Chapter

Strand-Based Engineered Wood Products in Construction

Zizhen Gao and Meng Gong

Abstract

Strand-based engineered wood products (EWPs) have been widely employed in construction since their emergence in the 1970s. The use of strand-based EWPs can significantly increase the yield of forest resources by utilizing submarginal logs and branches. In this chapter, the strand-based EWPs, including oriented strand board (OSB), laminated strand lumber (LSL), and oriented strand lumber (OSL), are discussed in terms of their fabrication, properties, and uses in construction. Specifically, the manufacturing requirements for elements (i.e., strands), such as dimension, density, and moisture content, are introduced. The major manufacturing processes, such as selection of adhesives, pressing parameters, and thickness control, are also discussed. In addition, the engineering properties and uses of these EWPs are illustrated. Furthermore, some innovative applications of these products, such as hybrid cross-laminated timber, are presented in this chapter.

Keywords: strand-based engineered wood products, oriented strand board (OSB), laminated strand lumber (LSL), oriented strand lumber (OSL), manufacturing process, mechanical properties, structural applications

1. Introduction

Prior to availability of steel and concrete, wood has been widely used as the primary structural material in North America. In the recent past, the concept of green building has become a mainstream and people have been becoming aware of potential environmental benefits of wood and wood-based materials [1–3]. With the increase in population and wood buildings across the world, there is an observable increase in demand for structural wood products [4]. However, the production and properties of solid lumber are hard to meet the demand of construction since the logs become smaller and the wood quality becomes lower due to the change in raw materials that come from the faster-growing plantation species. As a result, engineered wood products (EWPs), such as glue-laminated timber (GLT), cross-laminated timber (CLT), laminated veneer lumber (LVL), and oriented strand board (OSB), were developed as the alternative, since they commonly provide better and more predictable physical and mechanical properties than solid wood lumbers [5].

Plywood used to be the most common panel material widely used as sheathing materials in wood buildings before the advent of strand-based wood products. Relatively, LVL, as a thicker structural form of veneer-based products, was developed for beams, studs, and other components in wood buildings as the substitution of solid lumber. However, small, twisted, and juvenile logs are not suitable for producing veneer. In addition, up to 60% of the log volume delivered to a plywood plant is treated as residues [6, 7]. The cost of manufacturing veneer-based EWPs keep increasing because the logs of satisfying quality, such as straight and large diameter stems, have been in short supply [6, 7]. Therefore, strand-based materials were invented as a substitute for plywood or other solid wood products to manufacture panel- and beam-like components in buildings. In the early 1970s, strand-based wood panels called waferboard, which consisted of randomly placed wood strands, were patented by Armin Elmendorf [8]. Waferboard was the parent product of what would evolve into modern strand-based products like OSB. When people realized that the properties along the board could be improved by controlling the direction of strand lay-up, OSB was established in its present form and was subsequently produced as a commercial wood panel in North American [8]. In the next decade after the 1970s, the OSB industry had developed rapidly and began to rival traditional plywood in production. By the mid-1990s, the production of OSB had increased to more than 50% of the plywood volume [8, 9]. Due to the advantages of OSB and its great success achieved in the wood panel market, laminated strand lumber (LSL) and oriented strand lumber (OSL), which are other two forms of strand-based products, were developed as a substitute for LVL and dimensional lumber in the 1990s. In the early 2000s, OSB surpassed plywood in production and sales, taking the largest market share of the wood panel products. Up to now, OSB is the leading wood panel product and occupies a 75% market share in North America [9]. Moreover, LSL and OSL have also gained some market share in the lumber market [8, 9]. **Figure 1** illustrates the production of OSB and plywood in North America over the last six decades [10]. Overall, the production of OSB exceeded that of plywood around 2000 and there was a decrease in the production of both OSB and plywood between 2005 and 2010 due to the decline in the housing market in the USA [10].

Strand-based EWPs have become important members of the family of EWPs with development and advance in technologies. Over veneer- or lumber-based EWPs, strand-based EWPs have the advantages such as low requirements for raw materials, high-dimensional flexibility, and stable physical and mechanical properties [1]. In this chapter, the strand-based EWPs, including OSB and strand-based SCL such as LSL and OSL, are discussed in terms of their fabrication, properties, and uses in construction.

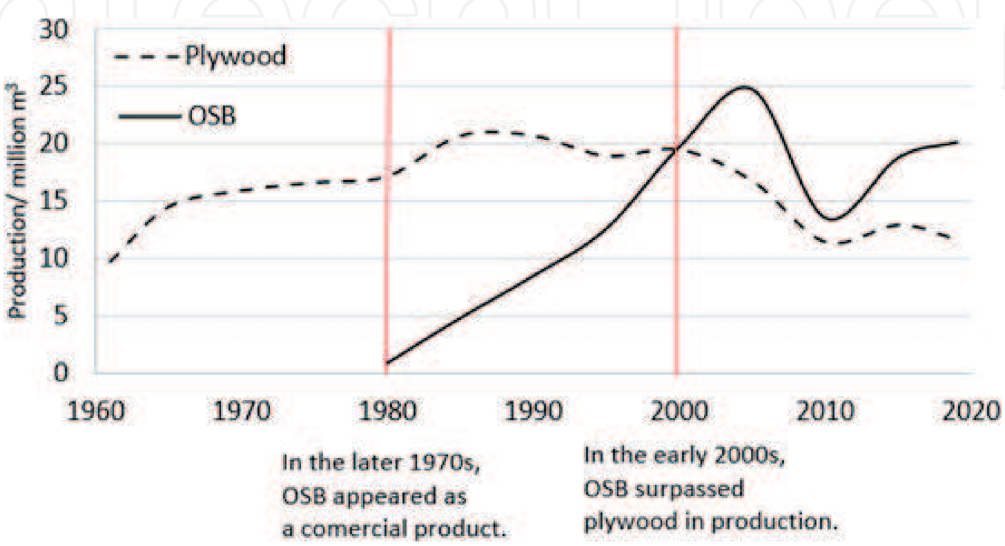

Figure 1.
Production of OSB and plywood in North America (source: FAOSTAT) [10].

2. Raw materials

2.1 Wood strands

One of the main advantages of strand-based EWPs compared to other types of EWPs is that a variety of wood sources are appropriate to be used in their manufacturing. In North America, aspen is one of the primary species for making OSB or other strand-based EWPs due to its low density, low cost, and rich abundance. In addition to aspen, southern pine, spruce, birch, yellow poplar, sweetgum, sassafras, and beech are also suitable raw materials for producing strands [1]. In reality, almost any low- to medium-density species (300–600 kg/m^3) can be utilized to make the elements, that is, strands also called wafers, chips or flakes, which have different sizes, in the fabrication of strand-based EWPs. In the real world, the strands made from high-density species, such as beech and birch, are often mixed with those made from low-density species to improve the mechanical properties of finished products [9]. In addition, wood with localized defects (such as knots), and wood-derived from small-diameter logs, forest residues (such as branches), or exotic and invasive species, can be also used in the manufacturing of strands. The yield of wood could reach 80–90% in the process of strand manufacturing since losses mainly coming from bark and broken strands during processing [1]. **Table 1** compares the quality requirements of raw materials between strand-based and other types of EWPs [11].

