3D Structural Panels: A Literature Review

John F. Hunt, P.E.

Forest Products Laboratory

Madison, WI 53726 USA

ABSTRACT

The world population has surpassed the 6 billion mark and many of these people live in rapidly developing countries that are and will continue to place increasing pressure on the world's natural fiber resources. The total demand for raw material from the forest for housing, packaging, and for office and home furnishings, to name a few; are increasing. Traditional solid lumber products will not be able to fully supply all these needs. Potential replacements include wood composites, plastics, and metals. In the wood composites arena, the tree resource is shrinking, so lower quality and smaller diameter trees are being used for many of the traditional composite panel products. This trend is expected to continue. The demand for many of these commodity products will drive up the cost for the raw material, as well as the production costs for resins and drying or curing energy. For some applications, however, it can be shown that equivalent or superior performance over these traditional composite panel components could be provided with engineered three-dimensional fiber-based panel structures. It is possible that these fiber-based structures can use a wide range of "unwanted, fibrous materials including agricultural residues and recycled fibers, thus relieving the total demand for "good" trees. To enhance our total forest sustainability and stewardship there is a need to examine the uses of engineered structures from low-grade trees, small-diameter trees, or thinnings. This paper reviews the patent literature for developments of three-dimensional fiber based structural panels and discusses trends and research needs to further develop this area of composite panels.

Keywords: three-dimensional structural panels, veneer, flakes, laminated paper, particles, fiber, non-woven, dry-formed, wet-formed, literature review

INTRODUCTION

The world's population reached 6 billion people on October 12, 1999, is expected to reach 7 billion in 2013 and 8 billion in 2028 (United Nations 1999). In many countries increasing population places increased pressure on land utilization practices between agricultural crops and natural wood resources. In addition to population growth, an increase in the standard of living for many countries is and will continue to put higher demands on our world's natural fibers resources. These and many other factors place an increasing demand on raw material resources that will continue to influence the manufacture of goods toward both material and energy efficiency. In the wood industry, how will the demand for goods and efficiency for the growing population be met?

For many applications three-dimensionally (3D) engineered wood products could be used to offset the demand on forest resources through reduced fiber resource or use of alternative fiber resources such as low-grade trees, small-diameter trees, forest thinnings, agricultural fibers, or recycled fibers. For example, in bending applications structural efficiency can be obtained through efficient placement of equal or higher strength materials on the faces and minimizing core material. This has been done quite effectively with wood I-beam trusses. From an engineering performance perspective, selective removal of core material for a 3D structural panel can be done with minimal loss of properties. In Fig. 1, a theoretical panel (1 by 1) structure's area moment of inertia and maximum bending stress (modulus of rupture) are shown as a function of percent material removed from the core. While the geometry of the material removed was not optimized for any particular application it shows the potential for engineered structures in bending. A reduction of core material (a by a) by 25% resulted in only a 6.25% loss of area moment of inertia and 6.75% increase in maximum bending stress. For many applications, the bending stiffness and stresses performance requirements are below the failure properties of the material and could be made from 3D engineered panels. In other situations, the use of a 3D structural panel would result not only in significant savings of raw materials but also the reduced costs for resins and energy.

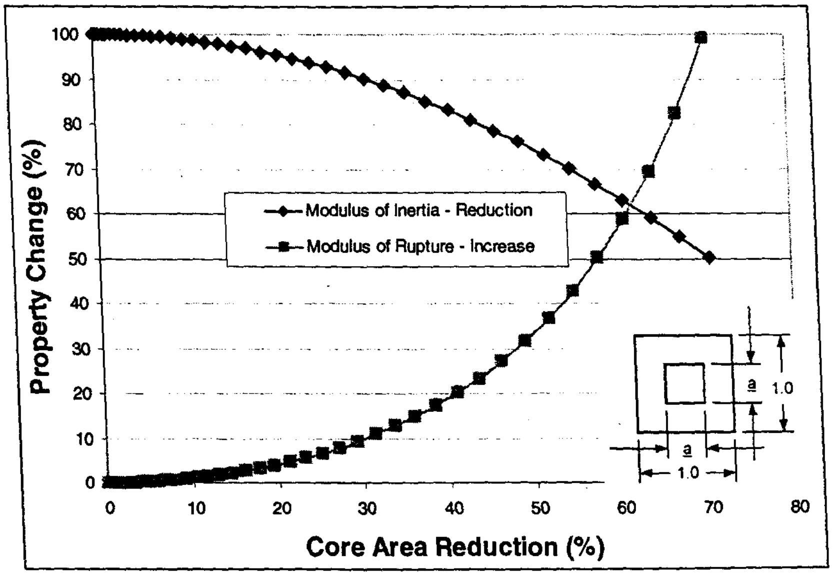

Figure 1 - Effect of reduction of the core area (a by a) on the theoretical beam's area moment of inertia and modulus of rupture at the surface of the beam.

