ideal single-point cutting tool, which can follow highly complicated patterns. It eliminates crushing or deformation of the material such as corrugated paper board and generation of dust. Water jet technology reduces cutting noise significantly and offers the ability to cut without high temperatures. The greatest use of liquid-jet cutting is in the paper and paperboard industry where it has been quite successful in cutting laminated paperboard into upholstery frames. In the paper industry liquid-jet slitting systems are used to cut paper at higher speeds than with a mechanical knife – as high as 3200 m min^{-1}.

See also: **Solid Wood Processing**: Finishing. **Solid Wood Products**: Construction; Logs, Poles, Piles, Sleepers (Crossties); Lumber Production, Properties and Uses; Structural Use of Wood. **Wood Formation and Properties**: Formation and Structure of Wood; Mechanical Properties of Wood; Physical Properties of Wood. **Wood Use and Trade**: History and Overview of Wood Use.

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SOLID WOOD PRODUCTS

Contents

Glued Structural Members

J A Youngquist, Forest Products Consultant, Verona, WI, USA
R Youngs, Virginia Polytechnic Institute and State University, Blacksburg, VA, USA

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Introduction

The material in this article is adapted from the Forest Products Laboratory *Wood Handbook*, which is especially concerned with use of wood as an engineering material in the USA. However, the use of wood in laminated form is common worldwide and the same principles apply. Glued structural members are manufactured in a variety of configurations. Structural composite lumber (SCL) products consist of small pieces of wood glued together into sizes common for solid-sawn lumber. Glued-laminated timber (glulam) is an engineered stress-rated product that consists of two or more layers of lumber in which the grain of all layers is oriented parallel to the length of the lumber.

Glued structural members also include lumber that is glued to panel products, such as box beams and I-beams, and structural sandwich construction.

Structural Composite Lumber

Structural composite lumber (SCL) was developed in response to the increasing demand for high-quality lumber at a time when it was becoming difficult to obtain this type of lumber from the forest resource. SCL products are characterized by smaller pieces of wood glued together into sizes common for solid-sawn lumber. SCL is a growing segment of the engineered wood products industry. It is used as a replacement for lumber in various applications and in the manufacture of other engineered wood products, such as prefabricated wood I-joists, which take advantage of engineering design values that can be greater than those commonly assigned to sawn lumber.

Types

One type of SCL product is manufactured by laminating veneer with all plies parallel to the length. This product is called laminated veneer lumber (LVL) and consists of specially graded veneer. Another type of SCL product consists of strands of wood or strips of veneer glued together under high pressures and temperatures. Depending upon the component material, this product is called laminated strand lumber (LSL), parallel strand lumber (PSL), or oriented strand lumber (OSL) (**Figure 1**). These types of SCL products can be manufactured from raw materials, such as aspen (*Populus* spp.) or other underutilized species, that are not commonly used for structural applications. Different widths of lumber can be ripped from SCL for various uses. Production of LVL uses veneers 3.2–2.5 mm thick, which are hot pressed with phenol-formaldehyde adhesive into lengths from 2.4 to 18.3 m or more. The veneer for the manufacture of LVL must be carefully selected for the product to achieve the desired engineering properties and is often sorted using ultrasonic testing. End joints between individual veneers may be staggered along the product to minimize their effect on strength. These end joints may be butt joints, or the veneer ends may overlap for some distance to provide load transfer. Some producers provide structural end joints in the veneers using either scarf or fingerjoints. LVL may also be made in 2.4-m lengths, having no end joints in the veneer; longer pieces are then formed by end-jointing these pieces to create the desired length. Sheets of LVL are commonly produced in 0.6–1.2-m widths in a thickness of 38 mm. Continuous presses can be used to form a potentially endless sheet, which is cut to the desired length. Various widths of lumber can be manufactured at the plant or the retail facility.

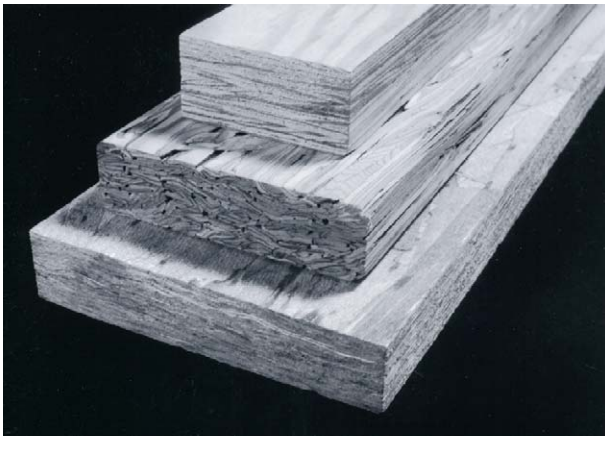

Figure 1 Examples of three types of SCL (top to bottom): laminated veneer lumber (LVL), parallel strand lumber (PSL), and oriented strand lumber (OSL).