The manufacturing of strands contains the following key processes. Logs are first soaked in a hot water pond before debarking. This helps loosen the bark from logs and soften logs by increasing the moisture content of the logs to achieve a more desirable strand size during the stranding process. The fresh logs are then carried to a drum- or disc-type strander to make strands after debarking. Generally, strands produced are 75–300 mm in length, 15–25 mm in width, and 0.3–0.8 mm in thickness. Strand geometry has an essential influence on the performance of finished products [12, 13]. Therefore, strand grading using screens is critical to separate out strands that do not meet the dimensional requirement. The moisture content of strands has also a great influence on the bonding quality between strands. Typically, a cylindrical dryer is used to dry strands to a final moisture content of 2–6%, which is dependent on the type of adhesives [9, 11].

2.2 Adhesives

As the main raw material besides wood strands in the manufacturing of strand-based wood products, adhesives play a critical role in the determination of

Products	Generic raw material requirements	Preferred feedstock
Lumber-based EWPs such as GLT and CLT	Adequate strength, stiffness, and stability; small knots	Lumber from mature trees, but low-grade lumber for central layers
Veneer-based EWPs such as plywood and LVL	Large diameter logs; easy of being peeled	Mature trees with a large diameter
Strand-based EWPs such as OSB, LSL, and OSL	No specific requirements in mechanical properties and dimension of logs	Mature or juvenile logs, wood derived from small-diameter logs, forest residues, and wastes from the production of lumber or veneer

Table 1.
Quality requirements for raw materials of manufacturing EWPs.

the performance of finished products, in which phenol-formaldehyde (PF) and polymeric methylene di-isocyanate (pMDI) are the most commonly used structural adhesives [1, 6]. The adhesives to be used must meet the specific requirements for the mechanical properties and durability performance of the final products [1].

PF is one of the most common adhesives used in wood composites that are used as structural components for exterior uses due to its good mechanical properties and durability performance [1]. Therefore, PF resins are used in the manufacture of EWPs, which are exposed to weather or other moisture exposure situations during construction and use. Cured PF resins could remain stable chemical and physical properties in high temperature and humidity environments [14]. Therefore, PF has the ability to maintain the dimensional stability and mechanical properties of EWPs under wet conditions [1, 14]. The main disadvantage of PF is that its curing is a slow process compared with other structural adhesives, which requires a longer press time and higher press temperature during the manufacturing process [15]. As a result, phenol-resorcinol-formaldehyde (PRF) adhesives were developed as the substitution of PF [7]. As the name implies, it contains resorcinol in addition to phenol and formaldehyde. PRF has the advantage over PF of being curable at room temperature due to being much faster in reaction, and has similar good mechanical properties and durability performance to PF [7]. Some manufacturers have used PRF as the adhesives for strand-based wood products.

pMDI is usually used as an alternative to PF resin in strand-based EWPs. Although the costs of pMDI are higher than PF, it is taking the market share away from PF due to its rapid cure rate and higher tolerance of moisture content in the wood strands [1, 16]. Typically, pMDI is used in the core layer of strand-based EWPs since PF is used in the surface layers because pMDI provides good bonding strength, which makes the panel more waterproof and requires a lower curing temperature than PF. It is worth noting that mold release is needed if pMDI is used in the surface layer because it could bond strongly to the mental platens of the press [6, 16]. Special precautionary protective measures are required to use pMDI because the uncured resin can result in the chemical sensitization of persons exposed to it [1]. Fortunately, cured pMDI resin poses no recognized health concerns [1].

3. Oriented strand board (OSB)

3.1 Overview

OSB is multi-layered panels made from wood strands bonded together with adhesives under pressure and heat, which was first developed as the substitution of plywood in the 1970s [17]. Typically, OSB panels are made up of three orthogonal layers of strands, as shown in **Figure 2** [18]. The strands in surface layers are parallel to the long axis of the panel, whereas those in the core layer are perpendicular to the long axis of the panel or laid randomly. The performance of OSB panels can be engineering-designed by changing the strand size, orientation, and layered construction, allowing OSB to suit different uses [16]. OSB has been widely used for sheathing panels, web stocks of I-joists, packaging materials, and decorative and other purposes.

3.2 Manufacturing process

OSB can be produced using small-diameter logs from fast-growing trees, cores from veneering, and forest residues (such as branches and treetops). Only fresh

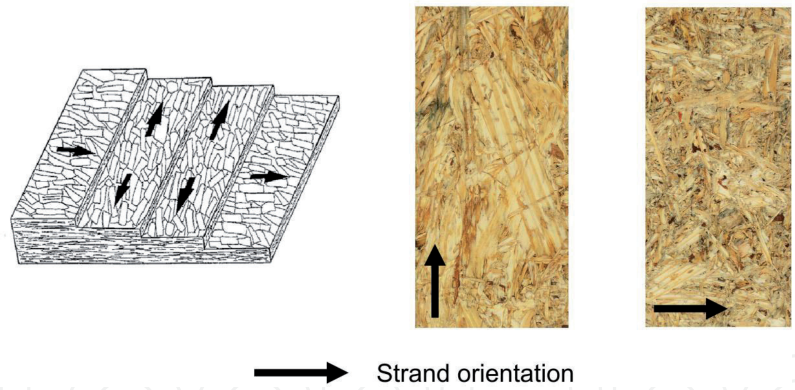

Figure 2.
Strand orientation of OSB panels: Schematic (left) (source: Picture obtained from FAPC) [18]; large-size strands in the surface layer (center) and small-size strands in the core layer (right).

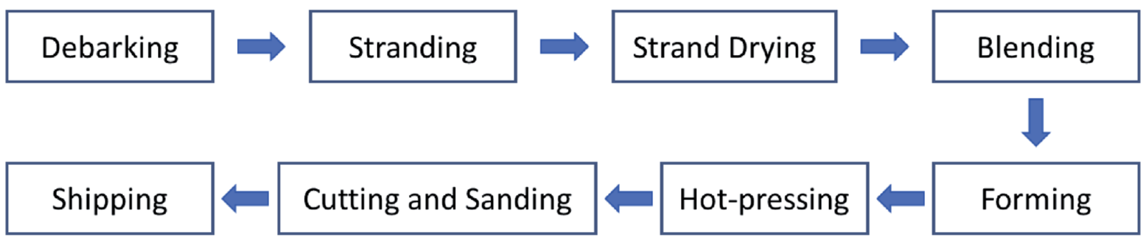

Figure 3.
The key manufacturing processes of OSB.

wood, rather than recycled wood, can be used for making stands and OSB [6]. A typical production process is given in **Figure 3**.

