Chapter

Wood and Engineered Wood Products: Stress and Deformation

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Abstract

Wood, as a natural, sustainable, and renewable bio-composite material, has a long history of serving humanity as construction materials. With the advance in technologies, many modern engineered wood products (EWPs) have been invented, produced, and used in construction, such as laminated veneer lumber, oriented strand board, and cross laminated timber. This chapter first introduces the classification, rationales, and pros and cons of EWPs. Secondly, it discusses the stress-related topics, including growth stresses in living trees, the evolution of wood strength from the molecular level to the actual design implementation. Thirdly, this chapter discusses moisture-induced deformation with examples. Finally, it mentions the benefits of using EWPs and their market shares.

Keywords: wood, engineered wood products, classification, growth stresses, strength evolution, design principle, moisture-induced deformation, market shares

1. Introduction

Wood is a gift from nature. Wood is a sustainable and renewable bio-composite material, which has a long history of serving human beings in the form of fuel, construction materials, furniture, paper, sports equipment, musical instruments, and transportation components. Wood is "manufactured" in a living tree with aims to grow it by transporting water and minerals and providing strength and rigidity to anchor it to the ground. A tree is optimally "designed" to resist the loads created by gravity, wind, snow, and others, rather than produce lumber and boards. The anatomical structure of wood is adapted to generate maximum strength in the stressed directions; yet in other directions, the strength is quite low [1]. This results in the anisotropic nature of wood, i.e., the properties of wood in a given direction are different from those in another. In addition, wood, as a biomaterial, maintains its fairly high variability of anatomical structures and physical properties; therefore, it requires a very large sampling size in research practice.

The dimensions of solid wood are entirely dependent on the dimensions of trees. The largest tree in the world is, in terms of the overall volume of its trunk, reported to be the Giant Sequoia (*Sequoiadendron giganteum*), which takes about 2300–2700 years to form its current dimensions, roughly 84 m in height and 11 m in diameter at the base [2]. On the other hand, the free span of composite glue laminated timber arch beams used in the Richmond Olympic Oval, Vancouver, Canada reaches 100 m with a depth of 1.6 m [3]. Undoubtedly, natural wood fails to meet the requirements for constructing modern timber structures, suggesting a need for "man-made" wood products. Furthermore, to address climate change and protect the earth's environment, logging in old-growth forests has been, in the last several decades, restricted or almost banned in most of the countries in the world. Consequently, available trees are largely from faster-growth plantations, which usually produce small-diameter logs of low-density wood and large-percentage juvenile wood. Traditional large-diameter solid timber, which was often used for long-span wood buildings in the past, has been phasing out. However, there is an increasing demand for using wood, as a green building material, to construct large and tall residential, commercial, and industrial buildings. In order to address the foregoing challenges of sourcing raw wood materials and catering to the market demands, an ever-growing number of value-added wood-based commodities and building materials have been created through the advances of technology. Contemporarily, modern engineered wood products (EWPs) have been widely used in construction [4].

An EWP is a product fabricated with wood materials and adhesives and/or fasteners (such as nails) targeted mainly for structural applications. An EWP has gone through an engineering design, which is often inspired by nature, and innovative technology. With the great efforts made by scientists and engineers in the last century, EWPs have grown into an extended family. **Figure 1** illustrates commonly used EWPs and their respective abbreviations.

EWPs offer many advantages over traditional solid timber products [5, 6]: (1) EWPs can reach a size that is not confined by the tree dimension. Theoretically, EWPs are only limited in width and length under transportation considerations; (2) EWPs accommodate a wide spectrum of species and sizes of trees, allowing more efficient

Figure 1.
Major types of engineered wood products and their abbreviations (source: images obtained from archiproducts.com, canac.ca, diy.com, globalsources.com, leben.co.in, nrcan.gc.ca, and structurecraft.com).

utilization of raw wood materials in the form of fibers, strands, veneers, and lumber; (3) EWPs have more uniform and reliable properties than solid wood, since the strength-reducing defects present in solid wood can be removed to a large degree or placed in a less critical zone(s) in the products; (4) EWPs exhibit greater dimensional stability and tolerances than sawn timber, due to the use of adhesives, dry wood elements, heat and pressure during their manufacturing processes; and (5) EWPs can make themselves much easier to adapt to market requirements than solid wood due to their designability. **Figure 2** illustrates the yields of raw wood material usage from logs to various EWPs. It can be found that laminated strand lumber (LSL) and oriented strand board (OSB) have a higher yield (larger than 75%) than plywood, laminated veneer lumber (LVL), and parallel strand lumber (PSL) (less than 65%). It can also be reasonably estimated that finger-jointed lumber, glue laminated timber (GLT), cross laminated timber (CLT), nail laminated timber (NLT), or dowel laminated timber (DLT) has a yield being less than that of sawn lumber due to the loss of wood materials during their manufacturing. A higher raw wood material yield means less waste and lower production cost, suggesting that EWPs are a great solution to the utilization of wood resources.