To achieve these savings, however, more detailed and engineering design work is involved. First, there is a need to understand the detail loads and performance characteristics of the specific product in consideration. Second, there is a need to select the material properties, geometry optimization, manufacturing method, and cost analysis. As these two work together it would be possible to fabricate a product from 3D engineered panels with the potential of improved performance and cost savings with less material. As the demand for the world's wood resources increases there will be a need to implement more 3D engineered panels to extend the resources.

Structural panel optimization is not new and is used quite extensively in the concrete, metal, and plastic industries where optimum performance is obtained through optimized geometry for a particular application with a given material. In the wood industry, however, there are fewer examples. For example, in the United States, structural insulated panels are used for some home and industrial buildings for wall, floors, and roofs. Hollow core doors are another examples of 3D structural panel applications. For many other products, however, solid flat wood composite panels are the main component or components in wood structures resulting in overly designed and heavy products thereby wasting resources.

The decision to manufacture or use 3D engineered structural panels is based on many factors, but three seem to be more important in the decision process. First, the performance requirements for the particular product needs to be defined. The performance requirements are product specific and requires detailed analyses, which is beyond the scope of this paper. Second, the processing methods and the 3D geometries available from various processing methods need to be evaluated. Selecting what processing method to use and the 3D geometry potential requires a good knowledge of the available technologies. This presentation will cover processing methods and 3D structural panel products made from wood veneers, flakes, particles, laminates, and fibers as described in the US patent literature. And third, the available composite materials and their strength properties to meet the performance requirements need to match those for the product. This is very important but also outside the scope of this paper. A second paper, to be published later, will explore the availability of this information.

PROCESSING METHODS

The process of producing a 3D structural panel generally requires transforming the material from solid wood into another usable form for 3D structural composites. This can be accomplished using several wood processing methods. The following are US patents that describe different processing methods used to reform wood into 3D structural panel compents. For convience, the patents are separated into broad material catagories of reprocessed wood. The patents listed do not represent an exhaustive list, but are presented to show the numerous options for fabricating 3D structural panels. The organization of this paper will start with wood material closest to wood then progress down to small material size of fibers.

Veneer

Wood veneer is much like wood in longitudinal, radial, and transverse directions, but can be converted to a 3D structural panel by corrugating the veneer in the transverse wood direction. The radius of curvature of the corrugations dependents on the individual thickness of the veneers. There are several patents which describe various corrugating processes and apparatus. Two of the patents, 4,816,103 and 4,943,339, are process and apparatus patents. They describe a batch articulated-platen press system for applying the corrugations. A primary goal was to simplify the equipment necessary to corrugate wood veneer. Woven fluorocarbon/fiberglass "cauls" are used to assist the laminates into the corrugations.

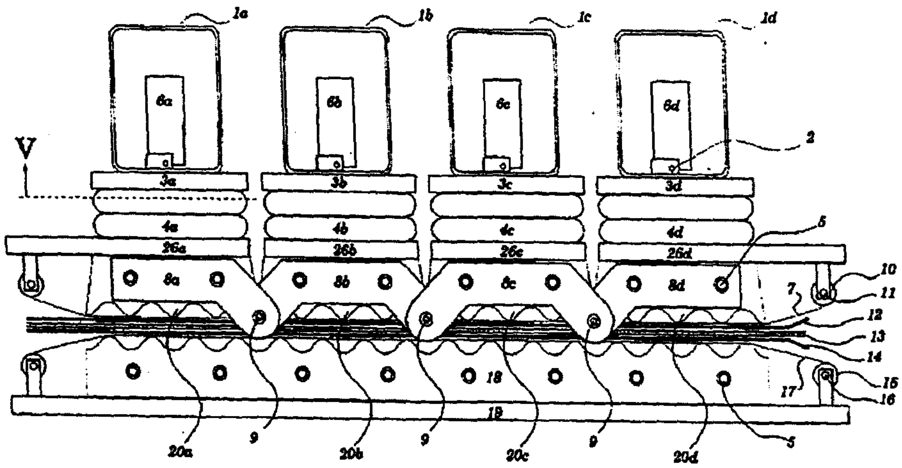

Figure 2 - Patents 4,816,103 and 4,943,339 use an articulated hinged batch press to corrugate wood veneer.