3.2.1 Stranding

The sizes of strands are given in Section 2.1, which results in a length-to-width ratio of about 3 [1, 19]. There are two types of stranders, drum and disc, producing strands. The disc stranders have advantages of simple structure, low price, and high production efficiency. The dimensions of the disc strands can be adjusted according to the requirements of different products when they are produced using a disc strander. However, it can only use large-size logs as raw materials. In contrast to disc stranders, the drum stranders have the adaptability to various shapes of raw materials, which means lower production costs for strand production. The larger-size strands are usually used in the surface layers, whereas the smaller-size strands in the core layer, constituting an optimized composite structure of better bending and shear properties.

3.2.2 Blending

Good adhesion between strands is a key factor to ensure the good performance of OSB panels. The process of adding a structural adhesive(s) and waxes to the strands is called blending. The adhesive content used in the surface layers is 3–6% while that in the core layer is 4–8%. Application of more adhesive in the core layer than the surface ones is a practical process in a production line. This is because the strands in the core layer have relatively smaller sizes than those in the surface ones, producing a larger surface area [6]. During blending, the wax with amount of 0.25–2% by weight is commonly added to improve the water resistance and reduce the thickness swelling of final OSB panels [4, 9]. Blending for surface and core layers of strands is usually done separately due to the difference in the spread amount of adhesive and wax, strand size, and type of adhesives between the surface and core layers. Therefore, at least two blenders are needed in a production line, one for surface layer strands and the other for core layer strands [9, 20].

3.2.3 Forming

The orientation and proportion of long strands in the surface layers significantly affect the bending properties of OSB. In general, about 80% of strands are oriented parallel to the long axis to meet the performance requirements of OSB [16]. Therefore, the process of depositing blended strands into the form of a mat is called forming. In addition to the orientation of the strands, the forming can also assist to produce a uniform weight across the area of a board, which can ensure the final OSB panels to have uniform density and mechanical properties. Although some new technologies, such as electrostatic strand orientation, have been developed, mechanical orientation is still the most reliable technology and is widely used in industrial manufacturing [6, 9]. Following the forming process, a heavy steel drum is often used to pre-press the mat before hot-pressing, albeit this step is not a must [16]. Pre-pressing can effectively reduce the risk of edge collapse during hot pressing. In addition, pre-pressing can also shorten press cycle time and reduce the risk of resin pre-curing, since pre-pressing squeezes much of air out of the mat [21].

3.2.4 Hot pressing

Hot pressing is the most important process, which cures the adhesives between strands under heat and pressure. This is the real step of turning the strands to a panel. A multi-opening press is widely used in the manufacturing of OSB in North America [9]. The size of press platens in a multi-opening press is generally 3.66 × 7.63 m (12 × 25 ft) but can be up to 3.66 × 12.2 m (12 × 40 ft). Large-press platens are favorable because they can greatly increase the production capacity of a production line. In addition, large single-opening presses and continuous presses are also used to manufacture OSB panels in some mills [9].

Heated press platens are enough to generate and transfer heat from the surfaces of a mat to the core to cure the adhesives since most of OSB panels are relatively thin with a thickness range of 7.9–28.6 mm (5/16 to 1–1/8 in.) [22]. The temperature during hot pressing ranges from 175 to 205°C (350–400°F) for PF adhesives. The pressing usually lasts for 3–6 min, which is depended on the type of adhesives, board density, and thickness [1, 9]. Theoretically, the relationship between the press time and the thickness of the OSB panel is quadratic when the densities are similar. For example, the time of hot pressing an 18-mm-thick OSB panel is about four times a 9-mm-thick one [9]. That means the time and cost of processing OSB panels greatly increase with increasing the thickness. To decrease the press time and reduce the cost, a high-frequency press or a steam injection press is adopted when making relatively thick OSB in some mills [1, 9]. Typically, the pressure used in the hot press is 4800–5500 kPa [9]. In short, the key to hot-press process is to reduce hot pressing time and improve production efficiency. Therefore, in industrial production, hot stacking of pressed materials is implemented shortly after emergence from the press to reduce the press time and energy consumption [6]. After the adhesive has completely cured, the OSB panels are cut to desired dimensions and sanded to nominal thickness. Finally, the edges of each panel are coated with zinc borate and oxine copper to improve its durability [18].

3.3 Properties and grading of OSB

As an alternative material of plywood, the nominal dimension of an OSB panel is typically 1.2 × 2.4 m (4 × 8 ft) in North America. Moreover, some OSB manufacturers also provide oversized panels with a dimension of 2.4 × 7.2 m (8 × 24 ft) for panelized roof and wall systems, facings for structural insulated panels (SIPs), and modular floors [22]. The physical and mechanical properties of OSB are directly related to wood species, strand size, adhesive type, and processing parameters. The density of OSB panels is usually 500–800 kg/m^3 [1]. Because the layers of OSB are oriented, its mechanical properties are different in the parallel-to- and perpendicular-to-orientation directions. Since both plywood and OSB are used as wood structural panels in wood buildings, the structural properties of OSB are similar to plywood. **Table 2** presents the major properties of OSB and plywood [1, 7, 18].

As a type of construction materials, the fire performance of OSB is critical. The flame spread index (FSI) is one of important indexes, which is commonly evaluated in conformance with ASTM E84"Standard test method for surface burning characteristics of building materials" [1, 23]. According to the International Building Code (IBC), the FSI is classified into Class A (0–25), Class B (26–75), and Class C (76–200) [1, 24]. The OSB panels without fire-treatment typically fall into Class C, while that of plywood panels are Class B or Class C [25]. The FSI values of OSB and plywood are also given in **Table 2**.

In North America, OSB panels are manufactured in conformance with Voluntary Product Standard PS 2 "Performance Standard for Wood Structural Panels" or Canadian Standard CSA O325 "Construction sheathing" [22]. According to PS2 and CSA O325, OSB panels are large, based on their intended use in construction, classified into three grades, namely Sheathing, Structural I sheathing, and Single floor [26, 27]. The minimum requirements of the typical properties and their testing methods of OSB panels with different grades are specified by PS2 and CSA O325, respectively. For

Property	Direction	OSB	Plywood
Density		500–800 kg/m^3	400–600 kg/m^3
Modulus of rupture	Parallel	21–48 MPa	33–48 MPa
	Perpendicular	8–30 MPa	—
Modulus of elasticity	Parallel	4.8–8.3 GPa	7–11 GPa
	Perpendicular	1.9–3.2 GPa	—
Tensile strength	Parallel	6.9–10.3 MPa	10.3–27.6 MPa
Compressive strength	Parallel	10–17 MPa	20.7–34.5 MPa
Shear strength	—	6.9–10.3 MPa	4.1–6.9 MPa
Shear modulus	—	1.2–2.0 GPa	—
Linear hygroscopic expansion in thickness (30–90% RH)	—	0.15%	—
Internal bond strength	—	0.28–0.57 MPa	—
Flame spread index	—	100–172	35–180
Flame spread class	—	C	B or C

Source: Data from Handbook of Wood Chemistry and Wood Composite, American Wood Council and Wood Handbook [1, 7, 25].