However, there are some disadvantages associated with EWPs [5, 6], one of which is that the process of manufacturing of an EWP requires more variables to manipulate than that of sawn lumber. Thus, highly automated equipment and technologically intense processes are essential in the production of an EWP, which significantly increases the capital cost of establishing an EWP mill. Therefore, the production of an EWP with the existing technologies is very costly compared to that of sawn lumber. Another shortcoming of most EWPs is that the use of adhesives in those glue-bonded EWPs causes a negative impact on the ecological image of wood as a natural biomaterial [5].

From **Figure 1**, it can be easily distinguished that there exist two groups, i.e., beam-like and panel-like EWPs. The beam-like EWPs is a group of relatively large length and depth compared to width, which is commonly used for beams and columns. The beam-like EWPs include finger-jointed lumber, GLT, LVL, PSL, LSL, and oriented strand lumber (OSL). The panel-like EWPs are of relatively small thickness and large width and length, which are usually used for floors, walls, and roofs. The panel-like EWPs can be further classified into two sub-groups, in terms of thickness: (1) thick-panel-like EWPs, containing CLT, NLT, and DLT, and (2) thin-panel-like EWPs, consisting of plywood and OSB. However, there is not a widely accepted criterion for sorting EWPs according to their dimensions and shape. For example, GLT can be used flat as panels for decking like NLT. For another

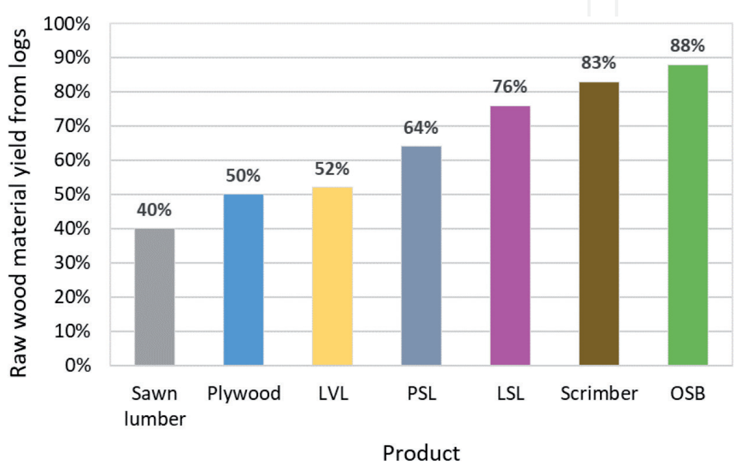

Figure 2.
Raw wood material yields of sawn lumber and EWPs from logs (data from [7, 8]).

example, LSL can be manufactured in the form of panels at the beginning and then ripped along the panel length direction to make beam-like or lumber-like products. In addition to those EWPs listed in **Figure 1**, there are many other types of EWPs such as I-joist (or I-beam), timber concrete composite (TCC), and fiberglass-reinforced GLT. It is noteworthy that **Figure 1** also lists two types of fiber-based EWPs, which are made of wood fibers as "fibers" and plastic or cement as "matrix". These two fiber-based EWPs are not commonly used for structural components in wood buildings nowadays, but they can be used for ceilings and decking. Wood plastic composite (WPC) has found its applications in the automotive, marine, and construction industries. Wood cement fiberboard (WCF) has also been steadily invading the housing and construction market.

With advancing wood-based nanotechnology, nanomaterials, such as nanocrystalline cellulose (NCC), have been derived from woody biomass and other cellulose sources such as straws. NCC is the celluloses in their crystalline form, which can be extracted by removing the amorphous sections from the celluloses and processed into solid flake, liquid, and gel forms. NCC can be employed, for instance, to reinforce the adhesive bond in EWPs. There is another innovative EWP called scrimber that is made of "scrims", a kind of interconnected loose webs. The steps of manufacturing scrims include crushing small diameter logs into webs, drying the webs, applying an adhesive into the webs, cutting the webs to the required length and width, laying up the webs into a mat, and pressing the mat into a billet using a radio frequency heating press [5]. However, scrimber has not been well commercialized because of the application of large quantity of adhesive (causing the high cost of production), and damaged wood generated while preparing scrims (reducing the strength of wood).

