

POTENTIAL FOR STRUCTURAL LUMBER SUBSTITUTES

Theodore L. Laufenberg
Research General Engineer
U.S. Department of Agriculture
Forest Service, Forest Products Laboratory
Madison, Wisconsin

Abstract

The potential for substitution of structural wood composites into solid-sawn lumber markets is presented from the technological viewpoint. Technological limitations of existing composite processes and products are reviewed in the context of the present laminated veneer lumber (LVL), flakeboard, and fiber/paper industries. The limits of mechanical property potential are presented to show that strength and stiffness may be enhanced through innovative processing of structural wood composites. The routes for introduction of these composites are presented as (1) direct substitution for solid-sawn lumber, (2) introduction of new materials and components, and (3) development of new structural systems for light-frame construction.

Introduction

Structural lumber substitutes are a high-growth and high end-value product in today's marketplace. New product development, production facility announcements, and vigorous standardization activity from several sources will be discussed in this session demonstrating the vitality and potential for continued growth of these composite products. I have further divided these wood-based lumber substitutes into three categories;

- Laminated Veneer Lumber (LVL) which is made of parallel-laminated veneers bonded with durable adhesives. This product is now manufactured and sold commercially,
- Oriented Strand Lumber (OSL) (2) or Parallel Strand Lumber (PSL) (17), which is made with wood elements that are smaller than veneer sheets, aligned, and bonded with durable adhesives. Several potential manufacturers are developing this product.

- COM-PLY™ Lumber which is made with veneer faces and a flake or particle core. This material represents a mix of LVL and PSL technology and is currently under development.

The potential for revolutionary change in the forest products industry is great, largely because of composite technology. In the last 50 years, solid-sawn lumber and timber construction has given way to this composites revolution. The introduction of glue-laminated beams in the 1940's represented an early step toward composite wood members. Plywood became a superior replacement for nominal 1-inch lumber in sheathing of floors, walls, and roofs in the 1950's and 1960's.

In the sheathing market, plywood currently has stiff competition from the structural flakeboards. In joist, header, and rafter applications, 2-by or built-up sections from 2-by material are now subject to being replaced by built-up structural components that use LVL.

Direct replacement of structural components is a simple means of gaining light-frame market penetration, but innovations in processing and design will lead toward development of new structural systems and materials based on structural and material optimizations. Some leaders in the composites field have begun development of this generation of structural composites and I will use their work as examples to illustrate four high-potential approaches to advancing composites as structural lumber substitutes. My discussion of the avenues for growth in composite lumber substitutes is organized as follows:

- Processing innovations and efficiencies leading to reduced cost or improved performance.
- Substitution of composites for solid-sawn lumber products.

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- Innovative designs of components and systems based on the engineered properties of the composites.
- Interdisciplinary education and training of technologists, engineers, scientists, and wood users.

Processing Innovations

Structural wood composite processing implies mass production capability. High-volume production capability is needed in all parts of the process line. Techniques for generating veneers, flakes, strands, and fiber are fairly well established, but other techniques may be needed to produce new types of wood elements (Fig. 1) to satisfy structural requirements and utilization needs. Innovations may also be applied to the mat formation, pressing, or end-jointing phases of the processing.

Wood Elements for Composites

The wood particles that have performed well in randomly oriented structural panel products have traditionally had length-to-thickness ratios of more than 150. These dimensions permit the wood particle and its associated bondline to meet the shear strength requirements of its randomly oriented neighbors in the wood composite. For aligned composites, length-to-thickness ratios in excess of 200 are required for efficient transfer of stresses in bondlines for composite action (14).

Another factor to consider, besides capability to carry bondline stresses, is the statistical variance in properties of the individual elements. For example, a composite made up of wood elements with coefficients of variation (COV) in strength equal to 40 percent, such as is found in solid wood, would theoretically require at least 12 laminations to disperse this variation to bring the COV to 12 percent. Additional laminations are required to maintain this low COV when the laminations are not infinitely long, as was assumed in the example. Several studies (4,11) have shown that flake and veneer ends influence the stress field of aligned wood composites up to 10 lamination thicknesses from the lamination end. A 12-laminate composite would then require wood elements possessing a minimum length

in excess of 240 thicknesses to avoid overlap of these "stress risers."

