Mechanical Properties of Wood-Based Composite Materials

Zhiyong Cai, Project Leader
C. Adam Senalik, Research General Engineer
Robert J. Ross, Supervisory Research General Engineer

Contents

The term *composite* is used to describe any wood material bonded together with adhesives. The current product mix ranges from fiberboard to laminated beams and components. For this chapter, wood-based composite materials are classified into the following categories: panel products (plywood, oriented strandboard (OSB), particleboard, fiberboard, medium-density fiberboard (MDF), hardboard); structural timber products (glued-laminated timber (glulam), laminated veneer lumber (LVL), laminated strand lumber, parallel strand lumber); and wood–nonwood composites (wood fiber–thermoplastics, inorganic-bonded composites).

Wood-based composites are used for a number of structural and nonstructural applications. Product lines include panels for both interior and exterior uses, furniture components, and support structures in buildings. Knowledge of the mechanical properties of these products is of critical importance to their proper use.

Wood-based composites are made from a wide range of materials—from fibers obtained from underutilized small-diameter or plantation trees to structural lumber. Regardless of the raw material used in their manufacture, wood-based composites provide uniform and predictable in-service performance, largely as a consequence of standards used to monitor and control their manufacture. The mechanical properties of wood composites depend upon a variety of factors, including wood species, forest management regimes (naturally regenerated, intensively managed), the type of adhesive used to bind the wood elements together, geometry of the wood elements (fibers, flakes, strands, particles, veneer, lumber), and density of the final product (Cai 2006).

A wide range of engineering properties are used to characterize the performance of wood-based composites. Mechanical properties are typically the most frequently used to evaluate wood-based composites for structural and nonstructural applications. Elastic and strength properties are the primary criteria to select materials or to establish design or product specifications. Elastic properties include modulus of elasticity (MOE) in bending, tension, and compression. Strength properties usually reported include modulus of rupture (bending strength), compression strength parallel to surface, tension strength parallel to surface, tension strength perpendicular to surface (internal

Table 12–1. Static bending properties of different wood and wood-based composites

Material	Specific gravity	Static bending properties: Modulus of elasticity GPa	Modulus of elasticity ($\times 10^6$ lb in^{-2})	Modulus of rupture MPa	Modulus of rupture (lb in^{-2})
Clear wood					
White oak	0.68	12.27	(1.78)	104.80	(15,200)
Red maple	0.54	11.31	(1.64)	92.39	(13,400)
Douglas-fir (Coastal)	0.48	13.44	(1.95)	85.49	(12,400)
Western white pine	0.38	10.07	(1.46)	66.88	(9,700)
Longleaf pine	0.59	13.65	(1.98)	99.97	(14,500)
Panel products					
Hardboard	0.9–1.0	3.10–5.52	(0.45–0.80)	31.02–56.54	(4,500–8,200)
Medium-density fiberboard	0.7–0.9	3.59	(0.52)	35.85	(5,200)
Particleboard	0.6–0.8	2.76–4.14	(0.40–0.60)	15.17–24.13	(2,200–3,500)
Oriented strandboard	0.5–0.8	4.41–6.28	(0.64–0.91)	21.80–34.70	(3,161–5,027)
Plywood	0.4–0.6	6.96–8.55	(1.01–1.24)	33.72–42.61	(4,890–6,180)
Structural timber products					
Glued-laminated timber	0.4–0.6	9.00–14.50	(1.30–2.10)	28.61–62.62	(4,150–9,080)
Laminated veneer lumber	0.4–0.7	8.96–19.24	(1.30–2.79)	33.78–86.18	(4,900–12,500)
Wood–nonwood composites					
Wood plastic		1.53–4.23	(0.22–0.61)	25.41–52.32	(3,684–7,585)

bond strength), shear strength, fastener holding capacity, and hardness. Model building codes in the United States stipulate that plywood used for structural applications such as subflooring and sheathing must meet the requirements of certain U.S. Department of Commerce standards. Voluntary Product Standard PS 1–07 for construction and industrial plywood (NIST 2007) and Performance Standard PS 2–04 for wood-based structural-use panels (NIST 2004) spell out the ground rules for manufacturing plywood and establishing plywood or OSB properties, respectively. These standards have evolved over time from earlier documents (O'Halloran 1979, 1980; APA 1981) and represent a consensus opinion of the makers, sellers, and users of plywood products as well as other concerned parties.

Many of the questions that arise with wood-based composites have to do with their mechanical properties, especially how properties of one type of material compare with those of clear wood and other wood products. Although an extensive review that compares all properties of wood-based materials and products is beyond the scope of this chapter, Table 12–1 provides some insight to how static bending properties of these materials vary and how their properties compare with those of solid, clear wood. Although the mechanical properties of most wood composites might not be as high as those of solid wood, they provide very consistent and uniform performance.

The mechanical property data presented in this chapter were obtained from a variety of reports of research conducted to develop basic property information for a wide range of wood-based composite materials. The wood-based composites industry is very dynamic, with changes occurring frequently in the manufacture of these materials and corresponding changes in design information. Consequently, this chapter primarily focuses on presenting fundamental mechanical property information for wood-based composite materials. For design procedures and values, the reader is encouraged to contact appropriate industry trade association or product manufacturers. Current design information can be readily obtained from their websites, technical handbooks, and bulletins.

The organization of this chapter follows closely that of Chapter 5. Basic mechanical property information is presented following a brief background discussion of these products. A discussion of performance and testing standards covering their manufacture and use is also presented.

Elastic Properties

Modulus of Elasticity

Elasticity implies that deformations produced by low stress below the proportional limit are completely recoverable after loads are removed. When loaded to stress levels above the proportional limit, plastic deformation or failure occurs. Typically, the stress–strain curve for wood-based composites is linear below the proportional limit. The slope of the linear curve is called the MOE. In compression or tensile tests, this slope is sometime referred to as Young's modulus to differentiate it from bending MOE. Bending MOE is a measure of the resistance to bending deflection, which is relative to the stiffness. Young's modulus is a measure of resistance to elongation or shortening of a member under tension or compression. The procedure to determine MOE is fully described in ASTM D1037 for fiber- and particle-based panel products, ASTM D3043 for structural wood-based panels, ASTM D5456 for structural composite lumber products, ASTM D7031 for wood–plastic composites, and ASTM D7341 for glulam products.

Shear Modulus

Shear modulus, also called modulus of rigidity, indicates the resistance to deflection of a member caused by shear stresses. Shear stress is different from tension or compression stress in that it tends to make one side of a member slip past the other side of a member adjacent to it. There are two main types of shear in different planes of wood-based panels: interlaminar shear and edgewise shear or shear through-the-thickness. Interlaminar shear is also commonly called planar shear (or rolling shear, or horizontal shear) in plywood panels to describe stress that acts between the veneers that are glued with grain direction in adjacent pieces perpendicular to one another. For example, when the plywood panel is loaded in the middle with its two ends simply supported, the layers or veneers tend to slip horizontally past each other as the panel bends. The glue-bonding between the laminates of veneers resists the slipping and often dictates the panel stiffness. Edgewise shear is also commonly called racking shear. The moduli of rigidity vary within and between species, resin application, moisture content, and specific gravity. The procedure to determine different shear moduli for fiber- and particle-based panels is described in ASTM D1037 and for structural panels in ASTM D3044.

Strength Properties

Strength refers to the maximum stress that can be developed in a member due to applied loads prior to failure. Mechanical properties most commonly measured and represented as "strength properties" for design include modulus of rupture in bending, tension strength parallel-to-surface, tension strength perpendicular-to-surface, compression strength parallel-to-surface, shear strength, fastener holding strength, and hardness. Strength tests are typically made on specimens at moisture equilibrium under prescribed conditions or after soaking. The procedures to determine strengths for wood-based composites are described in ASTM D1037, ASTM D3044, ASTM D5456, ASTM D3737, and ASTM D7031.