Parallel strand lumber (PSL) is defined as a composite of wood strand elements with wood fibers primarily oriented along the length of the member. The least dimension of the strands must not exceed 6.4 mm, and the average length of the strands must be a minimum of 150 times the least dimension. PSL is manufactured using veneer about 3 mm thick, which is then clipped into strands about 19 mm wide. These strands are commonly at least 0.6 m long. The manufacturing process was designed to use the material from roundup of the log in the veneer cutting operation as well as other less than full-width veneer. Thus, the process can utilize waste material from a plywood or LVL operation. Species commonly used for PSL include Douglas-fir (*Pseudotsuga menziesii*), southern pines (*Pinus palustris*, *P. echinata*, *P. taeda*, and *P. elliottii*), western hemlock (*Tsuga heterophylla*), and yellow-poplar (*Liriodendron tulipifera*), but there are no restrictions on using other species. The strands are coated with a waterproof structural adhesive, commonly phenol-resorcinol formaldehyde, and oriented in a press using special equipment to ensure proper orientation and distribution. The pressing operation results in densification of the material, and the adhesive is cured using microwave technology. Billets larger than those of LVL are commonly produced; a typical size is 0.28 by 0.48 m. This product can then be sawn into smaller pieces, if desired. As with LVL, a continuous press is used so that the length of the product is limited by handling restrictions.

Laminated strand lumber (LSL) and oriented strand lumber (OSL) products are an extension of the technology used to produce oriented strandboard

(OSB) structural panels. One type of LSL uses strands that are about 0.3 m long, which is somewhat longer than the strands commonly used for OSB. Waterproof adhesives are used in the manufacture of LSL. One type of product uses an isocyanate type of adhesive that is sprayed on the strands and cured by steam injection. This product needs a greater degree of alignment of the strands than does OSB and higher pressures, which result in increased densification.

Advantages and Uses

In contrast with sawn lumber, the strength-reducing characteristics of SCL are dispersed within the veneer or strands and have much less of an effect on strength properties. Thus, relatively high design values can be assigned to strength properties for both LVL and PSL. Whereas both LSL and OSL have somewhat lower design values, they have the advantage of being produced from a raw material that need not be in a log size large enough for peeling into veneer. All SCL products are made with structural adhesives and are dependent upon a minimum level of strength in these bonds, and are made from veneers or strands that are dried to a moisture content that is slightly less than that for most service conditions. Thus, little change in moisture content will occur in many protected service conditions. When used indoors, this results in a product that is less likely to warp or shrink in service. However, the porous nature of both LVL and PSL means that these products can quickly absorb water unless they are provided with some protection.

All types of SCL products can be substituted for sawn lumber products in many applications. Laminated veneer lumber is used extensively for scaffold planks and in the flanges of prefabricated I-joists, which take advantage of the relatively high design properties. Both LVL and PSL beams are used as headers and major load-carrying elements in construction. The LSL and OSL products are used for band joists in floor construction and as substitutes for studs and rafters in wall and roof construction. Various types of SCL are also used in a number of nonstructural applications, such as the manufacture of windows and doors.

Glulam

Structural glued-laminated timber (glulam) is one of the oldest glued engineered wood products. Glulam is an engineered, stress-rated product that consists of two or more layers of lumber that are glued together with the grain of all layers, which are referred to as laminations, parallel to the length. Glulam is defined as a material that is made from suitably selected and prepared pieces of wood either in a straight or curved form, with the grain of all pieces essentially parallel to the longitudinal axis of the member. The maximum lamination thickness permitted is 5 mm and the laminations are typically made of standard 25- or 50-mm thick lumber. Because the lumber is joined end to end, edge to edge, and face to face, the size of glulam is limited only by the capabilities of the manufacturing plant and the transportation system.

Douglas-fir, larch (*Larix occidentalis*), southern pine, western hemlock, firs (*Abies lasiocarpa*, *A. magnifica*, *A. grandis*, *A. procera*, *A. amabilis*, and *A. concolor*), spruce (*Picea rubens*, *P. glauca*, and *P. mariana*), and pine (*Pinus monticola*) are commonly used for glulam in the USA. Nearly any species can be used for glulam timber, provided its mechanical and physical properties are suitable and it can be properly glued. Industry standards cover many softwoods and hardwoods, and procedures are in place for including other species.

