3D ENGINEERED FIBERBOARD: A NEW STRUCTURAL BUILDING PRODUCT

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SUMMARY

To help meet the need for sustainable forest management tools, the USDA Forest Products Laboratory is developing an economically viable process to produce three-dimensional structural fibreboard products that can utilize a wide range of lignocellulosic fibres contained in the forest undergrowth and in underutilized timber. This will encourage the public and private sector to undertake thinning or clearing of these components from the forest thereby reducing or removing dangerous fuels and minimizing costs to the federal government for fire mitigation.

The proposed product consists of a structural material which can be made from a wide range of little or no-value underutilized fibre sources; such as wood residues, agricultural biomass, and including recycled fibre. The new material is referred to as 3D Engineered Fiberboard and would have uses in construction, furniture, and packaging applications. Through continuous hot-pressing of lignocellulosic fibre between rigid mould elements, 3D panels can be moulded into a specially engineered form. Continuous hot-pressing produces strong inter-fibre bonds even using relatively low-quality fibre. When the moulded structural core is bonded to flat-panel exterior skins, a novel three-dimensional sandwich panel is formed that exhibits a high level of strength and stiffness.

INTRODUCTION

Forest management methods vary throughout the world. What is one person's "trash" species or fibrous material could be another person's "treasure". Historically, forest management policy looks only at providing the maximum solid wood yield from a plot of land rather than considering the potential of all the fibrous resources and. To achieve maximum yield of the larger trees, smaller trees are thinned to optimise growth of the "higher" quality trees. This thinned material is generally left in on the forest floor or stacked and burned. The smaller diameter material usually has a higher percentage of bark that costs too much to remove even for uses such as paper as well as containing higher percentages of juvenile wood. The strength properties of juvenile wood are also lower making it undesirable for structural lumber. Many times residues or thinnings become "trash" material when there is no valuable outlet. There needs to be a method(s) developed that provide value-added outlets for this underutilized residual and thinning material to help offset the costs of sustainable forest management.

This paper highlights ongoing research at the USDA Forest Products Laboratory (FPL) to develop economical processing method(s) that use this low value material for a variety of value-added applications in the packaging, furniture, and structural areas. Our goal is to be able to take almost any fibrous biomass material and economically process it into a three-dimensional (3D) engineered fibreboard panel that can be designed to meet various selected performance criteria.

BACKGROUND

The Fibre Resource

The National Fire Plan (NFP) of the USDA Forest Service has been initiated to help reduce the fire hazards in the National, State, and private forests. Our effort at the Forest Products

Laboratory (FPL) under the NFP is to develop an economical fibre processing method(s) to use underutilized material from these fire prone forests. Many forest stands in the USA are over crowded and need to be thinned as part of good forest management. However, because these thinned materials usually are of mixed species, too small for structural lumber, contain defects, or are too costly to transport out of the forest, they are left to decompose on the forest floor in dry environments typical of the western USA. In some cases this represents a significant amount of material which, after several years, poses a significant fire hazard (Figure 1). Logging operations also leave significant residue after the merchantable logs have been harvested. For example, the tops of trees too small for structural lumber or paper processing are left in the forest, which also creates a significant fire hazard. All of these materials could provide a good source of fibre for 3D engineered structures.

Figure 1: Thinned material after ~10+ years represents a significant amount of potential fibrous material that currently is very dry and an extreme fire hazard.