Thus to substitute composites for 1-1/2-inch-thick lumber, the aligned wood particles should be 1/8 inch or less in thickness (to minimize the number of bondlines while still providing a 12-laminate composite for low COV) and over 30 inches long (to prevent overlap of particle ends). Producing elements with these dimensions is at present limited to veneer peeling and slicing operations. Using smaller elements such as flakes, strands, particles, and fibers for production of 1-1/2-inch-thick material not only increases the adhesive-loading requirements of the composite but also dictates a far less-ordered composite than the laminated veneer material (Fig. 2). Absolute mechanical properties suffer due to reduced in-plane alignment of the wood elements, out-of-plane distortion of wood fibers, wood fiber damage, and springback or thickness swell inherent to compaction of a nonordered composite.

The nonordered composite has distinct advantages in processing, however. Lower quality raw material may be used with lower labor and wood costs than a lumber substitute made with veneer. As the particle size decreases from veneers to flakes to fibers, the quantity of resin needed increases, but greater defect dispersion reduces strength variance. As composite lumber substitutes are developed, each potential manufacturer will need to evaluate each of the aspects that have been discussed to choose a wood element that best fits the resource and technological situation.

Mat Formation

The exploitation of smaller-than-veneer wood elements in structural lumber substitutes will depend on improved technology for handling, blending, and alignment. Handling and blending are difficult for long and narrow flakes or veneer strips which tend to "jack straw" or become entangled with each other on large-volume process lines originally designed for smaller particles. Likewise, efficient blending techniques are needed for large-flake geometries that do not lend themselves to veneer-type glue-spreading

methods. Use of a cheaper wood raw material than veneer sheets may save a manufacturer in production expenses, but if the saw material requires more adhesive for adequate performance, the entire process may prove to be uneconomical.

An example of the use of smaller-than-veneer wood elements is a lumber substitute being developed in Australia (3). Logs and branches are run through a "scrimming" machine which crushes the wood into approximately 1/4- by 1/4-inch prismatic sections that run nearly the length of the log. These wood elements provide the length needed for good bondline stress transfer and are easily made with the low-quality raw material available.

Alignment of veneer sheets is simple because of their large size and consistent geometry. Conversely, the alignment of subveneer particles is difficult because of their smaller size and the variation in dimensions. Mechanical alignment using rotating disks or oscillating parallel plates is possible for uniformly sized wood elements possessing length-to-width ratios in excess of 2, but is more efficient as the ratio increases. A manufacturer whose product is discussed in a subsequent paper in this session uses narrow strips of veneer and maintains excellent mechanical alignment with length-to-width ratios in excess of 100.

Electrostatic alignment offers the potential of aligning furnish such as sawdust, slivers, fibers, or mixtures of furnish types which cannot be mechanically aligned. Preliminary work shows that electrostatic alignment provides ratios of bending stiffness parallel (MOE_{II}) to bending stiffness perpendicular (MOE_⊥) to the panel axis of up to 8, independent of particle size (18). By way of comparison, screened and tightly controlled dimensions of flake furnish can be aligned mechanically to MOE ratios near 13 (5).

The composite material's mat formation offers the potential for optimizing the placement of varying grades, qualities, or types of wood elements within the product to produce enhanced properties. This generates a quality profile in the product (Fig. 3). In LVL this quality profile may take the form of scarf-jointed veneers as the outer plies or high-quality material at

the surfaces with lower quality veneers in the inner plies as determined by visual or ultrasonic grading (20). For subveneer elements used in a composite lumber substitute, the quality profiling may exploit such particle characteristics as flaking method, screen fraction, resin content or other chemical treatments. This quality profiling may extend in the direction perpendicular to the product's faces, or it may be perpendicular to the long axis of the product for uses where edgewise strength or stiffness are important. Composite material can therefore be optimized for performance properties in all three dimensions.

Another concept in mat formation for lumber substitutes is the use of man-made reinforcements, such as E- or S-glass, graphite, or aramid fibers (15). Products containing such reinforcements can have more strength, stiffness, or durability than could be obtained with a simple wood composite, while retaining the weight and workability of a wood-based product. The declining cost of synthetic fibers (caused by rising volumes of production) will make them viable options for improving composite performance.

Pressing

Compaction and adhesive curing are critical to high-volume/low-cost production of substitutes for nominal 2-inch lumber. Hot-pressing of composites using traditional durable thermosetting resins require more than 10 minutes to achieve resin cure for the 1-1/2-inch thickness. Production capacity could be increased if press systems or adhesives are developed which can utilize steam or catalyst injection pressing technology (7), preheating of the laminate or mat (9), or microwave-curing techniques. Both basic and applied research in this area have high potential for reducing production costs of lumber substitutes.