Table 2.
Typical properties of OSB and plywood.

Span rating or performance category		Stiffness, EI × 10^3		Maximum moment	
		Major	Minor	Major	Minor
		N·mm^2	N·mm^2	N·mm	N·mm
Sheathing	Roof-24	292	85	330	130
	Roof-24/subfloor-16	395	94	390	140
	Roof-32/subfloor-16	490	113	460	190
	Roof-40/subfloor-20	1240	358	810	360
	Roof-48/subfloor-24	1790	763	920	510
Structural I sheathing	3/8	292	85	330	130
	7/16	395	141	390	220
	15/32	490	245	460	320
	1/2	490	273	460	330
	19/32 & 5/8	1240	471	810	500
	23/32 & 3/4	1790	763	920	650
Single floor	Single floor-16	876	198	650	230
	Single floor-20	1110	264	710	240
	Single floor-24	1600	546	910	320
	Single floor-32	4170	1270	1570	600
	Single floor-48	8660	2110	2080	820

Source: Data from the standard PS 2–18 [26, 28].
Note: Major and minor represent the stress applied parallel- and perpendicular-to-strength axis, usually the length direction of a panel.

Table 3.
Quality assurance minimum reference values for the bending stiffness and strength of dry small specimens.

example, the bending properties of OSB shall be evaluated in conformance with ASTM D3043 "Standard Test Methods for Structural Panels in Flexure," and the minimum reference values for its quality assurance are given in **Table 3** [26, 28]. In addition, PS2 and CSA O325 specify that the bonding performance of OSB for construction shall meet the Exposure 1 bond classification, which means that the OSB panels are suitable for uses subjected to non-permanent exposure to the weather [26].

According to PS 2, the grade and end-use of an OSB panel shall be evaluated and classified by a third-party inspection agency, such as APA-The Engineered Wood Association and TECO-Sun Prairie [26]. The third-party agency has to visit the mills on a regular unannounced basis and confirm the performance of the OSB panels still meets the requirements stipulated in the standard [1, 26]. OSB panels conforming to product performance standards are marked with grade stamps by the third-party agency [1]. The sample grade stamps are shown in **Figure 4** [28, 29].

3.4 Applications

3.4.1 Sheathing

One of the major uses of OSB is for sheathing such as roof sheathing, subflooring, and wall sheathing in light-frame construction (**Figure 5**). Typically, the OSB used as sheathing materials is the sheathing grade or structural-I sheathing grade [30, 31]. The common nominal thickness of OSB for sheathing is 7.9 mm (5/16 in.), 9.5 mm (3/8 in.), 11.1 mm (7/16 in.), 11.9 mm (15/32 in.), 12.7 mm (1/2 in.), 15.1 mm

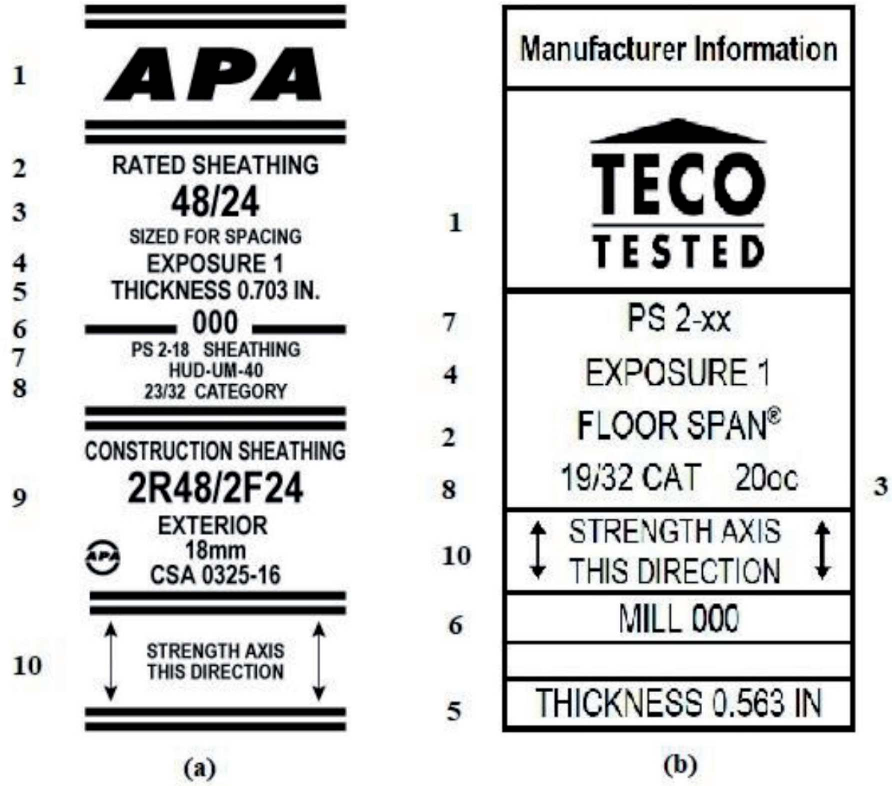

Figure 4.
Typical grade stamps for OSB: (a) APA grade stamp; and (b) TECO grade stamp. (1. Third-party inspection agency; 2. Panel grade; 3. Span rating; 4. Bond classification; 5. Thickness; 6. Mill number; 7. Product standards; 8. Performance category; 9. Canadian construction sheathing standard; 10. Panel face orientation indicator. Source: Pictures obtained from APA at https://www.apawood.org/apa-trademark and TECO at https://www.pfsteco.com).

(19/32 in.), 15.9 mm (5/8 in.), 18.2 mm (23/32 in.), and 19.0 mm (3/4 in.) [22]. When the OSB with the same performance category (same grade and same thickness) is used for different sheathings, the allowable maximum spacing of supports is different [30, 31]. Generally, the span rating of OSB, which donates the maximum spacing of supports for different sheathing, is marked on the grade stamps [28, 29]. For example, the span rating in **Figure 4(a)** is 48/24, which means the maximum spacing of supports is 48 in. when the panel is used for roof sheathing, and the maximum on center spacing of supports is 24 in when it is used for subfloors. According to PS 2 and CSA O325, OSB with roof span ratings of 24 or larger can be used as wall sheathing when the distance of studs is 24 in., whereas the panels with a roof span rating of less than 24 can only be used for wall sheathing with a distance of studs of 16 in. [26, 27, 30]. In addition, the minimum fastening schedule (such as nail spacing and nail size) and allowable live load of sheathing are also given in PS 2 and CSA O325.