EWPs (usually excluding fiber-based ones) can be also classified into parallel and cross-laminated groups. The parallel-laminated EWPs include LSL, OSL, LVL, PSL, GLT, NLT, and DLT; meanwhile, cross-laminated EWPs contain OSB, plywood, and CLT. The parallel-laminated EWPs are usually used for load-carrying members such as beams and headers; while the cross-laminated EWPs are used for floor plates and sheathing sheets. The way of lamination inspires a philosophy of designing EWPs, which will be briefly outlined in Section 2 "Stress" of this chapter.

Another way of grouping EWPs is rooted in the wood elements that make them, which include fiber, strand, veneer, and lumber-based EWPs, shown in **Figure 3**. It

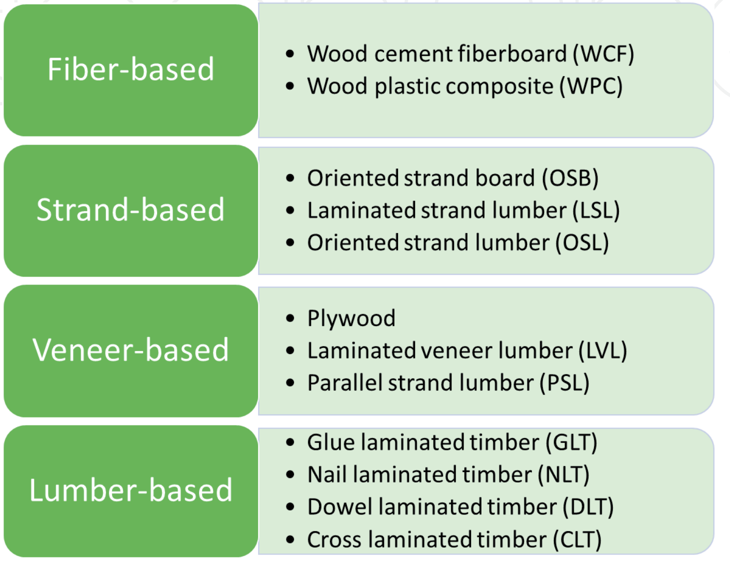

Figure 3.
Classification of EWPs in terms of the wood elements used for making them.

should be noted that PSL is made of long veneer strands (also called veneer strips). Thus, PSL is classified into the group of veneer-based EWPs rather than the group of strand-based EWPs albeit it has "strand" in its name. The wood elements largely govern, in terms of their dimensions, shape, moisture content (MC), species, the physical and mechanical properties of the product made from them. For instance, the density of an LVL made of yellow poplar is just slightly greater than that of yellow poplar veneer, which is attributed to the use of an adhesive(s) and slightly densified veneer during manufacturing. For another example, the equilibrium moisture content (*EMC*) of plywood is usually lower than the wood from which it is made due to the use of adhesive, dried veneer, and heat and pressure in the course of manufacturing. However, the *EMC* of GLT is very similar to that of the lumber used for making it, since only a relatively small amount of adhesive is applied in comparison to the volume of GLT itself, and the room temperature is applied during its manufacturing process.

In the course of discussing EWPs, it is worth introducing another two terms: structural composite lumber (SCL) and mass timber products (MTPs). SCL refers to those products that combine dried strands, veneer, or other small wood elements bonded with an exterior structural adhesive(s) to form thick-panel-like or beam-like EWPs [6, 9]. SCL basically includes LVL, LSL, OSL, and PSL. One outstanding characteristic of SCL is that the grain of the wood elements used is essentially aligned parallel to the length direction of its products with an aim to maximize its structural properties in this direction. Thus, SCL products are broadly used for beams and columns in wood buildings. MTPs connote a family of EWPs of a large section size, which can be employed to make strong but light load-bearing components for structural applications such as floors and walls [9]. MTPs basically include lumber-based EWPs, i.e., CLT, GLT, NLT, and DLT. However, MTPs also include SCL, TCC, and other large-size EWPs such as fiberglass-reinforced GLT, see **Figure 4**. Among EWPs, the lumber-based MTPs also possess other unique features, such as wood-look appearance, environmental friendliness, and low carbon emission. MTPs have been, since the mid-1990s, attracting architects, engineers, and builders to employ them in their design and construction of tall and large buildings with an aim to compete with or even substitute steel and concrete.