A natural part of the hot-pressing operation is the formation of a density profile through the thickness or across the width of the product (Fig. 4). Though not manipulated to a significant extent in today's composite products, it provides an opportunity far further control of product properties along with fiber alignment and average

product density. This may be exploited by creating a density profile (in addition to any quality profile given to the product) which improves the flatwise or edgewise flexural properties of the composite without loss of axial properties. This density profile may be an advantage in meeting other needed performance criteria as well. Use of truss plates or bolted connections and surfacing of the material are enhanced by the high-density faces of the product.

End-jointing

Another facet of processing potential lies in end jointing of lumber Substitutes to achieve long material lengths when producing material in a noncontinuous pressing scheme. Recent study of end jointing 3/4- and 1-1/2-inch LVL materials (24) showed that several types of scarf and finger joints provide good tensile strength and compare well with even the highest grades of visually-inspected structural lumber. This process option opens the door for production of LVL in plywood plants using visually graded veneer. End jointing and relamination of this 8-foot LVL can provide a high-strength lumber substitute.

Substitution of Composites for Solid-Sawn Products

The simplest method of gaining acceptance for a new product in the marketplace is to emulate an existing product's form and properties with an attendant reduction in market price or lifetime cost. Though this may have dictated the philosophies of early composite panel marketing, today's producers of substitutes for structural lumber have a product with significantly better properties than solid-sawn lumber (SSL). The declining properties of SSL, caused by either to lower qualities of logs or intensive grading, have fueled users' desires for a reliable/consistent material source.

Product Characterization

Attainment of the basic engineering design properties expected of lumber is a small part of providing a viable lumber substitute. Aside from meeting the obvious axial,

flexural, and shear mechanical requirements, a lumber substitute must address fastener performance, duration of load effects, durability, size effects, moisture effects, and dimensional properties. Complete characterization of the product's properties also require testing parallel and perpendicular to the primary orientation direction for most properties and through the thickness of the material for compression, interlaminar tension, and shear.

As if the program of testing outlined above were not extensive enough, each user of the lumber substitute has questions relating to his or her own use of the product. What data do you have on the material's electrical and thermal conductivity? acoustical properties? fire performance? toughness? or frictional constants? These seem to be reasonable questions until you look for a basis or a standard for comparing the substitute with SSL. Many of the properties we take for granted in SSL have not been catalogued, even for the most common species.

For example, a building code authority may question the fire performance of your lumber substitute. Two options present themselves: (1) perform fire tests on typical assemblies which use your material or (2) test your material under simple loading as a single building element, test SSL in the same manner, and attempt to rationally relate the results to any end assembly. Because use of SSL predates the building codes and standards, code authorities accepted it without the need to characterize its performance. Thus, manufacturers of lumber substitutes will find it difficult to gain blanket acceptance as a lumber product for even the most basic building elements until they have generated data on their product as well as the SSL it replaces.

The first wave of substitutes for structural lumber, the LVL products, possess physical and mechanical properties which are quite similar to those of SSL. As new materials come into the marketplace they will have smaller wood elements, more (or less) adhesive, higher densities, and possess wider ranges (and possibly lower variance) of mechanical properties. Performing less like SSL than LVL, these second-generation

lumber substitutes will encounter stiffer market resistance than LVL unless significant price differentials hasten their acceptance.

Mechanical Performance Limitations

Not knowing what form these lumber substitutes will take in the future prompts one to question: What limitations exist on composite wood material's mechanical performance?

To answer this, consider the basic wood element of structure, the wood fiber. Individual fibers have ultimate tensile strengths of more than 200,000 lb/in.² (16). Although each species has its own characteristics, clear wood (0.65 g/cc) tensile strengths exceed 20,000 lb/in.², only 10 percent of the fiber strength. Obviously, the fiber-fiber bonds are weak links in the solid wood structure.

The density of wood composites could theoretically reach 1.4 g/cc. This is approximately the density of a mixture of 80 percent cellulose and 20 percent lignin (i.e. no air or voids). Aligned flakeboards have been made to a density of 1.2 g/cc and laminated veneers have been densified to 1.4 g/cc. Tensile strengths in excess of 20,000 lb/in.² are reported for flakeboards with good flake alignment and density of 1.0 g/cc (6). The highest reported strengths are for densified veneers (1.4 g/cc) having reached tensile strengths of 45,000 lb/in.² (23). This strength value is nearly the upper boundary of strength for non-chemically treated wood composites.