Fibre Processing

We selected the wet-processing over the dry-processing method in order to maintain fibre length and retain the ability to bond the fibres with little or no resin. Because our goal is to fabricate uniformly thick 3D structures, wet-forming also provides more uniform forming characteristics compared to dry-formed processes. A wet-formed mat follows the contour of the 3D mould and has sufficient mat strength for minimal handling prior to hot-pressing. Previous research (Hunt and Vick, 1999) has shown the significant difference that fibre processing has on mat thickness. Refined fibres form a more dense mat compared to less refined material. In Figure 2, wet-formed mats made from low-yield highly refined old corrugated containers (OCC) form significantly thinner and denser mats than high-yield less refined hardboard fibres. It is also well known in the paper industry that refining significantly improves fibre bonding (Danforth, 1986), but too much refining can cause increased drainage times in the forming process. Our goal was to refine the fibres to provide good fibre-to-fibre bonding and denser mats without too much detrimental affect on drainage times.
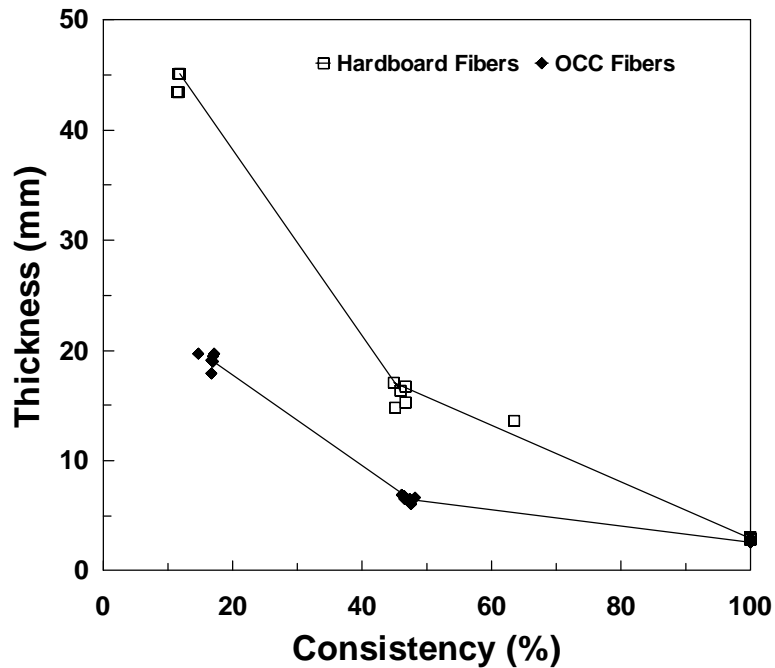
Figure 2: Wet-formed mat thickness comparison between refined old corrugated container fibre mat and a high-yield wet-formed hardboard fibre mat. (Hunt and Vick, 1999)

Mat and Mould Considerations

The effect of mat thickness has not been rigorously considered when designing 3D moulds. As shown in Figure 3, vertical pressing of a 3D fibre mat can cause non-uniform fibre distribution in some sections and fibre shear as the top mould comes in contact with the fibre mat in other sections. As the angle of the mould increases and the mat thickness increases, the extended section of the mould contacts the mat sooner and vertically displaces the fibres into the recessed sections of a mould. A mat that is too thick can cause non-uniform compression occur at the high spots of the non-uniform fibre profile and it can also cause the mat to separate or tear due to excessive fibre shear. Refining the fibres and pre-pressing can help minimize these problems. Other methods of pre-pressing will be investigated to compress the mat normal to the mould geometry.
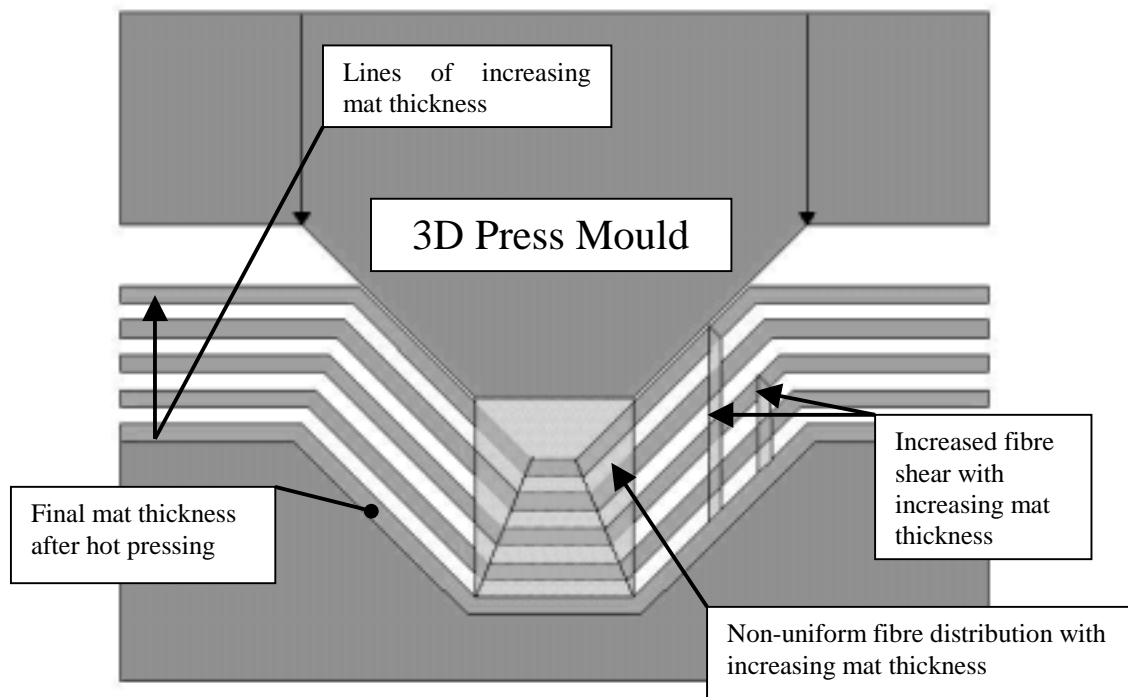
Figure 3: As the thickness of the 3D fibre mat increases problems occur during pressing that include non-uniform fibre distribution and fibre shear.