In all patents reviewed that used veneer, they always contoured the veneer in one direction creating a uniaxial corrugation or rib pattern.

Flakes

Reducing wood into flakes is significantly easier and can use most any tree diameter but is best suited for smaller diameter trees. The larger diameter trees are better used for higher value products such as solid lumber or veneer. US patents 6,511,567; 6,541,097; and 6,773,791 describe methods to fabricate composite building components (Fig. 3) using a corrugated core member made from flakes. The invention utilizes a specialized solid forming dies to create uniform density corrugated cores. These are bonded to suitable faces and end pieces. The panels are then resawn into a structural members. Alignment of the flakes in the direction of the corrugations could be used to increase strength and ease of formability.

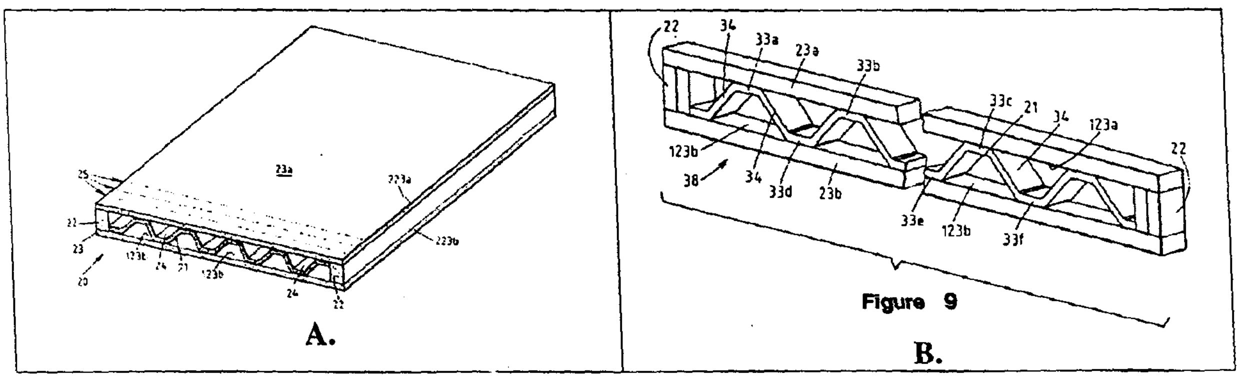

Figure 3 - Patent 6,511,567; 6,541,097; and 6,773,791 combines a uniform dense core made from flakes with face and end pieces to construct a structural lumber product.

Another approach to creating a core material uses movable pressing dies to press flakes into what is called a wave-board, patents 4,616,991; 4,675,138; 5,047,280; 5,290,621; and 5,443,891 describe the apparatus, process, and a high density variation for the wave-board structure. These all describe a process that distributes a mat of loose wood wafers between two platen surfaces. The two biasing platens together pre-compress the mat, substantially fixing the wafers together to limit their relative movements then converting the two platen surfaces from a planar to a corrugated configuration (Fig. 4) to produce a corrugated board.

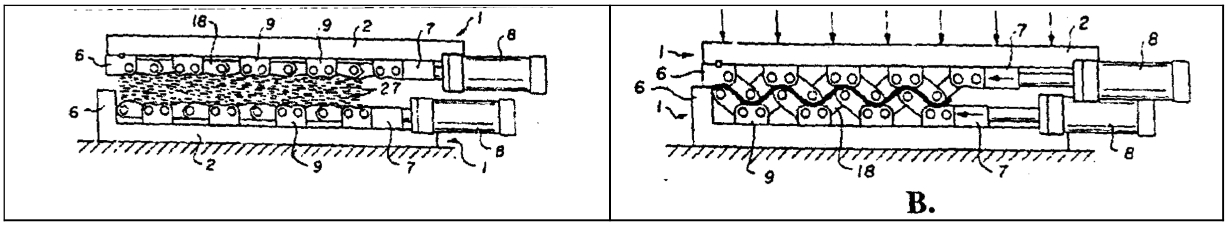

Figure 4 - Patents 4,616,991; 4,675,138; 5,047,280; and 5,443,891 consolidates a planer mat of wood wafers (A.) using movable platens (B.) to produce a corrugated structure.

In another patent, flakes can be formed into rib sections by forming additional flakes in specified areas, 4,904,517. The flakes in the ribs are generally aligned parallel to the major direction of the rib section through the use of curved forming heads (Fig. 5A). The ribs and mat are simultaneously pressed and consolidated into a relatively uniform density ribbed panel having one flat side and the other side ribbed (Fig. 5 B).