Stiffness performance limits may be rationalized in a manner similar to strength. Young's modulus for single wood fibers range from 0.8 million lb/in.² for earlywood fibers to 8.2 million lb/in.² for latewood fibers. Clear wood, being a mixture of earlywood, latewood, and air, typically has moduli in the range of 1.0-2.2 million lb/in.² (0.65 g/cc). Compressed veneer (1.4 g/cc) materials have reached moduli of 4.6 million lb/in.² (23), whereas aligned flakeboards (1.0 g/cc) have been reported at 4.1 million lb/in.² (6). Until techniques are developed to separate earlywood and latewood, these high-density composites may represent the limits on stiffness potential.

Variability

Strength and stiffness potentials for composites are encouraging but do not show the entire picture. Engineered uses for these materials require an assessment of working stresses. Derivation of these stresses by either the exclusion Limit philosophy or a reliability-based design procedure must account for the materials' mechanical property variability (Fig. 5). Reconstitution of wood products offers the potential of reducing variability by dispersion of natural wood defects. Reconstitution also offers the possibility of increasing variability through poor processing control. Published coefficients of variation show that reducing particle size used in the composite will decrease variation. This reduction in variation has significance when determining the 5 percent exclusion limit (assuming a normal distribution of the population) (Table 1).

The options available for engineering lumber substitutes are multidimensional. It is apparent that with engineered wood elements, adequate alignment, and densification, almost any grade or species of solid-sawn lumber may be effectively replaced by a composite product with superior basic mechanical properties. There are, however, a number of other properties to be considered in evaluating structural lumber substitutes.

Additional Properties

One of the larger design stress reduction factors applied to solid wood is the duration of load (DOL) adjustment. Although only limited work has been done on the creep-rupture behavior of LVL and PSL, these studies do show improved performance in time-to-failure under load when compared to SSL stressed to the same percentage of design stresses in bending. It is uncertain at this time how lumber substitute manufacturers will take advantage of these reduced DOL factors.

Another factor is the durability and dimensional stability in moist or exterior environments. This factor has traditionally been of concern for wood composites and nonveneered products in particular. Dimensional stability may be of less concern through improvements in pressing

schedules, use of additives, and bulking of the composites by acetylation (21). Tests for durability performance presently used in panel product standards are much more severe than exposures expected in end-use applications. Additional study of reasonable durability tests and condition-of-use adjustments are necessary before traditionally processed (nonordered) composites can be viable SSL substitutes.

Fastener performance and effect of treatments are other arenas of research needs which require exploration. Studies of LVL materials show that the veneers' lathe checks reduce horizontal shear strength perpendicular to the glue-lines (12). This same phenomena reduces fastener performance when the fastener is inserted perpendicular to the glue-lines (10). Ease of treating composite materials prior to the bonding operation and after pressing make definition of treatment effects particularly important for composite lumber substitutes.

Innovative Designs of Components and Systems

Increased knowledge of processing and performance relationships for composite materials allows multi-dimensional design of these materials to produce optimized structural components or systems. These innovations may be in the form of materials engineering of simple geometric shapes such as flat panels or rectangular beams. Another approach could be optimizing the component's geometry for a given structural need such as the design of an I-beam. These components could be made by secondary processing of currently available materials such as plywood, flakeboard, or LVL. The final design option is optimizing material and geometry with no constraints on material or form of the product, such as the design approach that applies to molded structural components.

Material/Product Engineering

All of the concepts for engineering a composite material have been introduced in the earlier discussion of processing. As a reinforcement of these concepts, the dimensions of engineering the material include raw material quality

(but not limited to, species, equipment used, geometry, or a nondestructive test parameter), fiber alignment, and density. When producing flat platen-pressed lumber substitutes the design freedom is only in the thickness direction for LVL but is two-dimensional for sub-veneer composites (Figs. 3 and 4).

Two examples of the material and product engineering possibilities for flat products are offered. The first is a roof-decking panel (Fig. 6) (8) which has design limits on flatwise bending deflection and strength. Using a given high-density species, the designers' goal was a minimum weight panel. Two flake qualities were chosen: high quality for the panel faces, lower quality in the core. Alignment perpendicular to the support directions was used for the faces while the core had no orientation (random) for shear strength and dimensional stability. The density profile through the thickness of the panel was effected by trial and error approaches which led to the choice of the final pressing schedule.

