OPTIMIZATION OF COMPOSITE WOOD STRUCTURAL COMPONENTS: PROCESSING AND DESIGN CHOICES

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ABSTRACT

Decreasing size and quality of the world's forest resources are responsible for interest in producing composite wood structural components. Process and design optimization methods are offered in this paper. Processing concepts for wood composite structural products are reviewed to illustrate manufacturing boundaries and areas of high potential. Structural optimization principles are introduced to provide an overview of design requirements for various structural elements. An approach to the optimal design of a simple joist is presented. The approach allows the optimization for a variety of possible limit states using minimum weight as the objective function. Three aligned flake materials are used in examples of: (1) minimum weight of the 2 by 10 joists and (2) maximum stiffness-to-weight ratio for a uniformly loaded long span. Results from the optimizations show how beam geometry affects efficiency. The beam volume that is critically stressed in shear is seen as controlling the efficiency

of rectangular members. Alternative shapes are introduced to minimize the shear critical volume of composite material in flexural members.

INTRODUCTION

Wood has been a basic, essential, and ever-renewing resource providing energy and shelter for mankind for thousands of years. In an advanced industrial economy such as the United States, the production of wood exceeds that of steel, aluminum, plastics, and cement combined (1). Wood is a renewable resource. However, it is an over-simplification to assume that the supply is without limit and, more particularly, that sufficient material of construction quality will be available in the future.

A large proportion of timber is harvested from virgin forest. The relentless demand for agricultural land has reduced this stock progressively to just under 20% of the world's land surface. Where forest regeneration is slow, as in Scandinavia for example, the rate of extraction is barely matched by new growth. Nevertheless, recent global estimates (2) suggest that world forests can sustain a quadrupling of the current annual harvest if intensive forest management is practiced. Regardless of the forestry practices used, there already is a shortage of large, defect-free logs for use in sawmills and plywood plants.

The answer to these supply problems lies with a broad group of materials known as reconstituted wood or wood composites. It is possible to control the density, the anisotropy, the dimensional properties, and the mechanical properties of these composite wood materials.

Engineering the material to suit particular needs is the forte of composites, and the properties are always a function of the manufacturing process. Understanding the complexity of the wood material and processing it to take advantage of its properties in engineering applications are the bases for moving into the structural components markets.

PROCESSING OPTIONS FOR COMPOSITE WOOD STRUCTURAL COMPONENTS

The basic steps in the manufacture of wood composites are generation of raw material or wood furnish adhesive application, mat formation, pressing, and secondary processes. Each of the operations has an interaction with the next process, providing an infinite number of processing options. A brief overview of the processing technologies which can influence the composite wood materials available for structural components will be reviewed here.

Raw Materials

Raw materials available for making wood composites range from veneer to flakes to fibers. Peeler-quality logs are needed for veneer production, but low quality logs and forest residue are acceptable for generation of the subveneer elements of flakes, particles, or fibers. Specially designed equipment is available for producing dimensionally consistent wood elements that resemble small pieces of veneer.

Experience has shown that length-to-thickness ratios of the wood elements must exceed 200 to provide high strength unidirectional wood composites (3). Few of the commercially available flakers used in the industry today can produce the length-to-thickness ratios required for exploiting the wood material's strength. It is generally accepted, at this time, that truly "unidirectional" wood composites can be produced in processes using veneer sheets or strips. Though the veneer pealing operation is an expensive way of producing a raw material, it is the only cutting operation that provides uniform sizes of furnish for high-strength wood composites.

Additional technology and equipment development is needed to enable the cutting of high-quality flakes for use in composite wood structural components. Given the declining quality of logs available for harvest, the solutions to this task are not trivial and represent a great potential.

Adhesives

Use of adhesives in wood composites represents the single largest cost item in most particleboard and flakeboard processes. Unless innovative adhesives are introduced to the composites industry, this aspect of the process should not be expected to change greatly as composite components come into the marketplace. Durability concerns, however, may dictate increased loadings of adhesive to assure performance in the wider ranges of environments to which structural members may be exposed.

