4.3)}$$

P_o = Critical crushing load applied perpendicular to the panel (lb)

α = Angle of rib wall (degrees)

P_{ultc} = Ultimate crushing load per rib (lb)

A crushing stress for the core, σ_{crc}, was assumed to be 2000 psi. This assumption is based on recommendations from Hunt and Winandy (2003); the tensile strength is assumed to be equivalent to the compression strength. The rib wall thickness, t_r, was assumed to be ¼ inch, the target wall thickness of the core layer. Figure 3.4.2 indicates graphically the dimension S, which was determined to be 2¼ inch. It was assumed that the ribs in the transverse direction are sufficient to prevent buckling at those locations.

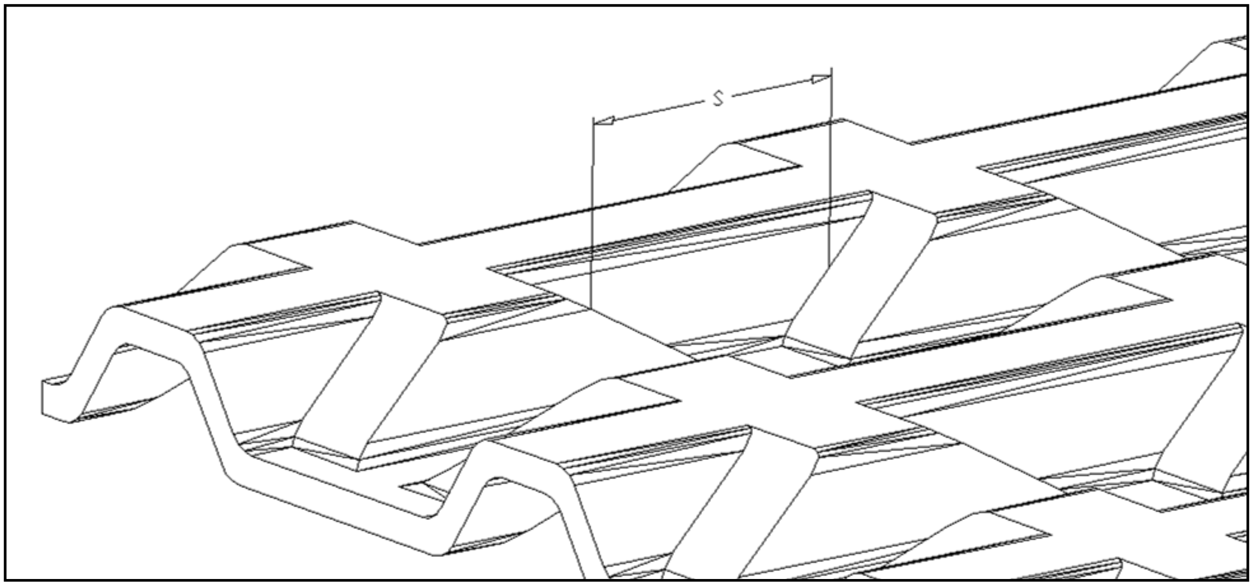

Figure 3.4.2: Above shows the measurement used for the span distance between transverse axis supports.

Finite Element Analysis (FEA) conducted of corrugated sandwich panel cores by Hunt (2004) indicates that a rib angle close to 50^o produces the stiffest panel for flexural analysis. 2D FEA of flatwise compression model indicated that a rib angle of 60^o produced the minimum deformations prior to failure (Hunt 2004). Based on these recommendations 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 was chosen as 56^o. Based on these geometric variables, an ultimate crushing load, P_{ultc}, was determined to be 1865 lb.

3.4.2 Core Buckling Design:

Buckling failure of the core is the other alternative to crushing of the core based on application of a load perpendicular to the sandwich panel. Buckling analysis of the core was performed to determine the maximum load prior to buckling failure, P_{crb}, using Equation 3.4.4 (Hunt and Winandy 2003).

$$P_{crb} = \frac{2 \cdot \pi^2 \cdot E \cdot I_r}{l_{cr}^2} \qquad \text{(Equation 3.4.4)}$$

P_{crb} = Critical Buckling load applied parallel to core wall (lb)

E = Modulus of Elasticity of core material (psi)

l_{cr} = Critical length of core wall (in)

I_r = Moment of Inertia of core wall (in^4)

The Modulus of Elasticity (MOE) was assumed to be 355000 psi, the average value of MOE from the transverse ONP tensile specimens. This assumption will yield a design that is conservative for wood-strands. The wood-strands, having a higher MOE in the transverse axis, would perform better, thus ensuring a crushing failure of a wood strand core. The moment of inertia, I_r, was determined by Equation 3.4.5 (Hunt and Winandy 2003), using the same values of t_r and S from the previous analysis.

$$I_r = \frac{S \cdot t_r^3}{12} \qquad \text{(Equation 3.4.5)}$$

S = Span between transverse axis supports (in)

t_r = Core wall thickness (in)

P_{ult} for buckling failure was determined to be 47,200 lbs. This analysis concludes that the designed core will fail in crushing far before it fails in buckling.

3.4.3 Sandwich Panel Flexural Design

The flexural design of the sandwich panel is a check to ensure that the sandwich panel design will fail in flexure prior to failure in the core discussed in the previous two sections. Equation 3.1.1 can be rearranged into Equation 3.4.6 (Hunt and Winandy 2003), which will determine the load at which failure in the faces of the sandwich panel will occur assuming simply supported 3-point loading scenario.

$$p_{ultf} = \frac{I_b \cdot \sigma_{cr}}{\left(\frac{L}{2}\right) \cdot y} \qquad \text{(Equation 3.4.6)}$$

P_{ultf} = Ultimate load applied to cause a flexural failure (lb)

I_b = Flexural moment of inertia (in4)

σ_{cr} = Ultimate compression/tension stress in faces (psi)

L = Span length of member (in)

y = Distance from the neutral axis to the exterior of the member (in)

The bending moment of inertia, I_b, was determined assuming simplified geometry shown in Figure 3.4.3. The calculated I_b from the assumed geometry was 0.55 in^4. The critical facing stress, σ_{cr}, is either the ultimate tension or compression strength of the faces. It was assumed to be the ultimate tensile strength of the wood-strands, 4500 psi, determined in the previous chapter. The span length, L, is assumed to be 18 inches long for these calculations; this was the to ensure flexural failure using the minimum span length for flexural testing of the sandwich panels set forth in ASTM D 7249 (2006). The ultimate load required to cause failure in the faces, P_{ultf}, was determined to be 440 lbs. These design equations for core crushing (Equation 3.4.3), core buckling (Equation 3.4.4) and sandwich panel flexural failure (Equation 3.4.6) (Hunt and Winandy 2003, Hunt, Harper and Friedrich 2004) determined that a flexural failure in the faces of the sandwich panel will occur prior to crushing or buckling of the core.

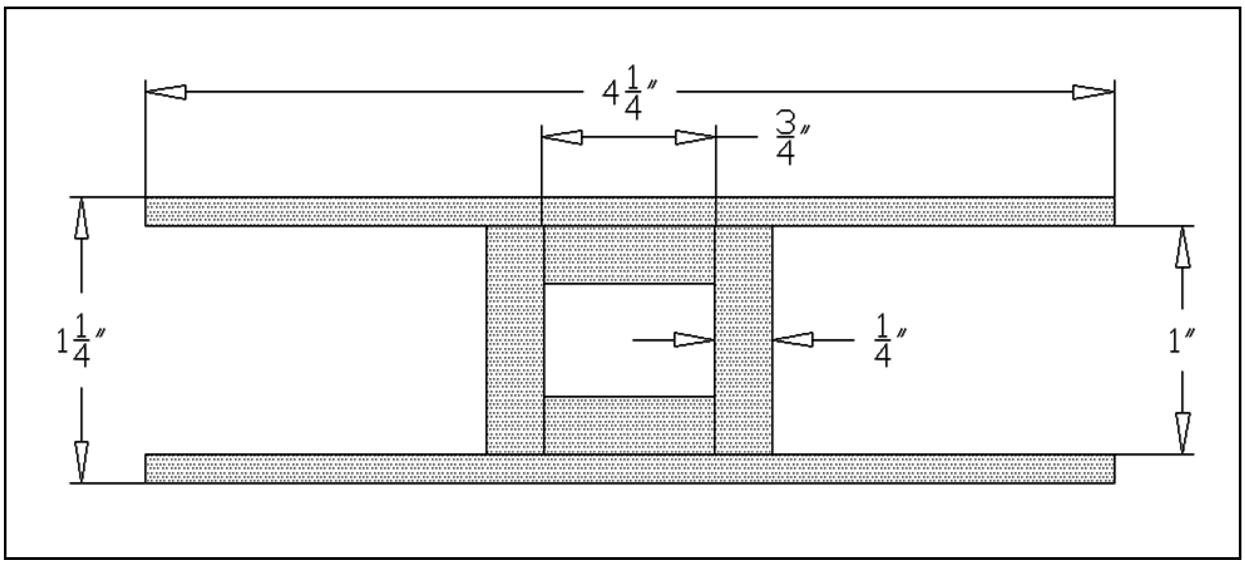

Figure 3.4.3: Above is the assumed simplified geometry based on Figure 3.3.2 for determination of I_b for the sandwich panel. I_b calculations assumed that the panel was made of the same material.

3.5 Final Mold Configuration:

The designed aluminum mold will produce a sandwich panel core of dimensions 31½ inches by 28 inches by 1.0 inch. The dimensioned design is detailed in Figure 3.5.1 a, b, and c. Figure 3.5.2 details the brackets that hold the aluminum mold in small press prior to manufacturing a sandwich panel core. The brackets allow a 1.0 inch thick plate to be held tightly to the top platen of the press. The mold was designed so that there is a 1.0 inch thick lip that extends out to the supporting brackets, shown in Figure 3.5.1 a. The top mold is held in rigid contact with the top platen, while the bottom mold is free to move to allow for alignment adjustments during the manufacturing process.

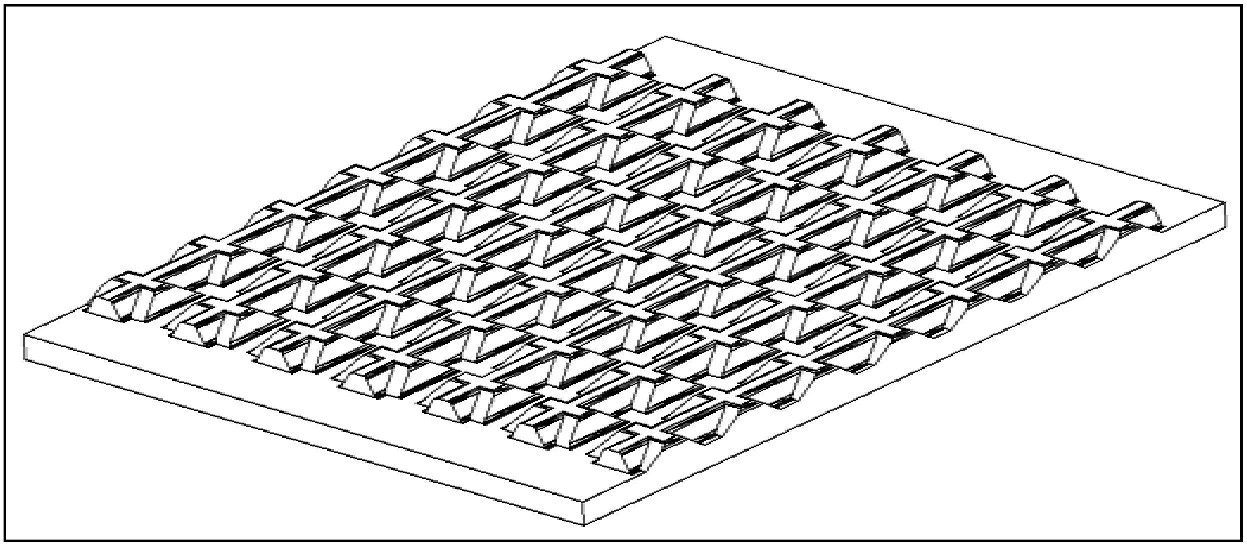

Figure 3.5.1 a: Isometric view of the aluminum mold for the small press.