3.4.2 Floor

The single-floor grade OSB is intended for flooring panels under carpet or pad (**Figure 6**). The common nominal thickness of OSB for flooring panels are 15.1 mm (19/32 in.), 15.9 mm (5/8 in.), 18.2 mm (23/32 in.), 19.0 mm (3/4 in.), 22.2 mm (7/8 in.), 25.4 mm (1 in.), and 28.6 mm (1–1/8 in.) [22]. Similar to the sheathing, the span rating of flooring panels is also given on the grade stamps; for example, the spacing rating in **Figure 4(b)** is 20 °C, which indicates that the maximum span of the flooring panel is 20 in. on center [28, 29]. Typically, the span ratings of single-floor OSB are 16, 20, 24, 32, and 48 oc [26, 27]. Allowable uniformly

Figure 5.
OSB sheathing used on floors (top), roofs (center), and walls (bottom) (source: Pictures obtained from APA at https://www.apawood.org/photography).

distributed live load at maximum span for flooring panels is 100 psf. The allowable uniformly distributed live load can be increased by reducing the spacing of supports of a floor [22]. The relationship between allowable uniformly distributed live load and span is given in **Table 4** [30].

3.4.3 Other applications

In addition to being used as panels, I-joints web stock is another major use of OSB, **Figure 7**, in wood buildings [9]. I-joints are manufactured using lumber or SCL flanges and OSB webs. Typically, flanges and webs are bonded using exterior-type adhesives such as PF and pMDI. The shear properties of I-joints are provided by OSB webs, while the flanges provide the bending properties of I-joints since OSB has higher shear properties than plywood (**Table 2**). OSB is also used in industrial applications such as shelving and packaging in commercial and industrial structures

Figure 6.
OSB used for floor sheathing and I-joist webs (source: Picture obtained from APA at https://www.apawood.org).

Span rating	Maximum span (in.)	Allowable live load (psf)						
		Span of supports						
		12	16	20	24	32	40	48
16 oc	16	185	100	—	—	—	—	—
20 oc	20	270	150	100	—	—	—	—
24 oc	24	430	240	160	100	—	—	—
32 oc	32	—	405	295	185	100	—	—
48 oc	48	—	—	425	290	160	100	55

Table 4.
Allowable live load of flooring panels with the different spans of supports (source: Data from APA at engineered wood construction guide) [30].

(**Figure 8**). In addition, some researchers tried to develop new applications of OSB panels. For example, Ma et al. developed a new type of lumber-like wood products made of OSB panels, namely laminated OSB, using a cold-cured structural adhesive, considering the cost and difficulty of manufacturing thick OSB [32].

4. Laminated strand lumber (LSL) and oriented strand lumber (OSL)

4.1 Overview

LSL and OSL are derivatives of OSB since they are all made from flaked wood strands (**Figure 9**). These two strand-based EWPs have more similarities than differences. The main difference is that the strands used in LSL are longer than OSL and OSB [1]. The length-to-thickness ratio of the strands used in LSL is approximately 150, while that of the strands for OSL is 75 [33]. As the two typical SCL, LSL and OSL were developed in response to the increasing demand for dimensional lumber [1]. LSL and OSL have become substitutes to solid lumber,

Figure 7.
I-joist made of OSB web and LVL flanges (source: Picture obtained from APA at https://www.apawood.org).

Figure 8.
OSB deck board of a pallet (source: Picture obtained from APA at https://www.apawood.org).

LVL, and PSL in many applications, such as studs, beams, and columns. The outstanding advantages of LSL and OSL are, in comparison with LVL and PSL, their lower material requirements, high yield of wood fibers, and stable properties [1]. LSL and OSL are, in terms of their manufacturing processes and product properties, thought to be exchangeable in the industry [34]. Therefore, the following discussion is mainly given to LSL, which can be used as references when readers are interested in OSL.

4.2 Manufacturing process

The manufacturing processes of LSL/OSL are similar to that of OSB [34], which can be seen in **Figure 3**. The low-density hardwoods, such as aspen and yellow poplar, are commonly used species for making LSL/OSL [34]. As mentioned in Section 4.1, the main difference between LSL and OSL is the dimensions of the strands. The dimensions of the strands used in LSL are 230–356 mm in length and

Figure 9.
LSL products (source: Pictures obtained from Weyerhaeuser at https://www.weyerhaeuser.com).

15–25 mm in width, while those of the strands for OSL are generally 100–150 mm in length and 15–25 mm in width [4, 9]. In addition, the thickness of LSL is larger than OSB; thus, the PF or PRF is not suitable adhesives for making LSL. Instead, the diphenylmethane diisocyanate (MDI) adhesive is used, which can significantly reduce the press time as compared with PF [9]. The blending and forming processes of LSL manufacturing are also similar to those of OSB manufacturing. The big difference between OSB and LSL goes to the orientation of strands in a mat/panel. The strands in the surface layers of OSB are mainly oriented parallel to the length direction, and those in core layers are perpendicular to the length direction or randomly. However, the strands in LSL are always aligned in its panel length direction through its thickness [4, 34]. This can help provide relatively high mechanical properties of the final products in the axis direction. The mat of LSL can be 406 mm (16 in.) in thickness and 2440 mm (8 ft) in width. The single opening is exclusively used in the manufacturing of LSL because it has the advantages of shortening press cycle time and being easy to make a uniform vertical density profile [4]. Sometimes, the steam injection is used during hot pressing to quickly increase the temperature of the core layers, reduce the press time, keep a uniform density profile through the thickness, and create a great resistance to warping [4]. It is worth noting, in some cases, specialized curved press platens could be used in the hot-pressing process of OSL to produce the products with some architectural shapes [9]. The LSL panels are cut to size and tested before receiving a protective end or edge seal. The moisture content of LSL products ranges from 7 to 10%.

4.3 Properties and grading of LSL and OSL

In North America, the nominal dimensions of LSL are generally similar to those of dimensional lumber on the market. Some manufacturers also provide special size products for special applications; for example, the size of TimberStrand®, which is the trade name of LSL manufactured by Weyerhaeuser Company, is up to 14.6 m in length, 1.2 m in width, and 140 mm in thickness [4, 35].