Mat Formation

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. For example, in laminated veneer lumber (LVL) this quality profile may take the form of higher quality material at the surfaces as determined by visual or ultrasonic grading. For subveneer elements the quality profiling may exploit such particle characteristics as flaking method, resin content, or other chemical treatments.

Consistent alignment of subveneer particles using rotating disks or oscillating parallel plates is possible for wood subunits possessing length–to–width ratios in excess of 5. Screened and tightly controlled dimensions of flake furnish can be aligned mechanically to modulus of elasticity (MOE) ratios near 13 (4). Electrostatic alignment offers the potential of aligning furnish which cannot be aligned mechanically such as sawdust, slivers, or fiber furnish types. Electrostatic alignment provides ratios of flexural stiffness parallel and perpendicular to the panel axes of up to 8, independent of particle size (5).

Looking at solid wood as an example of good fiber alignment efficiency, ratios of flexural stiffness between 15 and 25 can be found. Thus, with the alignment potentials discussed previously, composite products, aligned throughout their thickness, fall short of solid wood stiffnesses on the order of 15-45%. This shortfall can be eliminated by increases in density of the composite. With alignment technology as it presently stands, any composite wood structural component is sure to be heavier than its solid wood counterpart unless the component and process is designed to optimize the material use, perhaps, through such a simple refinement as varying the product density by control of the pressing phase.

Pressing

The hot pressing or consolidation of the wood mat is, perhaps, one of the least understood parts of the composite wood process. One of the most important phenomena in hot pressing is the formation of a density variation in composite panel products. This is accepted widely in the industry, yet, active control or manipulation of this "density profile" is practiced only on an empirical basis. Recently, attempts have been made to quantify the processes occurring (6). Simple control of the panel density variation from one face to the other can yield increases in flexural stiffness and strength and surface hardness. On the other hand, decreased internal bond (IB) strength, interlaminar shear strength, and fastening strengths must be accepted.

As the composite industry turns to structural components, increasing interest will be shown for molding of efficient Sections. These sections may be for direct replacement of solid wood components, such as molded I-sections to replace joists. Molded products also have the potential to replace assemblies of components such as wall or floor assemblies with corrugated or T-panels made entirely of composite materials. Molding techniques, however, are associated intimately with the hot-pressing part of the composite wood process, and, as such, represent a major development of process machinery. Some secondary processing of a flat panel product after pressing is another alternative for increasing the efficiency of structural components.

Secondary Processes

Fabrication of a structural component may be best achieved by some secondary manufacturing steps, such as bonding or fastening of different materials. The concepts of mixing material types to produce common structural shapes is apparent in a number of marketed I-beam and box-beam sections. These sections use lumber or LVL in the beam 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 lumber joists in light-frame construction, are the changes in the floor system's dynamics, fire performance, and the longterm creep deflection. These are valid questions which need to be studied for each new component offered to the engineering community.

A method of producing structural shapes that has promise for the use of wood 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 promise as channels, square-, hexagonal-, or octagonal-columns (7) , wall or floor sections, and box beams.

STRUCTURAL OPTIMIZATION BASICS

Structural optimization is the process of determining optimal values of design variables which minimize or maximize a specific objective function. These optimal values must satisfy all mechanical and geometrical conditions which are termed constraints. The complexity of achieving the objective of an optimization with more than two design variables and greater than two constraints limits modern optimizations to mathematical programming solutions.

The overriding engineering goal of designing efficient systems and, more specifically, efficient structures, generally has made structure weight the objective function to be minimized. Other objective functions such as reliability, energy requirements, or actual cost may be chosen as well. Transportation system applications frequently require minimum weight designs to reduce lifetime costs of moving the vehicle's weight. Static structures (buildings, towers, bridges, etc.) are designed to a given reliability level, but the objective function is nearly always minimum costs.