A second example of flat-panel material/product engineering is a reconstituted joist product designed for replacement of SSL 2 x 10 or 2 x 12 members in floor systems (Fig. 7). Again, the manufacturing variables were manipulated but this product contains horizontal variations in the material properties to provide the needed edgewise bending properties.

Secondary Processing

Fabrication of a structural component may be best achieved by some secondary manufacturing steps such as bonding or fastening of different materials. The concept of mixing material types to produce common structural shapes is readily apparent in a number of marketed I-beam (Fig. 8) and box beam sections for floor joists. These sections use SSL or LVL in the flanges which require high axial strength and stiffness. Webs of such members, glued to the flanges, must possess high shear strength and stiffness which are attributes of composite panel products. Some perceived problems with the use of these beams in place of SSL joists in light-frame construction are the altered dynamic

behavior of the floor system, changes in fire performance, and the possible long-term creep deflection. These are valid questions which need to be studied for each new component offered to the engineering and construction community.

Fabrication processes, commonly employed with SSL in truss manufacture using bolted connections or toothed truss plates, may be considered generally compatible with composite lumber substitutes. However, some reduction in shear strength of LVL in the plane of the veneer's lathe checks should be recognized for these uses. Sub-veneer composites may perform better than LVL and SSL because of better splitting resistance, shear strength, and fracture toughness than SSL due to the dispersion of wood fibers off the primary alignment axes.

A method of producing structural shapes that has promise for use of composites is that of panel folding. Machining of deep V-grooves in the panel precedes the folding, and subsequent bonding, along the fold line. These miter-folded sections have potential as engineered structural shapes such as channels, square, hexagonal, or octagonal columns (1), wall or floor sections, and box beams.

Molded Components

Molding of composite wood products may present the greatest potential for engineering materials and products. Aside from the other dimensions of composite processing, molding offers the potential for varying the thickness and relative position of the product surface. Early molded particleboard products were nonstructural as their primary function was to duplicate a complex geometry.

Molding of high-strength structural components entails use of large flakes and thicker sections than are associated with traditional molded products. Products that lend themselves to a continuous pressing operation will have flexibility in product length and will utilize the press investment better than a cycled press. One-step molding of structurally efficient I-sections, corrugated or rib-stiffened decking and sheathing, and open-section trusses (Fig. 9) will open doors to

engineered wood structures and stimulate the development of new structural systems.

There is, of course, much more research which should be done to define the relationships between processing and performance before the marriage of material and product engineering becomes totally workable. The examples presented show the creative flexibility that will be possible by understanding both the engineering and processing sides of composite wood products.

Interdisciplinary Education

Growth in use of structural lumber substitutes is possible only with the interaction of producers and users at all levels. Technology transfer (TT) systems need to be placed across widely divergent disciplines, including building contractors and scientists dealing in solid mechanics and polymer/adhesive chemistry. This must also be a horizontal information transfer effort at all levels. Sharing of research data and analysis techniques is a part of this horizontal TT effort, but the user-to-users discussions of experiences with use of lumber substitutes is where new sales and expanded uses begin.

Vertical information transfer between disciplines such as forest products technologists, engineers, architects, foresters, materials scientists, chemists, contractors, and building officials is an ongoing and dynamic task. As new technology concepts or problems surface, they must be brought before the appropriate audience for action. An example of insufficient TT occurred in the aircraft industry in the mid-to-late 1930's. Use of nondurable adhesives had been prevalent in manufacture of aircraft components such as laminated spars, ribs, and plywood fuselage and wing skins. Maintenance of the sealants and surface finishes was ignored, aircraft were stored outside under tarpaulins which remained on the craft, and predictably, laminated members and plywood skins began to deteriorate. Instead of coming back to the adhesives technologists of the era, the majority of the aircraft industry blamed the problems on "wood" and turned to the newly industrialized metal called aluminum. Had

sufficient TT ties been made with this industry, the migration to the metal aircraft would have been reduced. The 1980's aircraft industry does not have a high awareness of wood's mechanical properties. We have some reeducating to do.