The density of LSL is about 15% higher than that of OSB, ranging from 640 to 670 kg/m^3 (40–42 lbs/ft^3) [34]. The structural properties of LSL are evaluated in conformance with the standards ASTM D 5456 “Standard Specification for

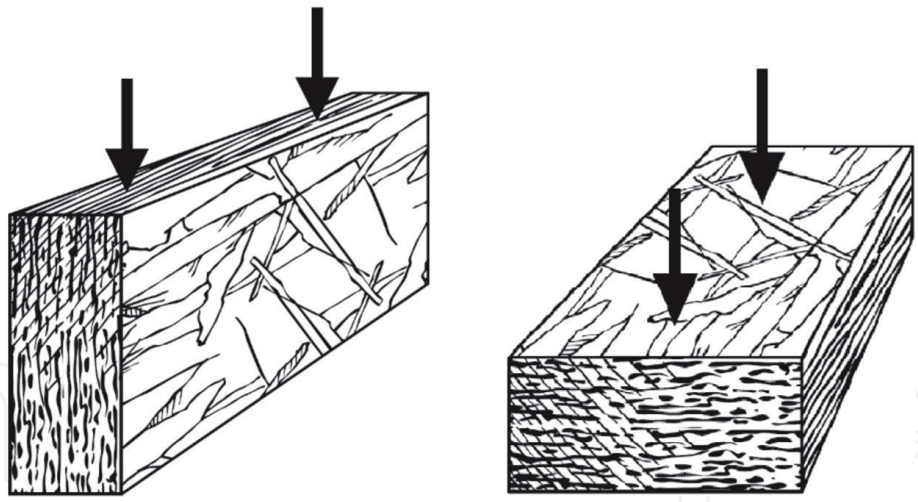

Figure 10.
Different directions of LSL: Beam direction (left) and plank direction (right) (source: Pictures obtained from Weyerhaeuser at https://www.weyerhaeuser.com).

Evaluation of Structural Composite Lumber Products" [36]. The stiffness of LSL is larger than that of LVL, and the tensile strength of LSL is similar to structure dimension lumber [34]. In general, the allowable modulus of elasticity (MOE) is used as the basis of LSL grading; for example, 1.5E grade indicates that the allowable MOE is 1.5×10^6 psi (8960 MPa) [4]. The allowable values of flexural strength, tensile strength, compression strength, and other structural properties of LSL produced by different manufacturers are slightly different [37, 38]. In addition, the allowable stress of LSL in the beam direction differs from that in the plank direction (**Figure 10**) [38, 39]. As an example, the allowable mechanical properties of LSL manufactured by Norbord Inc., Canada, are shown in **Table 5** [38].

Nail withdrawal and lateral resistance connection properties are also important for LSL when used in wood buildings. The equivalent specific gravity, which means the nail withdrawal and lateral resistance connection properties are deemed to be equivalent to that of the solid lumber with a specific gravity, is always used to estimate the connection properties of LSL [4, 39]. For example, the equivalent specific gravity of TimberStrand® LSL with 1.3E and 1.5E grade is 0.5, which means the standard bolted connection design values could be obtained in the adopt code for Douglas fir with a specific gravity of 0.5 [39, 40]. The grade of LSL/OSL

Grade	MOE	Axial		Beam direction			Plank direction		
		F_t	F_c	F_b	F_v	$F_{c\perp}$	F_b	F_v	$F_{c\perp}$
	MPa	MPa	MPa	MPa	MPa	MPa	MPa	MPa	MPa
1.7E LSL	11,720	14.13	14.13	14.82	2.76	8.27	19.31	1.03	2.24
1.55E LSL	10,690	13.34	15.00	16.27	3.62	7.93	18.06	1.07	3.76
1.35E LSL	9310	9.86	13.13	12.76	3.07	7.93	14.20	1.03	3.90
1.5E OSL	10,345	12.24	12.24	12.07	2.76	7.93	17.58	0.90	2.24
1.3E OSL	8960	8.96	8.96	11.20	2.41	7.93	13.79	0.79	1.97
0.8E OSL	5515	4.69	7.58	7.79	2.45	9.76	—	—	—

Source: Data from APA at https://www.apawood.org.
Note: MOE is Modulus of Elasticity; F_t is tensile strength; F_c is compression strength; F_b is bending strength and F_v is shear strength; $Fc_\perp$ is compression strength perpendicular to the axial direction.

Table 5.
Allowable mechanical properties of LSL and OSL with different grades.

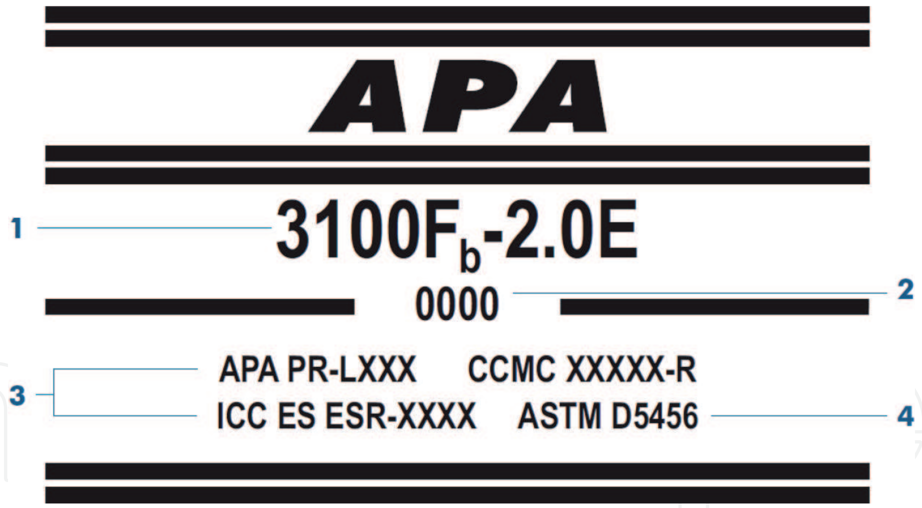

Figure 11.
A grade stamp for SCL: 1. Qualified SCL grade; 2. APA mill number; 3. Product evaluation reports (APA and ICC-ES in the United States and CCMC in Canada); 4. Standard specification for SCL (source: Pictures obtained from APA at https://www.apawood.org).

is evaluated and classified by APA-The Engineered Wood Association in North America. The structural design values for LSL/OSL are published on a proprietary basis by manufacturers, which are certified by APA. It is worth noting that this classification is for all SCL products including LSL and OSL. A sample grade stamp on SCL products is shown in **Figure 11** [33].

4.4 Applications of LSL and OSL

LSL/OSL has lower requirements for raw materials than veneer-based SCL and similar structural properties to dimension lumber, which has become a good alternative to solid timber. Presently, LSL products with different dimensions and grades have been used as headers, studs, and rim boards in residential wood frame construction (**Figure 12**) [4, 39]. Generally, the specific design values of LSL, such as allowable stresses, the distance between connections and allowable live load, can be found in the user's guides provided by the manufacturers [37–39]. LSL products are also used as nonstructural rated materials in the non-construction field such as molding, millwork, and furniture [9]. Moreover, some researchers have identified and developed the new applications of LSL. For example, the University of New Brunswick and the University of Alberta, Canada, have developed a hybrid cross-laminated timber (HCLT) panel product made of LSL/OSL and dimension lumber and explored its bending and rolling shear properties [41]. The racking performance of shear walls made of HCLT panels has been also examined under both monotonic and cyclic loadings. Another example is given by Wang et al. [42], who investigated the feasibility of manufacturing HCLT made of LSL (used as the surface layers or core layers) and Lodgepole pine lumber. Their results indicated that the bending properties and rolling shear properties of HCLT were significantly higher than those of generic CLT made of Lodgepole pine lumber only.