Structural systems considered for optimization are idealized as discrete elements such as rods, beams, or plates. These elements are then mathematically assembled into components or assemblies such as I-, channel-, or T-sections (sandwich panels, box beams, or trusses, to name a few major ones). Design variables may be cross-sectional variables or other parameters which describe the structural configuration or the material properties. Examples of cross-sectional variables are area, section modulus, or thickness.

Restrictions that must be satisfied for the design to be acceptable are termed constraints. Typically, these restrictions, on performance of the structural system, are on stresses or deflections. Other constraints that may be imposed may dictate such quantities as thickness of the structure. These types of constraints, called side constraints, may be aesthetic in nature or be dictated by tradition.

Commonly, the solution approach that is commonly used in optimized designs is intended to produce simultaneous modes of failure. Each mode of failure must have appropriate levels of safety or reliability applied which distorts the simplicity of the method. In its basic form, all members and all recognized modes of failure should occur at the same load level. Thus, the optimization consists of iteratively resizing each member to produce the maximum allowable stress at the critical load condition.

SIMPLE JOIST OPTIMIZATION

Application of the processing and optimization concepts to a simple span, rectangular composite wood member will be discussed in this section. Details of the processing and design procedures will not be presented here as they will be published elsewhere (8). The processing constraints were enforced as follows:

1. Section geometry is rectangular, 3.8 by 23.5 cm (1.5 by 9.25 in.). These dimensions correspond to nominal 2 by 10 lumber.
2. Only two flake types are to be used in each beam design. One type for the edges of the member (or flanges) and another type for the center or web (Figure 1).
3. Alignment of flakes, if any, is set at 700 (4).
4. Maximum density of the composite is limited to 0.9 g/cc (56 pcf).
5. Density is to be constant within a given flake type in the beam.

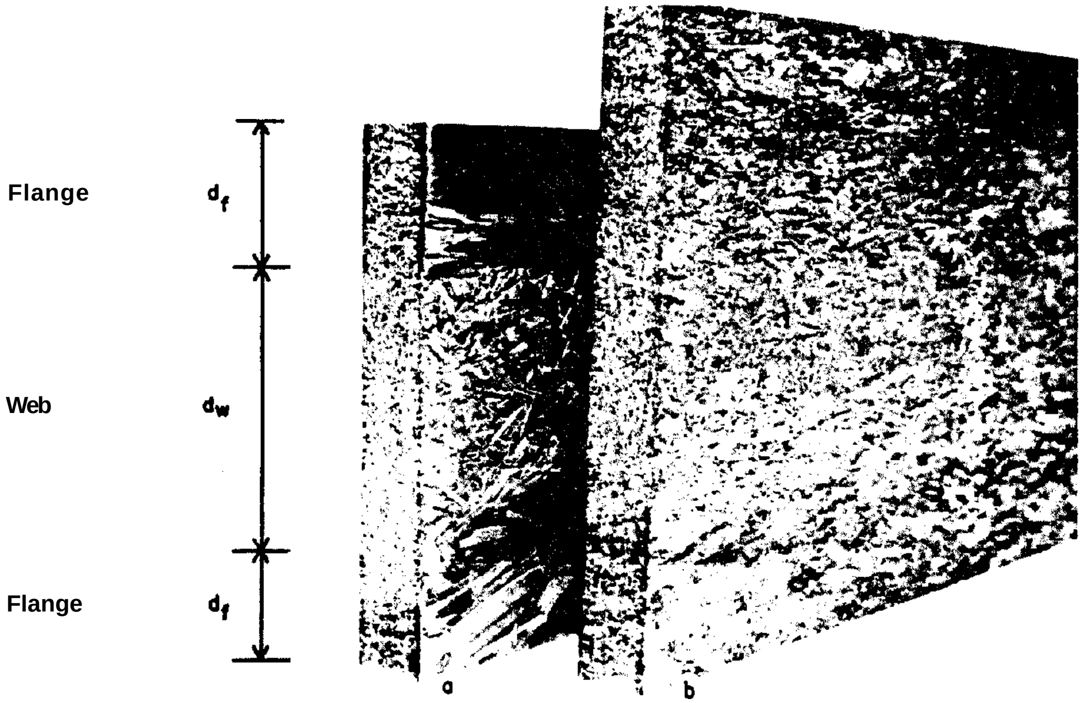

Figure 1.– –*Twoomposite wood joist sections, (a) 2 by IO and (b) 2 by 12, illustrating the flange (d^f = depth of flange) and web (d^W = depth of web) dimension for rectangular sections*