Modulus of rupture reflects the maximum load-carrying capacity of a member in bending and is proportional to maximum moment borne by the specimen. Modulus of rupture is an accepted measure of strength, although it is not a true stress because the formula by which it is computed is valid only to the elastic limit (McNatt 1973).

Tension strength parallel-to-surface is the maximum stress sustained by a specimen from a test with tension forces applied parallel to the surface. Tests are made with the long dimension of the specimen cut both parallel and perpendicular to the long dimension of the board to determine the strength in each of the primary panel directions.

Tension strength perpendicular-to-surface (internal bond strength) is the maximum stress sustained by a specimen from a test with tension forces applied perpendicular to the surface. Tests are made on specimens in the dry condition to determine the resistance of the specimen to delamination or splitting in the direction perpendicular to the plane of the board.

Compression strength parallel-to-surface is the maximum stress sustained by a specimen from a test with compression forces applied parallel to the surface. Tests are made with the long dimension of the specimen cut both parallel and perpendicular to the long dimension of the board to determine the material's resistance to crushing in each of the primary panel directions.

Interlaminar shear (planar shear) indicates the ability to resist internal slipping of one layer upon another within the panel. It is used to describe the glue line or bonding performance inside or between the test materials.

Hardness is measured as resistance to indentation using a modified Janka hardness test, measured by the load required to embed an 11.3-mm (0.444-in.) diameter ball to one-half its diameter.

Fastener holding strength is the maximum resistance to separate or withdraw a fastener in a plane normal to the testing face. It usually contains three tests: nail withdrawal, nail-head pull-through, and direct screw withdrawal.

Panel Products

Plywood

Plywood is separated in to two general classes: (a) construction and industrial plywood and (b) hardwood and decorative plywood. Construction and industrial plywood are covered by Product Standard PS 1–07 (NIST 2007), and hardwood and decorative plywood are covered by American National Standard ANSI/HPVA–1–2004 (HPVA 2004). Each standard recognizes different exposure durability classifications, which are primarily based on moisture resistance of the adhesive and the grade of veneer used. In addition, model building codes require that plywood manufacturers be inspected and their products certified for conformance to PS 1–07, PS 2–04, APA PRP–108, or TECO PRP–133 (TECO 1991) by qualified independent third-party agencies on a periodic unannounced basis. With PS 1–07, as long as a plywood panel is manufactured using the veneer grades, adhesive, and construction established in the standard's prescriptive requirements, the panel is by definition acceptable.

All hardwood plywood represented as conforming to American National Standard ANSI/HPVA–1–2004 (HPVA 2004) is identified by one of two methods: by marking each

Table 12–2. Selected properties of plywood sheathing products[a]

		Static bending									
		MOE		MOR		Fiber stress at proportional limit		Rail shear strength		Glue line shear strength	
Species	Specific gravity	GPa	($\times 10^6$ lb in^{-2})	MPa	(lb in^{-2})	GPa	(lb in^{-2})	MPa	(lb in^{-2})	MPa	(lb in^{-2})
Baldcypress	0.50	7.58	(1.10)	39.23	(5,690)	29.4	(4,260)	5.6	(805)	2.7	(389)
Douglas-fir	0.53	7.45	(1.08)	41.37	(6,000)	39.3	(5,700)	3.8	(556)	1.4	(207)
Lauan	0.44	7.43	(1.08)	33.72	(4,890)	28.1	(4,070)	4.3	(628)	1.3	(192)
Western redcedar	0.41	8.55	(1.24)	37.37	(5,420)	33.3	(4,830)	4.6	(674)	1.7	(240)
Redwood	0.41	6.96	(1.01)	42.61	(6,180)	37.4	(5,420)	5.3	(769)	1.5	(220)
Southern Pine	0.57	7.70	(1.12)	37.09	(5,380)	26.2	(3,800)	5.5	(800)	1.6	(233)

[a]From Biblis (2000).

panel with the Hardwood Plywood & Veneer Association (HPVA) plywood grade stamp or by including a written statement with this information with the order or shipment.

If design calculations are desired, a design guide is provided by the APA–The Engineered Wood Association in *Plywood Design Specification* (PDS) and APA Technical Note N375B (APA 1995a,b). The design guide contains tables of grade stamp references, section properties, and allowable stresses for plywood used in construction of buildings and similar structures. Table 12–2 shows selected properties of various species of plywood.

Oriented Strandboard (OSB)

Oriented strandboard is an engineered, structural-use panel manufactured from thin wood strands bonded together with water-resistant adhesive under heat and pressure. It is used extensively for roof, wall, and floor sheathing in residential and commercial construction. Design capacities of performance-rated products, which include OSB and waferboard, can be determined by using procedures outlined in Technical Note N375B (APA 1995a). In this reference, allowable design strength and stiffness properties, as well as nominal thickness and section properties, are specified based on the span rating of the panel. Additional adjustment factors based on panel grade and construction are also provided. Table 12–3 shows selected properties of OSB obtained from the literature.

Under PS 2–04, a manufacturer is required to enter into an agreement with an accredited testing agency to demonstrate that its panels conform to the requirements of the chosen standard. The manufacturer must also maintain an in-plant quality control program in which panel properties are regularly checked, backed by a quality assurance program administered by an independent third-party. The third-party agency must visit the mill on a regular unannounced basis. The agency must confirm that the in-plant quality control program is being maintained and that panels meet the minimum requirements of the standard.

Particleboard

Particleboard is typically made in three layers. The faces of the board consist of fine wood particles, and the core is made of the coarser material (Chap. 11). Particleboard is used for furniture cores and case goods, where it is typically overlaid with other materials for decorative purposes. Particleboard can be used in flooring systems, in manufactured houses, for stair treads, and as underlayment. Requirements for grades of particleboard and particleboard flooring products are specified by the American National Standard for Particleboard A208.1-1999 (CPA 1999). Table 12–4 represents some of selected properties of different particleboard manufacturers.

Hardboard

Basic hardboard physical properties for selected products are presented in ANSI A135.4–2004 (CPA 2004a). The uses for hardboard can generally be grouped as construction, furniture and furnishings, cabinet and store work, appliances, and automotive and rolling stock. Typical hardboard products are prefinished paneling (ANSI A135.5–2004 (CPA 2004b)), house siding (ANSI A135.6–2006 (CPA 2006)), floor underlayment, and concrete form board. Table 12–5 shows selected physical and mechanical properties of hardboard from different manufacturers. Hardboard siding products come in a great variety of finishes and textures (smooth or embossed) and in different sizes. For application purposes, the Composite Panel Association (CPA) classifies siding into three basic types:

Lap siding—boards applied horizontally, with each board overlapping the board below it

Square edge panels—siding intended for vertical application in full sheets

Shiplap edge panel siding—siding intended for vertical application, with the long edges incorporating shiplap joints

The type of panel dictates the application method. The CPA administers a quality conformance program for hardboard