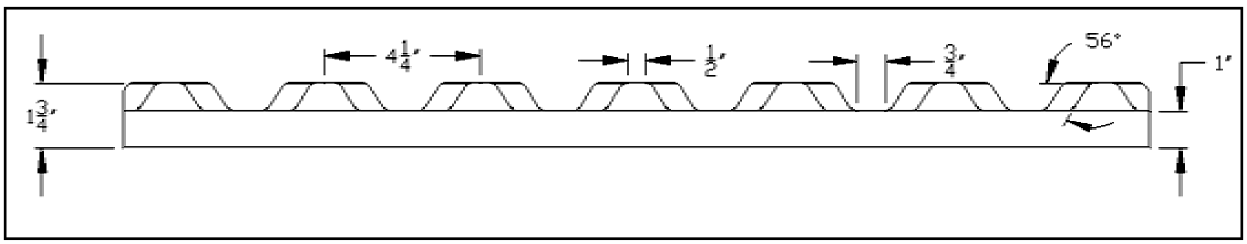

Figure 3.5.1 b: Front profile schematic of the final mold design.

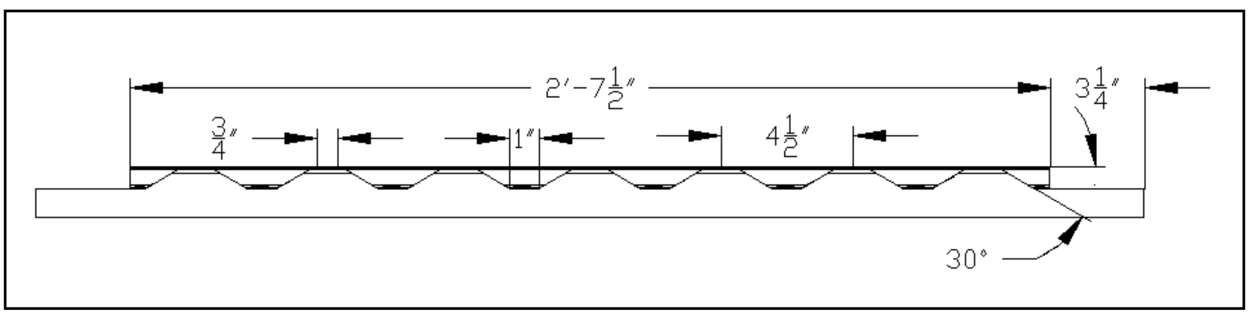

Figure 3.5.1 c: Side Profile schematic of the final mold design.

Figure 3.5.2: Above is the aluminum mold fastened into place in the small press by tightening the bolts in the bracket shown. The bottom mold is then aligned with the top mold prior to manufacturing.

3.6 Sensitivity Analysis of the Design Equations

In an attempt to understand the attributes that contribute the most to the desired failure modes and required shear area at the interfaces between core and the face plies, a sensitivity analysis of the design equations (Hunt & Winandy 2003) was developed. All of the analyses were performed using the properties of the Ponderosa Pine wood-strand plies. A Young's Modulus of 924 ksi was assumed based on wood-strand tensile tests discussed in the previous chapter. A tensile and compression stress of 4500 psi was assumed based on the tensile specimen data discussed in the previous chapter. The assumption is that the compression strength is approximately equal to the tensile strength. This is a reasonable first approximation (Hunt & Winandy 2003). A shear stress of 300 psi was assumed (U.S. Department of Agriculture, Forest Service 1999). Based on these analyses, certain elements of the core geometry can be modified to maximize the effectiveness of the core.

The crushing failure load analysis is detailed in Figure 3.6.1. Rib angle, α, and core wall thickness, t_r, were the only variables that had significant effect on the crushing failure load. The only other assumed variable for this analysis was the span length, S (Figure 3.4.2), between weak axis supports. This value was assumed to be the same as the final mold design for this study, 2 ¼ in. Alternatively, this analysis could be done assuming a unit length of the corrugated geometry. The span length between weak axis buckling supports was chosen to conform with the designed geometry of the core for this study. Analysis indicates that the core wall has the greatest impact on the crushing failure load, which matches conventional thinking. Interestingly, the rib angle has a greater impact on the crushing failure load when the core walls get thicker. Note the difference in slopes along the rib angle axis at a core wall thickness of 0 inches and 0.375 inches. Rib angle has more significant effect as the core wall thickness increases.

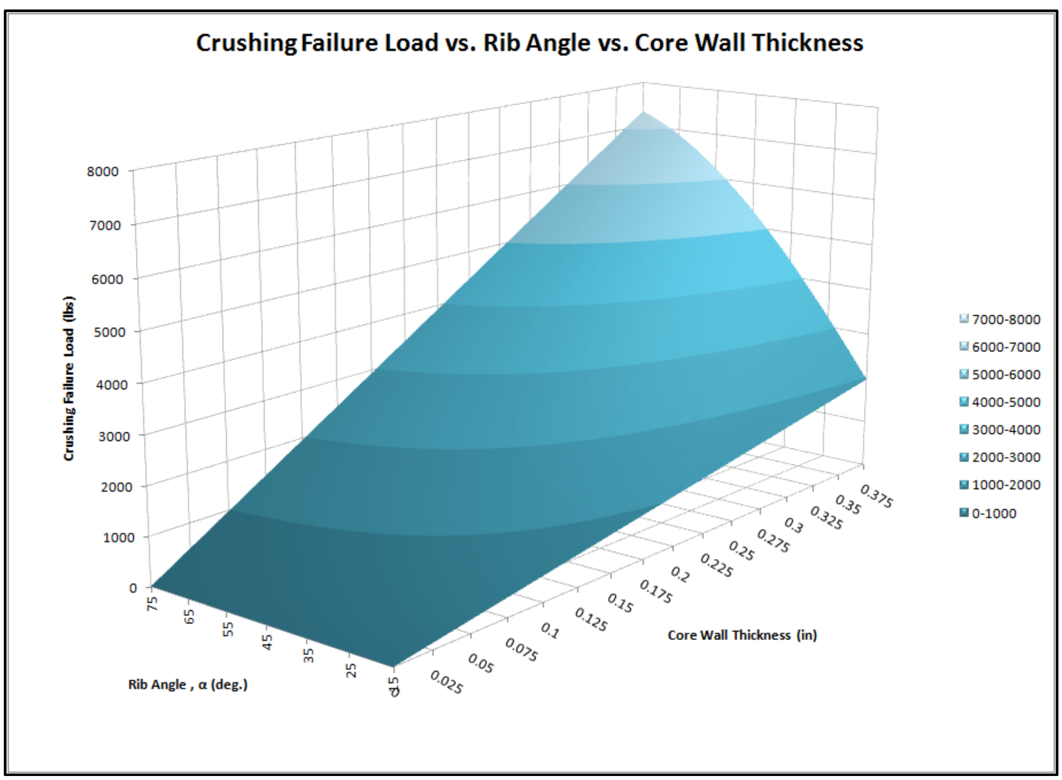

Figure 3.6.1: Sensitivity analysis of the failure crushing load. The analysis is between the two main contributors to the Crushing load: rib angle and core wall thickness.

The buckling analysis has more variables that affect the failure load than the crushing analysis. Figure 3.6.2 displays the variations of the buckling failure load based on core wall thickness and core depth, two most significant factors. A rib angle of 56^{o} was assumed and a span between weak axis supports was assumed to be 2¼ in. Figure 3.6.3 details core wall thickness and rib angle effect on the buckling failure load. Both figures were cut off at 8000 lbs so that a direct comparison can be made with Figure 3.6.1 above. Core depth has a significant effect on the buckling failure load when panel thickness is adequate to resist buckling; the core wall thickness has a greater impact on the buckling failure load, especially with thinner panels. Core depth is shown to play a significant role above a panel thickness of 1/8-inch.

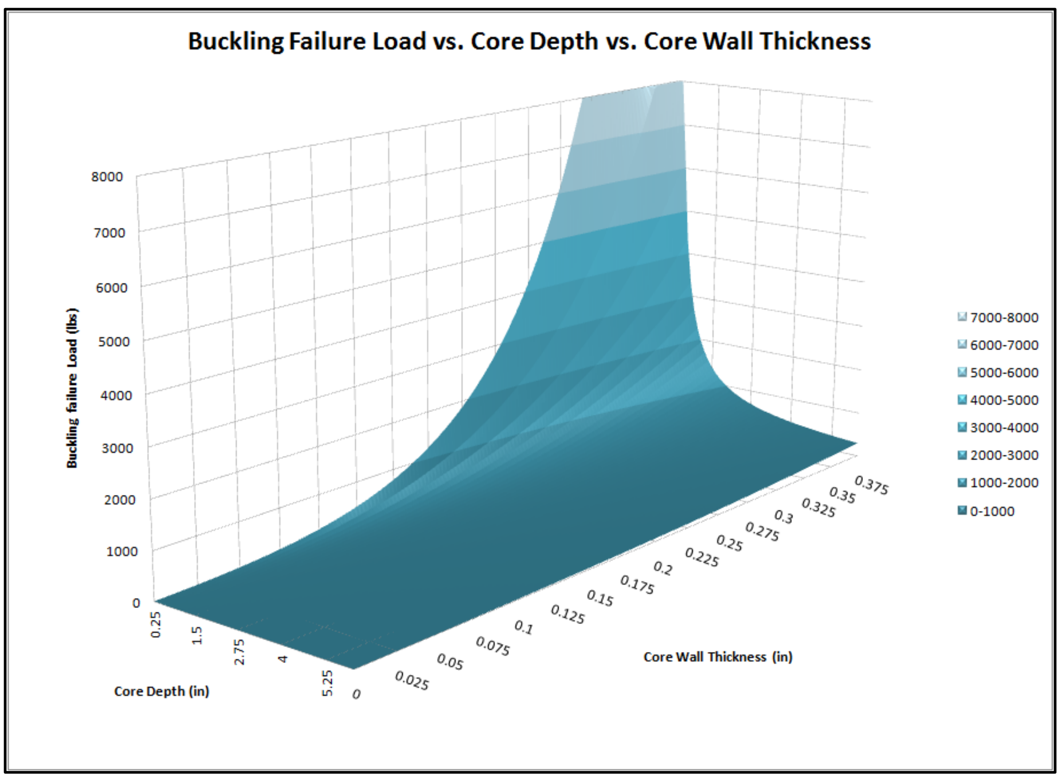

Figure 3.6.2: Sensitivity analysis of the buckling failure load due to core depth and core wall thickness. Scaled for direct comparison with Figure 3.6.1.

For direct comparison of the buckling failure load and the crushing failure load, an analysis was conducted under the same conditions as Figure 3.6.1 but looking at buckling failure. In the calculations for Figure 3.6.3, the core depth was assumed to be 1.0 inch and like, Figure 3.6.2, the span length between weak axis supports was assumed to be 2¼ in. The rib angle was determined to not have a significant effect in causing a buckling failure in a sandwich panel. Despite having extremely thin core walls, once the rib angle gets above 45^{o}, the core's failure mode will be governed by crushing as can be seen in Figure 3.6.1. For future studies, the rib angle should only be undertaken to insure that fracture of the wood-strands does not occur over a sharp change in the slope of the core geometry.