Fibre Mat Press-Drying

Once wet-formed and pressed, the fibres must bond together with sufficient strength to produce a 3D fibreboard products with sufficiently improved value and performance to make harvesting this residue material an economic possibility. In previous research (Hunt and Vick, 1999), panels made from refined OCC fibres yielded significantly stronger panels than those made from commercial hardboard fibres. The panels made from OCC had a 3 times higher tensile strength and a 2 times higher tensile modulus of elasticity than those from high-yield low refined hardboard fibre, Table 1. Research found that continuous pressure as compared to intermittent pressure during paper drying resulted in significantly improved properties (Gunderson, 1984). Continuous pressure during drying is being used as part of this research program. Currently, most wet-formed products use a venting press-cycle that includes a period at low-pressure to vent moisture from the board. We believe it is critical for optimum bonding to maintain the pressure through the entire process. Through both fibre refining and continuous pressing during drying we expect to achieve improved bonding and performance of the 3D fibreboard material.

Table 1: Tensile strength and modulus of elasticity comparison of panels made from refined old corrugated containers with panels made from commercial hardboard fibres (Hunt and Vick, 1999).

	Tensile Strength MPa	Tensile Modulus GPa
Refined OCC	74.7	9.5
Commercial Hardboard	26.3	4.3

Structural Design

Proper structural design of any item is important for optimum performance. With the increasing availability of computer finite element analysis (FEA) software, it is possible to design, test, and optimise component strength properties as well as the whole structure performance computationally. However, the computational analysis is only as good as the input properties. Because wood composites usually have anisotropic or orthotropic properties it requires additional testing to obtain all the independent constitutive properties for proper analysis. However, for some applications approximations in FEA can be made assuming isotropic material properties. If we measure Modulus of elasticity (E) and Poisson's ratio (ν) we can estimated the Shear Modulus (G) using Equation 1.

Equation 1:   Isotropic material property relationship $G = \dfrac{E}{2(1+\nu)}$

EXPERIMENTAL

Fibre Furnish

The material for this research study is lodgepole pine tree tops (Figure 4) obtained from a suppressed growth area on the Bighorn National Forest, Wyoming and Wyoming State Forest lands. The tree tops were less than 4 inches in diameter and were residues from another research project that was using the small diameter trees for a structural lumber application (USDA FOREST SERVICE, 2001). The tree top material was de-limbed and stacked aside. Some of the tree top material, 1.8 metric tonnes (4000 lbs) was shipped to the Herty Foundation, Savannah, GA for processing in a wet fiberizing machine called a Tornado (Bolton-Emerson). The tree top material was chipped conventionally and processed wet through the Tornado. This material was next fiberized for 30 minutes in a batch system, dewatered, and shipped to the FPL. At FPL, a total of 19 different atmospheric refiner trials, Table 2, were made using the material without and with minimal NaOH pre-treatment and at 1, 2, or 3 times through the refiner set at two gap settings. The first pass through the refiner was at a gap setting of 0.43 mm (0.017 in), the second and third passes were at 0.25 mm (0.010 in). The refiner plate design C2976 from (Sprout-Waldron, 1979) is designed for smaller size material and fibre abrasion. The variables are outlined in Table 2.