Table 12–3. Selected properties of oriented strandboard (OSB) products

				Bending MOE				Bending MOR					
				Parallel		Perpendicular		Parallel		Perpendicular		Internal bond	
Reference	Species	Mill no.	Specific gravity	GPa	(×10^6 lb in^{-2})	GPa	(×10^6 lb in^{-2})	MPa	(lb in^{-2})	MPa	(lb in^{-2})	MPa	(lb in^{-2})
Biblis (1989)	Southern Pine	1	0.80	4.41	(0.640)	2.89	(0.419)	23.8	(3,445)	24.2	(3,515)	0.57	(83)
		2	0.70	4.78	(0.694)	2.61	(0.378)	26.0	(3,775)	22.1	(3,205)	0.28	(41)
		3	0.68	5.75	(0.834)	3.17	(0.460)	32.0	(4,645)	23.8	(3,445)	0.32	(47)
Pu and others (1992)	Southern Pine	4	0.51	4.41	(0.640)	2.40	(0.348)	21.8	(3,161)	25.4	(3,685)	0.23	(34)
		5	0.60	5.67	(0.822)	2.61	(0.378)	27.8	(4,039)	27.1	(3,925)	0.28	(41)
		6	0.58	4.41	(0.640)	2.97	(0.431)	23.9	(3,473)	28.7	(4,165)	0.26	(38)
	Aspen	7	0.65	6.28	(0.911)	2.03	(0.294)	32.2	(4,672)	30.4	(4,405)	0.43	(62)
		8	0.66	5.69	(0.825)	1.92	(0.278)	31.6	(4,584)	32.0	(4,645)	0.41	(60)
		9	0.74	6.31	(0.915)	2.79	(0.404)	34.7	(5,027)	33.7	(4,885)	0.34	(50)
Wang and others (2003a)	Southern Pine	10	0.63	5.01	(0.726)	2.26	(0.327)	30.2	(4,379)	16.8	(2,436)	0.36	(52)
		11	0.66	5.30	(0.769)	2.32	(0.336)	28.1	(4,075)	14.4	(2,088)	0.43	(62)
		12	0.67	5.12	(0.742)	2.56	(0.371)	30.7	(4,452)	21.1	(3,060)	0.32	(46)
		13	0.66	4.91	(0.712)	2.24	(0.325)	28.3	(4,104)	19.8	(2,871)	0.38	(55)
	Hardwood mixture	14	0.68	5.15	(0.747)	1.77	(0.257)	26.9	(3,901)	11.8	(1,711)	0.28	(40)
		15	0.67	5.87	(0.851)	1.40	(0.204)	33.9	(4,916)	7.8	(1,131)	0.23	(33)
		16	0.70	6.73	(0.976)	2.25	(0.326)	36.9	(5,351)	15.8	(2,291)	0.45	(66)
	Aspen	17	0.63	6.50	(0.943)	3.10	(0.450)	38.0	(5,510)	21.5	(3,118)	0.28	(41)
		18	0.62	7.90	(1.146)	3.10	(0.450)	38.8	(5,626)	23.2	(3,364)	0.46	(66)
		19	0.61	6.10	(0.885)	2.50	(0.363)	30.7	(4,452)	19.7	(2,857)	0.34	(49)
		20	0.61	6.50	(0.943)	1.80	(0.261)	35.5	(5,148)	13.7	(1,987)	0.25	(36)
		21	0.66	6.75	(0.979)	2.45	(0.356)	37.3	(5,409)	19.3	(2,799)	0.38	(55)
		22	0.63	5.80	(0.840)	2.40	(0.348)	26.9	(3,901)	17.9	(2,596)	0.40	(58)

Table 12–4. Selected properties of industrial particleboard products[a]

			Static bending properties				Tensile properties					
			Modulus of elasticity		Modulus of rupture		Modulus of elasticity		Ultimate tensile stress		Internal bond	
Mill	Moisture content (%)	Specific gravity	GPa	(×10^6 lb in^{-2})	MPa	(lb in^{-2})	GPa	(×10^6 lb in^{-2})	MPa	(lb in^{-2})	MPa	(lb in^{-2})
A	8.7	0.71	3.0	(0.44)	16.8	(2,430)	2.2	(0.32)	7.72	(1,120)	0.79	(115)
B	9.1	0.72	3.5	(0.51)	20.6	(2,990)	2.6	(0.38)	9.38	(1,360)	1.07	(155)
C	9.8	0.76	3.5	(0.51)	18.9	(2,740)	2.3	(0.34)	8.27	(1,200)	1.00	(145)
H	8.0	0.77	4.0	(0.58)	22.8	(3,310)	3.0	(0.44)	10.89	(1,580)	1.17	(170)
J	8.5	0.72	3.0	(0.43)	17.2	(2,500)	1.9	(0.28)	7.45	(1,080)	0.45	(65)
K	9.1	0.68	2.8	(0.40)	15.2	(2,206)	1.6	(0.23)	5.58	(810)	0.31	(45)
L	9.3	0.62	3.2	(0.46)	17.0	(2,470)	1.8	(0.26)	6.69	(970)	0.48	(70)
M	9.7	0.65	3.6	(0.52)	18.9	(2,740)	2.2	(0.32)	8.07	(1,170)	0.69	(100)
N	8.3	0.60	3.1	(0.45)	17.0	(2,470)	3.7	(0.54)	8.00	(1,160)	0.31	(45)

[a]From McNatt (1973).

for both panel and lap siding. Participation in this program is voluntary and is open to all (not restricted to CPA members). Under this program, hardboard siding products are tested by an independent laboratory in accordance with product standard ANSI A135.6.

Medium-Density Fiberboard

Minimum property requirements for MDF are specified by the American National Standard for MDF, ANSI A208.2-2002 (CPA 2002), and some of selected properties are given in Table 12–6 from different manufacturers. Medium-density fiberboard is frequently used in furniture applications. It is also used for interior door skins, moldings, flooring substrate, and interior trim components (Cai and others 2006, Youngquist and others 1993).

Table 12–5. Selected properties of hardboard products[a]

Mill	Type of hardboard	Moisture content (%)	Specific gravity	Modulus of elasticity GPa	Modulus of elasticity ($\times 10^6$ lb in^{-2})	Modulus of rupture MPa	Modulus of rupture (lb in^{-2})	Ultimate tensile stress MPa	Ultimate tensile stress (lb in^{-2})	Internal bond MPa	Internal bond (lb in^{-2})
A	1/8-in.	4.6	0.9	3.83	(556)	31.44	(4,560)	23.24	(3,370)	1.24	(180)
B	standard	6.5	1.02	4.36	(633)	33.92	(4,920)	23.17	(3,360)	2.76	(400)
C		5.2	0.94	4.20	(609)	45.85	(6,650)	37.58	(5,450)	2.17	(315)
D		5.6	0.9	3.32	(482)	38.75	(5,620)	28.61	(4,150)	1.55	(225)
E		6.5	0.95	3.55	(515)	47.50	(6,890)	32.96	(4,780)	3.52	(510)
F		7.7	0.91	3.23	(468)	37.85	(5,490)	25.72	(3,730)	1.93	(280)
B	1/4-in.	6.4	1.02	4.45	(645)	33.85	(4,910)	22.61	(3,280)	1.86	(270)
E	standard	6.0	0.90	3.88	(563)	38.96	(5,650)	23.65	(3,430)	1.65	(240)
A	1/4-in. tempered	4.9	0.99	5.30	(768)	53.02	(7,690)	31.58	(4,580)	1.79	(260)
F	1/4-in. tempered	6.9	0.98	5.14	(745)	55.57	(8,060)	30.61	(4,440)	1.86	(270)

[a]From McNatt and Myers (1993).

Table 12–6. Selected properties of medium-density fiberboard products[a]

Mill no.	Density (g cm^{-3})	Modulus of rupture MPa	Modulus of rupture (lb in^{-2})	Modulus of elasticity GPa	Modulus of elasticity ($\times 10^6$ lb in^{-2})	Internal bond MPa	Internal bond (lb in^{-2})	Screw-holding edge kg	Screw-holding edge (lb)	Capacity face kg	Capacity face (lb)
1	0.73	33.6	(4,873)	3.21	(466)	0.86	(125)	117	(257)	148	(326)
2	0.90	34.0	(4,932)	3.97	(576)	0.94	(136)	147	(325)	185	(407)
3	0.79	23.2	(3,366)	2.98	(432)	1.94	(282)	150	(330)	202	(445)
4	0.82	39.3	(5,703)	4.38	(635)	0.83	(121)	114	(252)	148	(326)
5	0.95	24.6	(3,565)	3.56	(517)	0.92	(133)	184	(405)	231	(509)
6	0.80	36.4	(5,278)	3.99	(578)	0.71	(103)	143	(315)	183	(404)
7	0.77	37.4	(5,421)	3.94	(572)	1.23	(179)	163	(360)	210	(464)
8	0.71	35.2	(5,107)	3.34	(485)	1.09	(158)	147	(324)	189	(416)

[a]From Suchsland and others (1979).