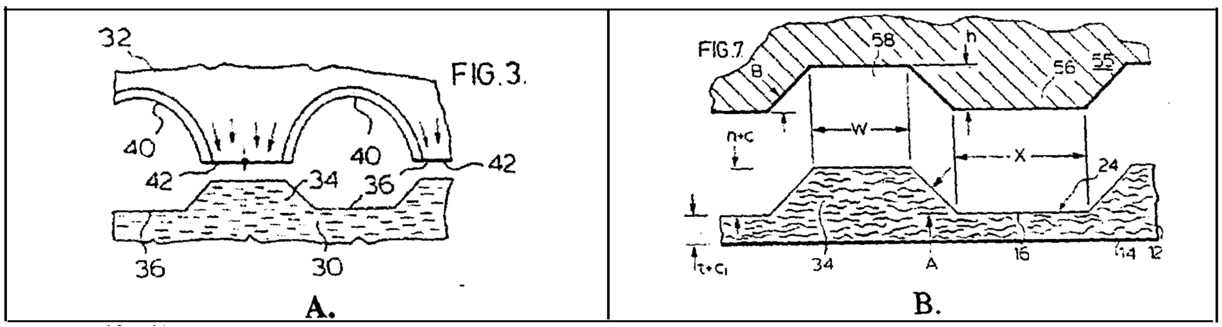

Figure 5 - Patent 4,904,517 (A.) selectively places additional flakes in areas for ribbed sections and (B.) using machined platens to produce a panel with one ribbed side and one flat side.

Particles and Dry-Fibers

Reducing the raw material further into particles and dry-fibers and used in 3D structural panels are described in many other patents. A significant number are for pallet structures. while these are 3D structures, it is not within the scope of the paper to look at this specific product type, however as a forming technology there are techniques or methods that could be used to produce core materials for structural panel products. For example, in patent 5,142,994 (Fig. 6) a pallet is made with oriented flakes and particles. Selective placement and orientations of the flakes allows for improved performance capabilities compared with those with only random flake orientation.

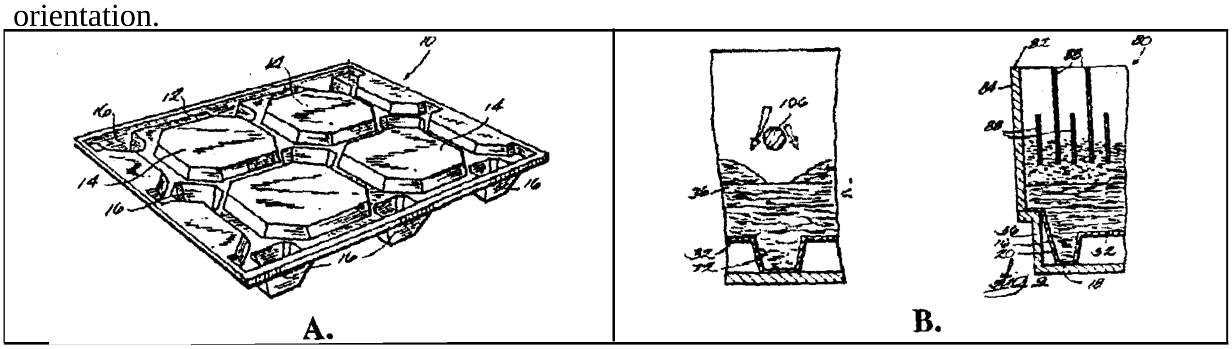

Figure 6 - Patent 5,142,994 consolidates wood flakes and particles into a pallet (A.). Flake and Particle distribution and orientation methods (B.) are also described.

There are also non-pallet patents that use wood particles to form structural panels. In patent 4,061,813 (Fig. 7) a process is described to fabricate ribbed panel sections for a building component system for roofs, walls, and floors that incorporates both the framing and sheathing components from particles.

There are numerous other patents that describe particle forming as well as fiber-based dry forming concepts. Many are variations of a similar idea to selectively place fibers into areas where needed during the pressing process to provide proper densification and strength development. These contribute to specific improvements in its performance characteristics, both uniform or non-uniform density distributions are considered in the various specific performance characteristics.