Advantages

Compared with sawn timbers as well as other structural materials, glulam has several distinct advantages in size capability, architectural effects, seasoning, variation of cross-sections, grades, and effect on the environment.

Glulam offers the advantage of the manufacture of structural timbers that are much larger than the trees from which the component lumber was sawn. By combining the lumber in glulam, the production of large structural elements is possible. Straight members up to 30 m long are not uncommon and some spans up to 43 m with sections deeper than 2 m have been used. Thus, glulam offers the potential to produce large timbers from small trees.

By curving the lumber during the manufacturing process, a variety of architectural effects can be obtained that are impossible or very difficult with other materials. The degree of curvature is controlled by the thickness of the laminations. Thus, glulam with moderate curvature is generally manufactured with standard 19-mm thick lumber. Low curvatures are possible with standard 38-mm lumber, whereas 13 mm or thinner material may be required for very sharp curves. As noted below, the radius of curvature is limited to between 100 and 125 times the lamination thickness.

The lumber used in the manufacture of glulam must be seasoned or dried prior to use, so that the effects of checking and other drying defects are minimized. In addition, design can be on the basis of seasoned wood, which permits greater design values than can be assigned to unseasoned timber.

Structural elements can be designed with varying cross sections along their length as determined by strength and stiffness requirements. The beams in **Figure 2** show how the central section of the beam can be made deeper to account for increased structural requirements in this region of the beam. Similarly, arches often have varying cross-sections as determined by design requirements.

One major advantage of glulam is that a large quantity of lower-grade lumber can be used within the less highly stressed laminations of the beams. Grades are often varied within the beams so that the highest grades are used in the highly stressed laminations near the top and bottom and the lower grade for the inner half or more of the beams. Species can also be varied to match the structural requirements of the laminations.

Much is being written and discussed regarding the relative environmental effects of various materials. Several analyses have shown that the renewability of wood, its relatively low requirement for energy during manufacture, its carbon storage capabilities, and its recyclability offer potential long-term environmental advantages over other materials (*see* **Wood Use and Trade**: Environmental Benefits of Wood as a Building Material). Although aesthetic and economic considerations usually are the major factors influencing material selection, these environmental advantages may increasingly influence material selection.

The advantages of glulam are tempered by certain factors that are not encountered in the production of sawn timber. In instances where solid timbers are available in the required size, the extra processing in making glulam timber usually increases its cost above that of sawn timbers. The manufacture of glulam requires special equipment, adhesives, plant facilities, and manufacturing skills, which are not needed to produce sawn timbers. All steps in the manufacturing process require care to ensure the high quality of the finished product. One factor that must be considered early in the design of large straight or curved timbers is handling and shipping.

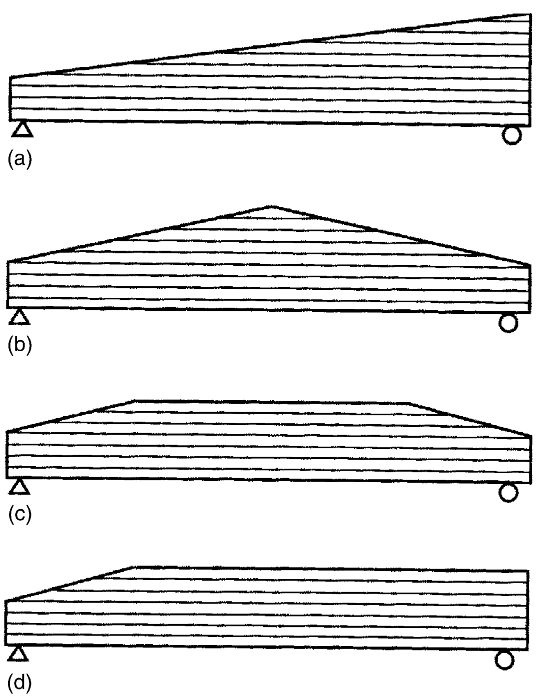

Figure 2 Glulam timbers may be (a) single tapered, (b) double tapered, (c) tapered at both ends, or (d) tapered at one end.

Types of Glulam Combinations

The configuring of various grades of lumber to form a glulam cross-section is commonly referred to as a glulam combination. Glulam combinations subjected to flexural loads, called bending combinations, were developed to provide the most efficient and economical section for resisting bending stress caused by loads applied perpendicular to the wide faces of the laminations. This type of glulam is commonly referred to as a horizontally laminated member. Lower grades of laminating lumber are commonly used for the center portion of the combination, or core, where bending stress is low, while a higher grade of material is placed on the outside faces where bending stress is relatively high. To optimize the bending stiffness of this type of glulam member, equal amounts of high quality laminations on the outside faces should be included to produce a 'balanced' combination.