Timber Elements/Structural Composite Lumber

Glued-Laminated Timber

Structural glued-laminated timber (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. Table 12–7 provides some selected properties of glulam products from different research studies.

Douglas–Fir–Larch, Southern Pine, yellow-cedar, Hem–Fir, and Spruce–Pine–Fir are commonly used for glulam in the United States. 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 using other species.

Manufacturers of glulam timber have standardized the target design values in bending for beams. For softwoods, these design values are given in “Standard for Wood Products: Structural Glued-Laminated Timber” (AITC 2007). This specification contains design values and recommended modification of stresses for the design of glulam timber members in the United States. The *National Design Specification for Wood Construction* (NDS) summarizes the design information in ANSI/AITC 190.1 and defines the practice to be followed in structural design of glulam timbers (AF&PA 2005). APA–The Engineered Wood Association has also developed design values for glulam under National Evaluation Report 486, which is recognized by all the building codes.

Structural Composite Lumber

Structural composite lumber (SCL) products are characterized by smaller pieces of wood glued together into sizes common for solid-sawn lumber. 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,

Table 12–7. Selected properties of glulam products

Reference	Species	Moisture content (%)	Number of laminations	Static bending properties: Modulus of elasticity GPa	($\times 10^6$ lb in^{-2})	Modulus of rupture MPa	(lb in^{-2})
Manbeck and others (1993)	Red maple	12	8	12.3	(1.78)	62.6	(9,080)
		12	12	12.2	(1.77)	55.0	(7,980)
		12	16	12.3	(1.78)	54.2	(7,860)
Moody and others (1993)	Yellow poplar	8.2	8	13.0	(1.89)	55.6	(8,060)
		7.5	12	13.4	(1.94)	52.1	(7,560)
		8	17	12.3	(1.79)	45.3	(6,570)
Shedlauskus and others (1996)	Red oak	12.8	8	13.0	(1.88)	60.5	(8,770)
		11.1	18	12.8	(1.86)	46.0	(6,670)
Janowiak and others (1995)	Red maple	12.6	12	12.2	(1.77)	55.0	(7,980)
		8.9	5	12.8	(1.86)		
		8.9	5	12.9	(1.87)	45.7	(6,630)
Hernandez and others (2005)	Ponderosa pine	8.8	8	9.44	(1.37)	31.4	(4,560)
		8.8	13	9.07	(1.32)	29.6	(4,290)
Hernandez and Moody (1992)	Southern Pine	—	10	14.1	(2.04)	61.7	(8,950)
		—	17	13.5	(1.96)	49.8	(7,230)
Marx and Moody (1981 a,b)	Southern Pine	10	4, 8, 10	11.2	(1.63)	46.5	(6,740)
		10	4, 8, 11	10.8	(1.56)	33.9	(4,920)
	Douglas-fir–larch	11	4, 8, 12	13.9	(2.02)	47.2	(6,840)
		11	4, 8, 13	13.6	(1.97)	40.7	(5,910)
Moody (1974)	Southern Pine	11.8	17	9.3	(1.35)	28.6	(4,150)
		11.9	17	10.3	(1.49)	31.4	(4,560)

this product is called laminated strand lumber (LSL), parallel strand lumber (PSL), or oriented strand lumber (OSL).

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 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. 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. Table 12–8 provides some selected properties of LVL products from different research studies.

Cross-Laminated Timber

Cross-laminated timber (CLT) is described in U.S. editions of the *CLT Handbook* (Karacabeyli and Douglas 2013). CLT panels are composed of three or more layers of lumber boards fixed together with differing grain orientations. The panels provide an alternative to some building applications that currently use concrete, masonry, or steel. Often the panels contain an odd number of layers with the grain angle alternating by 90° between consecutive layers. The outer layers are oriented in the direction of gravity loads or major spans. The wide faces of the lumber boards abut between layers, and the layers are connected by glue, nails, or dowels. When glue is used, the narrow face of the boards abutting within a layer may also be glued.

In the United States and Canada, softwood species are the primary source of lumber used in the construction of CLT products. All seven stress classes of CLT listed in the *CLT Handbook* are composed of softwood species. The *CLT Handbook* presents an extensive history of CLT development in North America; therefore, only a summary is provided here. The current standard describing construction of CLT in the United States is ANSI/APA PRG 320 (APA 2019). Softwood species with a minimum specific gravity of 0.35 as specified in the *National*

Table 12–8. Selected properties of laminated veneer lumber for structural composite lumber products

		Static bending properties								Tensile properties			
		Modulus of elasticity				Modulus of rupture				Modulus of elasticity		Ultimate tensile stress	
		Edge		Flat		Edge		Flat					
Reference	Species	GPa	($\times 10^6$ lb in^{-2})	GPa	($\times 10^6$ lb in^{-2})	MPa	(lb in^{-2})	MPa	(lb in^{-2})	GPa	($\times 10^6$ lb in^{-2})	MPa	(lb in^{-2})
Bohlen (1974)	Douglas-fir	—	—	—	—	—	—	—	—	15.2	(2.20)	28.99	(4,205)
Youngquist and others (1984)	Douglas-fir	—	—	—	—	—	—	—	—	14.0–15.0	(2.03–2.17)	28.1–39.0	(4,080–5,650)
										11.1–12.4	(1.61–1.80)	18.3–38.1	(2,660–5,520)
Jung (1982)	Douglas-fir	15.5–19.2	(2.25–2.79)	15.4–19.3	(2.23–2.80)	58.0–71.7	(8,420–10,400)	54.2–62.5	(7,860–9,060)	15.6–20.3	(2.27–2.94)	37.9–46.2	(5,500–6,700)
Kunesh (1978)	Douglas-fir	15.9	(2.31)	16.1	(2.34)	—	—	78.8	(11,430)	14.1	(2.04)	44.4	(6,435)
Koch (1973)	Southern Pine	13.2	(1.91)	0.0	0.00	64.2	(9,310)	—	—	—	—	—	—
Moody (1972)	Douglas-fir	—	—	—	—	—	—	—	—	14.3	(2.07)	37.6	(5,450)
	Southern Pine	—	—	—	—	—	—	—	—	13.5	(1.96)	34.6	(5,025)
Moody and Peters (1972)	Southern Pine	14.1	(2.04)	14.7	(2.13)	80.8	(11,720)	86.0	(12,480)	—	—	—	—
Wang and others (2003b)	Red maple	10.8	(1.56)	11.3	(1.64)	83.3	(12,081)	—	—	—	—	—	—
Hindman and others (2006)	Southern Pine	15.8	(2.29)	17.4	(2.54)	—	—	—	—	—	—	—	—
Kretschmann and others (1993)	Douglas-fir	9.0–12.8	(1.30–1.86)	9.0–13.7	(1.30–1.98)	37.9–67.9	(5,500–9,850)	33.8–63.9	(4,900–9,270)	8.5–12.8	(1.24–1.86)	20.8–49.1	(3,020–7,100)
	Southern Pine	9.8–13.7	(1.34–1.98)	8.8–13.0	(1.27–1.89)	51.9–70.3	(7,530–10,190)	47.8–66.5	(6,940–9,650)	9.6–13.6	(1.39–1.97)	36.6–51.2	(5,310–7,430)

Design Specification for Wood Construction (NDS) and recognized under the American Softwood Lumber Standard PS 20 (ASLS 2020) by the American Lumber Standards Committee can be used in the manufacture of CLT.

The reference design values provided in ANSI/APA PRG 320 were predominantly developed using experience gained from European usage and manufacturing, known material properties of dimension lumber, and composite material models. CLT manufacturers produce product in accordance with the standard. Both the manufacturing facility and the CLT product undergo rigorous qualification scrutiny. Yeh and others (2012) provide background information on the development of the standard, including the quality assurance procedures. Quality assurance requirements within the standard specify testing for bending strength, bending stiffness, and interlaminar shear in both major and minor directions. Qualification testing plans are plant, product, and equipment specific (SmartLam 2019). Samples of the CLT product are produced in accordance with the plan and tested for conformance with the standard. Other than the documentation that the product meets the reference design standard, the testing data are not available to the public.