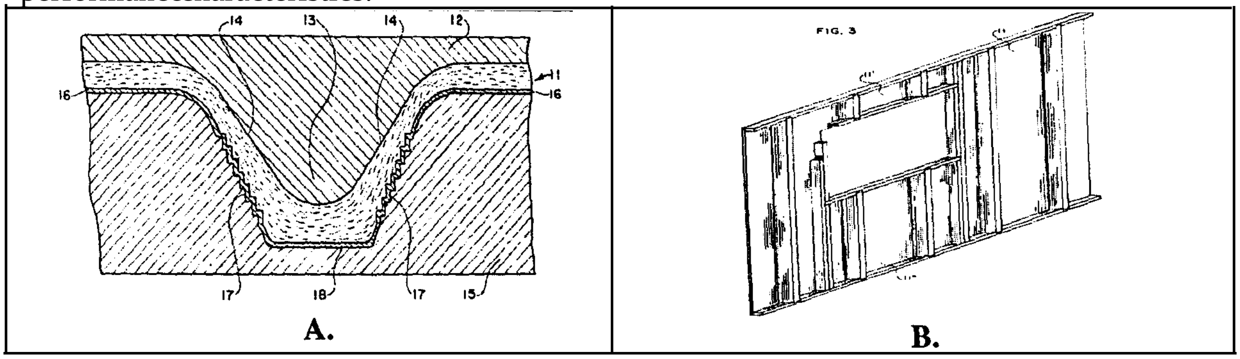

Figure 7 - Patents 4,061,813 consolidates wood flakes or particles (A.) to form a complete sheathing and framing wall system.

Non-Woven Fibers

Non-woven needled fibrous mats are generally described by the method where shorter wood fibers are combined with longer synthetic binder fibers through a needling process. The needling entangles the longer fibers to produce a loosely felted mat. Generally the synthetic fibers are thermoplastic and are used first as a carrier fiber to provide uniform stretch of the mat into the 3D molds. After the consolidation process, the thermoplastic fibers melt and act then as a binder. Additional resin can be added in needed. Most applications for this technology are in the automotive industry for interior panel products, but this method could also be used to fabricate structural panel products. Patents 4,865,788 and 4,957,809 (Fig. 8) describe variations in the non-woven process to fabricated parts. The non-woven process is specifically used to produce deep-drawn products.

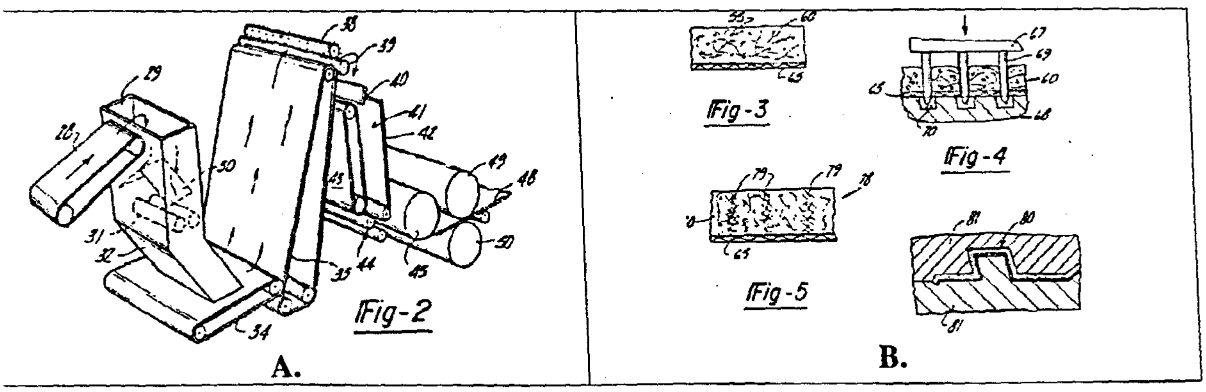

Figure 8 - Patents 4,865,788 and 4,957,809 use non-woven needling process (A.) to produce structural products (B.).

Wet-Formed Fibers

Wet-forming can also be called pulp molding. In the packaging industry, pulp molding is used for many cushioning applications such as egg cartons, part separators, and corner protectors. It uses a low-density fiber forming and pressing process to fabricate these types of components. It is beyond the scope of this paper to cover the low-density applications. Instead, it is of interest to look at higher density wet-formed fiber products that can be used for structural applications.

Two patents 5,900,304 and 6,451,235 (Fig. 9) describe a wet-forming method to form a structural panel between solid molds using heat and pressure. All the water passes through the bottom sections of the troughs on the top and bottom molds. Several configurations are shown that are used to improve the two-directional stiffness characteristics over uniaxial corrugated geometry. The core structures are stackable.

While all the previous patents use solid molds to press the 3D structural panels, several patents use deformable or resilient molds to form and apply pressure during the curing step. Patents 4,702,870 and 5,277,854 (Fig. 10) describe a wet-fiber forming process where fibers form in and around resilient rubber molds that are used for both initial fiber forme geometry and then for pressing to dewater and cure the fiber structure. This processing method can produce an integral face and rib or open-grid rib structures.