Glulam axial combinations were developed to provide the most efficient and economical section for resisting axial forces and flexural loads applied parallel to the wide faces of the laminations. Members having loads applied parallel to the wide faces of the laminations are commonly referred to as vertically laminated members. Unlike the practice for bending combinations, the same grade of lamination is used throughout the axial combination. Axial combinations may also be loaded perpendicular to the wide face of the laminations, but the nonselective placement of material often results in a less efficient and less economical member than does the bending combination. As with bending combinations, knot and slope-of-grain requirements apply based on the intended use of the axial member as a tension or compression member.

Efficient use of lumber in cross-sections of curved glulam combinations is similar to that in cross-sections of straight, horizontally laminated combinations. Tension and compression stresses are analyzed as tangential stresses in the curved portion of the member. A unique behavior in these curved members is the formation of radial stresses perpendicular to the wide faces of the laminations. As the radius of curvature of the glulam member decreases, the radial stresses formed in the curved portion of the beam increase. Because of the relatively low strength of lumber in tension perpendicular-to-the-grain compared with tension parallel-to-the-grain, these radial stresses become a critical factor in designing curved glulam combinations.

Glulam beams are often tapered to meet architectural requirements, provide pitched roofs, facilitate drainage, and lower wall height requirements at the end supports. The taper is achieved by sawing the member across one or more laminations at the desired slope. It is recommended that the taper cut be made only on the compression side of the glulam member, because violating the continuity of the tension-side laminations would decrease the overall strength of the member. Common forms of straight, tapered glulam combinations include: (1) single tapered, a member having a continuous slope from end to end on the compression side; (2) double tapered, a member having two separate slopes sawn on the compression side; (3) tapered at both ends, a member with slopes sawn on the ends, but the middle portion remaining straight; and (4) tapered at one end, similar to (3) with only one end having a slope. These four examples are illustrated in **Figure 2**.

Glued Members With Lumber and Panels

Highly efficient structural components can be produced by combining lumber with panel products through gluing. These components include box beams, I-beams, 'stressed-skin' panels, and folded plate roofs.

These highly efficient designs, although adequate structurally, can suffer from lack of resistance to fire and decay unless treatment or protection is provided. The rather thin portions of the cross-section (the panel materials) are more vulnerable to fire damage than are the larger, solid cross-sections.

Box beams and I-beams with lumber or laminated flanges and structural panel webs can be designed to provide the desired stiffness, bending, moment resistance, and shear resistance. The flanges resist bending moment, and the webs provide primary shear resistance. Proper design requires that the webs must not buckle under design loads. If lateral stability is a problem, the box beam design should be chosen because it is stiffer in lateral bending and torsion than is the I-beam. In contrast, the I-beam should be chosen if buckling of the web is of concern because its single web, double the thickness of that of a box beam, will offer greater buckling resistance.

In recent years, the development of improved adhesives and manufacturing techniques has led to the development of the prefabricated I-beam industry. This product is a unique type of I-beam that is replacing wider lumber sizes in floor and roof applications for both residential and commercial buildings (**Figure 3**). Significant savings in materials are possible with prefabricated I-beams that use either plywood or oriented strandboard (OSB) for the web material and small-dimension lumber or SCL for the flanges. The high-quality lumber needed for these flanges has been difficult to obtain using visual grading methods, and both mechanically graded lumber and SCL are being used by several manufacturers. The details of fastening the flanges to the webs vary between manufacturers; all must be glued with a waterproof adhesive. Prefabricated I-beams are becoming popular with builders because of their light weight, dimensional stability and ease of construction. Their accurate and consistent dimensions, as well as uniform depth, allow the rapid creation of a level floor. Utility lines pass easily through openings in the webs.

Constructions consisting of structural panel 'skins' glued to wood stringers are often called stressed-skin panels. These panels offer efficient structural constructions for floor, wall, and roof components. They can be designed to provide desired stiffness, bending moment resistance, and shear resistance. The skins resist bending moment, and the wood stringers provide shear resistance.