Structural composite materials, along with their capability for engineered performance, may be conceived as being too complex for designers, engineers, architects, or materials specifiers to analyze within a structural assembly. Also, the diversity of products that will be available on the market will probably make a generic approach to setting design properties unworkable. To simplify the designer's work, an association that supported structural composite manufacturers could provide composite properties on a computerized database which would be updated as new products and mill data became available. This system would provide interactive support for existing products being used in deterministic designs, allow quick incorporation of new materials' properties into reliability-based designs, and may be an effective two-way medium for field support of these materials and the structural elements made from them.

Summary

The potential for substitution of structural wood composites for solid-sawn lumber products depends upon three factors: economics, technology, and creativity. This paper examines the technological potential for composite Lumber substitutes. In view of the advances made by composites in the last decade, the potential for their continued introduction looks very good.

Technological limitations of existing composite processes and products are reviewed in the context of the present LVL, flakeboard, and fiber/paper industries. The processes of particle generation; mat forming for alignment, density, and quality of raw material; and pressing provide sufficient opportunities for production of viable structural lumber substitutes. Simple replacement of solid-sawn lumber with these composites is occurring now, but even greater market potential exists in engineered applications such as I-beams and trusses. Further use of the

processing options of molding will allow more design innovation than was ever possible with dimensioned lumber. Key to the further development of these materials in structural markets is the continued education of wood users and researchers at all levels to assure proper and safe applications.

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Table 1.--THE EFFECT OF VARIABILITY ON THE USUAL
BASIS FOR ESTABLISHING DESIGN STRESSES,
THE 5 PERCENT EXCLUSION LIMIT

	Ultimate tensile strength (UTS)	COV	5 percent exclusion limit (EL) ¹	Ratio of $\frac{5\% \text{ EL}}{\text{UTS}}$
	<u>1,000 lb/in.²</u>	<u>%</u>	<u>1,000 lb/in.²</u>	
Clear wood (23)	20	20	13.6	0.68
Visually graded lumber (19)	7	40	2.2	.31
LVL (13)	7	18	4.6	.66
Oriented flakeboard (6)	7	12	4.8	.69
MDF (22)	2.5	8	2.2	.88

¹5 percent exclusion limit = UTS - 1.6 (COV) UTS.

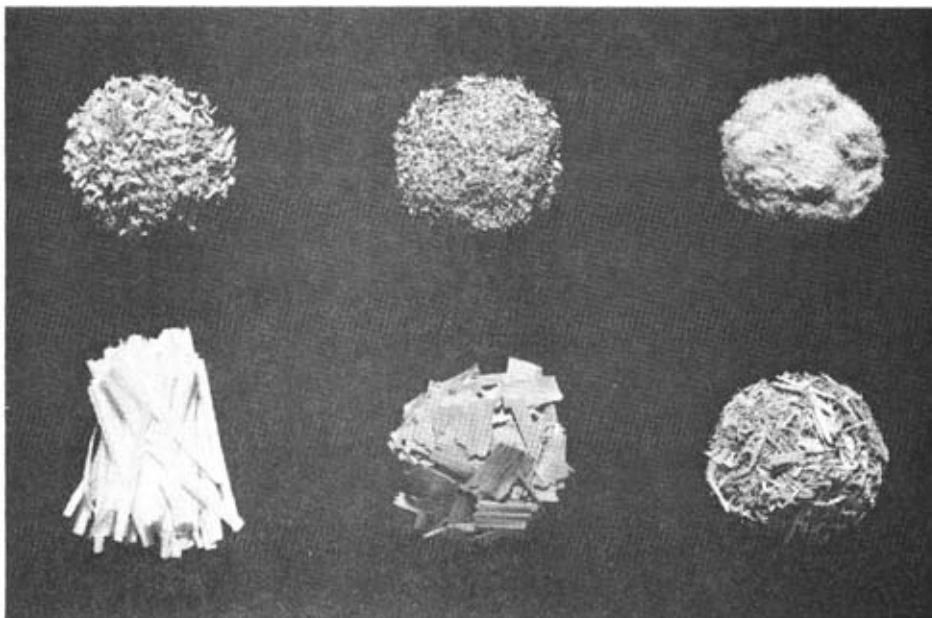


Figure 1. Wood elements for use in sub-veneer wood composites. (M84 0289)