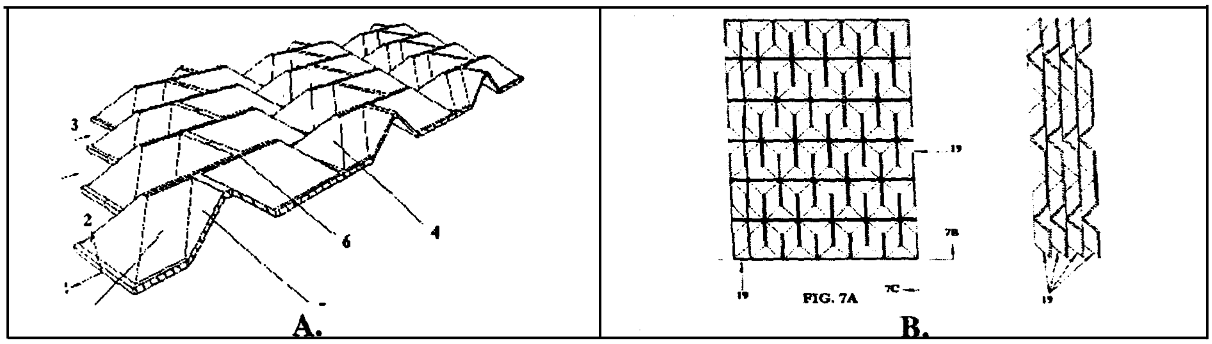

Figure 9 - Patent 5,900,304 and 6,451,235 uses a wet-slurry process to produce a 3D structural panels (A.) that have unique two-direction pyramid like rib structure and are stackable (B.).

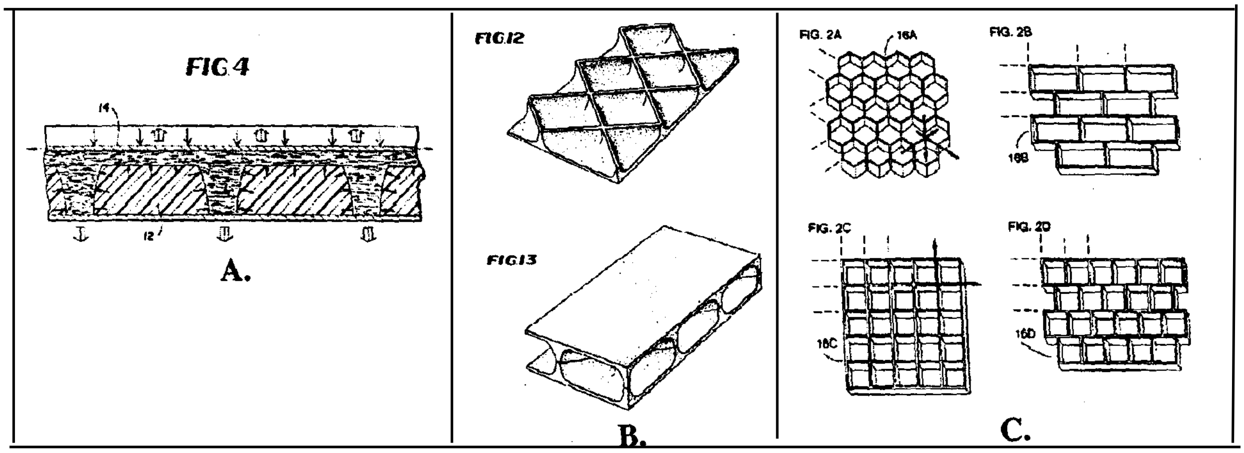

Figure 10 - Patents 4,702,870 and 5,277,854 uses resilient molds (A.) for both forming and pressing to produce integral face and ribs structures (B.) as well as open grid structures (C.), both with various geometry ribs.

Laminates - Folded Paper Cores

The patent literature is full of lightweight core structural panels made with various forms of corrugated or honeycomb paper laminated cores. Obviously each has its specific differences, many are generally described by forming strips of paper or paper-like material using various corrugated or honeycomb processes. The strips are bonded to maintain the structure. Face materials are bonded to the tops to provide panel bending properties. The latest lightweight core patent is 6,711,872 granted on March 30, 2004 (Fig. 11). It is a lightweight honeycomb core panel faced with a thin layer of gypsum board to form a composite panel that has the same surface characteristics and appearance as a sheet of conventional gypsum board.