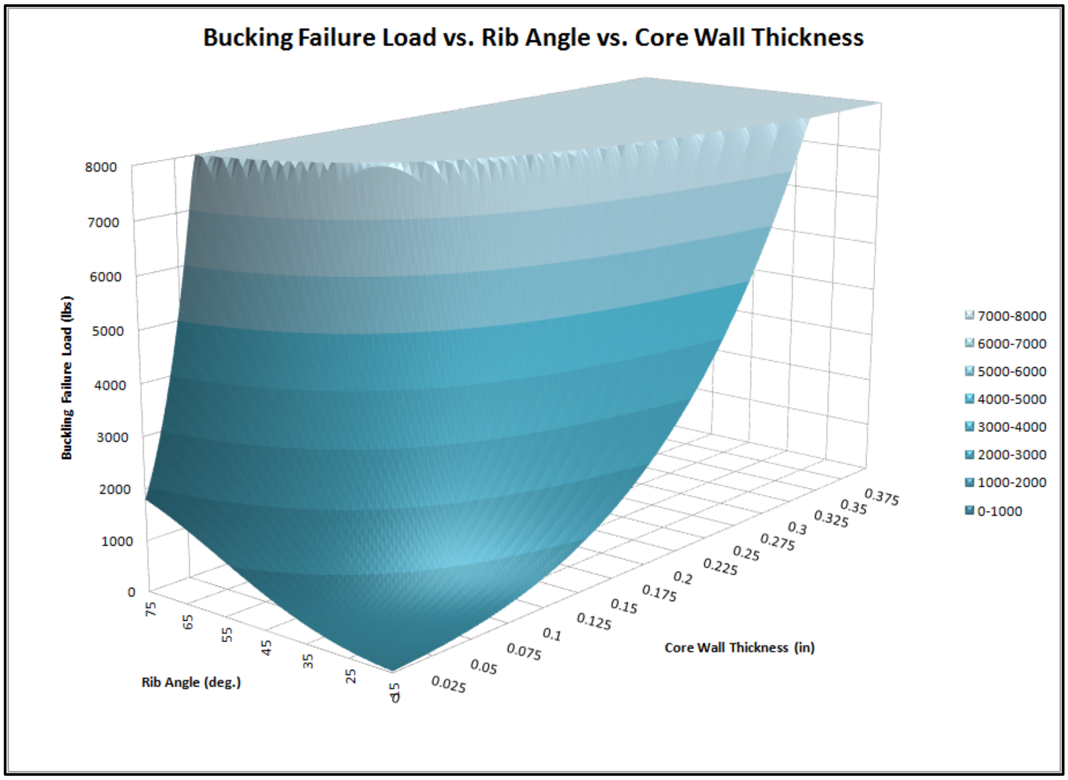

Figure 3.6.3: Sensitivity analysis of the buckling failure load based on rib angle and core wall thickness (assumed core depth of one-inch). This figure is scaled for direct comparison with Figure 3.6.1.

The flexural failure load sensitivity analysis produced two main contributors to the flexural failure load; span length and core depth. For this analysis, a repetitious element unit width of 4¼ inches was assumed along with a core wall thickness of ¼ inch. The repetitious element unit width for the core designed in this study is shown in Figure 3.3.1 for reference. Unlike the previous analyses where the failure load was maximized, this analysis is attempting to find a maximum load that still falls below that of the buckling analysis and crushing analysis so that flexural failure governs the failure mechanisms. From Figure 3.6.4, it can be seen that ensuring a flexural failure based on Hunt and Winandys' (2003) equations is not a difficult accomplishment. The only time to be concerned about not having a flexural failure based on Equation 3.4.6 is when a configuration produces a short span and a large core depth.

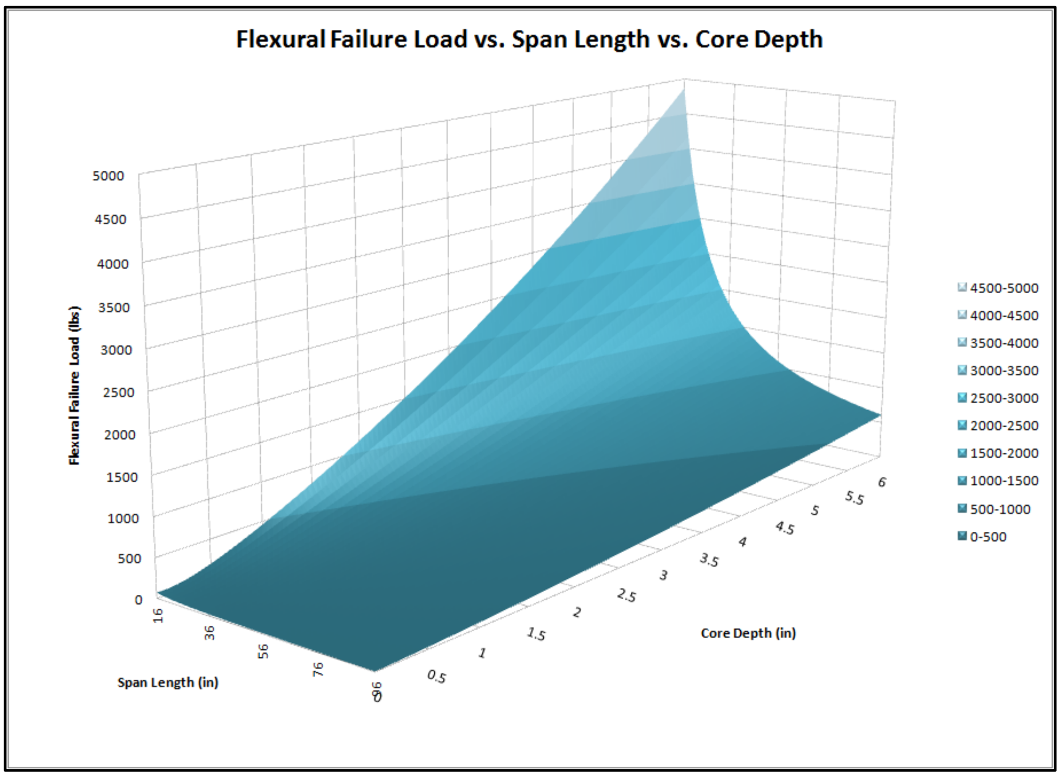

Figure 3.6.4: Sensitivity analysis of the flexural failure load. The analysis is between the flexural failure load's two main contributors: span length and core depth.

The most important variable of this type of sandwich construction is the required width of the gluing surface at the interface between the core and face plies denoted as $x_{req'd}$. The two variables analyzed in Figure 3.6.5 are span length and repetitious element unit width. For this analysis the only assumed variable besides the material properties discussed above was the core depth of 1.0 in. Since most residential construction deals with panel supports spaced at 16 in or 24 in on center (o.c.), it is important to reduce the repetitious element unit width as much as possible to increase the number of ribs within a panel and to reduce $x_{req'd}$. Note in Figure 3.6.5 how the combination of the shorter spans and longer repetitious element unit width magnify the required width of the shear area. A possibility for this type of sandwich panels could be specified more for longer spans such as 48 in oc. This would allow the design of the core to be more effective. Increase in span length exponentially increases the required shear width at the interface. Increasing the shear width at the interface will create a weaker panel in the transverse direction due to the fewer number of ribs that help support the panel face plies in that direction leading to localized failures between the ribs.

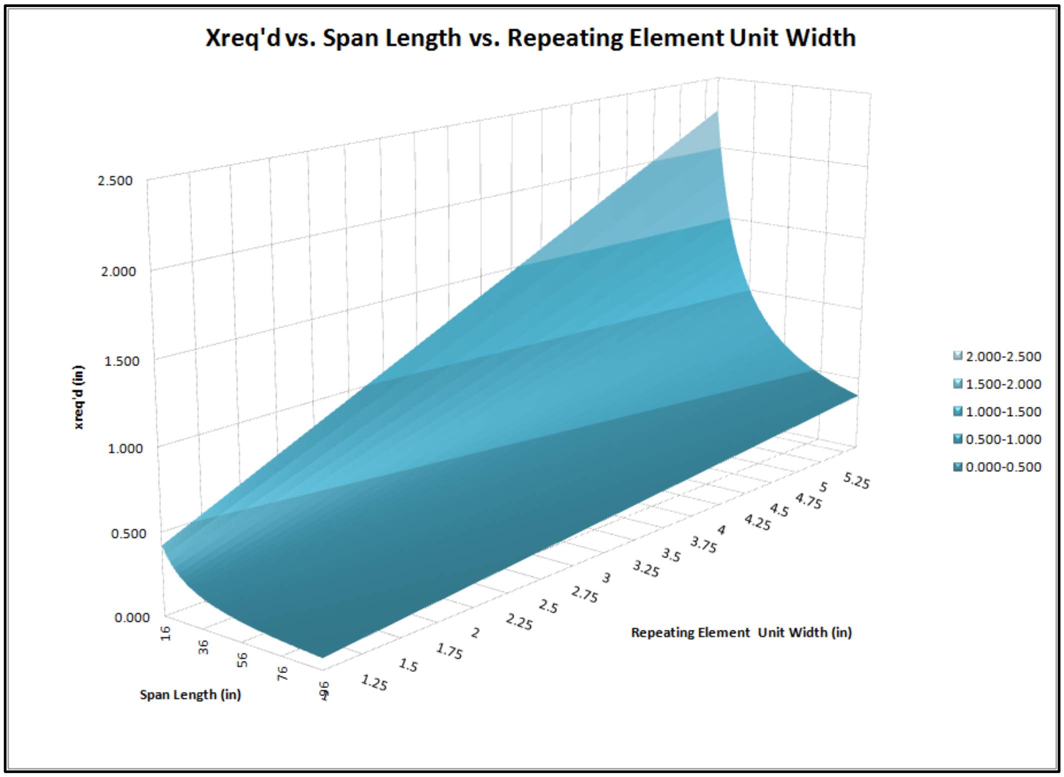

Figure 3.6.5: Sensitivity analysis of the required width of the gluing interface between the core and face plies. This analysis compares the span length with the repeating element width of the core geometry.

The other variable that affects the required width of the shear area at the interfaces of core and the face plies is the core depth. The last analysis compares the span length with the core depth to determine the effect the core depth has on the required width of the shear area. From Figure 3.6.6, the required shear area is hardly impacted by the core depth especially after a core depth of ½ inch compared to the effect that the repetitious element unit width of the core geometry has. For practical design purposes, the core depth should not be a significant concern for the required width of the shear area at the interfaces of the core and face plies. The core depth should be of concern only to achieve the desired allowable flexural load for the panel.

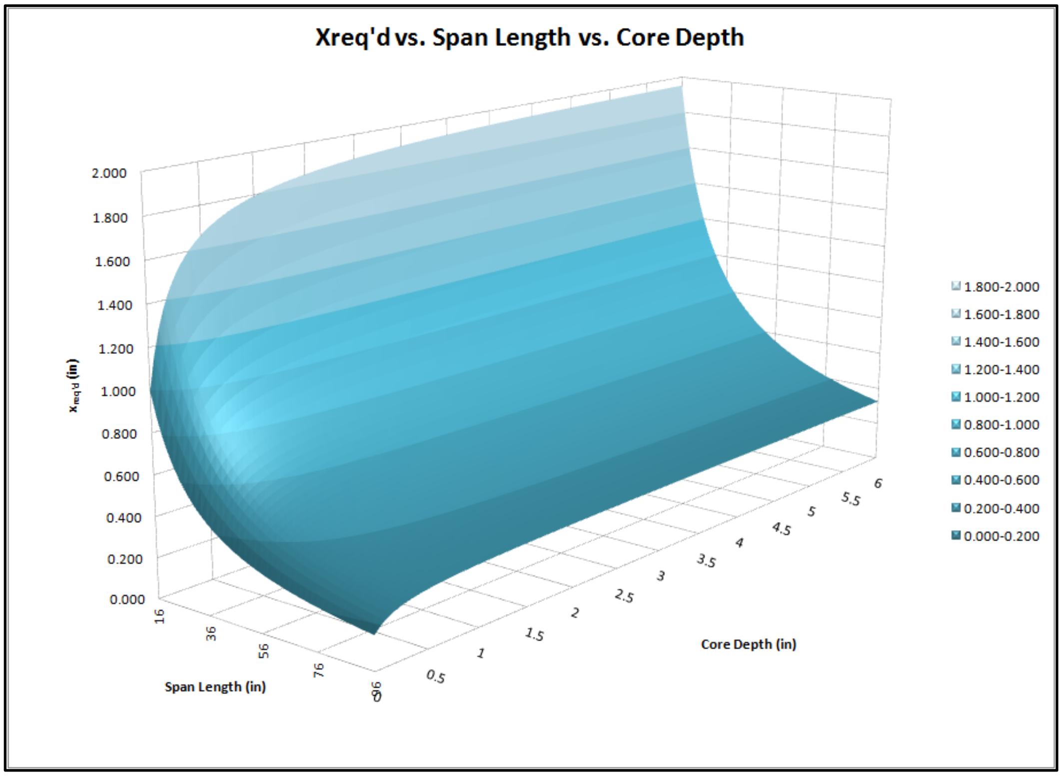

Figure 3.6.6: Sensitivity analysis of the required width of the shear area at the interfaces between the core and face plies. Note the insignificant effect the core depth has on the required width compared to the repetitious element unit width shown in Figure 3.6.5.