There is limited information on fundamental mechanical properties of CLT in the United States. Given the high cost of CLT production, confidence in the composite material model used to estimate strength, and input from industry, government, academia, and manufactures (Williamson and Ross 2016, Zelinka and others 2019), research funding on full-sized softwood CLT panels has been focused on seismic performance, fire resistance, moisture behavior, and response to agents of degradation. van de Lindt and others (2016) describe the development of seismic performance factors in accordance with the FEMA P695 methodology. Zelinka and others (2020) provide an overview of North American CLT fire testing and code adoption. Schmidt and Riggio (2019) and Riggio and others (2019) present information on monitoring CLT moisture during extended exposure periods during building construction. Kordziel and others (2018) explored both monitoring and modeling of moisture content in mass timber structures. Stokes and others (2019) provide an overview of current research related to termite attack on CLT panels.

Although limited, some mechanical testing research on softwood CLT panels is available. Serrano and Enquist (2010) examined compression strength perpendicular to grain for CLT and noted that modeling the performance of CLT was best achieved when a nonlinear plasticity model was used in conjunction with a fracture mechanics model. Bogensperger and others (2011) found that orthogonal cross layers of CLT resulted in compression properties perpendicular to the plane of the panel that were significantly better than those of comparable glulam beams. Both research projects were conducted in Europe. He and others (2018) examined bending and compressive properties of CLT constructed from Canadian hemlock. Vessby and others (2009) examined the properties of panels constructed of Norway spruce, but with a focus on evaluation of fasteners. One of the few studies available to the public regarding mechanical properties of softwood CLT was conducted by Hindman and Bouldin (2015), who present experimental test values for Southern Pine that include bending strength, bending stiffness, shear strength, moisture content, and specific gravity.

Slavid (2013) noted that softwoods have dominated CLT panel construction because of density, stiffness, and strength requirements. In recent years, greater attention has been paid to the use of hardwoods in CLT panels. The overlapping layup construction of CLT reduces the deleterious effect of individual knots on the overall panel strength, opening the potential use of lower grade timber in CLT construction without loss of quality or strength.

Stauder (2013) provided an overview of CLT and briefly discussed the benefits of using undervalued hardwood in CLT panels. Hardwood as a base material for CLT construction is becoming more widely investigated. Hardwoods may allow CLT panels to be constructed with higher bending stiffness and greater shear resistance without increasing the overall dimensions, and in some cases reducing the thickness of the panels. CLT panels could have vertically oriented layers made of softwoods for compressive strength and transverse layers of hardwoods to take advantage of superior rolling shear and bending stiffness. Finger jointing can be used to overcome potential feedstock dimension limitations, and low-grade wood can be used in CLT. As demand for low-grade wood increases, the potential to use undervalued hardwoods becomes more viable.

Callegari and others (2010) described a project of constructing CLT panels made of chestnut (*Castanea sativa* Mill.) and poplar wood (*Popolus* × *euroamericana*) using the industrial framework then available locally in the area of Piedmont, Italy. The focus of the project was increasing the value of the local construction timber supply chain. Two industrial partners were identified: a sawmill that worked with chestnut wood and a plywood company capable of producing the panels. The project confirmed the feasibility of producing reduced size CLT panels using equipment available in the plywood sector. A notable problem with the process was the presence of shakes. Prior to panel construction, shakes were not evident and within allowable tolerance. After board production, excessively large shakes could develop during the panel conditioning phase.

Brandner (2013) described the use of hardwood in CLT in Brucknerstrasse, Graz, Austria. A three-story building was constructed of CLT panels composed of silver birch (*Betula pendula*). Several other hardwoods were identified as possible candidates for use in CLT because of their physical characteristics, availability, and economic viability including poplar (*Populus* spp.) and ash (*Fraxinus excelsior*). The use of hardwoods in CLT may allow for additional optimization of CLT properties by utilizing hardwoods in transverse layers and exploiting the higher rolling shear of such species or using species with high bending strength as outer CLT layers.

Ehrhart and others (2015) examined the rolling shear properties of several European hardwood species for use in CLT. The performance of hardwood species birch (*Betula pendula* Roth), beech (*Fagus sylvatica* L.), poplar (*Populus* spp.), and ash (*Fraxinus excelsior* L.) were compared with those of softwood species Norway spruce (*Picea abies* (L.) Karst.) and pine (*Pinus sylvestris* L.). When all species were examined together, a strong correlation was found between both density and rolling shear modulus and density and rolling shear strength. With respect to the rolling shear properties, poplar was comparable to both softwood species, birch slightly exceeded both softwoods, and ash and beech had property values between two to three times those of either Norway spruce or pine. The findings indicated that beech, ash, birch, and poplar all had great potential for use in CLT.

Beagley and others (2014) examined the use of yellow-poplar (or tulipwood) (*Liriodendron tulipifera*) for potential use in CLT panels. Yellow-poplar has a specific gravity that meets the current CLT requirements (APA 2019). In this study, six five-layer CLT panels were constructed using yellow-poplar. Preliminary results from nondestructive tests of CLT panels constructed of yellow-poplar indicate that they met requirements for bending and shear stiffness as dictated by ANSI/APA PRG 320-2019 (APA 2019). The research showed that yellow-poplar had great potential as a feed material for CLT construction. Slavid (2013) explained that yellow-poplar is a hardwood of particular interest for CLT construction because it has mechanical properties close to many softwoods, grows tall and straight, and has fewer knots than many other hardwoods. Yellow-poplar is one of the fastest drying hardwoods as well, meaning that less time is required to kiln dry it than for other wood types. It is also abundant in the United States and relatively low cost. Stauder (2013) noted that yellow-poplar was likely to be among the first hardwoods accepted for CLT construction, and research has been conducted on use of yellow-poplar in CLT (Mohamedzadeh and Hindman 2015).

Vetsch (2015) constructed CLT panels from aspen (*Populus tremuloides*), which is a locally abundant and underutilized wood in Minnesota. Panels were constructed using locally acquired aspen wood. The panels were tested in accordance with ASTM D198-09 Standard Test Methods of Static Tests of Lumber in Structural Sizes and ANSI/APA PRG 320-2012. The maximum loads from the aspen panels exceeded those required in the standards; however, the modulus of elasticity (MOE) and modulus of rupture (MOR) fell below standard levels. It was noted by Vetsch that during failure testing, complete delamination occurred between some panel layers; at some point during the testing, there was no bonding between adjacent layers. As tested, the sample performance was close to meeting standard levels. It was theorized that improved panel manufacturing would prevent delamination during testing and the resulting panels would exceed standard requirements. The preliminary study showed that aspen had potential to be used in CLT panels, but additional testing was needed due to the delamination and small sample size before a conclusion could be drawn.

Kramer (2014) and Kramer and others (2014) demonstrated the viability of using plantation-grown, low-density hybrid poplar (*Pacific albus*) in performance-rated CLT panels. The shear and bending performance of the panels used in the study was evaluated against ANSI/APA PRG-320-2012 (APA 2012). The available supply of hybrid poplar in the Pacific Northwest has increased because of decreasing use by the pulp and paper industry. Panels constructed of hybrid poplar will likely meet or exceed bending and shear strength requirements, but the panels did not meet stiffness (MOE) requirements. Hybrid poplar could be used in conjunction with higher density wood species to create panels with greater property efficiency that fully comply with standard requirements.

Wood–Nonwood Composites

Wood–Plastic Composite

The use of wood–plastic composite lumber in North America has experienced tremendous growth in the past decade, largely because of residential construction applications. Common applications in North America include decking, railings, window profiles, roof tiles, and siding. These lumber products are generally manufactured using profile extrusion. The properties of wood–plastic composite lumber can vary greatly depending upon such variables as type, form, and weight fractions of the constituents, types of additives, and processing history. Because the formulations from each commercial manufacturer are proprietary, design data should be obtained directly from the manufacturer.