The structural constraints applied are:

1. Deflection is limited to the span (1) length divided by 360 (1/360).
2. Stresses will be limited to the maximum allowable in flexure, bearing compression perpendicular to alignment, and in–plane shear.

The allowable unit stresses for each flake type and density were determined from average test values (8) or previously published data (4, 9).

In these examples, the adjustments for fifth percentiles, duration of load and size effects, and a factor of safety produced a 3.31 divisor to be applied to average stress values (11).

Three flake types ranging from high to low quality were used in the optimization model. The flakes produced on a Turner lathe flaker were deemed the highest quality of a nominal size of 0.51 mm thick by 12.7 mm wide by 178 mm long (0.020 in. thick by 0.5 in. wide by 7.0 in. long). Disk-cut flakes were classified as intermediate in quality at a nominal size of 0.51 mm thick by 12.7 mm wide by 76.2 mm long (9.920 in. thick by 0.5 in. wide by 3 in. long). The lowest quality flakes were ring-cut from chips and were nominally 0.51 mm thick by 25.4 mm long (0.020 in. thick by 1 in. long). Since the alignment was set by the process constraint, only the density was permitted to be adjusted for each flake type used in the composite joist configuration. Material properties are given in Table 1.

Table 1.--Allowable properties of flange materials used in the optimization model (SG = 0.9)

Flake Type	Stiffness MPa (psi)	Bending strength MPa (psi)	Compression perpendicular MPa (psi)
Aligned Turner* lathe	24.8×10^3 (3.60×10^6)	46.6 (6760)	4.13 (700)
Aligned disk-cut	19.3×10^3 (2.80×10^6)	33.6 (4870)	4.8 (700)
Aligned ring-cut	11.0×10^3 4$1.60 \times 10^6$)	17.7 (2560)	4.6 (670)

*Produced on a Turner lathe flaker

The center, or web, of the composite joist is random (no orientation) and as such contributes little to the flexural stiffness of the joist. The moment of inertia for the web material of a beam is minimal (≤ 10%) when more than 30% is flange material and the flake type, density, and alignment of the web and flange are identical (Figure 2). Thus, the assumption of no flexural stiffness gain from the web is a small error, but conservative in design.