Figure 4: Small diameter trees (left) cut for another study with the tree top residual material (right) used for this study.

Basic fibre properties were measured for each refiner run; Canadian Standard Freeness (CSF), shive content, fibre length, fibre curl, and fibre kink. Refiner power was recorded to estimate refiner energy for each condition.

Table 2: Atmospheric refiner conditions used with the Tornado pin chip fibres.

Pre-treatment	NaOH	Refiner Gap(s) mm		
		0.43	0.43 / 0.25	0.43 / 0.25 / 0.25
Atmospheric @ 90°C	0.0%	Run 1	Run 2	Run 3
Atmospheric @ 90°C	0.5%	Run 4	Run 5	Run 6
Atmospheric @ 90°C	1.0%	Run 7	Run 8	Run 9
Atmospheric @ 90°C	2.0%	Run 10	Run 11	Run 12
Atmospheric @ 90°C	4.0%	Run 13	Run 14	Run 15
Pressurised @ 110°C	0.5%	Run 16	Run 17	
Pressurised @ 110°C	1.0%	Run 18		
Pressurised @ 110°C	4.0 %	Run 19		

Panel Fabrication

Flat panels were made from fibres from each refiner run to determine the effects of fibre refining and chemical additives on fibre bond strength. No adhesives were used in order to isolate the effects of fibre-to-fibre bonding. The fibre mats were formed in a 0.5 by 0.5 m forming box. The formed mats were placed between two screens and two stainless steel cauls and hot-pressed for 10 minutes at 163°C (325°F) with continuous 1175 kPa (170 psi) pressure. The final target panel thickness was 3.2 mm (0.125 in) with a specific gravity of 1.0.

Panel Testing

Flat panels were tested in tension and bending following ASTM D-1037 (ASTM, 1996) test standards. Tensile specimens also had speckle patterns placed on the back surface for digital image evaluation of Poisson's ratio using surface displacement software. The Modulus of Elasticity (MOE) and Poisson's ratio were used for FEA modelling.

Structural Analysis, Mould Design, and Testing

Bending and tensile tests on flat panels were conducted to obtain basic isotropic material properties for use in the initial FEA and mould design process. Later, two mould geometries, Figure 5, were evaluated using two selected fibre processing methods. The first geometry will be a bi-directional corrugated shape called Trusscore. Its geometry and size will be set by an existing mould designed to produce a 0.6x1.8 m (2x6 foot) engineered fibreboard structure with a nominal core thickness of 10 mm (0.39 in). The second geometry will be a uniaxial corrugated mould designed using simplified beam equations and FEA. Its nominal core thickness will be approximately 25 mm (1.0 in). Three-layer panels will be fabricated using the both the Trusscore and corrugated designs for the core. Flat panels made from the same material will be used for the top and bottom faces.
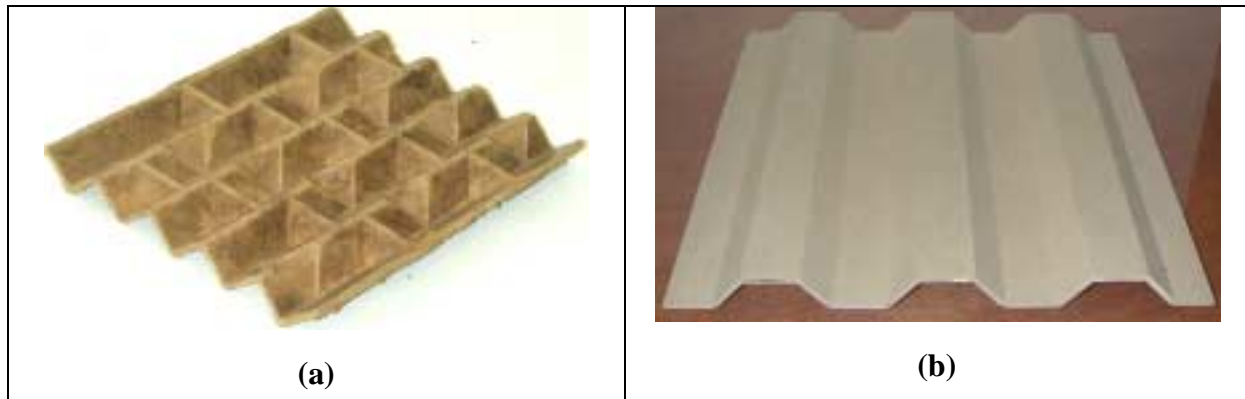
(a)　　　　　　　　　　　　　　　　**(b)**

Figure 5: 3D engineered fibreboard designs used for fabricating the test panels. (a) Trusscore (b) Simple corrugated.