In comparison with LSL, OSL is a relatively newer strand-based SCL product, and its market is still under development. The OSL products have similar applications to LSL, which are usually used for band joists in floor construction and as substitutes for rafters in roof construction [1]. The feasibility of using OSL as a transverse layer(s) for manufacturing CLT has been proven [5, 41]. In addition, because OSL can be manufactured to an architectural shape, it also can be used in architectural windows and doors, furniture parts, and other specialty applications [9].

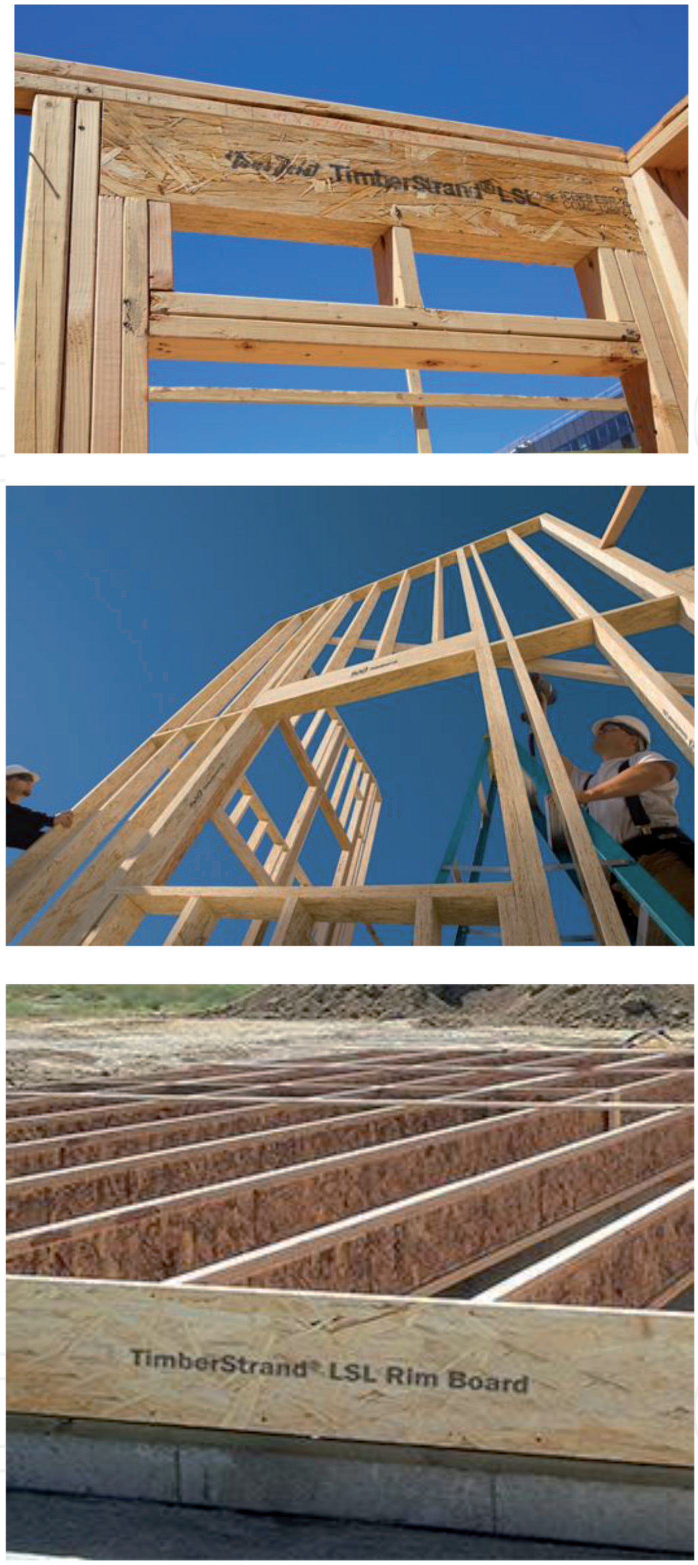

Figure 12.
Applications of LSL in residential frame construction. Top: LSL header; center: LSL studs; bottom: LSL rim board (source: Pictures obtained from Weyerhaeuser at https://www.weyerhaeuser.com/woodproducts/).

5. Endnotes

The strand-based EWPs, such as OSB, LSL, and OSL, has all the environmental advantages of other EWPs, such as low carbon emissions. However, the strand-based EWPs have, due to their relatively complex manufacturing process by adding more fossil-based adhesives, higher environmental impacts than lumber-based and veneer-based EWPs. A study by the University of British Columbia, Canada, indicated that the veneer-based EWPs were more sustainable products than the strand-based wood products, which showed lower energy utilized and fewer emissions of CO_2, SO_x, NO_x, and other volatile organic compounds (VOCs) and particulate matters generated during the manufacturing [20]. Therefore, the manufacturing process of strand-based EWPs requires further research and development. For example, use of bio-based adhesives to produce strand-based EWPs can assist to reduce their environmental footprint.

In summary, the strand-based EWPs have become important members of the family of EWPs, providing a way of producing relatively large sizes of man-made lumber with a high-yield wood fibers from small-diameter and low-quality logs. With the anticipated increase in demand for EWPs in construction and change in accessibility and quality of mature forest resources, the development and application of strand-based EWPs keep increasing in the future. With the rise of tall wood buildings, strand-based EWPs will have great market potential and will be a new research hotspot.

Acknowledgements

This piece of work was financially supported by the New Brunswick Innovation Research Chair Initiative Program by the New Brunswick Innovation Foundation (Canada) and the Discovery Grant by Natural Sciences and Engineering Research Council of Canada (RGPIN 2017-03994).

Conflict of interest

I confirm there are no conflicts of interest.