Based on this analysis, a procedure for designing a sandwich panel core's geometry can be developed. The span length, core depth, and face ply thickness are the first determinations to make. They will be determined by application use and the design load requirements to ensure a flexural failure using Equation 3.4.6. Several geometry and ply property assumptions will need to be made to give initial values for the core design. Once the flexural loading scenario has been developed and the depth of the panel set, analysis into the repeating element unit width, core wall thickness, and rib angle can be completed using an iterative process to reduce the shear width required and maximize the crushing and buckling failure loads of the core as necessary for the intended end use application.

3.7 Summary and Conclusion:

The core geometry was designed assuming an ONP core and MDF faces. These assumptions should provide a flexural failure of a sandwich panel using the designed materials rather than a shear failure at the interface of the core and face plies. The core walls are designed not to buckle or crush assuming a crushing stress equivalent to the ultimate tensile stress of ONP. These panels should be ideal for non-structural applications in which flexural behavior is primary design criterion.

While the design of the core geometry was based on ONP core and MDF face plies, it was necessary to understand the behavior of a wood-strand core if a stiffer ply, such as wood-strand ply, was used on the faces. Due to the increased stiffness and strength of the wood-strand plies discussed in the previous chapter, the assumed material properties that were used for the design of the mold are not conservative for a core consisting of wood-strands. Increased tensile strength of the exterior face plies allows for larger loads to be applied prior to failure. Consequently, greater shear stresses will develop at the interfaces between the core and face plies. Because of the inaccurate assumption regarding the shear capacity of the face plies, a shear failure is expected to occur during specimen testing. The unaccounted shear area from the transverse ribs could make up for a portion of the difference, but it is unlikely that it will prevent a shearing failure.

The sensitivity analysis provides the most useful information for future design of lightweight sandwich panel cores of this type. The analysis shows that once a span length and core depth are determined based on application and design loads, the most significant factor to determine is the required shear width. The best way to minimize the required shear width is to have it as small as possible for the repetitious element unit width. Decreasing the repetitious element unit width will allow more ribs per sandwich panel, thus increasing the stiffness of the sandwich panel. Core wall thickness and rib angle can then be adjusted to provide sufficient buckling and crushing strength while maintaining a flexural failure of the sandwich panel.

3.8 References:

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Chapter 4: Sandwich Panel Fabrication and Analysis

4.1 Introduction

Before implementation of either of the sandwich panels discussed herein, analysis of their capabilities and performance in structural and non-structural applications must be assessed. These sandwich panels must provide sufficient incentives for manufacturers to invest in these sandwich panels. Such incentives could be increased output of panels with reduced material costs and not necessarily increased structural properties. The analysis discussed herein was conducted so that structural properties of these panels could be compared with more conventional plywood or OSB panels for structural applications and particle board or medium density fiberboard (MDF) for non-structural applications.

4.2 Objectives

The goal of the final part of this study includes fabrication, evaluation of properties, and analysis of the finished sandwich panels made from old newsprint (ONP) and wood-strands in structural and non-structural applications. The primary objectives are to:

- Determine and implement a manufacturing process to produce finish sandwich panels made with wood-strand faces and both ONP and wood-strand cores.
- Determine the mechanical properties associated with both ONP and wood-strand sandwich panels.
- Analyze the benefits in reduced resin content, material furnish, as well as mechanical properties in comparison with OSB and other commercially viable products.
- Analyze the effectiveness of ONP and wood-strand sandwich panels in structural and non-structural applications.

4.2 Manufacturing Challenges

Despite having a manufacturing process determined for fabrication of 1/8 inch flat panels, new challenges presented themselves in fabrication of the ¼ inch thick cores. Initial trials with ONP suffered from significant delaminations during the pressing process. Through several iterations, it was determined that the problem was a forming issue related to the density of the ONP panel. As the ONP was being shredded, several layers of ONP stick together that formed a thicker, heavier strip. During the resin application and forming process two problems occurred. First, these heavy strips of ONP would cause low spots in the furnish mat making it appear to be a location of low density and therefore more ONP furnish was applied to that location making it denser than its surroundings. Secondly, because several layers of ONP were stuck together, the powder PF resin did not adhere to the interior layers of this thicker group of strips. Due to the denser location and lack of resin to bond the layers together, this produced significant delaminations within initial ONP cores. This problem was solved by individually separating all the ONP strips prior to the application of resin, so that the ONP strips were of consistent weight and each individual strip was capable of bonding with the resin.

ONP cores also required adjustments to the pressing schedule. The surface of the cores produced in initial trials suffered from surface roughness and portions of ONP strips not adhering entirely. This was caused by the pre-curing of resin prior to the press closing which led to poor bonding between the ONP strips. As the interface between the core and the faces is critical, it was imperative to have a smooth adhering surface on the core. The pressing schedule was adjusted to increase press closing rate to minimize resin pre-cure. Pressing schedules for both the ONP and wood-strand cores are located in Appendix C.

4.3 Methods and Materials

4.3.1 Manufacturing Process:

The manufacturing process for the cores was very similar to that of the flat mats produced for tensile specimens in Chapter 2. Calculations for furnish and resin content were based on forming a mat with dimensions of 36 inches by 26 inches by ¼ inch thick. Target resin content based on solid content for ONP and wood-strand cores was 10 and 8 percent respectively. The final dimensions of the cores were approximately 31½ inches by 26 inches by ¼ inch thick.

The wood-strand faces followed the same protocol as those of previous manufacturing processes. Calculations for mat furnish and resin content were based on dimensions of 36 inches by 27 inches by 1/4 inch. Wood-strands were dried to a moisture content (MC) of less than 4-5%. The press schedule was adjusted to allow for vapor pressure to escape prior to reaching the final thickness and during the degassing stages of the pressing schedule by cycling the press. See Appendix D for the pressing schedule for the wood-strand faces.

The faces were bonded to the core using a modified diisocyanate (MDI) adhesive. MDI reacts with ambient moisture to expand and cure. Both the faces and cores were placed in a conditioning room to bring their MC up so the adhesive would cure faster. Approximately 16.5 ounces of MDI was applied to each core along the interface surface. The panels were clamped and allowed to dry for 24 hours prior to cutting for test specimens. A light sanding of the bonding surfaces on the cores was conducted to improve the bonding penetrations of the MDI resin.

4.3.2 Test Specimens:

Prior to the fabrication of the sandwich panels, core measurements were taken in accordance with ASTM C 271 (2005) to determine core density. Three sandwich panels were made of ONP core and wood-strand faces, and three sandwich panels were made entirely of wood-strands. Test specimens were taken for beam flexure tests (ASTM D 7249 2006), core shear flexure tests (ASTM C 393 2006), and flatwise compression tests (ASTM C 365 2005).

The flexural specimens were tested on a 2 kip Instron test frame, Model 4466. The test apparatus is shown in Figure 4.3.1. Due to the limitations on the supports for the test frame, a span length S of 20½ inches was selected. Load was applied with a 4-point loading configuration at 1/3 span. The geometry of the sandwich panel core required the use of non-standard specimen geometry. Since the contours of the core geometry in the strong axis repeat every 4¼ inch, this width was chosen for all test specimens. The panel length remained consistent with ASTM D 7249 (2006) at 24 inch. Four different specimen configurations were tested. Five specimens were cut in each of the following configurations: strong axis ONP core, weak axis ONP core, strong axis wood-strand core, and weak axis wood-strand core. All specimens were oriented so that the peak of the strong axis rib was oriented upwards. Deflections were measured using a +/- 1.0 inch LVDT located at the mid-span of the testing specimens. Bending stiffness, D, was determined according to Equation 4.3.1. These values are utilized in comparison with OSB products in structural applications in Section 4.4.4.

$$D = \frac{P_{max} \cdot l^3}{28 \cdot \Delta}$$ (Equation 4.3.1)

Δ = Deflection at mid-span (in)

P_{max} = Maximum load prior to failure (lbs)

l = span length (in)

D = EI, MOE (psi) multiplied by moment of inertia (in^4)

A sandwich panel's bending stiffness is proportional to the geometry of the specimen tested. MOE is constant from panel to panel, but the moment of inertia can change based on the width of the specimen being tested. Since specimens of 4¼ inch width were tested, the bending stiffness values need to be normalized to a unit width of the panel. The bending stiffness values presented herein are reported as a bending stiffness per unit width (lb-in^2/in).

Core shear flexural tests were conducted on specimens measuring 10 inch by 4¼ inch. These specimens were test on a 30 kip Instron testing frame, Model 44R1137. Specimens were tested under a 3-point, mid-span loading configuration. The span length, S, was set at 8 inch to ensure a shear failure in the test specimens. Similar to the beam flexural tests, five specimens were cut in four different configurations: strong axis ONP core, weak axis ONP core, strong axis wood-strand core, weak axis wood-strand core. Due to irregularities caused by the geometry of the core being tested, specimens were attempted to be selected so that they all contained the same core geometry. However, due to the limited panels fabricated, not all specimens contained the exact geometry and therefore this could cause irregularities in the data. All the specimens were oriented so that the peak of the ribs was oriented upwards as shown in Figure 4.3.2. Equation 4.3.2 was utilized for determination of core shear rigidity, U (lb/in).

$$U = \frac{P_{max} \cdot L}{4 \cdot \left[\Delta - \frac{P_{max} \cdot L^3}{4 \cdot E \cdot \left(d^3 - c^3\right) \cdot b} \right]} \qquad \text{(Equation 4.3.2)}$$

Δ = max deflection at mid-span (in)

P_{max} = Max load (lbs)

L = Span length (in)

U = Shear rigidity (lbs)

d = Total depth (in)

c = Core depth (in)

b = Panel Width (in)

Knowing the shear rigidity of the panel, the core shear modulus, G (psi), was calculated using Equation 4.3.3.

$$G = \frac{4 \cdot c \cdot U}{(d + c)^2 \cdot b} \qquad \text{(Equation 4.3.3)}$$

G = Core shear modulus (psi)

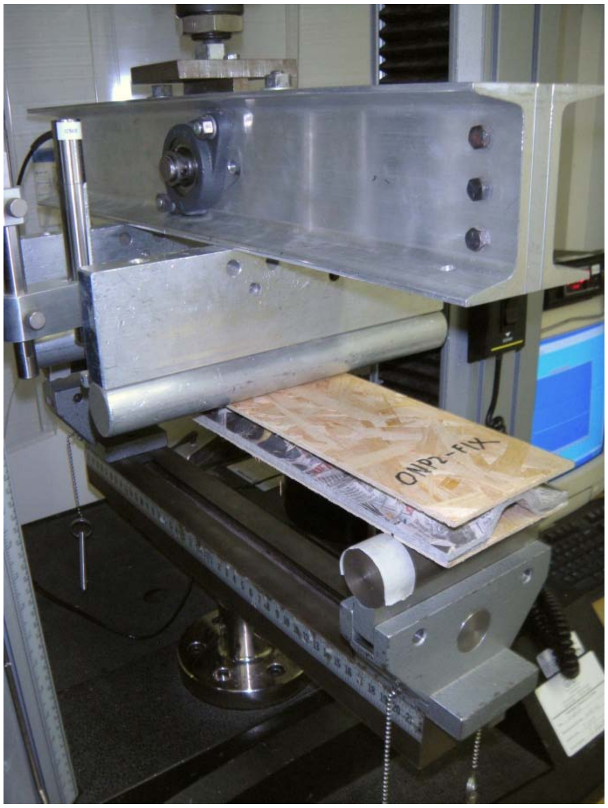

Figure 4.3.1: Flexural specimen testing apparatus. Note the orientation of the specimens' core geometry. All flexural specimens were tested using the same orientation.