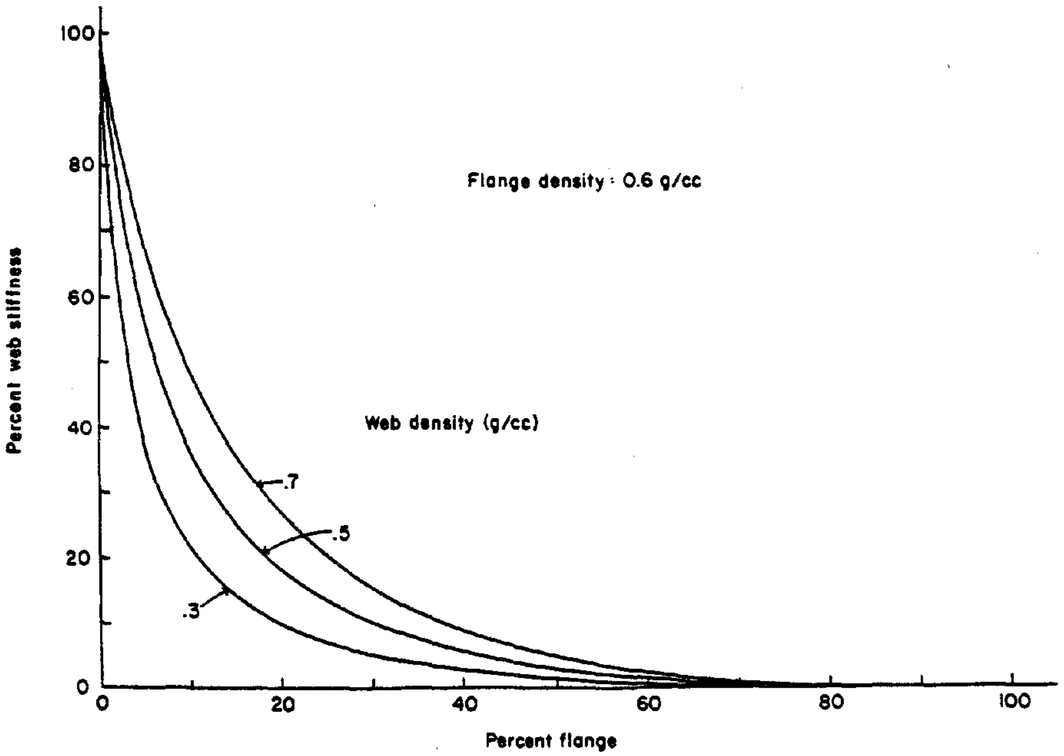

Figure 2.--*Contribution of the web-to-beamstiffness with alignment and flake-type uniform throughout beam*

Shear stresses were assumed to be carried in the classic parabolic distribution. The allowable in-plane shear strength of the random ring-cut flake web material is

$$F_v = -3.35 + 9.76\ (SG) \quad \text{MPa} \tag{1}$$
$$(F_v = -486 + 1415\ (SG))\ (\text{psi})$$

where, F_V = allowable in-plane shear stress

SG = specific gravity of the material.

Note that in this simple expression relating shear strength and density, the allowable shear strength is assumed to be zero up to a density of 0.34 g/cc.

Example 1

Matching the Performance of 2 by 10 Solid-Sawn Joists Under Residential Floor Loads

No. 2 Douglas fir-larch and No. 2 Englemann spruce-alpine fir 2 by 10s (Western Wood Products Association [WWPA]) were chosen as the structural elements to match in this optimization. The structural constraints were defined as follows:

for deflection control or stiffness

$$EI_f \leq 675\, w' l^3 \qquad (2)$$

flexural stress,

$$F_b \leq w\, l^2 d / 16\, I_f \qquad (3)$$

bearing or compression perpendicular

$$F_c \leq wl/4b, \qquad (4)$$

and in-plane shear stress

$$F_v \leq 3\, wl/4bd \qquad (5)$$

Where,

E = modulus of elasticity (MOE) of the beam flange material in flexure,
I_f = moment of inertia of the beam flange around an axis through the center of the beam, parallel to the narrow face,
w = force per unit length, live and dead load,
w' = force per unit length, live load only,
l = simple span length,
b = small dimension of joist cross section, 3.8 cm (1.5 in.),
d = large dimension of joist cross section, 23.5 cm (9.25 in.)
F_b = allowable extreme fiber stress, and F_c = allowable compression perpendicular stress.

Using the process constraints as guidelines, the structural design of the composite beams proceeded with the assumption that the flanges were to be made of the highest density composite material with either stiffness or strength of the member controlling the depth of the flanges. Composite material at the 0.9 g/cc density was the most efficient method of providing strength and stiffness for the beams, but only the stiffness constraint controlled the actual designs. Flexural stresses and compression perpendicular stresses were sufficiently low to not dictate design parameters.

In-plane shear strength was the only structural constraint on the web of these beams. Since the loading and span were dictated by the solid-sawn 2 by 10 lumber capabilities, the density of the web remains fixed, regardless of flake type, for any composite beam product designed to match a given 2 by 10 lumber product.