Some generalizations can be made regarding the performance of wood–plastic composites, but there are exceptions. Flexural and tensile properties of wood–plastic composite lumber generally fall between those of solid wood lumber and unfilled plastics. Most commercial wood–plastic composites are considerably less stiff than solid wood but are stiffer than unfilled plastic (Clemons 2002). Compared with solid wood lumber, wood–plastic composites have better decay resistance and dimensional stability when exposed to moisture. Compared with unfilled plastics, wood–plastic composites are stiffer and have better dimensional stability when exposed to changes in temperature.

Table 12–9. Selected properties of wood–plastic products[a]

		Tensile properties				Flexural properties				Izod impact energy (J m^{-1})	
		Strength		Modulus		Strength		Modulus			
Composite	Specific gravity	MPa	(lb in^{-2})	GPa	(×10^6 lb in^{-2})	MPa	(lb in^{-2})	GPa	(×10^6 lb in^{-2})	Notched	Unnotched
Polypropylene (PP)	0.90	28.5	(4,134)	1.53	(0.22)	38.30	(5,555)	1.19	(0.17)	20.9	656
PP + 40% wood flour	1.05	25.4	(3,684)	3.87	(0.56)	44.20	(6,411)	3.03	(0.44)	22.2	73
PP + 40% wood flour + 3% coupling agent	1.05	32.3	(4,685)	4.10	(0.59)	53.10	(7,702)	3.08	(0.45)	21.2	78
PP + 40% wood fiber	1.03	28.2	(4,090)	4.20	(0.61)	47.90	(6,947)	3.25	(0.47)	23.2	91
PP + 40% wood fiber + 3% coupling agent	1.03	52.3	(7,585)	4.23	(0.61)	72.40	(10,501)	3.22	(0.47)	21.6	162

[a]From Stark and Rowlands (2003).

Table 12–9 shows mechanical properties of unfilled polypropylene and several wood–polypropylene composites. One of the primary reasons to add wood filler to unfilled plastics is to improve stiffness. Strength of the unfilled plastic can also increase but only if the wood component acts as reinforcement with good bonding between the two components. Table 12–9 illustrates how wood–plastic composite properties can vary with changing variables. For example, adding wood fiber instead of wood flour to polypropylene improved the strength and stiffness. Generally, adding a coupling agent to the mix also improved mechanical properties. Adding wood to polypropylene was not without tradeoffs. Impact resistance of such composites decreased compared with that of unfilled polypropylene.

Inorganic-Bonded Composites

Inorganic-bonded wood composites are molded products or boards that contain between 10% and 70% by weight wood particles or fibers and conversely 90% to 30% inorganic binder. Acceptable properties of an inorganic-bonded wood composite can be obtained only when the wood particles are fully encased with the binder to make a coherent material. This differs considerably from the technique used to manufacture thermosetting-resin-bonded boards, where flakes or particles are "spot welded" by a binder applied as a finely distributed spray or powder. Because of this difference and because hardened inorganic binders have a higher density than that of most thermosetting resins, the required amount of inorganic binder per unit volume of composite material is much higher than that of resin-bonded wood composites. The properties of inorganic-bonded wood composites are significantly influenced by the amount and nature of the inorganic binder and the woody material as well as the density of the composites.

Inorganic binders fall into three main categories: gypsum, magnesia cement, and Portland cement. Gypsum and magnesia cement are sensitive to moisture, and their use is generally restricted to interior applications. Composites bonded with Portland cement are more durable than those bonded with gypsum or magnesia cement and are used in both interior and exterior applications. Inorganic-bonded composites are made by blending proportionate amounts of lignocellulosic fiber with inorganic materials in the presence of water and allowing the inorganic material to cure or "set up" to make a rigid composite. All inorganic-bonded composites are very resistant to deterioration, particularly by insects, vermin, and fire. Typical properties of low-density cement–wood composite fabricated using an excelsior-type particle are shown in Table 12–11.

Testing Standards

The physical and mechanical properties of wood-based composite materials are usually determined by standard ASTM test methods. The following are the commonly used methods described in ASTM (2009):

ASTM C208–08. Standard specification for cellulosic fiber insulating board.

ASTM D1037–06a. Standard test methods for evaluating the properties of wood-based fiber and particle panel materials.

ASTM D2718–00 (2006). Standard test method for structural panels in planar shear (rolling shear).

ASTM D2719–89 (2007). Standard test methods for structural panels in shear through-the-thickness.

ASTM D3043–00 (2006). Standard test methods of testing structural panels in flexure.

Table 12–10. Selected properties of extruded wood–plastic products

Composite	Tensile strength (MPa (lb in^{-2}))	Compression strength (MPa (lb in^{-2}))	Bending strength (GPa (×10^{6} lb in^{-2}))	Bending modulus (MPa (lb in^{-2}))	Shear strength (MPa (lb in^{-2}))	Dowel bearing strength (MPa (lb in^{-2}))
Polypropylene (PP)[a, b]	20.0 (2,900)	55.2 (8,000)	3.49–5.97 (0.506–0.866)	22.2–60.8 (3,220–8,820)	22.0 (3,190)	84.8 (12,300)
High-density polyethylene (HDPE)[c]	5.5–15.2 (800–2,200)	11.7–26.9 (1,700–3,900)	1.79–5.17 (0.260–0.750)	10.3–25.5 (1,500–3,700)	7.79–10.3 (1,130–1,500)	35.7 (5,180)
Polyvinylchloride (PVC)[c]	25.1 (3,640)	61.2 (8,880)	4.81–7.58 (0.697–1.100)	35.9–54.5 (5,200–7,900)	20.2 (2,930)	72.4–128.2 (10,500–18,600)

[a]From Slaughter (2004).
[b]From Kobbe (2005).
[c]From Wolcott (2001).

Table 12–11. General properties of low-density cement–wood composite fabricated using an excelsior-type particle[a,b]

Property	Value range (MPa (lb in^{-2})) Low	High
Bending strength	1.7 (250)	5.5 (800)
Modulus of elasticity	621 (90,000)	1,241 (180,000)
Tensile strength	0.69 (100)	4.1 (600)
Compression strength	0.69 (100)	5.5 (800)
Shear[c]	0.69 (100)	1.4 (200)
E/*G* ratio[d]	40.0	100.0

[a]Data present compilation of raw data from a variety of sources for range of board properties. Variables include cement–wood mix, particle configuration, density, and forming and curing method.
[b]Specific gravity range from 0.5 to 1.0.
[c]Shear strength data are limited to small samples having a specific gravity of 0.5 to 0.65.
[b]*E*/*G* is ratio of bending modulus of elasticity to shear modulus. For wood, this ratio is about 16.

ASTM D3044–94 (2006). Standard test method for shear modulus of wood-based structural plywood.

ASTM D3500–90 (2003). Standard test methods for structural panels in tension.

ASTM D3501–05a. Standard test methods of testing plywood in compression.

ASTM D3737–08. Standard practice for establishing allowable properties for structural glued laminated timber (glulam).

ASTM D5456–09. Specification for evaluation of structural composite lumber products.

ASTM D7031–04. Standard guide for evaluating mechanical and physical properties of wood-plastic composite products.

ASTM D7032–08. Standard specification for establishing performance ratings for wood-plastic composite deck boards and guardrail systems.

ASTM D7341–09. Standard practice for establishing characteristic values for flexural properties of structural glued laminated timber by full-scale testing.

ASTM E1333–96 (2002). Test method for determining formaldehyde concentration in air and emission rate from wood products using a large chamber.

Literature Cited

AF&PA. 2005. Guideline—wood I-joist ASD manual for engineering wood construction. ANSI/AF&PA NDS–2005. National Design Specification® (NDS®) for Wood Construction. Washington, DC: American Forest & Paper Association.