Author details

Zizhen Gao* and Meng Gong
University of New Brunswick, Fredericton, NB, Canada

*Address all correspondence to: zz.gao@unb.ca

References

[1] Ross RJ. Wood handbook: Wood as an engineering material. USDA Forest Service, Forest Products Laboratory, General Technical Report FPL-GTR-190. 2010. 509 p

[2] Pajchrowski G, Noskowiak A, Lewandowska A, Strykowski W. Wood as a building material in the light of environmental assessment of full life cycle of four buildings. Construction and Building Materials. 2014;**52**:428-436. DOI: 10.1016/j.conbuildmat.2013.11.066

[3] Gustavsson L, Pingoud K, Sathre R. Carbon dioxide balance of wood substitution: Comparing concrete-and wood-framed buildings. Mitigation and Adaptation Strategies for Global Change. 2006;**11**(3):667-691. DOI: 10.1007/s11027-006-7207-1

[4] Thelandersson S, Larsen HJ, editors. Timber Engineering. Chichester: John Wiley & Sons; 2003. 446 p

[5] Gong M. Lumber-based mass timber products in construction. In: Concu G, editor. Timber Buildings and Sustainability. Rijeka: IntechOpen; 2019. pp. 7-16. DOI: 10.5772/intechopen.85808

[6] Nishimura T. Chipboard, oriented strand board (OSB) and structural composite lumber. In: Ansell M, editor. Wood Composites. Cambridge: Woodhead Publishing; 2015. pp. 103-121. DOI: 10.1016/B978-1-78242-454-3.00006-8

[7] Rowell RM, editor. Handbook of Wood Chemistry and Wood Composites. Boca Raton, Florida, USA: CRC Press; 2012. 473 p

[8] Zerbe JI, Cai Z, Harpole GB. An evolutionary history of oriented strand board (OSB). USDA Forest Service, Forest Products Laboratory, General Technical Report, FPL-GTR-236. 2015. 10 p

[9] Shmulsky R, Jones PD. Forest Products and Wood Science: An Introduction. 6th ed. Chichester: Wiley Blackwell; 2019. 477 p

[10] Food and Agriculture Organization of the United Nations (FAO). 2021. Available from: http://www.fao.org/faostat/en/#data/FO [Accessed: 20 March 2021]

[11] Moore JR, Cown DJ. Processing of wood for wood composites. In: Ansell M, editor. Wood Composites, Cambridge: Woodhead Publishing; 2015. pp. 27-45. DOI: 10.1016/B978-1-78242-454-3.00002-0

[12] Kruse K, Dai C, Pielasch A. An analysis of strand and horizontal density distributions in oriented strand board (OSB). European Journal of Wood and Wood Products. 2000;**58**(4):270-277

[13] Beck K, Cloutier A, Salenikovich A, Beauregard R. Effect of strand geometry and wood species on strandboard mechanical properties. Wood and Fiber Science. 2009;**41**(3):267-278

[14] Pizzi A, Mittal KL. Handbook of Adhesive Technology. Boca Raton, Florida, USA: CRC Press; 2017. 643 p

[15] Walker JC. Primary Wood Processing: Principles and Practice. Dordrecht, NED: Springer Science & Business Media; 2006. 576 p

[16] Cai Z. Wood-based composite board. In: Wiley Encyclopedia of Composites. Chichester: John Wiley & Sons; 2012. DOI: 10.1002/9781118097298.weoc262

[17] Thoemen H. Wood-based Panels: An Introduction for Specialists. London: Brunel University Press; 2010. 283 p

[18] Hiziroglu, S. Oriented strand board as a building material. Stillwater, Oklahoma, USA: Oklahoma State university Extension Fact Sheet, FAPC-146, Food and Agricultural Products Research Center; 2006. 4p.

[19] Lam F, Craig BA. Shear strength in structural composite lumber. Journal of Materials in Civil Engineering. 2000;**12**(3):196-204

[20] Chan G. Sustainability Assessment of OSB and Softwood Plywood Manufacturing in North America. Vancouver, BC, Canada: University of British Columbia; 2012. 71 p

[21] Hsu WE. Oriented Strand Board Manufacturing. Scotts Valley, California, USA: CreateSpace Independent Publishing Platform; 2013. 316 p

[22] The Engineered Wood Association (APA). Product Guide: Oriented Strand board. 2021. Available from: https://www.apawood.org [Accessed: 25 March 2021]

[23] American Society for Testing and Materials. ASTM D E84-21a. Standard Test Method for Surface Burning Characteristics of Building Materials. 2021

[24] International Code Council. International Building Code. Country Club Hills, Ill: ICC; 2018

[25] American Wood Council. Flame spread performance of wood products. Design for code acceptance No. 1. 2019. Available from: https://www.awc.org/codes-standards/publications/dca1 [Accessed: 02 September 2021]

[26] PS VPS. Performance Standard for Wood Structural Panels. Washington, D.C., USA: National Institute of Standards and Technology (Department of Commerce); 2019

[27] CSA O325, Construction Sheathing, CSA O325. Toronto, ON, Canada: Canadian Standards Association; 2003

[28] The Engineered Wood Association (APA). APA Panel Trademark. 2021. Available from: https://www.apawood.org [Accessed: 25 March 2021]

[29] PFS-TECO. PS 1 and PS 2 Gradestamp Explanation. Sun Prairie, Wisconsin: TECO; 2021. Available from: https://www.pfsteco.com/library. [Accessed: 30 March 2021]

[30] The Engineered Wood Association (APA). Engineered Wood Construction Guide. 2021. Available from: https://www.apawood.org [Accessed: 10 April 2021]

[31] PFS-TECO. OSB design and Application Guide. Sun Prairie, Wisconsin: TECO; 2021. Available from: https://www.pfsteco.com/library [Accessed: 10 April 2021]

[32] Ma, ZY. Effect of surface treatments on the bond quality of laminated OSB products [thesis]. Fredericton, NB, Canada: University of New Brunswick; 2019

[33] The Engineered Wood Association (APA). Structural Composite Lumber Selection and Specification. 2021. Available from: https://www.apawood.org [Accessed: 25 March 2021]

[34] Blau K. Personal Communications. Product Development and Quality. Vernon, BC, Canada: Tolko Industries Ltd. Canada; 2021

[35] Weyerhaeuser Company. 2021. Available from: https://www.weyerhaeuser.com/ [Accessed: 25 March 2021]

[36] American Society for Testing and Materials. ASTM D 5456-19. Standard Specification for Evaluation of Structural Composite Lumber Products. 2019

[37] The Engineered Wood Association (APA). Joint Evaluation Report ESR-2725, 2021. Available from: https://www.apawood.org [Accessed: March 25, 2021]

[38] The Engineered Wood Association (APA). Joint Evaluation Report ESR-1053. 2019. Available from: https://www.apawood.org [Accessed: 25 March 2021]

[39] Weyerhaeuser. Specifier's Guide for Beams Headers and Column. 2021. Available from: https://www.weyerhaeuser.com/ [Accessed: 25 March 2021]

[40] Canadian Standards Association (CSA). Engineering Design in Wood. Mississauga, ON, Canada: CSA; 2014. 280 p.

[41] Chui YH, Gong M, Niederwestberg J. Development of a lumber-SCL massive timber panel product. Final Report #: WSTC2013-015. Fredericton, NB, Canada: Wood Science and Technology Centre, the University of New Brunswick; 2015. p. 55

[42] Wang Z, Gong M, Chui YH. Mechanical properties of laminated strand lumber and hybrid cross-laminated timber. Construction and Building Materials. 2015;**101**:622-627. DOI: 10.1016/j.conbuildmat.2015.10.035