The densities and dimensions of the optimized joists (Table 2) that meet the structural needs of the solid-sawn material show no weight, and hence material savings, in processing this structural item. Rather the opposite is true. Average density of the composite joists is between 8% and 60% higher than their solid wood competition and the high density (0.9 g/cc) of the flanges may make fastening difficult. Note that the aligned ring-cut flake material could not match the stiffness of the Douglas fir-larch (DF-L) lumber. This may be seen easily by comparing the DF-L stiffness (Table 2) (11.7×10^3) with the ring-cut flake material stiffness at 0.9 g/cc (Table 1) (11.0×10^3 MPa). Thus, even with the entire composite beam made of aligned ring-cut flakes (i.e., no web) at a density of 0.9 g/cc, the flake material is incapable of matching the DF-L stiffness. The No. 2 Englemann spruce was chosen to permit an evaluation of the aligned ring-cut flake material.

The previously discussed designs were optimized within the constraints imposed. Obviously the greater the number of constraints, the fewer design choices are available. Designers working wood members in flexure, will attest that lightly loaded beams usually are deflection critical. Optimization of the stiffness of 2 by 10 composite beams may better illustrate the optimization principles.

Example 2

Optimizing the Flexural Stiffness of 2 by 10 Composite Beams Over a Uniformly Loaded 6 m (20 ft) Span

Given the process and structural constraints listed previously, the objective function for this example is to maximize the stiffness of the component in relation to its weight. Thus, the maximum stiffness/weight ratio is the objective. Again, the structural constraints are as listed in Example 1.

Table 2.--Properties, dimensions, and densities of composite wood and solid-sawn 2 by 10 joists determined from structural requirements

Material	Beam stiffness 10^3 MPa	Beam stiffness (10^6 psi)	SG (flange) g/cc	SG (web) g/cc	SG (beam) g/cc	Single flange depth cm	Single flange depth (in.)
No. 2 Douglas fir-Larch lumber	11.7	(1.7)	--	--	0.5	--	
Turner lathe flakes	11.7	(1.7)	0.90	0.44	0.54	2.5	(1.0)
Disk-cut flakes	11.7	(1.7)	0.90	0.44	0.60	4.1	(1.6)
No. 2 Englemann spruce lumber	7.6	(1.1)	--	--	0.35	--	
Ring-cut flakes	7.6	(1.1)	0.90	0.43	0.56	3.2	(1.3)

As with the previous example, the strength considerations were not critical, except in the web where shear strength controlled the density. The optimized configurations for the density levels of each flake type (Table 3) have flange depths in the range of 6.4-8.1 cm to produce the optimum Stiffness/weight ratio. Overall beam stiffnesses range from 7.6-24.8 MPa, primarily due to the differences in flange material stiffnesses.

Table 3.--Properties, dimensions, and densities of composite 2 by 10 joists with optimum stiffness-to-weight ratios

Flange material	Flange density g/cc	Web density g/cc	Single flange depth cm (in.)	Beam stiffness 10^3 MPa (10^6 psi)
Turner lathe flakes	0.60	0.46	8.1 (3.2)	17.9 (2.6)
Turner lathe flakes	0.75	0.48	7.4 (2.9)	21.4 (3.1)
Turner lathe flakes	0.90	0.50	6.6 (2.6)	24.8 (3.6)
Disk-cut flakes	0.60	0.43	7.9 (3.1)	10.3 (1.5)
Disk-cut flakes	0.75	0.47	7.4 (2.9)	13.8 (2.0)
Disk-cut flakes	0.90	0.53	6.9 (2.7)	17.9 (2.6)
Ring-cut flakes	0.60	0.42	7.9 (3.1)	7.6 (1.1)
Ring-cut flakes	0.75	0.43	6.9 (2.7)	9.0 (1.3)
Ring-cut flakes	0.90	0.45	6.4 (2.5)	10.3 (1.5)

The optimum beams are all deflection critical, thus, the forces that may be applied per unit length are proportional to the beam stiffness. This statement may be illustrated by the lowest and highest stiffnesses of the optimum joists. The 0.90 g/cc Turner lathe flakes flange joist (24.8 MPa) and the 0.60 g/cc ring-cut flakes flange joist (7.6 MPa) have maximum load carrying capabilities at a ratio of 3.2:1 (24.8:7.6).