AITC. 2007. Standard for wood products: structural glued-laminated timber. ANSI/AITC 190.1–2007. Centennial, CO: American Institute of Timber Construction.

ASLS. 2020. American softwood lumber standard, voluntary product standard PS 20-20. Washington, DC: U.S. Department of Commerce.

APA. 1981. Performance standards and policies for APA structural use panels. Tacoma, WA: American Plywood Association. 1 p.

APA. 1991. Performance standards and policies for structural use panels. APA PRP–108. Tacoma, WA: APA–The Engineered Wood Association.

APA. 1995a. Design capacities of APA performance-rated structural-use panels. Tech. Note N375 B. Tacoma, WA: APA–The Engineered Wood Association. 12 p.

APA. 1995b. Plywood design specification. Tacoma, WA: APA–The Engineered Wood Association. 10 p.

APA. 2019. Standard for performance-rated cross-laminated timber. ANSI/APA PRG 320-2019. Tacoma, WA: APA–The Engineered Wood Association.

ASTM. 2007. Annual book of ASTM standards. Philadelphia, PA: American Society for Testing and Materials.

Beagley, K.S.M.; Loferski, J.R.; Hindman, D.P.; Bouldin, J.C. 2014. Investigation of hardwood cross-laminated timber design. In: Proc., World Conference on Timber Engineering: Renaissance of Timber Construction, August 10–14, 2014.

Biblis, E.J. 1989. Properties of commercial OSB from three Southern Pine mills. Forest Products Journal. 39(1): 55–57.

Biblis, E.J. 2000. Effect of weathering on surface quality and structural properties of six species of untreated commercial plywood siding after 6 years of exposure in Alabama. Forest Products Journal. 50(5): 47–50.

Bogensperger, T.; Augustin, M.; Schickhofer, G. 2011. Properties of CLT-panels exposed to compression perpendicular to their plane. In: Proceedings to International Council for Research and Innovation in Building and Construction, Working Commission W18—Timber Structures: 1–15.

Bohlen, J.C. 1974. Tensile strength of Douglas-fir laminated-veneer lumber. Forest Products Journal. 24(1): 54–58.

Brandner, R. 2013. Production and technology of cross laminated timber (CLT): a state-of-the-art report. In: COST Action FP1004, Focus STS–European Conference on Cross-Laminated Timber (CLT): 2–36.

Cai, Z. 2006. Selected properties of MDF and flakeboard overlaid with fiberglass mats. Forest Products Journal. 56(11/12): 142–146.

Cai, Z.; Muehl, J.H.; Winandy, J.E. 2006. Effects of panel density and mat moisture content on processing medium density fiberboard. Forest Products Journal. 56(10): 20–25.

Callegari, G.; Cremonini, C.; Rocco, V.M.; Spinelli, A.; Zanuttini, R. 2010. The production of hardwood X-Lam panels to valorize the forest-wood chain in Piemonte (Italy). In: Proceedings of the World Conference on Timber Engineering.

Clemons, C.M. 2002. Wood-plastic composites in the United States: the interfacing of two industries. Forest Products Journal. 52(6): 10–18.

CPA. 1999. Particleboard standard. ANSI A 208.1–1999. Leesburg, VA: Composite Panel Association.

CPA. 2002. MDF standard. ANSI A 208.2–2002. Leesburg, VA: Composite Panel Association.

CPA. 2004a. Basic hardboard. ANSI A 135.4–2004. Leesburg, VA: Composite Panel Association.

CPA. 2004b. Prefinished hardboard paneling. ANSI A 135.5–2004. Leesburg, VA: Composite Panel Association.

CPA. 2006. Hardboard siding. ANSI A 135.6–2006. Leesburg, VA: Composite Panel Association.

Ehrhart, T.; Brandner, R.; Schickhofer, G.; Frangi, A. 2015. Rolling shear properties of some European timber species with focus on cross laminated timber (CLT): test configuration and parameter study. Doctoral dissertation, Andrea Frangi.

He, M.J.; Sun, X.F.; Li, Z. 2018. Bending and compressive properties of cross-laminated timber (CLT) made from Canadian hemlock. Construction and Building Materials. 185: 175–183.

Hernandez, R.; Moody, R.C. 1992. Improved performance of Southern Pine structural glued-laminated timber. Res. Pap. FPL–RP–514. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 22 p.

Hernandez, R.; Green, D.W.; Kretschmann, D.E.; Verrill, S.P. 2005. Improved utilization of small-diameter ponderosa pine in glulam timber. Res. Pap. FPL–RP–625. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 38 p.

Hindman, D.P.; Bouldin, J.C. 2015. Mechanical properties of southern pine cross-laminated timber. Journal of Materials in Civil Engineering. 27(9): 04014251. http://ascelibrary.org/doi/abs/10.1061/(ASCE)MT.1943-5533.0001203

HPVA. 2004. American national standard for hardwood and decorative plywood. ANSI/HPVA–1–2004. Reston, VA: Hardwood Plywood & Veneer Association. 35 p.

Janowiak, J.J.; Manbeck, H.B.; Hernandez, R.; Moody, R.C.; Blankenhorn, P.R.; Labosky, P. 1995. Efficient utilization of red maple in glued-laminated timber beams. Res. Pap. FPL–RP–541. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 23 p.

Jung, J. 1982. Properties of parallel-laminated veneer from stress-wave tested veneers. Forest Products Journal. 32(7): 30–35.

Karacabeyli, E.; Douglas, B., eds. 2013. CLT handbook: cross-laminated timber: U.S. edition. Special publication. ISSN 1925-0495; SP-529E. Pointe-Claire, QC, Canada: FP Innovations and Binational Softwood Lumber Council.

Koch, P. 1973. Structural lumber laminated from 1/4-inch rotary-peeled Southern Pine veneer. Forest Products Journal. 23(7):17–25.

Kordziel, S.; Glass, S.V.; Pei, S.; Zelinka, S.L.; Tabares-Velasco, P.C. 2018. Moisture monitoring and modeling of mass-timber building systems. In: Proceedings, WCTE 2018-World conference on timber engineering. Seoul, Republic of South Korea: Korean Institute of Forest Science. 7 p.

Kramer, A. 2014. Cross-laminated timber engineering: improvement and application. M.S. thesis. Corvallis, OR: Oregon State Univ.

Kramer, A.; Barbosa, A.; Sinha, A. 2014. Viability of hybrid poplar in ANSI approved cross-laminated timber applications. Journal of Materials in Civil Engineering. 26(7): 10.

Kretschmann, D.E.; Moody, R.C.; Pellerin, R.F.; Bendtsen, B.A.; Cahill, J.M.; McAlister, R.H.; Sharp, D.W. 1993. Effect of various proportions of juvenile wood on laminated veneer lumber. Res. Pap. FPL–RP–521. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 35 p.

Kunesh, R.H. 1978. MICRO-LAM: structural laminated veneer lumber. Forest Products Journal. 28(7): 41–44.

Manbeck, H.B.; Janowiak, J.J.; Blankenhorn, P.R.; Labosky, P.; Moody, R.C.; Hernandez, R. 1993. Red maple glulam timber beam performance. FPL–RP–519. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 32 p.

Marx, C.M.; Moody, R.C. 1981a. Bending strength of shallow glued-laminated beams of a uniform grade. Res. Pap. FPL–RP–380. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 19 p.

Marx, C.M.; Moody, R.C. 1981b. Strength and stiffness of small glued-laminated beams with different qualities of tension laminations. Res. Pap. FPL–RP–381. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 48 p.

McNatt, J.D. 1973. Basic engineering properties of particleboard. Res. Pap. FPL–206. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

McNatt, J.D. Myers, G. 1993. Selected properties of commercial high-density hardboards. Forest Products Journal. 43(4): 59–62.

Mohamedzadeh, M.; Hindman, D. 2015. Mechanical performance of yellow-poplar cross laminated timber. Report no. CE/VPI-ST-15-13. Blacksburg, VA: Virginia Polytechnic Institute and State University. 34 p.