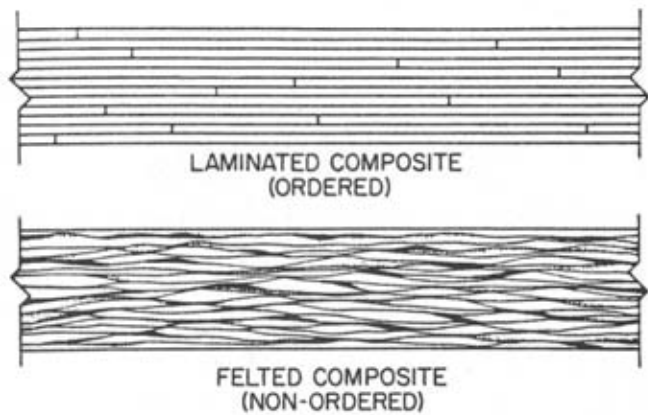


Figure 2. Schematic of products made by the two basic reconstitution processes. (ML84 5856)

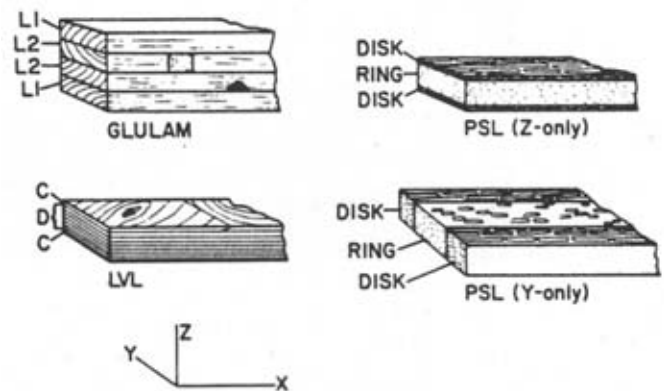


Figure 3. Quality profile concept for several composite products. (ML84 5857)

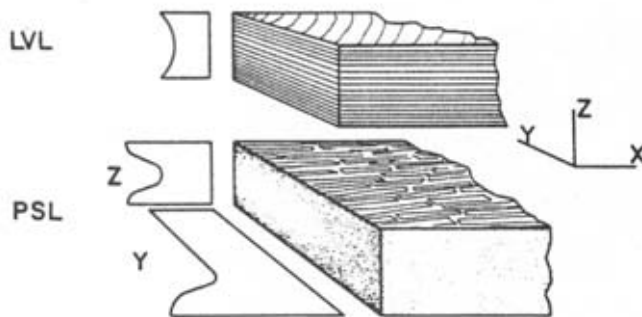


Figure 4. Density profile concept can be used to control composite properties. (ML84 5858)

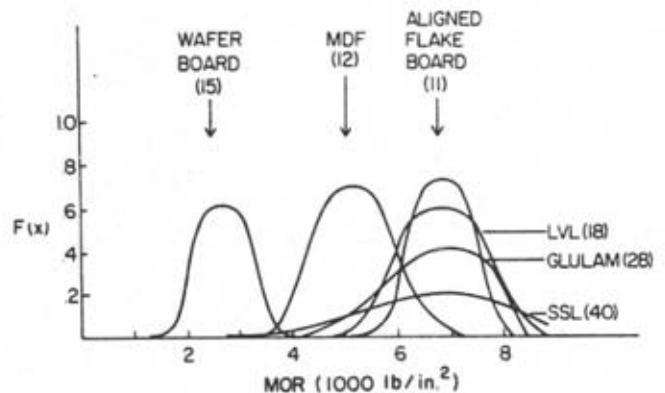


Figure 5. Strength distributions for various wood materials assuming normality. (Coefficient of variation in parentheses.) (ML84 5855)