Another way of showing the optimization results of this example is to plot flange depth against the beam stiffness/weight ratio (Figure 3). Due to the assumption of no web contribution to flexural strength or stiffness, the stiffness/weight ratio is zero at zero flange depth. However, the random ring-cut flake web would possess a small level of stiffness. The optimum depth of beam flange for any flake/density material curve corresponds with the point at which the slope is zero. To put this into a verbal definition, the optimum depth of beam flange is reached when the stiffness gain (produced by adding another unit of flange depth) is smaller, proportionately, than the weight gain (produced by the additional unit of "high" density flange). This "high" density is of course relative to the density of the web material that the flange replaces. The slope of the curves at the maximum flange depth (23.5 cm) is indicative of the weight gain developed when the last unit of web material is replaced by a unit of flange material.

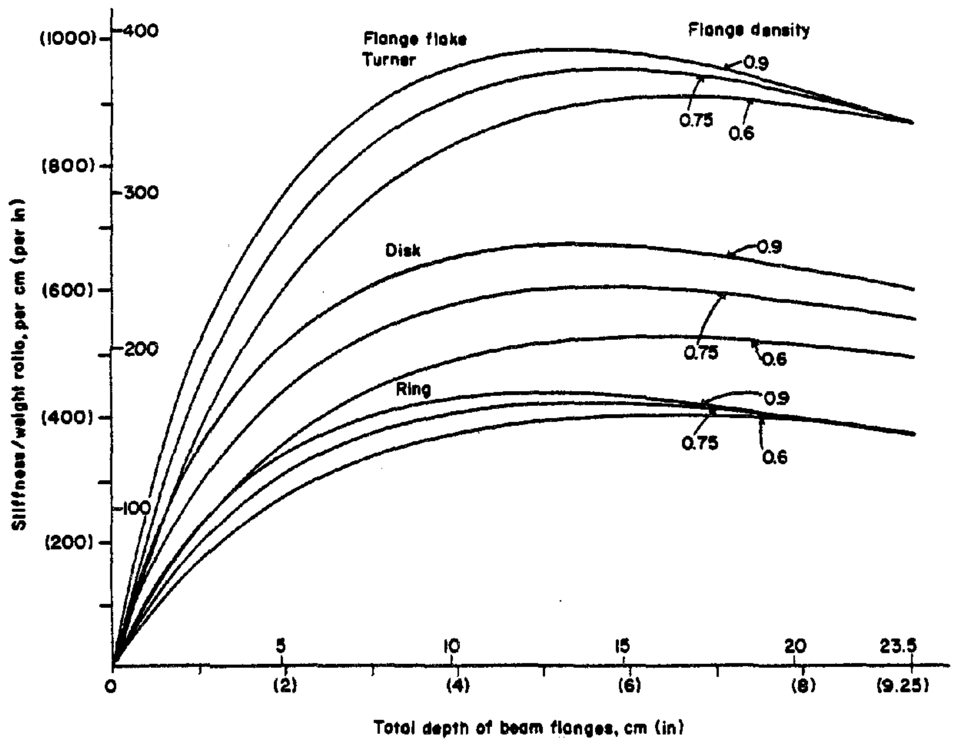

Figure 3. – – *Results of optimization for 6 m (20 ft) span, uniformly loa loaded, 3.8 by 23.5 cm (1.5 by 9.25 in.) composite beam*

For long span applications, the shear strength requirements are low with respect to the flexural strength needs, hence, a low density web would appear to be needed. However, the shear strength of reconstituted products is minimal until the wood particles are compacted to approximately 80% of the parent species density. The implication being that the web is penalizing the beam weight up to the point at which the web starts carrying shear stresses. In the case of the random ring-cut flakes used in these designs, this "penalty density" of 0.34 g/cc is a large percentage of the density needed to carry the shear stresses. As higher densities of shear webs are used in designs for joists with heavier loadings or short-span shear-critical designs, this penalty density will became a smaller proportion of the beam weight supporting shear forces.