Figure 4.3.2: Core shear flexural specimen testing apparatus. Note the orientation of the specimens' core geometry. All core shear flexural specimens were tested using the same orientation.

Flatwise compression tests were conducted on a 30 kip Instron testing frame, Model 44R1137. A specimen geometry of 4 ¼ inch by 4 ¼ inch was selected for each flatwise compression specimen. Five specimens of ONP core and five specimens of wood-strand core were tested. The standard head displacement rate of 0.02 in/min was changed to 0.05 in/min so that specimens failed closer to the 3-6 minute window of failure. The testing apparatus was setup as shown in Figure 4.3.3. All flatwise compression specimens were tested oriented so that the peaks of the ribs in both directions were positioned on the top of the specimen as seen in Figure 4.3.3. Flat wise compressive strength and compression modulus were calculated using the following equations:

$$\sigma = \frac{P_{max}}{A} \quad \text{(Equation 4.3.4)}$$

$$E_c = \frac{S \cdot t}{A} \quad \text{(Equation 4.3.5)}$$

Figure 4.3.3: Details the testing apparatus for the flatwise compression specimens. Note the peak of the core ribs oriented upwards. All flatwise compression specimens were tested under this same orientation.

4.4 Results and Discussion

4.4.1 Flexure Tests:

The wood-strand flexural specimens in the longitudinal axis failed with a flexural failure at the bottom edge of the core after delamination along the interface between the core and bottom face ply as seen in Figure 4.4.1. Shear failure at the interface was expected as it was realized that bonding area between the outer plies and the core was not adequate. The transverse axis specimens for both ONP and wood-strand cores failed due to a local compression in the top face of the panels as seen in Figure 4.4.2. This local failure could be due to the location of the loading heads in relation to the core geometry. The longitudinal axis ONP specimens failed due to transverse shear within the core just a few layers from the interface between the core and the bottom face as seen in Figures 4.4.3 and 4.4.4. MOR, bending stiffness (D), and specimen densities are tabulated in Table 4.4.1.

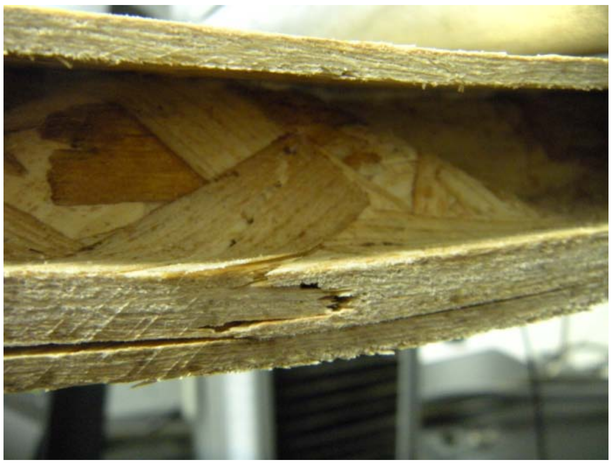

Figure 4.4.1: Above is a flexural failure located in the bottom region of the core as well as failure along the bottom interface between the core and face ply for a wood-strand specimen tested in the longitudinal axis.

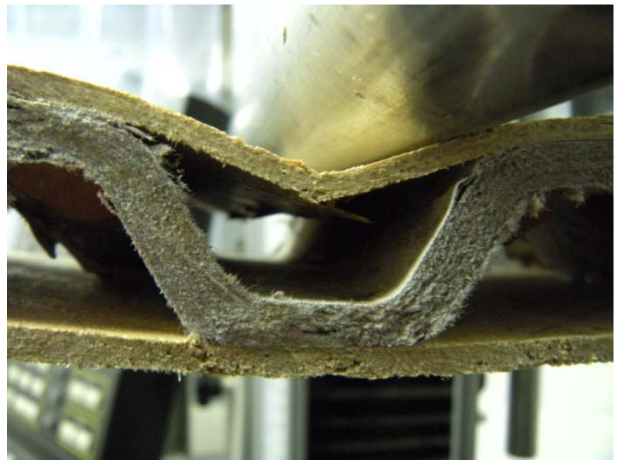

Figure 4.4.2: Above is a local failure in the top face of an ONP flexural specimen tested in the transverse axis.

Figure 4.4.3: Above is a transverse shear failure occurring a few layers of ONP within the core just above the bottom face.

Figure 4.4.4: To the right, a detailed view of the internal bond within the ONP failing. This is not a failure of the core to face interface.

4.4.2 Core Shear Flexure Tests:

Strong axis wood-strand core shear flexural specimens failed as intended at the interface between the core and faces. Failure generally occurred at the interface on the bottom of the test specimen. Weak axis wood-strand specimens failed either by delaminations at the bottom interface near the supports or by crushing of the core near the loading head or supports depending on the orientation of the core geometry. Both strong and weak axis ONP panels failed near the interface at the bottom of the specimens. Figures 4.4.5a-d detail typical failure modes in four specimens. Sandwich panel properties obtained are summarized in Table 4.4.1.

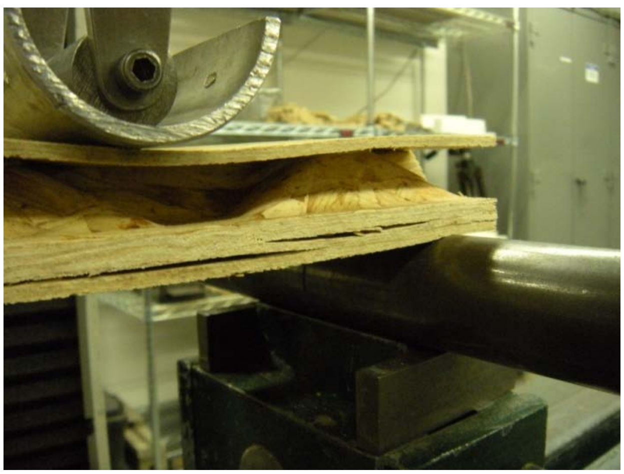

Figure 4.4.5 a: Above is a typical shear failure along the bottom interface between the core and face for strong axis wood-strand core shear specimens.

Figure 4.4.5 b: Above is a typical weak axis wood-strand failure for these core shear specimens.

Figure 4.4.5 c: Above is a typical shear failure of a strong axis ONP core shear flexural specimen.

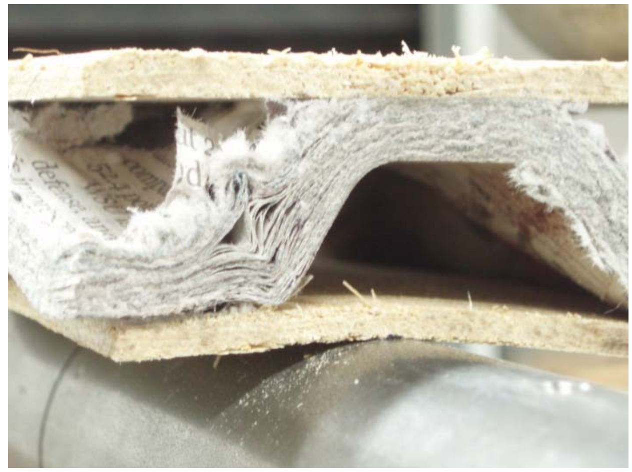

Figure 4.4.5 d: Above is a typical weak axis ONP failure for the core shear flexural specimens.

4.4.3 Flatwise Compression Tests:

Flatwise compression specimens for both ONP and wood-strand cores failed by delamination at the bottom interface between the core and face. After the delaminations occurred, continual compression would cause a flexural failure in the top of the core as seen in Figure 4.4.6. The wood strand core specimens had a mean compression strength of 61.6 psi. The ONP core specimens had a mean compression strength of 27.3 psi. Paneltecs' ALP series, half inch Kraft honeycomb cores compression strength for a one inch thick specimen is 32 psi (APA The Engineered Wood Association 2005). The ONP panels are comparable to this product and the wood-strand cores are approximately double. Table 4.4.1 details the rest of the properties determined by specimen testing.

Figure 4.4.6: Above is the typical failure of the flatwise compression specimens. Failure and the interface between the core and bottom face occurs first, followed by flexural failure in the rib.

Table 4.4.1: Summary of Wood-Strand (WS) and ONP Core Sandwich Panel Properties

			Max Flexural Load (lbs)	Max Flexural Deflection (in)	Bending Stiffness (lb-in^2/in)	Panel Shear Rigidity (lb)	Core Shear Modulus (psi)	Comp. Strength (psi)	Comp. Modulus (psi)	Density (pcf)
WS Core	Long Axis	Mean	609	0.56	91200	5440	980	61	1240	19.5
		Std. Dev.	101	0.1	23200	2685	500	18	515	1.2
		%COV	16.6	24.9	25.4	49.3	50.6	29.9	41.6	5.9
	Trans Axis	Mean	157	0.51	30600	3200	575	---	---	19.2
		Std. Dev.	27	0.2	7150	775	140	---	---	0.2
		%COV	17.4	34.0	23.4	24.1	24.4	---	---	1.2
ONP Core	Long Axis	Mean	233	0.52	74400	2340	445	27	825	19.5
		Std. Dev.	23	0.1	16700	1300	250	11	225	1.0
		%COV	9.9	20.5	22.4	55.6	56.0	40.4	27.7	4.9
	Trans Axis	Mean	120	0.49	26800	1600	300	---	---	19.4
		Std. Dev.	22	0.1	4800	200	38	---	---	0.6
		%COV	18.5	18.0	17.9	12.7	12.5	---	---	3.0

4.4.4 Density vs. Properties Comparison:

Viability of these panels depends on comparison of their properties to commercial products. For manufacturers and consumers to buy these sandwich panels over plywood or OSB panels, there has to be a significant advantage in properties or economics. Figure 4.4.7 plots the bending stiffness (D or EI lb-in^2/in) of Plywood, OSB, wood-strand core sandwich panels, and ONP core sandwich panels. The 5-ply plywood panel properties were calculated using longitudinal and transverse MOE's of 920,000 psi and 300,000 psi respectively (APA The Engineered Wood Association 2005). Similarly, OSB properties were calculated using longitudinal and transverse MOE's of 840,000 psi and 300,000 psi respectively (APA The Engineered Wood Association 2005). Calculations are located in Appendix E. The longitudinal bending stiffness of the wood-strand sandwich panels is 67% of the OSB's bending stiffness and 61% of the 5-ply plywood panel of equal thickness.

Alternatively, a comparison can be made based of the specific bending stiffness of the panels. The bending stiffness in Figure 4.4.7 was normalized based on the specific gravity of each panel. Figure 4.4.8 compares the specific bending stiffness for each of the panels discussed herein with that of OSB and plywood panels. The OSB and plywood panels were assumed to have a density of 40 pcf. Both the wood-strand panels' and the ONP panels' density was assumed to be 19.5 pcf based on the densities determined from the flexural specimens. The wood-strand sandwich panels' specific bending stiffness was 71% stiffer than the plywood and 88% stiffer than the OSB panel. The ONP sandwich panel had a 40% and 53% increase in stiffness over the plywood and OSB respectively. These results indicate that material usage (wood and resin) can be reduced by substituting thicker sandwich panels for currently used OSB panels in variety of applications.