RESULTS AND DISCUSSION

The following section represents a brief discussion of progress to-date for this research program. Much of the data presented is preliminary. Detailed analysis and presentation of the data will be published as we progress through the program. The FUTURE WORK section summarizes research and analysis planned for the upcoming year.

Fibre Furnish

It was interesting to observe, after cutting the small diameter trees for another research study (USDA FOREST SERVICE, 2001) the remaining pile of tree tops represented a significant amount of potentially useful material that would otherwise be left in the forest, Figure 4. The tree top material processed at Herty Foundation produced a high length-to-diameter ratio fibre bundles with minimal fines, see Figure 6 and Table 3. The Tornado was chosen because of its reported ability to reduce fibrous material into this type of material. The chipping step in this study was used for convenience in material processing rather than expected use in practice. Future studies will examine using the Tornado to directly reduce tree top or thinning material directly into the fibre bundles.

The Tornado pin-chips were further refined at FPL. Our goal in refining is to minimize loss in fibre length and freeness while maximizing strength increase. Fibre length ranged from a minimum length of 0.87 mm (0.034 in) for the control trial, Run 3, to approximately 1.3 mm (0.051 in) for the pressurized pulping trial with 4% NaOH, Run 19. After the first pass through the refiner we still had a high percentage of shives, between 45 to 60%. Fibre shive content is described as material not able to pass through a 0.10 mm (0.004 in) slotted screen. For all process methods, the shive content decreased to around 25% after the third refiner pass. Papermaking cannot tolerate even small percentages of shive content, however, this thicker 3D structural material can tolerate a higher percentage of shives as well as bark specks. Refining does a good job of breaking up both, but they are still visually evident in the panels. The benefits to being able to use higher shive content material is less energy is used to process the material and mat freeness is higher which reduces overall processing time. Freeness is an index of water flow where higher values equals higher water flow and lower values equals lower flow. Freeness values after the first pass through the refiner ranged from 670 ml to 780 ml Canadian Standard Freeness (CSF), after the second pass freeness ranged from 580 ml to 740 ml, and the third pass freeness ranged from 440 ml to 705 ml.

Figure 6: Tornado fibre (centre) has a high percentage of high length-to-diameter ratio fibre bundles with a minimum amount of fines. Conventional chips (left) and refined pulp fibres (left) are for reference.

Table 3:   Fibre size distribution for the Tornado.

	Fibre (%)						
SIEVE#	+ 8	- 8/+ 12	-12/+ 16	-16/+ 20	-20/+ 35	-35/ Pan	Total
Tornado	13.0	16.7	28.4	18.5	14.5	9.0	100

Panel Fabrication
The flat panels were oven dry after pressing for 10 minutes. For this study, we opted to press a little longer to be sure that the panels were dry and not risk blowing the panels if the internal moisture content was too high. Additional research is needed to determine optimum pressing conditions for refined thicker fibreboard panels using continuous pressure.

Flat Panel Testing
Flat panel testing is complete and we are now analysing the results. Preliminary test results are provided in Table 4. These results will be used for material property inputs for initial FEA simulations. Initial data shows bending strengths for the refined panels have equal to and greater strengths than the minimum standards for hardboard or particleboard, even with no resin added. This shows the potential of a residue material that could perform with equal or improved performance characteristics as current industry standards.

Structural Analysis, Mould Design, and Testing
Using the simply supported beam deflection equation with the corrugated design we

Equation 2:   Simply support beam deflection. $Deflection = \dfrac{Load * Length^3}{E * I * 48}$

can calculate estimated beam deflections (Figure 7) where the cross section of the panel is same or similar to Figure 8. The calculations were for a cross section having a nominal thickness of 38.1 mm (1.5 in), repeated corrugated rib patterns of 50.8, 76.2, or 101.6 mm (2, 3, or 4 in) wide, corrugated web angles of 50, 70, or 90 degrees, with a 4.5 N/cm (50 lb/in) width centre load, for a 50.8 cm (20 in) span. Figure 7 shows that with an increase in bending

MOE from 3.1 to 5.0 GPa (Table 4), the beam deflection can be significantly reduced compared to high-density particleboard at the same thickness. If the higher tensile MOE values, 4.9 to 6.2 GPa, rather than bending MOE were used in the calculation, then even lower deflections would be predicted.