The philosophy of designing a timber structure/component/connection is largely rooted in two aspects: safety, limiting the maximum load-carrying capacity (i.e., strength) and serviceability, restricting excessive deflection (i.e., deformation) [10, 11]. The reaction of a material (such as wood) or a product (such as EWP) to the action of external forces is indicated by its mechanical properties, or

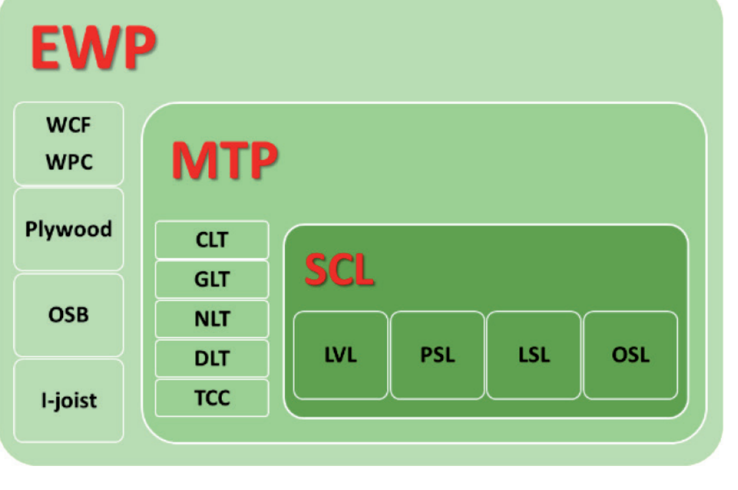

Figure 4.
Classification of commonly used EWPs.

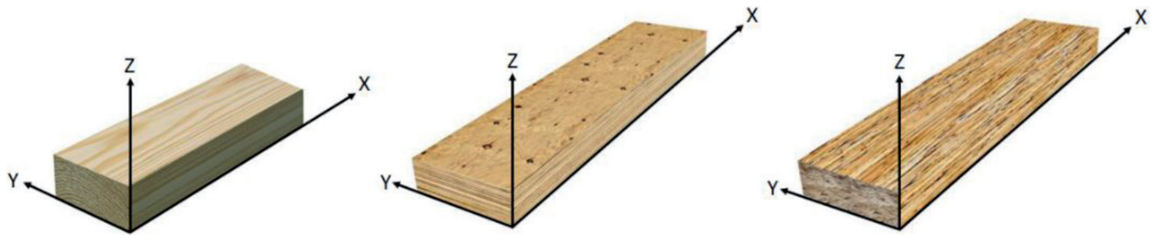

Figure 5.
Cartesian coordinate system for wood/lumber (left), LVL (middle) or PSL (right).

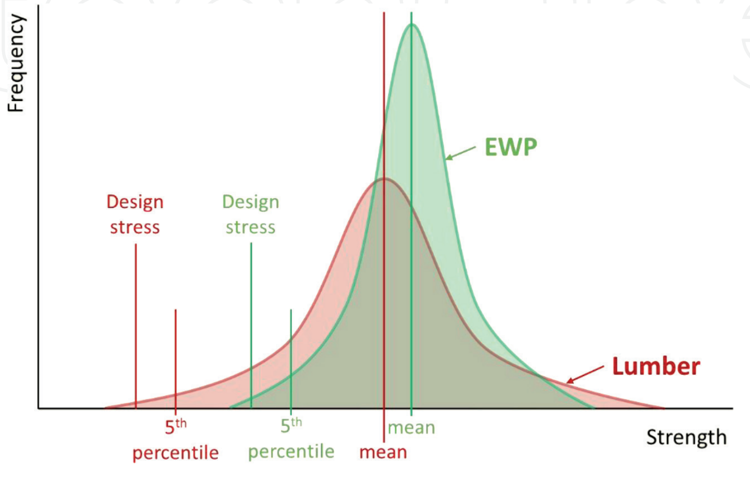

Figure 6.
Probability density functions for strength of lumber and EWP.

otherwise known as engineering properties, including tensile strength, compressive strength, shear strength, bending capacity, ductility, and creep. When an external load is applied on a wood component/connection/structure, it causes the stresses inside the wood component/connection/structure, generating deformations and eventually leading to failure. Failure can be, from an engineering point of view, defined as a fracture, when stress exceeds the strength of the wood component/connection/structure or failure as deformation exceeds the design value.