Moody, R.C. 1972. Tensile strength of lumber laminated from 1/8-inch-thick veneers. Res. Pap. FPL–RP–181. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 28 p.

Moody, R.C.; Peters, C.C. 1972. Strength properties of rotary knife-cut laminated Southern Pine. FPL–RP–178. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 1 p.

Moody, R.C. 1974. Flexural strength of glued-laminated timber beams containing coarse-grain Southern Pine lumber. Res. Pap. FPL–222. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 42 p.

Moody, R.C.; Hernandez, R.; Davalos, J.F.; Sonti, S.S. 1993. Yellow poplar glulam timber beam performance. Res. Pap. FPL–RP–520. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 30 p.

NIST. 2004. Voluntary product standard PS 2–04. Performance standard for wood-base structural-use panels. National Institute of Standards and Technology. Gaithersburg, MD: U.S. Department of Commerce.

NIST. 2007. Voluntary product standard PS 1–07. Construction and industrial plywood. National Institute of Standards and Technology. Gaithersburg, MD: U.S. Department of Commerce.

O'Halloran, M.R. 1979. Development of performance specifications for structural panels in residential markets. Forest Products Journal. 29(12): 21–26.

O'Halloran, M.R. 1980. The performance approach to acceptance of building products. In: Proceedings, 14th Washington State University particleboard symposium. Pullman, WA: 77–84.

Pu, J.; Tang, R.C.; Davis, W.C. 1992. Creep behavior of commercial oriented strandboard under high relative humidity. Forest Products Journal. 42(4): 49–54.

Riggio, M.; Schmidt, E.; Mustapha, G. 2019. Moisture monitoring data of mass timber elements during prolonged construction exposure: the case of the forest science complex (Peavy Hall) at Oregon State University. Frontiers in Built Environment. 5: 98. doi:10.3389/fbuil.2019.00098

Schmidt, E. Riggio, M. 2019. Monitoring moisture performance of cross-laminated timber building elements during construction. Buildings. 9: 144. doi:10.3390/buildings9060144

Serrano, E.; Enquist, B. 2010. Compression strength perpendicular to grain in cross-laminated timber (CLT). In: World Conference on Timber Engineering (WCTE), Riva del Garda, 2010.

Shedlauskas, J.P.; Manbeck, H.B.; Janowiak, J.J.; Hernandez, R.; Moody, R.C.; Labosky, P., Jr.; Blankenhorn, P.R. 1996. Efficient use of red oak for glued-laminated beams. Transactions of ASAE. 39(1): 203–209.

Slavid, R. 2013. Endless stair—a towering Escher-like structure made from American tulipwood CLT for the London Design Festival 2013. https://www.americanhardwood.org/sites/default/files/publications/download/2017-04/AHEC%20The%20Endless%20Stair_pages.pdf (Accessed February 24, 2020.)

SmartLam. 2019. SmartLam V1M2 CLT qualification. APA supplied CLT qualification test plan. (Reference not for public distribution.)

Stark, N.M.; Rowlands, R.E. 2003. Effects of wood fiber characteristics on mechanical properties of wood/

polypropylene composites. Wood Fiber Science. 35(2): 167–174.

Stauder, C. 2013. Cross-laminated timber—an analysis of the Austrian industry and ideas for fostering its development in America. Austrian Marshall Plan Foundation. September.

Stokes, C.E.; França, T.S.F.A.; Tang, J.D. 2019. Ongoing termite studies on cross laminated timber (CLT) panels. In: Proceedings, American Wood Protection Association, Orlando, FL: 173–178.

Suchsland, O.; Lyon, D.E.; Short, P.E. 1979. Selected properties of commercial medium-density fiberboard. Forest Products Journal. 29(9): 45–49.

TECO. 1991. Performance standards and policies for structural-use panels. TECO PRP–133. Eugene, OR: Timber Engineering Company.

van de Lindt, J.; Amini, M.O.; Rammer, D.; Line, .; Pei, S.; Popovski, M. 2016. Developing seismic performance factors for cross laminated timber in the United States. In: Proceedings, the 11th Canadian conference on earthquake engineering. Vancouver, BC: Canadian Association for Earthquake Engineering: 1–10.

Vessby, J.; Enquist, B.; Petersson, H.; Alsmarker, T. 2009. Experimental study of cross-laminated timber wall panels. European Journal of Wood Products. 67: 211–218.

Vetsch, N. 2015. A performance evaluation of cross-laminated timber manufactured with aspen. University of Minnesota Digital Conservancy. http://hdl.handle.net/11299/172229

Wang, S.; Gu, H.; Neimsuwan, T.; Wang, S.G. 2003. Layer thickness swell and related properties of commercial OSB products: a comparative study. In: Proceedings, 37th international particleboard and composite materials symposium. 2003 April 7–10. Pullman, WA: Washington State University. 65–76.

Wang, X.; Ross, R.J.; Brashaw, B.K.; Verhey, S.A.; Forsman, J.W.; Erickson, J.R. 2003. Flexural properties of laminated veneer lumber manufactured from ultrasonically rated red maple veneer. A pilot study. Res. Note FPL–RN–0288. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 5 p.

Williamson, T.; Ross, R.J., eds. 2016. Proceedings: mass timber research workshop 2015. General Technical Report FPL–GTR–241. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 364 p.

Yeh, B.; Gagnon, S.; Williamson, T.; Pirvu, C.; Lum, C.; Kretschmann, D. 2012. The North American product standard for cross-laminated timber. Wood Design Focus. 22(2): 13–21.

Youngquist, J.A.; Laufenberg, T.L.; Bryant, B.S. 1984. End jointing of laminated veneer lumber for structural use. Forest Products Journal. 34(11/12): 25–32.

Youngquist, J.A.; Myers, G.E.; Muehl, J.M. 1993. Composites from recycled wood and plastics. Final Rep., U.S. Environmental Protection Agency, Project IAG DW12934608–2. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 3 p.

Zelinka, S.L.; Williamson, T.; Martinson, K.L.; Ritter, M.A. 2019. Research needs assessment for the mass timber industry: Proceedings of the 2nd North American mass timber research needs workshop. General Technical Report FPL–GTR–273. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 41 p.

Zelinka, S.L.; Hasburgh, L.E.; Bourne, K.J. 2020. Overview of North American CLT fire testing and code adoption. Wood & Fire Safety. 2020: 232–237.

Wood Handbook

Wood as an Engineering Material

Forest Products Laboratory | United States Department of Agriculture Forest Service | Madison, Wisconsin

Abstract

Summarizes information on wood as an engineering material. Presents properties of wood and wood-based products of particular concern to the architect and engineer. Includes discussion of designing with wood and wood-based products along with some pertinent uses.

Keywords: wood structure, physical properties (wood), mechanical properties (wood), lumber, wood-based composites, plywood, panel products, design, fastenings, wood moisture, drying, gluing, fire resistance, finishing, decay, preservation, wood-based products, heat sterilization, sustainable use

March 2021

Forest Products Laboratory. 2021. Wood handbook—wood as an engineering material. General Technical Report FPL-GTR-282. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 543 p.

A limited number of free copies of this publication are available to the public from the Forest Products Laboratory, One Gifford Pinchot Drive, Madison, WI 53726-2398. This publication is also available online at www.fpl.fs.fed.us. Laboratory publications are sent to hundreds of libraries in the United States and elsewhere.

The Forest Products Laboratory is maintained in cooperation with the University of Wisconsin.

Pesticide Precautionary Statement

This publication reports research involving pesticides. It does not contain recommendations for their use, nor does it imply that the uses discussed here have been registered. All uses of pesticides must be registered by appropriate State and/or Federal agencies before they can be recommended.

Caution: Pesticides can be injurious to humans, domestic animals, desirable plants, and fish or other wildlife, if they are not handled or applied properly. Use all pesticides selectively and carefully. Follow recommended practices for the disposal of surplus pesticides and pesticide containers.