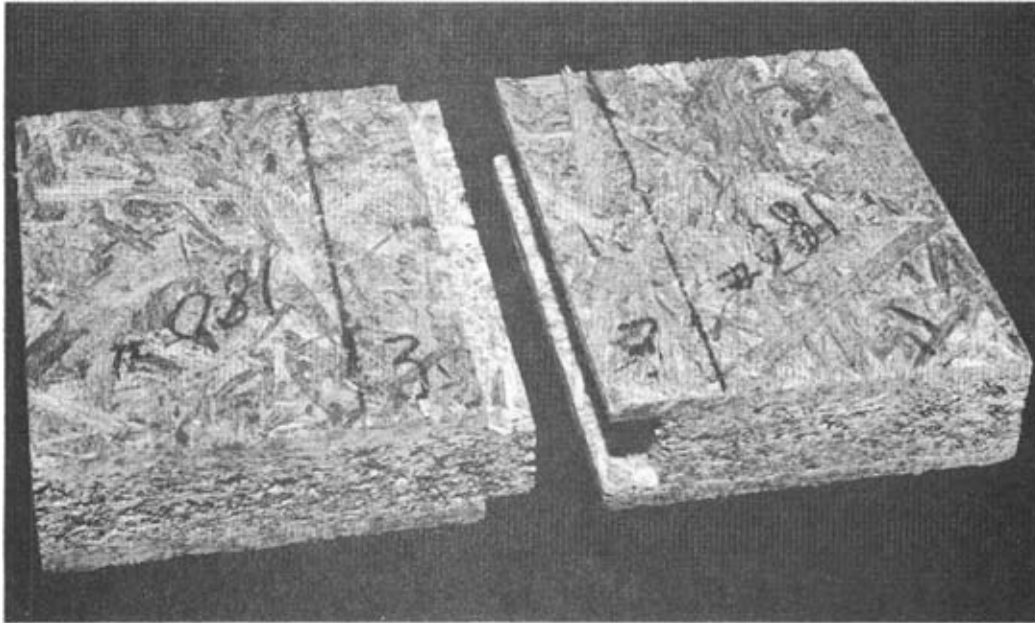


Figure 6. Layered red oak structural particleboard designed for roof deck applications. (M147 726)

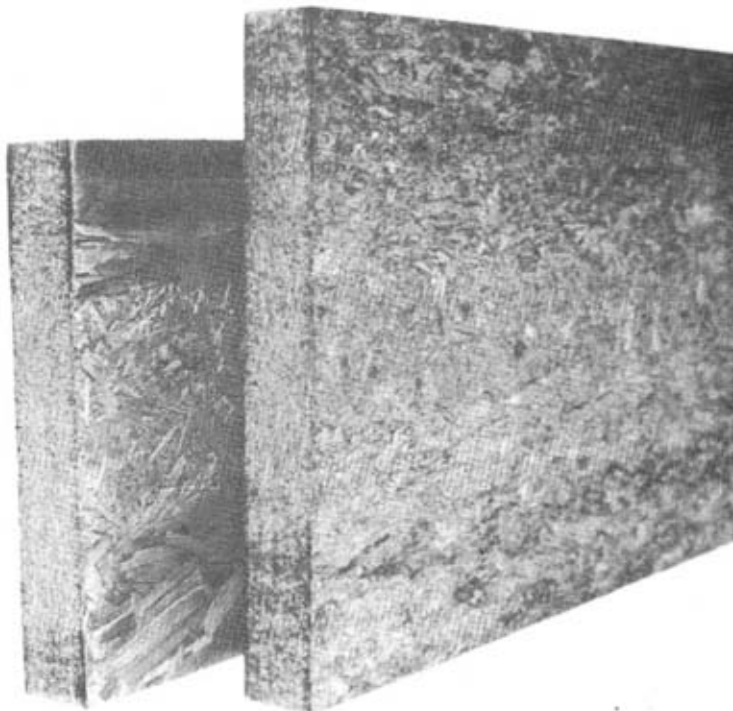


Figure 7. Reconstituted joist products with optimized placement of fiber density, alignment and quality to perform as floor joists for light-frame construction. (M84 0482-11)



Figure 8. I-beam components having LVL flanges and webs of hardboard, flakeboard or plywood. (M84 0468)

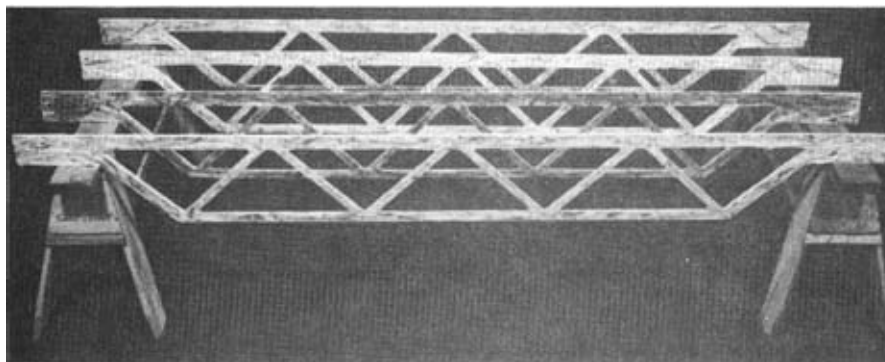


Figure 9. Molded structural trusses. (M84 0468)