Under certain assumptions, such as ignorance of natural growth characteristics (e.g., knots and eccentricity) and growth ring curvature, a three-dimensional Cartesian coordinate system can be introduced in **Figure 5**, representing the wood/lumber longitudinal or EWP major direction (X), wood/lumber tangential or EWP minor direction (Y), and wood/lumber radial or EWP thickness direction (Z). On this basis, an orthotropic model can be built to simulate the mechanical behavior of wood, lumber, and EWPs in scientific research and engineering design. As mentioned above, the mechanical properties of natural wood vary much more than those of EWPs, which is illustrated in **Figure 6**. The lumber product has a relatively wide distribution of strength due to the nature of its biomaterial, and the EWP has a fairly narrow range since it goes through an engineering design during its manufacturing. Overall, the EWP has greater design stress, 5^{th} percentile, and mean values than sawn lumber. The following two sections will discuss these two basic mechanical terms (stress and deformation) from the standpoint of tree growth and wood uses.

2. Stress

The strength of wood is a measure of its resistance to failure. If the stress applied to the wood exceeds the strength of the wood, will break. Stress accompanies wood during its formation in a living tree and its services over its life span. As mentioned, a tree is subjected to various types of stresses during its growth. Mattheck and Kubler depicted external loading and internal stresses distributed in a tree [1], **Figure 7**. By neglecting the weights of the stem and branches, and loads generated by wind and snow, they simplified their model by only considering the weights of the upper and lateral crowns (F_1 and F_2). The compressive stresses (σ_1) produced by F_1 act on the area (A_1) of the stem above the lateral branch, equaling to F_1/A_1. The bending moment generated by F_2 is applied on the lateral branches, which increases linearly towards the stem. Thus, the stem below the branch joint bears both bending moment (tensile and compressive stresses) and axial compressive stress (σ_1).

These stresses refer to the mechanical stresses permanently supported by wood in a living tree during its growth, which are called tree growth stresses. The tree growth stresses result from the combined effects of the increase of dead weight and maturation of cell walls [12]. There is an interesting phenomenon that can be viewed in a leaning stem when it is subjected to a bending moment. In this situation, the stem tries to resume its original, usually upright, position, thus, it needs to counteract the bending moment. In such a stem, the growth stresses often differ on its two opposite sides, resulting in abnormally wide growth rings appearing in the upper or lower side of a leaning stem, **Figure 8**. The wood of such abnormally wide growth rings is called reaction wood. Reaction wood in hardwoods or softwoods is named tension wood or compression wood, respectively. Understanding compression wood is of great importance since softwood lumber is commonly used in construction of wood buildings. Compression wood has a relatively large longitudinal

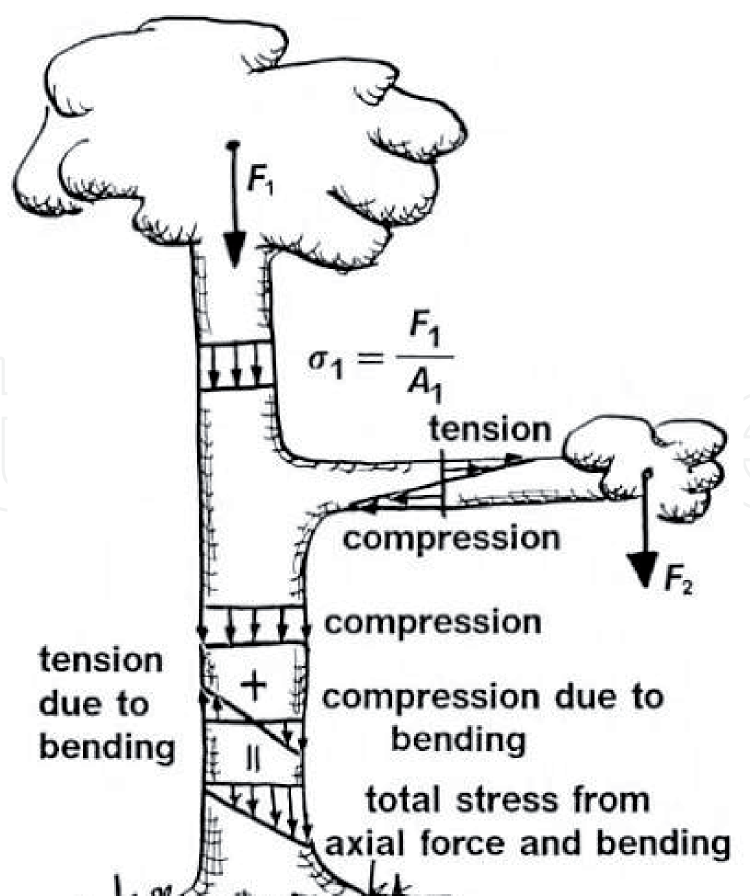

Figure 7.
Combined axial stresses and bending stresses in a tree generated by its crown weights [1].