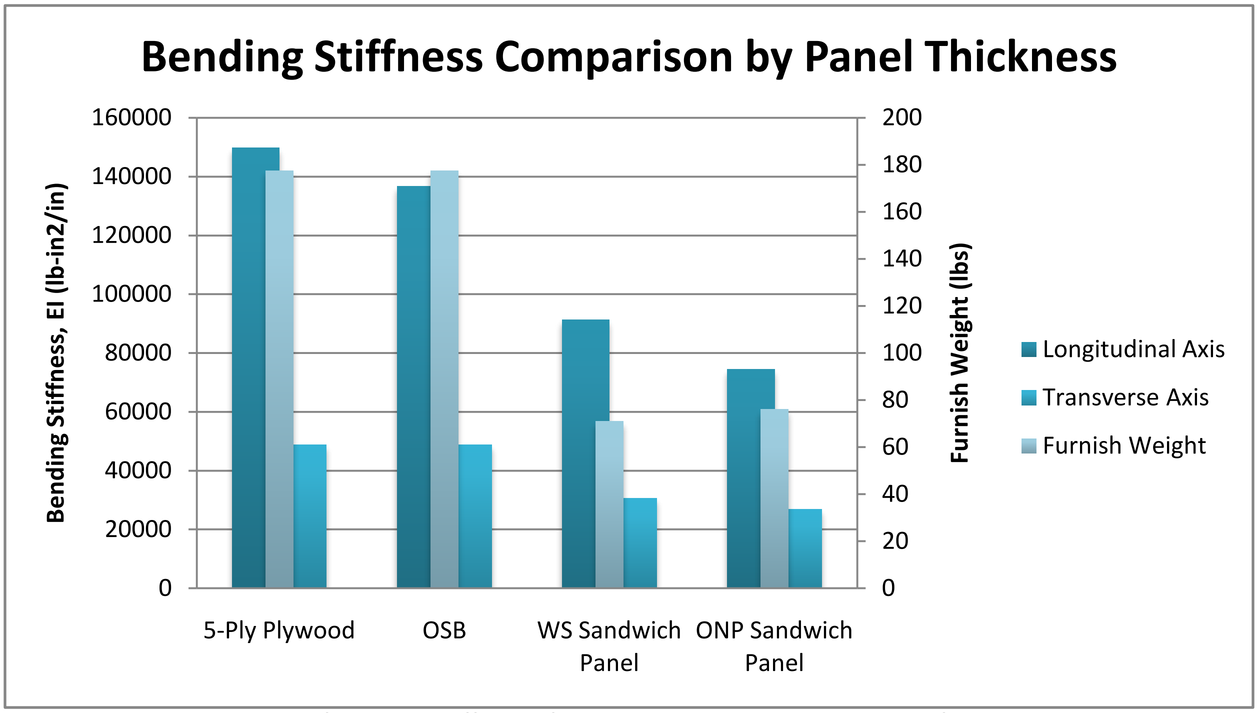

Figure 4.4.7: Comparison of bending stiffness of selected panels vs. their weight of their constituent materials. Bending stiffness values determined for 1¼ inch panels of 5-ply plywood and OSB.

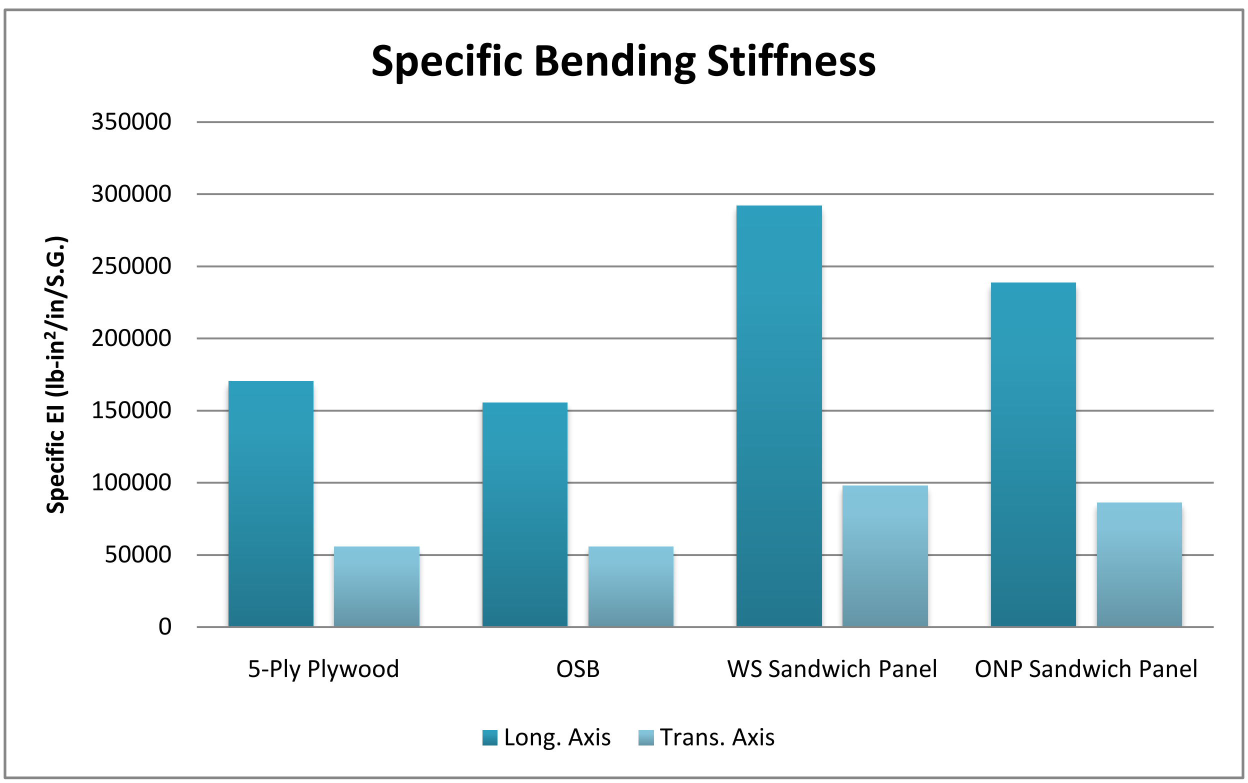

Figure 4.4.8: Specific bending stiffness comparison between plywood and OSB panels of 40 pcf density and the sandwich panels discussed within this study.

4.4.5 Material and Resin Reduction:

To determine the beneficial aspects of a lightweight sandwich panel with thin-wall core, calculations on efficiency of material usage were conducted. These calculations compared the sandwich panels from this study (wood-strand core and ONP core) with that of conventional OSB of equal thickness. It is assumed that the panel dimensions for these calculations are 4 ft by 8 ft by 1¼ inches thick and that the resin used for the OSB Panel is the same liquid PF resin used in this study. MC for the wood furnish for both the sandwich panel and OSB was assumed to be 5% and the MC for the ONP was assumed to be 12%. Appendix E contains several details and the assumptions for these calculations. The wood-strand sandwich panel in this study uses 40% of the wood-strand furnish and 40% of the resin used in the OSB panel of same dimensions. The ONP sandwich panel uses 41.7% of the OSB furnish and 49.9% of the OSB resin. These percentages are calculated based on weight of material. Another way to think about it is to think of making a 1¼ inch thick sandwich panel out of the same amount of material used to make a 9/16-inch thick OSB panel.

4.4.6 Flooring Application Case Study:

Analysis of the allowable applied loads was conducted using the APA Panel Design Specifications (APA The Engineered Wood Association 2008). OSB properties selected for comparison were chosen based on an OSB span rating of 48 inches o.c. A span rating of 48 inches o.c. is the typical rating for OSB panels of equivalent thickness to the sandwich panels discussed within this study (IBC 2006). A comparison between the maximum allowable uniform loads applied to each. Equation 4.4.1 (APA The Engineered Wood Association 2008) determines the maximum allowable load to be applied to each panel respectively for the panels to fail in flexure.

$$w_b = \frac{96 \cdot F_b \cdot S}{l^2} \qquad \text{(Equation 4.4.1)}$$

w_b = Allowable uniform load based on flexural strength (psf)

F_b = Bending strength (psi)

S = Section modulus (in3/ft)

l = Span length (in)

Equation 4.4.2 (APA The Engineered Wood Association 2008) determines the maximum allowable load that can be applied to each respective panel based off of deflection limits.

$$w_d = \frac{\Delta_{all}}{\Delta} \qquad \text{(Equation 4.4.2)}$$

w_d = uniform live load based on deflections (psf)

Δ_{all} = allowable deflection (in)

Δ = deflection (in)

Equations 4.4.3 and 4.4.4 (APA The Engineered Wood Association 2008) are used to determine the actual deflection of the panels. The uniform load in Equation 4.4.3 (APA The Engineered Wood Association 2008) is assumed to be a unit load for this analysis.

$$\Delta = \frac{w \cdot l_1^{\,4}}{2220 \cdot E \cdot I} \qquad \text{(Equation 4.4.3)}$$

$$l_1 = CS + SW \qquad \text{(Equation 4.4.4)}$$

w = Assumed unit uniform load (psf)

l_1 = clear span plus a support factor (in)

CS = clear span (in)

SW = Support factor (in)

It was assumed that the loading configuration for both panels was based on supports at 48 inches o.c. and a two span condition. Also, it was assumed that the longitudinal axis or strong axis of both panels were spanning across the supports. The support width was assumed to be 1½ inch wide for determination of l_1 using Equation 4.4.3. The allowable deflection was determined to be L/240 for live loads (LL) and L/360 for total loads (TL) (IBC 2006). Table 4.4.2 summarizes the results. The allowable applied load for both the OSB and wood-strand sandwich panel for them to fail in flexure is incredibly large. Deflection controlled both the OSB panels and the wood-strand (WS) sandwich panels. The table reports that both panels could support a LL of 40 psf assuming a DL of 20 psf. This loading configuration would produce a TL of 60 psf, which meets the TL deflection requirements set forth by IBC (2006). The wood-strand sandwich panels could support 91% of the load that the OSB panel could support based on deflections. More importantly, the wood-strand sandwich panels are capable of supporting typical residential loads in actual application as a structural flooring panel.

Table 4.4.2: Allowable Uniform Loads Based on APA Equations

Panel	w_b (psf)	TL: w_d (psf)	LL: w_d (psf)
OSB	2109	74	111
WS Sandwich Panel	1112	67	101

4.4.7 Bookshelf Case Study:

To analyze the potential of the ONP panel in a non-structural application, a bookshelf configuration was selected to determine the deflection differences between the ONP sandwich panel and a solid particle board of grade M-1 and a MDF panel of grade 120 (Composite Panel Association 2004). The bookshelf was assumed to be 36 inches long and the cross-section of the shelf was assumed to be 12 inch wide and 1¼ inch thick. The MOE for the particle board was assumed to be 250200 psi (Composite Panel Association 2004). The MOE for the MDF panel was assumed to be 203100 psi (Composite Panel Association 2004). A uniform load of 3 lb/in was assumed for the loading of the bookshelf. Table 4.4.5 details the calculated the mid-span deflection, y (in), for the assumed configuration.

Deflection was calculated at the center of the span using Equation 4.4.5. The deflection of both the wood-strand and ONP core sandwich panel are less than the commercially viable particle board and MDF panels. There are no known published deflection requirements for bookshelves; however, compared with IBC 2006's deflection limits for flooring, L/360, the ONP sandwich panel would provide sufficient stiffness for a bookshelf application. This type of application would certainly be a viable application for the ONP core sandwich panel due to its increased bending stiffness over commercially viable alternatives like particle board and MDF.

$$y = \frac{5 \cdot q \cdot l^4}{384 \cdot E \cdot I} \qquad \text{(Equation 4.4.5)}$$

y = Deflection at mid-span (in)

q = Uniform load (lb/in)

E = MOE of the material (psi)

I = Moment of inertia of the cross-section (in^4)

Table 4.4.3: Deflection Results for Bookshelf Case Study

Panel	Bending Stiffness ($lb\text{-}in^2$)	Deflection (in)	Deflection Criteria
Particle Board (M-3)	488672	0.134	L/286
MDF (120)	396680	0.165	L/218
WS Sandwich Panel	1095000	0.060	L/600
ONP Sandwich Panel	893380	0.073	L/493

4.5 Summary and Conclusion

Despite the mold being designed incorrectly to cause flexural failures in the tested specimens, the wood-strand sandwich panels exhibited sufficient structural properties to be viable in residential flooring applications. The wood-strand sandwich panel exhibits 88% increase of the specific bending stiffness of a solid OSB panel. The greater efficiency of the material usage with limited reduction in properties validates a potential application of sandwich panels of similar design for structural and non-structural applications. The ONP core sandwich panels were not as effective concerning structural properties as the wood-strand core sandwich panels; however, they still would be superior then current products for non-structural applications as described above with the bookshelf case study.