It is interesting to note that the predicted deflection data represented a 3D shape where 2/3 of the material has been removed from the panel. The reduction in deflection is significant and it was done with a reduction in material. This reduction in material with equal or better performance from a residue resource has many positive implications from resource management to cost savings.

Table 4: *Preliminary flat panel test data compared to hardboard and medium density fibreboard minimum standards.*

	50% RH Low/High Range		90% RH Low/High Range	
	Max Stress (MPa)	Modulus of Elasticity (GPa)	Max Stress (MPa)	Modulus of Elasticity (GPa)
Cantilever Vibration	-	3.3 to 5.4	-	2.3 to 3.4
Bending	34.7 to 59.1	3.1 to 4.9	19.2 to 29.3	1.80 to 2.72
Tensile	25.5 to 41.1	4.9 to 6.2	12.2 to 20.1	3.7 to 4.8
AHA Bending Standard[a]	31	-	-	-
AHA Tension Standard[a]	15.2	-	-	-
PB Bending H-1[b]	16.5	2.40	-	-
PB Bending H-3[b]	23.5	2.75	-	-

[a] American Hardboard Association, AHA, ANSI/AHA A135.4, 1995, Palatine, IL
[b] High-Density Particleboard (PB), National Panel Association (1993)
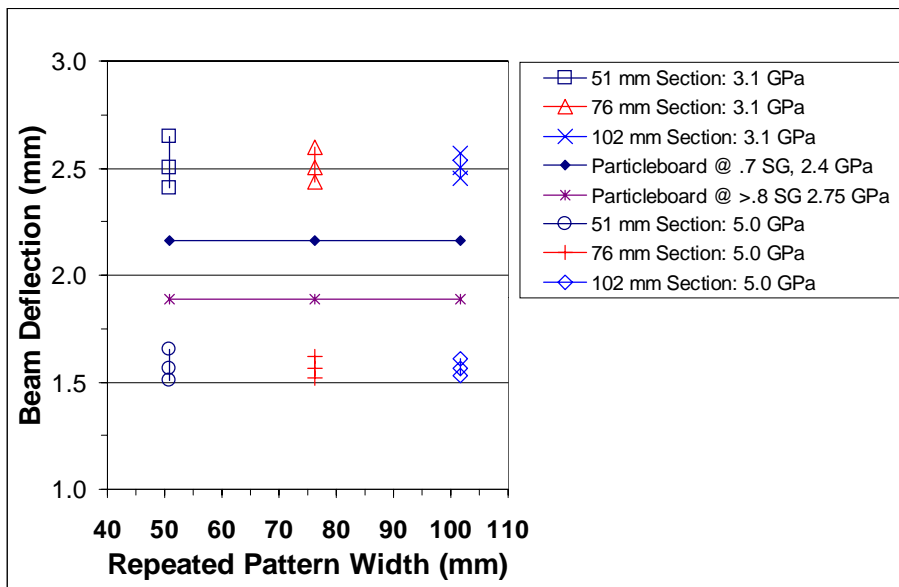
Figure 7: Beam deflections of nominal thickness of 38.1 mm (1.5 in), repeating patterns of 51, 76, and 102mm (2, 3, and 4 in) and web angle of 50, 70, and 90 degrees with MOEs of 3.1 and 5.0 GPa. Comparison with minimum medium and high-density standard particleboard properties.
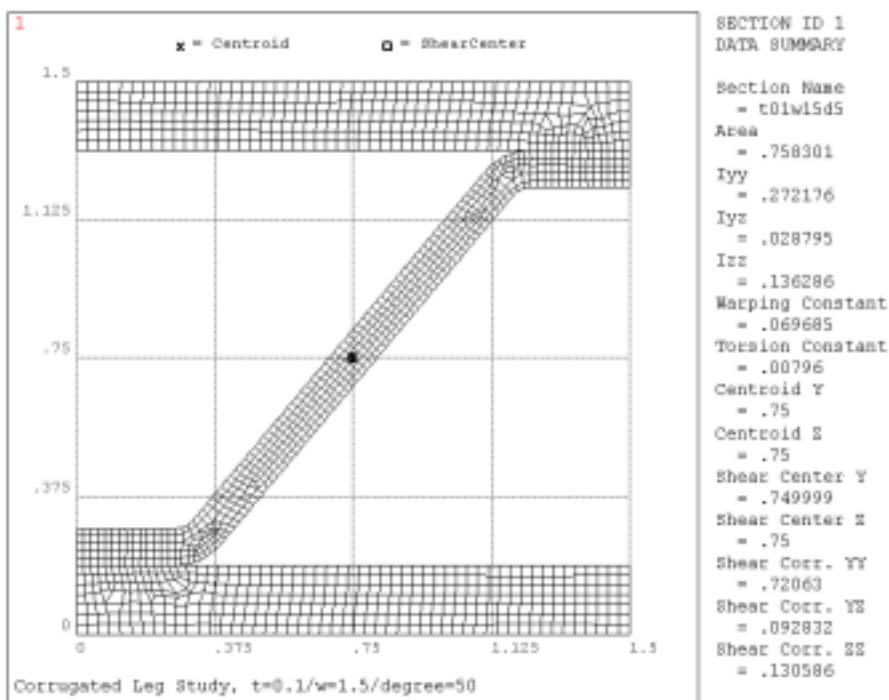