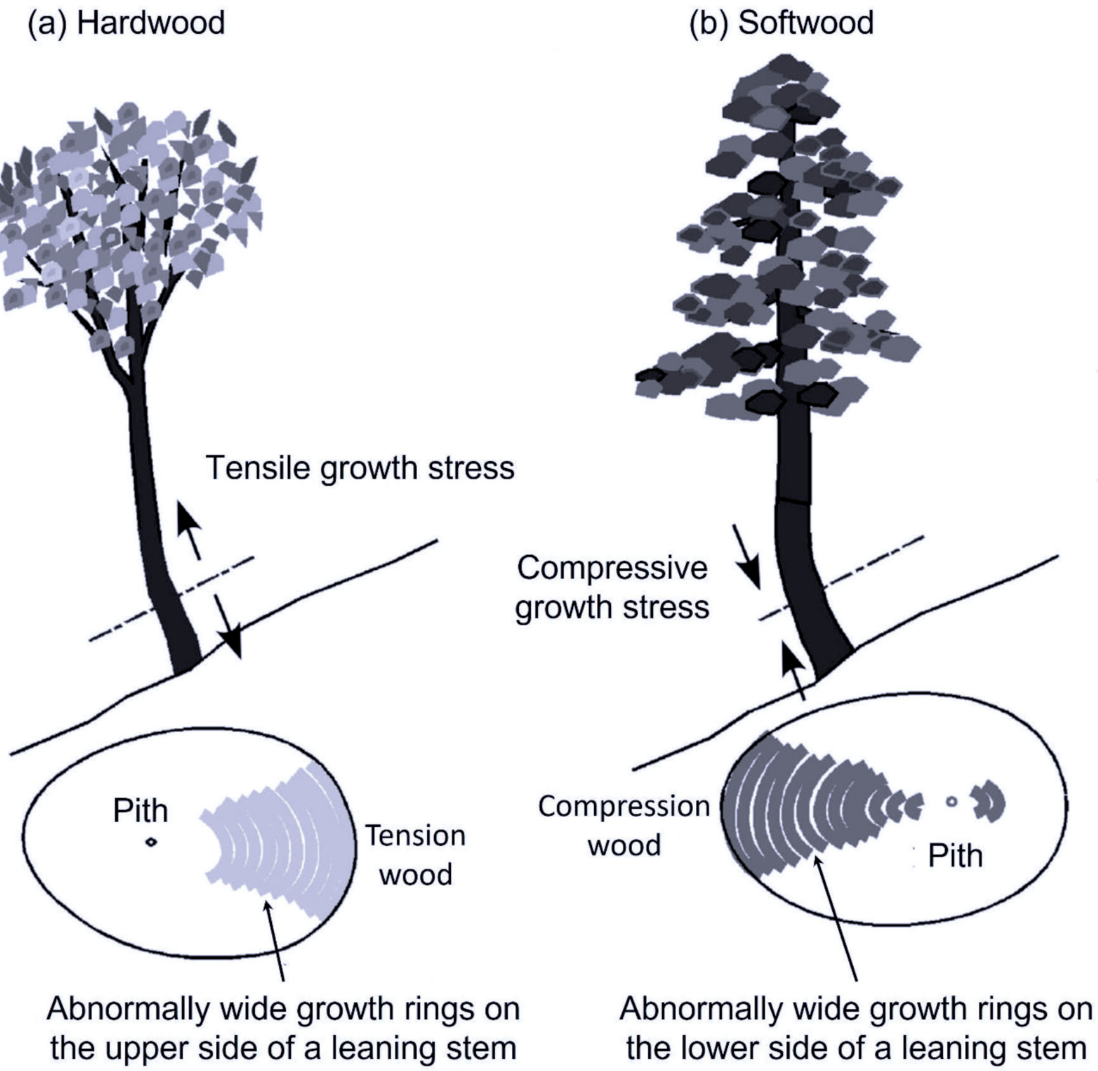

Figure 8.
Reaction wood in a leaning stem: (a) tension wood in hardwood, and (b) compression wood in softwood (modified from [12]).

shrinkage compared to normal wood, which can reach 1–2% [13], around 10 times as large as that of normal wood. As a result, warping and even cracks, often emerge in softwood lumber. In comparison to normal wood, compression wood has a relatively high density but similar strength, resulting in a low strength-to-weight ratio [13].