The limiting condition for the sandwich panels discussed herein is the deflection of the panels. Deflection control must be a primary goal of further investigation into these sandwich panels. Based on the APA panel design equations, the wood-strand sandwich panels are sufficient for supporting typical flooring loads in residential structures. Redesign of the core using information presented can be utilized for improved mold designed. Once delamination along the adhesion surface is prevented, the panel bending stiffness will be increased and therefore, deflections will decrease.

4.6 References:

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Chapter 5: Project Summary and Conclusion

The successful implementation of products using small-diameter timber and recycled newsprint requires that the structural properties of such materials be comparable to products that are already commercially viable. With growing environmental concerns and increasing competition, any future development of product and process should strive to reduce material consumption, minimize emissions, and consume less energy. The structural sandwich panels discussed in this study are an attempt to develop products that reduce the usage of fiber and resin while utilizing low value small-diameter timber and recycled newsprint.

Production of wood-strand sandwich panels using the mold design in this study can create panels with 40% of the materials required to create a solid panel of same thickness. This will also significantly reduce the petroleum-based resin consumption which accounts for over 25% of the production costs. These panels achieve significantly greater stiffness values than solid OSB panels using the same amount of constituent materials due to the 88% increase in specific bending stiffness. Not only does this sandwich panel process increase the efficiency of material usage in terms of structural properties, but it also can be made using under-valued materials such as small-diameter timber and recycled newsprint.

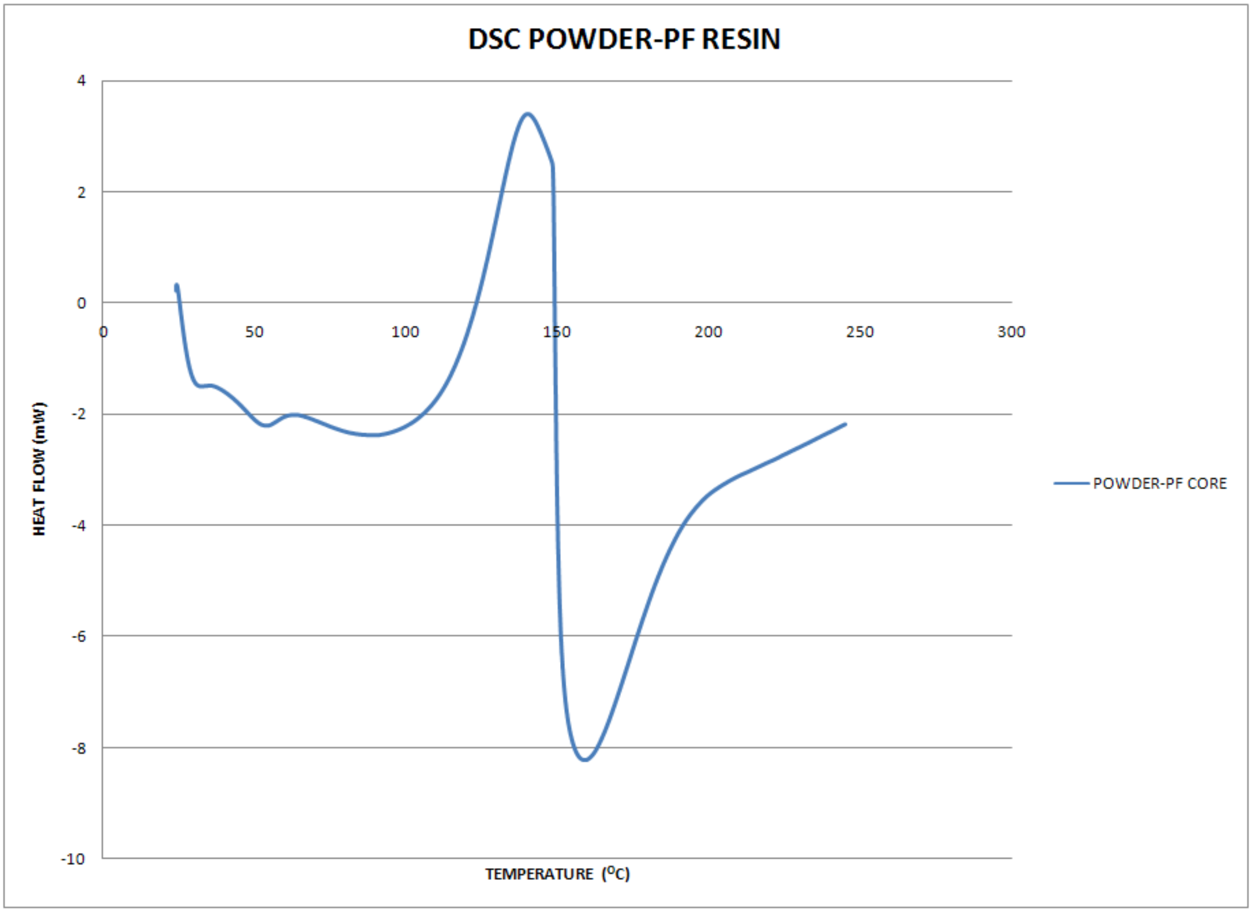
The recycled newsprint cores investigated in this study produce reasonable properties for a recycled material. The recycled newsprint does not have the structural properties with the manufacturing process discussed within this study to produce structural panels for light timber-framed construction. However, these panels can be used for non-structural use in applications such as shelving units, doors, and furniture. The bookshelf case study determined that the ONP sandwich panels are stiffer (by 83% for particle board, by over 125% for MDF) than commercially viable products like particleboard and MDF.

Despite the viability of the panels investigated in this study, improvements can be made on the core geometry analyzed. A design procedure for hot-pressing lignocellulosic-based three dimensional cores has been developed to achieve the desired failure modes for the corresponding lightweight sandwich panel. The span length and core depth of future designs will be governed by application and design loads for a flexural failure. Achieving the required width of the transverse shear area at the interfaces between the core and face plies is the most important factor to determine. In an attempt to achieve a width capable of allowing the sandwich panel to fail in flexure rather than shear at the interfaces, the most significant property to reduce is the repetitious geometry unit width of the core. Decreasing the repetitious geometry unit width will increase the number of corrugated ribs to divide the required shear area between and therefore decrease the required shear area width per rib. With an increased number of ribs within a panel, the bending stiffness will be increased as well. The limiting factor on the repetitious geometry unit width of the core will be the formability of the wood-strands or other constituent material under investigation. Core crushing will almost always govern the compression of the core, unless the core depth gets significantly large and the core walls are significantly thin. Buckling only becomes a concern with deep cores and thin core walls. The rib angle has minimal effect on the structural properties besides that it contributes to the repetitious element unit width.

This study is the basis for a larger work in determining all aspects of the structural design of lightweight sandwich panels with a thin-walled core discussed within this study. There are many steps between this investigation and commercial application. Several of the foreseen challenges or investigations that need to be undertaken prior to implementation in field applications are listed below.

- Successfully design and test specimens that fail in the face plies. These should be designed for a specific application such as structural flooring with joists spaced at 24 inches o.c.. A design load should be selected prior to fabrication of a mold or panels.
- An investigation into the formability limits of small-diameter timber wood-strands. This is a necessary investigation to determine the minimum limits on the repetitious element unit width of the core geometry. This type of investigation will determine the maximum rib angle that a wood-strand can be formed over without fracturing.
- To achieve increased performance using ONP would require further work in determining a manufacturing process to increase the internal bond between the ONP strips and investigation of its water absorption and thickness swell behavior this would require investigating alternate adhesives and their application systems.
- Analysis of connections for these panels needs to be investigated. Innovative fasteners are necessary to improve fastener holding properties, and innovative connection systems are required to have an effective interface between adjacent panels for load transfer.
- Finite element analysis to confirm the design of the mold for structural applications and designed failure criterion will be necessary especially since the core geometry is complex.
- Insulation properties of the panels have to be investigated to determine any potential advantages over conventional OSB panels.

Appendix A
DSC Graphs


DSC POWDER-PF RESIN
HEAT FLOW (mW)
TEMPERATURE (⁰C)
POWDER-PF CORE
4
2
0
-2
-4
-6
-8
-10
0
50
100
150
200
250
300

Appendix B

Furnish Weight Calculations

ONP ply furnish calculations:

Panel density ?	40	Lb/ft^{-3}				
Panel width ?	12	in.				
Panel length ?	12	in.				
Panel thickness ?	0.1875	in.				
Solids per panel	0.625	lb.	0.283	kg		
% surface ?	100	%				
Solids for surface	0.625	lb.	0.283	kg		
Surface resin content ?	10	%				
Surface resin solids weight	0.0625	lb.	0.028	kg		
Solids content of surface resin?	100	%				
Surface resin weight	0.063	lb.	0.028	kg	Blender	0.07 lb. 0.034 kg
Surface wood solids	0.5625	lb.	0.255	kg		
Surface wood m.c	13.4	%				
Surface wood weight	0.64	lb.	0.289	kg	Blender	0.70 lb. 0.318 kg

Wood-strand core calcs:

Panel density ?	40	$lb.ft^{-3}$		
Panel width ?	26	in.		
Panel length ?	38	in.		
Panel thickness ?	0.25	in.		
Solids per panel	5.7176	lb.	2.593	kg
% surface ?	100	%		
Solids for surface	5.7176	lb.	2.593	kg
Surface resin content ?	8	%		
Surface resin solids weight	0.4574	lb.	0.207	kg
Solids content of surface resin?	55.71	%		
Surface resin weight	0.821	lb.	0.372	kg
Surface wood solids	5.2602	lb.	2.386	kg
Surface wood m.c	5.5	%		
Surface wood weight	5.55	lb.	2.517	kg
Former Total surface weight	6.37	lb.	2.890	kg

Blender			
0.90	lb.	0.447	kg

Blender			
6.10	lb.	2.769	kg

Appendix C

Pressing Schedules

ONP Flat plies:

Proj. Ref.: 13x13 flat mat Date......: 09-09-2009 Time......: 10:44:54

Prod. Ref.: 380f Panel ID..: 1/8 File Name.: CV125.REG

Press ID..: WSU300 Mat Length: 13.0 in. Mat Width.: 13.0 in.

Density...: 40.00 lb/ft3 Thickness.: 0.125 in. Caul Thick: 0.188 in.

Segment	Control	Setpoint	Seg. Time (s)
1	Fastposn	-0.5 in/s	10
2	Position	50%	1
3	Position	.75 in.	20
4	Position	.125 in.	30
5	Position	.125 in.	210
6	Position	.135 in.	30
7	Fastposn	.5 in/s	10

Wood-Strand plies:

Proj. Ref.: Wood Std Face Date......: 10-16-2009 Time......: 12:43:11

Prod. Ref.: 380f Panel ID..: 1/8 File Name.: CVF125.REG

Press ID..: WSU300 Mat Length: 36.0 in. Mat Width.: 28.0 in.

Density...: 40.00 lb/ft3 Thickness.: 0.125 in. Caul Thick: 0.188 in.

Segment	Control	Setpoint	Seg. Time (s)
1	Fastposn	-0.5 in/s	10
2	Position	50%	1
3	Position	.75 in.	20
4	Position	.25 in.	20
5	Position	.25 in.	10
6	Position	.125 in.	10
7	Position	.13 in.	40
8	Position	.125 in.	10
9	Position	.125 in.	210
10	Position	.135 in.	40
11	Fastposn	10 in	20

ONP Core:

Proj. Ref.: NP Core Date......: 09-23-2009 Time......: 12:18:23

Prod. Ref.: 380f Panel ID..: 1/4 File Name.: CVCNP25.REG

Press ID..: WSU300 Mat Length: 31.5 in. Mat Width.: 26.0 in.

Density...: 40.00 lb/ft3 Thickness.: 0.250 in. Caul Thick: 3.250 in.

Segment	Control	Setpoint	Seg. Time (s)
1	Fastposn	-0.5 in/s	10
2	Position	50%	1
3	Position	.25 in.	10
4	Position	.25 in.	360
5	Position	.26 in.	40
6	Position	.28 in.	30
7	Position	.3 in.	30
8	Fastposn	.5 in/s	20

Wood-Strand core:

Proj. Ref.: WS Core Date......: 09-14-2009 Time......: 09:40:50

Prod. Ref.: 380f Panel ID..: 1/4 File Name.: CVCST25.REG

Press ID..: WSU300 Mat Length: 31.5 in. Mat Width.: 26.0 in.