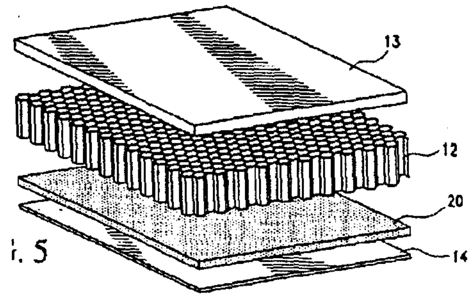

Figure 11 –Patent 6,711,872 shows common light-weight gypsum panel with the core made from honeycomb paper.

In another configuration patent 5,128,195 (Fig. 12) shows that paper or other planer ribbon material once folded could be "interwoven" to create a core structure with designable flatwise compression and shear performance properties. The ribbons are secured to the inner surfaces of the face sheets. The first set of ribbons extend transversely to, and preferably perpendicular to the second set of ribbons. The first and second sets of ribbons are woven such that they are spaced apart from and generally opposite the second set of ribbons. This arrangement permits an increase in the contact area with the face sheets to enhance the bond strength between the ribbons and the face sheets and to increase the skin deformation strength of the structure. The angle between the ribbons and the face sheets can be adjusted to optimize shear strength versus tension/compression strength. The thickness, material properties, and geometry of the folded material can be changed to optimize the performance properties.

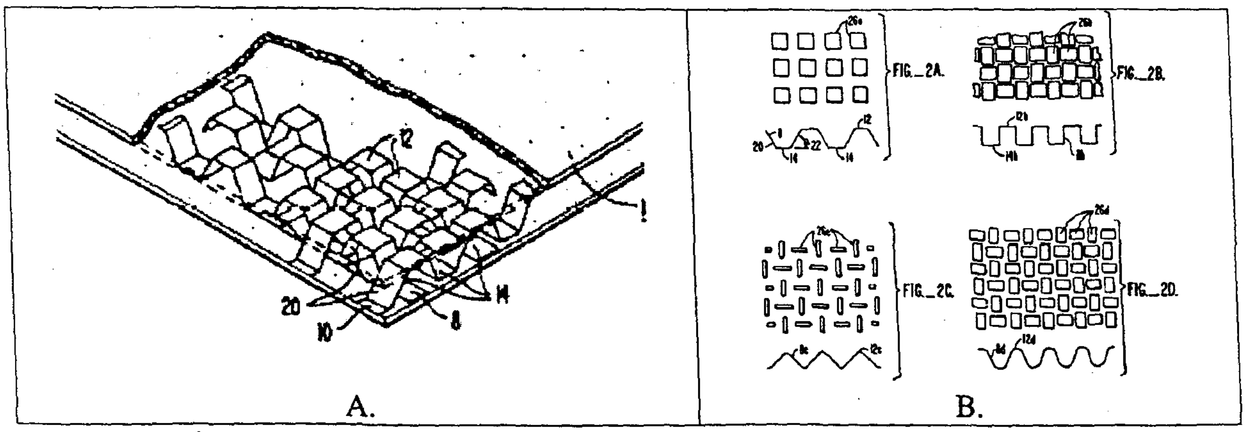

Figure 12. - Patent 5,128,195 shows a folded core sheet material: A. "Woven" strips for a core structure; and B. Four sheet-folding patterns to achieve different face bonding surfaces, structural ribs angle, and alignment options.

Structural Core - Miscellaneous

There are always those patents that do not fall into any one specific category but use a combination of methodologies to achieve the end goal. The following patent for structural panels uses various techniques to reduce the weight of the core but still demonstrate the **3D** structural panel concept. In patent 5,738,924 (Fig. 13) sandwich construction building panels are described using conventional facings with the inner core being made from a wide variety of woody or cellulosic materials such as from bamboo, corrugated elongate strips, or hollow tubes. These materials form an open inner core network pattern to separate the two faces.