Wood is a complicated hollow structure consisting of substances and voids. The substance is the basic building materials constructing cell walls made of an ordered association of cellulose, hemicellulose, and lignin, with an average density of 1.5 g/cm^3 under oven-dry conditions [13]. The voids in wood appear in the form of cell lumens, pit openings, pit cavities, and intercellular spaces. The density of wood is largely governed by these voids, i.e., if a wood species has a larger volume of voids, its wood has a lower value of density. **Figure 9** illustrates the tensile strength values of wood at various levels. At the molecular level, the strength of wood is extremely high in the longitudinal direction, with estimates exceeding 7000 MPa [14]. Wood strength is about 15 times larger than that of structural steel, which has a strength of 400–550 MPa. Bundles of cellulose molecules form so-called microfibrils, the basic cell wall elements constituting cell walls in association with hemicellulose and lignin. From the composite theory point of view, wood is a natural composite, i.e., nature's fiberglass, in which celluloses are the "fibers" and hemicellulose and lignin are the "matrix". Microfibrils have a strength of about 480 MPa and individual cells are estimated to have a strength of about 140 MPa [14]. The tensile strength of clear

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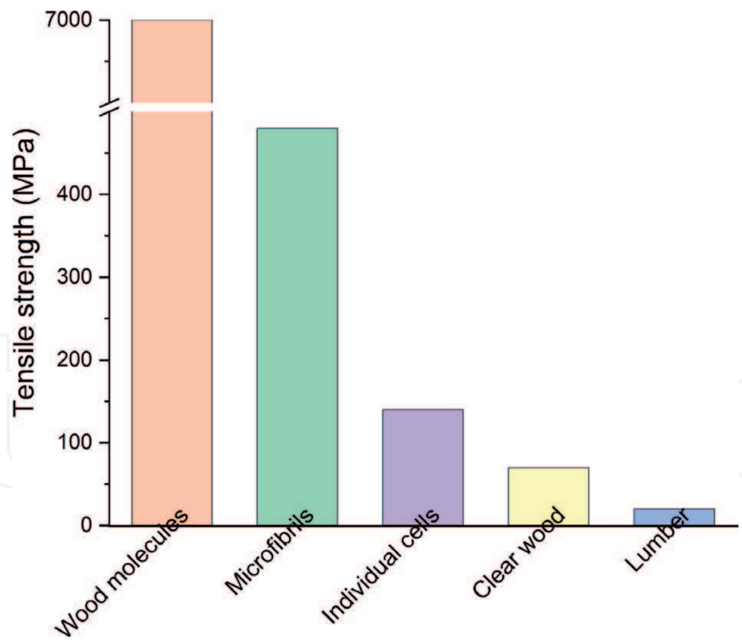

Figure 9.
Tensile strength of wood at various levels.

softwoods in the longitudinal direction has values ranging from 40 to 200 MPa [5]. However, lumber has, in the same longitudinal direction, a tensile strength of only 15–40 MPa [5] due to the existence of many strength-reducing characteristics such as knots, the slope of grain, checks, and splits. In the derivation of the design value of lumber, its characteristic strength properties, such as characteristic tensile strength in the longitudinal direction, are determined using the lower 5th percentile value of the Weibull distribution, which is much lower than the mean. From here, an allowable property value can be calculated by dividing the 5th percentile with a property reduction factor (n), or a so-called adjustment factor. For example, allowable tensile strength is equal to the 5th percentile divided by n, where n = 2.1 [15]. Finally, design value can be derived by multiplying the allowable property value with modification factors such as load duration, service condition, size, treatment, system, and other factors. For instance, the tensile strength of wood in the longitudinal direction can be as low as 2.5 MPa in the design of a structural component, which is fully attributed to the biomaterial nature of wood and its service conditions.