Another way to view this example of optimization is as a trade off between beam volume dedicated to adding stiffness, and beam volume dedicated to shear strength. Since stiffness and, hence, stiffness volume was maximized, the corollary is that shear volume was minimized. The high density of the stiffness material (0.6–0.9 g/cc) precluded its use over the entire beam section. As long as the shear material density was lower than the stiffness material density, the shear material had justification to be retained in these maximum stiffness-minimum weight designs.

DISCUSSION

The rectangular beam represents one of the simplest of structural elements to optimize. Its optimization here has served to show how the structural needs of the component, (i e., stiffness, strength) affect component weight and, hence, cost. A number of the observations made in the optimizations can assist in formulating new designs for composite flexural members.

The poor efficiency of low density composite materials to provide shear strength is perhaps the greatest detractor from its use as a lightly-loaded flexural member. However, shear carrying capacity is good at higher densities. This high-density material may be used in rectangular cross section beams that are shear critical, such as heavily loaded short spans.

Two processing options present themselves for reducing the volume of shear critical material in a beam. Reduction of the rectangular beam section to an I-shape is the most obvious option. This may be done through a secondary processing step where the flanges are glued or otherwise attached to the high density composite web. Molding of an I-shape (11) in the pressing operation would produce the high density web but this option requires substantial equipment development.

Another approach would eliminate nearly all shear-carrying volume. A composite wood truss (12), molded to form the required chords and diagonal web members would (a) allow axial loading (tension or compression) of all members, (b) provide joints with no slippage, and (c) allow engineering of efficient components for carrying a wide range of loads over long spans.

Again, as with the molded I-section, the processing equipment is unavailable at this time for manufacturing this product.

SUMMARY AND CONCLUSIONS

The potential for composite wood structural components into markets now held by solid wood products looks very promising. As shortages of higher quality solid lumber develop, processes technology and design will need to be implemented for composite wood structural members, components, and assemblies. Process changes that appear most promising for upgrading the technical feasibility of composite wood structural components are: (a) use of high-quality particles that are amenable to alignment; (b) greater control of the mat formation processes of alignment, mat placement, and multi-level/multi-quality raw material use across the panel profile; (c) development of advanced pressing concepts to control density profiles and speed curing the thick composite products; (d) added emphasis on molding equipment to allow continuous pressing of molded shapes; and (e) complete structural and economic evaluations of composite components assembled in secondary processes.

Optimization of the structural products made of composite wood materials require two matched optimization schemes, one for the process that produces the product and the other for the structural needs of the product. A simple joist was chosen to illustrate the optimization approach. The properties of 2 by 10 solid-sawn joists were imitated using a two-component composite beam. The rectangular beam flanges were aligned-flake composite material while the beam web was a random flake composite. Deflection or stiffness of the beam was seen to control the design. Minimum weight optimizations resulted in composite joist sections that were heavier than the solid wood joists.

A second example of joist optimization used the 2 by 10 geometry and flange/web configuration, but these structural sections were optimized for maximum stiffness-to-weight ratio for various flange densities of three aligned-flake composite materials. Optimum rectangular beam configurations possessed single flange depths ranging from 27-35% of total beam depth. Optimized beam stiffnesses are over twice that of typical solid lumber joists. Shear strengths required of these beam's webs are low, but web density remains high. This low efficiency in carrying shear stresses is the primary limitation of rectangular beams used for medium to long spans.

Several structural members that provide greater efficiency in carrying loads over long spans are I-beams and truss components. These products reduce the volume of the shear-carrying web structure so that higher shear stresses are produced. Composite wood materials provide excellent shear capacity and efficiency at these higher shear loadings. The optimization techniques presented provide a means of evaluating the efficiency of various parts of the structure. This, in turn, improves the designer's capability to direct process improvements and developments where they may be most beneficial to the industry and the public.

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