Figure 8 A potential geometry for the 3D fibreboard structure, showing only one-half width section 38.1 mm (1.5 in) thick of with the division of elements for a typical finite element analysis.

FUTURE WORK

The mechanical strength data, MOE and Poisson's ratio, from the flat panel testing will be used with FEA modelling. This will then be used to develop a mould design with minimum stress and deflection within a given 3D fibre structural geometry. Figure 8 is one possible geometrical shape for the simple corrugated 3D engineered fibreboard structure. Using the FEA computer program we will also be able to simulate flat and edge-wise loading that are difficult or impossible with conventional equations. We will look at varying the core and face thickness of each of the components. It will also be possible to look at stress levels over an array of loading conditions. Learning how to minimize stress levels will minimize creep response. Material properties for the analysis will be assumed isotropic until more specific tests can be conducted to obtain the other independent orthogonal constitutive properties. The isotropic simulations, however, will provide the first estimates for design of the mould geometry.

From the optimum geometry and fibre processing data we will design a mould and develop the processing conditions to try to achieve a 3D engineered structure with similar performance properties as predicted by the simple beam calculations and the FEA model. Similar drying methods as with the flat panels will be used for the 3D fibre structures. Care will be taken to minimize non-uniform fibre distribution and fibre shear, as shown in Figure 3, through pre-pressing and mould design.

After full size moulds, 0.6 by 2.4 m (2 by 8 ft), are fabricated, 3D fibreboard panels will be formed and bonded with flat top and bottom panels to make sandwich panels. These sandwich panels will be tested in bending, flatwise and edgewise compression. Deflection data will be compared to the FEA modelling deflection predictions. Corrections to the model will be made to improve the modelling assumptions.

The proposed 3D engineered fibreboard technology has a number of promising uses in construction, furniture and packaging applications. The economic feasibility of constructing panels from these materials will be assessed as part of our on-going research program. Once all the processing data is complete, an economic analysis will be initiated to determine estimated costs to remove and process the residue material. Economic comparisons will be made to existing panel products to determine benefits for a 3D engineered fibreboard structure.

SUMMARY

Preliminary results from flat panel mechanical properties indicate that residue material such as tree-tops can be made into panels with equal or stronger strength than some conventional wood composites and could potentially be used for structural panels.

Simple beam calculations predict significantly improved bending properties are possible with a 3D engineered fibreboard structure compared to particleboard panels. In applications where bending is the predominant loading condition and weight is a significant factor, a 3D engineered structure could be advantageous. There are many applications in the packaging and furniture industries where this is the main loading condition and such applications product performance could benefit from using this 3D engineered structure.

Providing an outlet for this residue material as a value-added 3D engineered fibreboard structure could provide improved forest management options as well as local community jobs in harvesting the material and in manufacturing the 3D engineered fibreboard structures

ACKNOWLEDGEMENT

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