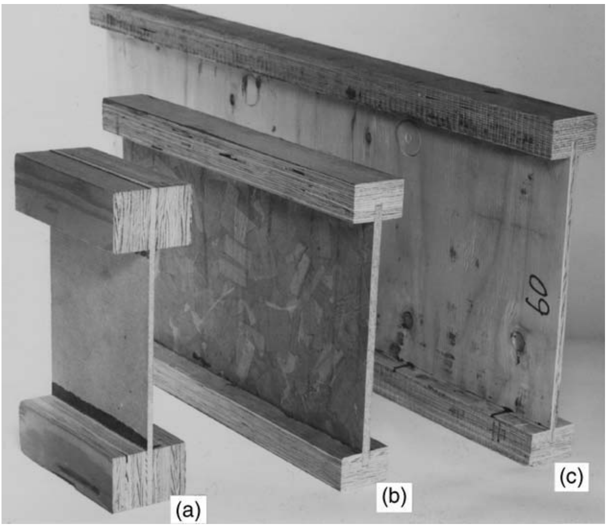

Figure 3 Prefabricated I-beams with laminated veneer lumber flanges and structural panel webs. (a) one experimental product has a hardboard web. The other two commercial products have (b) oriented standboard and (c) plywood webs.

Structural Sandwich Construction

Structural sandwich construction is a layered construction formed by bonding two thin facings to a thick core (**Figure 4**). The thin facings are usually made of a strong and dense material because they resist nearly all the applied edgewise loads and flatwise bending moments. The core, which is made of a weak and low-density material, separates and stabilizes the thin facings and provides most of the shear rigidity of the sandwich construction. By proper choice of materials for facings and core, constructions with high ratios of stiffness to weight can be achieved. As a crude guide to the material proportions, an efficient sandwich is obtained when the weight of the core is roughly equal to the total weight of the facings. Sandwich construction is also economical because the relatively expensive facing materials are used in much smaller quantities than are the usually inexpensive core materials. The materials are positioned so that each is used to its best advantage.

Specific nonstructural advantages can be incorporated in a sandwich construction by proper selection of facing and core materials. An impermeable facing can act as a moisture barrier for a wall or roof panel in a house; an abrasion-resistant facing can be used for the top facing of a floor panel; and decorative effects can be obtained by using panels with plastic facings for walls, doors, tables, and other furnishings. Core material can be chosen to provide thermal insulation, fire resistance, and decay resistance. Because of the light weight of structural sandwich construction, sound transmission problems must also be considered in choosing sandwich component parts.

Methods of joining sandwich panels to each other and other structures must be planned so that the joints function properly and allow for possible dimensional change as a result of temperature and moisture variations. Both structural and nonstructural advantages need to be analyzed in light of the strength and service requirements for the sandwich construction. Moisture-resistant facings, cores, and adhesives should be used if the construction is to be exposed to adverse moisture conditions. Similarly, heat-resistant or decay-resistant facings, cores, and adhesives should be used if exposure to elevated temperatures or decay organisms is expected.

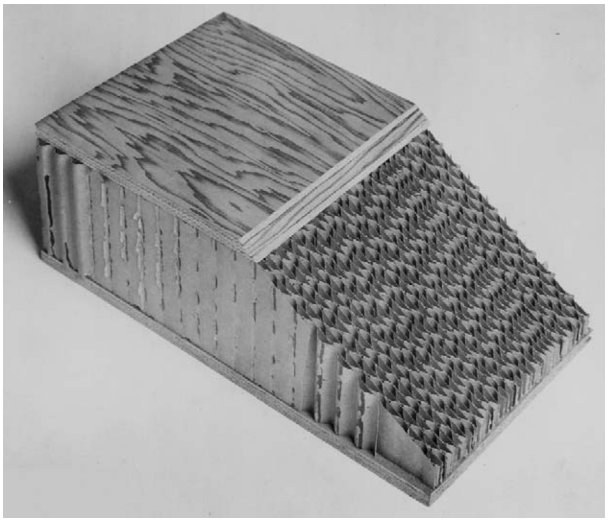

Figure 4 Cutaway section of sandwich construction with plywood facings and a paper honeycomb core.

See also: **Solid Wood Processing**: Adhesion and Adhesives; Machining; Protection from Fire. **Solid Wood Products**: Lumber Production, Properties and Uses; Wood-based Composites and Panel Products. **Wood Formation and Properties**: Physical Properties of Wood. **Wood Use and Trade**: Environmental Benefits of Wood as a Building Material.

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Structural Use of Wood

S Smulski, Wood Science Specialists Inc., Shutesbury, MA, USA

Introduction

Wood is an indispensable structural material worldwide and has been so since antiquity. The global prominence of wood as a construction staple is owed not only to its desirable attributes, but also to the fact that the forest resources from which it is derived are universally distributed, abundant, and renewable. Whether in the form of traditional solid-sawn lumber or a modern engineered wood I-joist, wood is unique among load-bearing building products. The only structural material of biological origin, wood has a high strength-to-weight ratio, is easily cut to size and shape with simple tools, is readily joined with