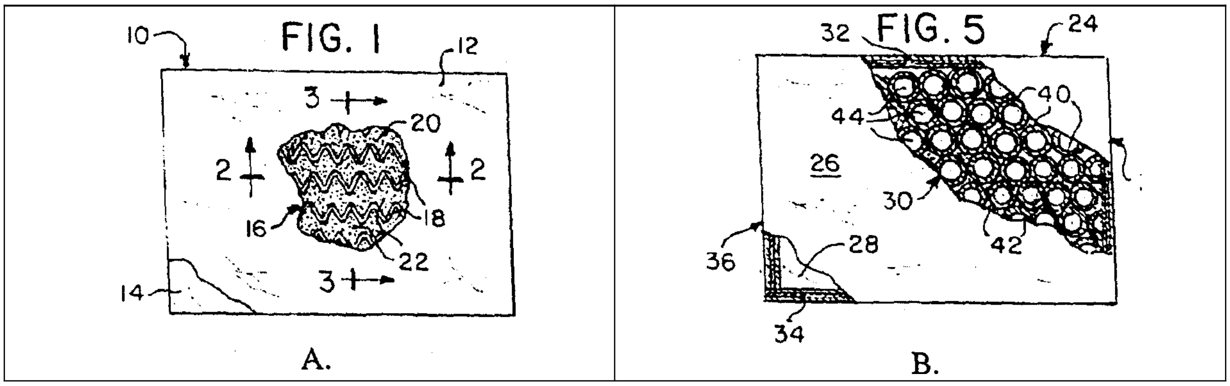

Figure 13. - Patent 5,738,924 showsthe top view of two structural core embodiments: (A.) corrugated material on edge; and (B.) bamboo or tubes of some fabrication.

SUMMARY

This is not an exhaustive list of patents but demonstrates the various methods that could be used for producing 3D structural panels. While many are similar each patent has its unique fabrication process that results in unique performance characteristics. The patent literature is full of many other examples of 3D structural panel concepts that could be used for engineered structures, a further examination of these and other patents will be done and published later. In any decision to use 3D structural panels will depend on the required performance needs of the application. It is possible that these fiber-based structures can use a wide range of “unwanted” fibrous materials including agricultural residues and recycled fibers, thus relieving the total demand for "good" trees. To enhance our total forest sustainability and stewardship there is a need to further examine efficient methods for fabricating engineered structures made from low-grade fiber sources. If these and other 3D structural panel patents were put into practice around the world, significant raw material savings could be realized.

REFERENCES

United Nations Population Division., 12, October 1999. “The World at Six Billion,” *Department of Economic and Social Affairs, United Nations Secretariat*, ESA/P/WP.154

US Patent 4,061,813. June 14, 1976. “Combination sheathing support-member building product,”. Geimer, R.L. and Lehmann, W.F.

US Patent 4,616,991. October 14, 1986. “Apparatus for the manufacture of a corrugated wafer board panel,”. Bach, L., and Stenk, E.

US Patent 4,702,870. October 27, 1987. "Methods and apparatus for forming three dimensional structural components from wood fiber,". Setterholm, V.C. and Hunt, J.F.

US Patent 4,675,138. June 23, 1987. "Process for the manufacture of a corrugated wafer board panel,". Bach, L., and Stenk, E.

US Patent 4,865,788. September 12, 1989. "Method for forming fiber web for compression molding substrates for panels and fiber web," Davis, A.L.

US Patent 4,904,517. February 27, 1990. "Ribbed waferboard product," Lau, K.K. and Knudson, R.M.

US Patent 4,957,809. September 18, 1990. "Fiber web for compression molding structural substrates for panels," Davis, A.L.

US Patent 5,047,280. October 9, 1991. "High density corrugated wafer board panel product,". Bach, L.

US Patent 5,128, 195. July 7, 1992. "Woven core structure," Hegedus, Andreas G., San Francisco, CA.

US Patent 5,277,854. January 11, 1994. " Methods and apparatus for making grids from fibers,". Hunt, J.F.

US Patent 5,290,621. March 1, 1994. " Flat-Topped wave-board,". Bach, L., Stark, E.

US Patent 5,443,891. August 22, 1995. " Low amplitude wave-board,". Bach, L.

US Patent 5,738,924. April 14, 1998. "Sandwich construction building materials," Sing, Peter, Winslow, WA.

US Patent 5,900,304. May 4, 1999. " Molded wood fiber web and structural panels made utilizing the fiber web," Owens, T.L.

US Patent 6,451,235. September 17, 2002. " Forming a three dimensional fiber truss from a fiber slurry," Owens, T.L.

US Patent 6,511,567. January 28, 2003. "Composite building components and method of making same," Ruggie, M.A., Bonomo, B., Braddock, L.L, Koledin, T., Liang, B.H., Lynch, S.K., Nemivant, K., Pearce, B., Weldon, M.A.

US Patent 6,541,097. April 1, 2003. "Ribbed Board," Lynch, S.K., Liang, B.H., Frein, F., Luetgert, K.A., Farrell, D.J.

US Patent 6,711,872. March 30, 2004. "Lightweight panel construction," Anderson, D. W. - Middletown, New York.

US Patent 6,773,791. August 10, 2004 "Composite building components and method of making same," Ruggie, M.A., Bonomo, B., Braddock, L.L, Koledin, T., Liang, B.H., Lynch, S.K., Nemivant, K., Pearce, B., Weldon, M.A.

The 7th Pacific Rim Bio-Based Composites Symposium

PROCEEDINGS

Volume II

Nanjing, China
October 31-November 2
2004