Density...: 40.00 lb/ft3 Thickness.: 0.250 in. Caul Thick: 3.250 in.

Segment	Control	Setpoint	Seg. Time (s)
1	Fastposn	-0.5 in/s	10
2	Position	50%	1
3	Position	.75 in.	10
4	Position	.25 in.	30
5	Position	.25 in.	240
6	Position	.275 in.	40
7	Position	.3 in.	30
8	Position	.5 in.	30
9	Position	0.5 in/s	20

Appendix D

Mold Design Calculations

Calculations for required surface area between the core and faces of a sandwich panel. The total depth of the panel should be 1.25". The core thickness should be 1,0" and the two MDF faces are each .125" thick

$$\sigma_x = \frac{M \cdot c}{I} \qquad M = \frac{w \cdot l^2}{8}$$

$$\sigma_x = \frac{w \cdot l^2}{8} \cdot \frac{c}{I} \text{ solve}, w \rightarrow \frac{8 \cdot I \cdot \sigma_x}{c \cdot l^2}$$

$$V = \frac{w \cdot l}{2} \qquad V = \frac{8 \cdot I \cdot \sigma_x}{c \cdot l^2} \cdot \frac{l}{2} \rightarrow V = \frac{4 \cdot I \cdot \sigma_x}{c \cdot l}$$

Shear Flow:

$$q = \frac{V \cdot Q}{I}$$

$q = \tau \cdot x$ where τ is the shear stress of the outer ply and x is the width of the surface attached to the outer ply

$$q = \frac{4 \cdot I \cdot \sigma_x}{c \cdot l} \cdot \frac{Q}{I} \rightarrow q = \frac{4 \cdot Q \cdot \sigma_x}{c \cdot l}$$

$$Q = A_{ply} \cdot y$$

A_{ply} is the center to center distance between ridges multiplied by the thickness of the ply. y is the distance from the N.A. to the centroid of the outer ply.

$$Q := (4.25in \cdot .125in) \cdot .5625in \rightarrow 0.29882813 \cdot in^3$$

OSB in-plane shear stress: $\tau_{high} := 1929 \frac{lbf}{in^2}$ $\qquad \tau_{low} := 522 \frac{lbf}{in^2}$

OSB bending stress: $\sigma_{x\_high} := 4381 \frac{lbf}{in^2}$ $\qquad \sigma_{x\_low} := 2321 \frac{lbf}{in^2}$

MDF Bending Stress: $\sigma_x := 3480 \frac{lbf}{in^2}$

Mold Parameters:

c and l are used to calculate the maximum flexure stress.

$l := 18in \qquad c := 0.625in$

Required width of surface area:

$$x_{reqd} \cdot \tau = \frac{4 \cdot Q \cdot \sigma_x}{c \cdot l}$$

Worst case: σ_{xhigh} and τ_{low}

$$x_{reqd} := \frac{4 \cdot Q \cdot \sigma_x}{c \cdot l \cdot \tau_{low}} \rightarrow 0.7083 \cdot in$$

Mold Design: Core Failure vs Flexural Failure

$b := 2.125in$ $\quad l_{cr} := 0.8491in$ $\quad S := 2.25in$

$t := .125in$ $\quad L := 18in$ $\quad t_r := .25in$

$d := 1.25in$ $\quad l := 1.1839in$ $\quad \alpha := 56deg$

Crushing Load:

$\sigma_{crc} := 2000psi$

$P_{crc} := \sigma_{crc} \cdot t_r \cdot S$

$P_{crc} = 1125\,lbf$

$P_o := P_{crc} \cdot \cos(90deg - \alpha)$

$P_o = 932.667\,lbf$

$P := 2 \cdot P_o = 1865.335\,lbf$

Buckling Load:

$E := 355000psi$ $\quad I_r := \frac{S \cdot t_r^{3}}{12} = 0.003 \cdot in^4$

$$P_{crb} := \frac{2 \cdot \pi^2 \cdot E \cdot I_r}{l_{cr}^{2}} = 28474.867\,lbf$$

$P_o := P_{crb} \cdot \cos(90deg - \alpha) = 23606.735\,lbf$

$P := 2 \cdot P_o = 47213.47\,lbf$

Flexural Failure in the Faces:

$$I := 2\left[\frac{\left(4.25in \cdot .125in^3\right)}{12} + 4.25in \cdot .125in \cdot (.5625in)^2\right] + 2\left[\frac{.25in \cdot (1in)^3}{12}\right] + 2\left[\frac{.75in \cdot .25in^3}{12} + .75in \cdot .25in \cdot (.375in)^2\right]$$

$I = 0.55 \cdot in^4$ $\quad y := .625in$

$\sigma_{cr} := 4500psi$

$$P := \frac{\sigma_{cr} \cdot I}{\left(\frac{L}{2}\right) \cdot y}$$

$P = 440.299\,lbf$

Calculations for required surface area between the core and faces of a sandwich panel. The total depth of the panel should be 1.5". The core thickness should be 1" and the two wood-strand faces are each .125" thick

$$\sigma_x = \frac{M \cdot c}{I} \qquad M = \frac{w \cdot l^2}{8}$$

$$\sigma_x = \frac{w \cdot l^2}{8} \cdot \frac{c}{I} \text{ solve}, w \rightarrow \frac{8 \cdot I \cdot \sigma_x}{c \cdot l^2}$$

$$V = \frac{w \cdot l}{2} \qquad V = \frac{8 \cdot I \cdot \sigma_x}{c \cdot l^2} \cdot \frac{l}{2} \rightarrow V = \frac{4 \cdot I \cdot \sigma_x}{c \cdot l}$$

Shear Flow:

$$q = \frac{V \cdot Q}{I} \qquad q = \tau \cdot x$$

where τ is the shear stress of the outer ply and x is the width of the surface attached to the outer ply

$$q = \frac{4 \cdot I \cdot \sigma_x}{c \cdot l} \cdot \frac{Q}{I} \rightarrow q = \frac{4 \cdot Q \cdot \sigma_x}{c \cdot l}$$

$$Q = A_{ply} \cdot y$$

A_{ply} is the center to center distance between ridges multiplied by the thickness of the ply. y is the distance from the N.A. to the centroid of the outer ply.

$$Q := (4.25in \cdot .125in) \cdot .5625in \rightarrow 0.29882813 \cdot in^3$$

OSB in-plane shear stress: $\tau_{high} := 1929 \frac{lbf}{in^2}$ $\tau_{low} := 300 \frac{lbf}{in^2}$

OSB bending stress: $\sigma_{x\_high} := 4381 \frac{lbf}{in^2}$ $\sigma_{x\_low} := 2321 \frac{lbf}{in^2}$

MDF Bending Stress: $\sigma_x := 4500 \frac{lbf}{in^2}$

Mold Parameters:

c and l are used to calculate the maximum flexure stress.

$l := 18in \qquad c := 0.625in$

Required width of surface area:

$$x_{reqd} \cdot \tau = \frac{4 \cdot Q \cdot \sigma_x}{c \cdot l}$$

Worst case: σ_{xhigh} and τ_{low}

$$x_{reqd} := \frac{4 \cdot Q \cdot \sigma_x}{c \cdot l \cdot \tau_{low}} \rightarrow 1.5938 \cdot in$$

Failure calculations for wood-strands:

Mold Design: Core Failure vs Flexural Failure

$c := 1in$ $b := 2.125in$ $l_{cr} := 0.8491in$ $S := 2.25in$

$t := .125in$ $L := 18in$ $t_r := .25in$

$d := 1.25in$ $l := 1.1839in$ $\alpha := 56deg$

Crushing Load:

$\sigma_{crc} := 2860psi$ from hunt's paper

$P_{crc} := \sigma_{crc} \cdot t_r \cdot S$

$P_{crc} = 1608.75\,lbf$

$P_o := P_{crc} \cdot \cos(90deg - \alpha)$

$P_o = 1333.714\,lbf$

$P := 2 \cdot P_o = 2667.428\,lbf$

Buckling Load:

$E := 847600psi$ $I_r := \frac{S \cdot t_r^3}{12} = 0.003 \cdot in^4$

$$P_{crb} := \frac{2 \cdot \pi^2 \cdot E \cdot I_r}{l_{cr}^2} = 67986.754\,lbf$$

$P_o := P_{crb} \cdot \cos(90deg - \alpha) = 56363.573\,lbf$

$P := 2 \cdot P_o = 1.127 \times 10^5\,lbf$

Flexural Failure in the Faces:

$$I := 2\left[\frac{\left(4.25in \cdot .125in^3\right)}{12} + 4.25in \cdot .125in \cdot (.5625in)^2\right] + 2\left[\frac{.25in \cdot (1in)^3}{12}\right] + 2\left[\frac{.75in \cdot .25in^3}{12} + .75in \cdot .25in \cdot (.375in)^2\right]$$

$y := .625in$ $\sigma_{cr} := 4500psi$ $I = 0.55 \cdot in^4$

$$P := \frac{\sigma_{cr} \cdot I}{\left(\frac{L}{2}\right) \cdot y}$$

$P = 440.299\,lbf$

Appendix E
OSB and Plywood Comparison Calculations

Calculations for bending stiffness of OSB and plywood:

Calculations for bending stiffness of plywood and OSB:

$b := 1\frac{in}{in}$ $\quad h := 1.25in$

$$I := \frac{b \cdot h^3}{12} = 0.163 \cdot \frac{in^4}{in}$$

$E_{ply} := 920000psi$ $\quad E_{OSB} := 840000psi$

$$E_{ply} \cdot I = 149739.583 \cdot lbf \cdot \frac{in^2}{in} \qquad E_{OSB} \cdot I = 136718.75 \cdot lbf \cdot \frac{in^2}{in}$$

Assumptions and calculations for OSB comparisons:

	Target Density (pcf)	Panel Dimensions (ft)	Resin Content (%)	Furnish MC (%)	Furnish Weight (lb)			Resin Weight (lb)			Total Weight (lb)	% Furnish to OSB	% Resin to OSB
					Core	Faces	Total	Core	Faces	Tota			
OSB	40	4 x 8 x 1 1/4"	8	5	N/A	N/A	154.56	N/A	N/A	23	177.56	100	100
WS Core	40	4 x 8 x 1 1/4"	8	5	30.91	15.46	61.83	4.6	2.3	9.2	71.03	40.0	40.0
ONP Core	40	4 x 8 x 1 1/4"	10	12	32.26	16.13	64.52	5.74	2.87	11.48	76	41.7	49.9
OSB	40	4 x 8 x 1/2	8	5	N/A	N/A	56.67	N/A	N/A	8.42	65.09	109	
OSB	40	4 x 8 x 9/16	8	5	N/A	N/A	63.76	N/A	N/A	9.48	73.24	116.	

APA Load Calculations:

$w := 1$ $\quad l := 48 - 1.5 + .25$ $\quad EI := 1196000$ $\quad c := .5625in$

$l = 46.75$

Uniform Load Based on Deflections:

$$\Delta := \frac{w \cdot l^4}{2220 \cdot EI}$$

$$\Delta = 0.002$$

$$\Delta_{all} := \frac{48}{240}$$

$$w := \frac{\Delta_{all}}{\Delta}$$

$$w = 111.17$$

Uniform Based on Bending Strength:

Assuming a two span condition of 24 in.

$$I := 2\left[\frac{\left(4.25in \cdot .125in^3\right)}{12} + 4.25in \cdot .125in \cdot (.5625in)^2\right] + 2\left[\frac{.25in \cdot (1in)^3}{12}\right] + 2\left[\frac{.75in \cdot .25in^3}{12} + .75in \cdot .25in \cdot (.375in)^2\right]$$

$I = 0.55 \cdot in^4$ $\quad L := 48in$

$$S := \frac{3 \cdot I}{c \cdot 1ft} = 2.935 \cdot \frac{in^3}{ft}$$

$$F_b := 758psi$$

$$w_b := \frac{96 \cdot F_b \cdot S}{L^2} = 1112.49 \cdot psf$$