The above discussion suggests that human beings have not fully utilized the strength of wood. Contributed by the recent technological progress, the optimized use of wood has been improved to a certain degree in terms of strength. Song et al. selected three hardwood species (basswood, oak, and poplar) and two softwood species (western red cedar and eastern white pine) as test materials, and took two steps to transform bulk natural wood directly into super strong and tough densified wood [16], **Figure 10**. Step 1 used a chemical treatment to partially remove lignin/hemicelluloses and Step 2 mechanically hot-pressed the chemically treated wood at 100°C to reduce its thickness by about 80%. They discovered that the tensile strength of densified wood reached about 550 MPa, which was 12 times as large as that of natural wood. This value is higher than that of microfibrils (about 480 MPa). They indicated that most of the densified wood consisted of well-aligned cellulose nanofibers, greatly enhanced hydrogen bond formation among neighboring nanofibers. Their research provides a promising method of maximizing the use of wood strength by removing most voids and some lignin/hemicellulose. As mentioned in Section 1, NCC derived from wood attracts increasing attention due to the non-renewability of petroleum and the global promotion of green materials and products. NCC made from bleached softwood kraft pulp exhibits a diameter of 10 nm and a length of 150 nm [17].

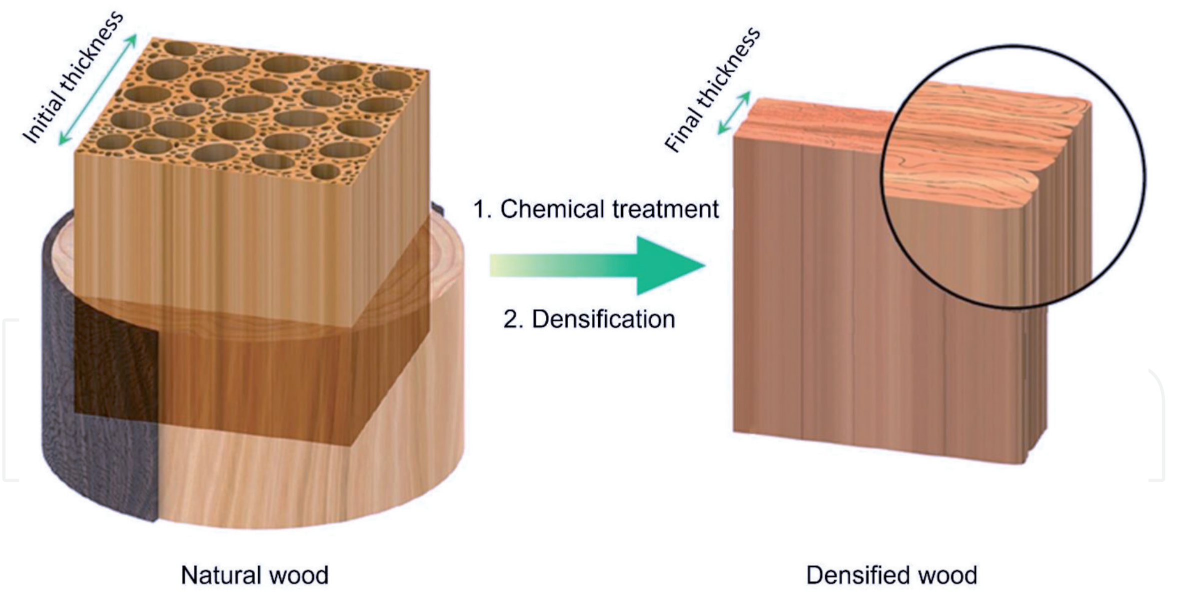

Figure 10.
Two-step processing approach for making densified wood (modified from [16]).

The Young's modulus of NCC can reach about 137 GPa [18]; while that of Douglas fir clear wood, one of the strongest softwoods, reaches only about 14.5 GPa [19]. This is one of the key reasons for applying NCC as high-performance "fibers" to "matrix" to produce composite materials of increased stiffness and tensile strength.

EWPs are fabricated through an engineering process, the basic principle of which is to place stronger materials at the most stressed zones [5, 7, 9]. Each lamination, such as lumber and veneer, must be graded visually or mechanically. **Figure 11** illustrates two lumber-based EWPs, GLT, and CLT. GLT here is made of sawn lumber of various visual grades, notably select structural (SS, the highest grade), No. 1, No. 2, and No.3 (the lowest grade here). The GLT in **Figure 11** (left) is intended to be used as a beam subject to the bending of a simple span. Therefore, an unbalanced layup is designed with an aim to optimally and efficiently use lumber by locating SS-grade lumber on the bottom face and No. 3 lumber in the core layers. **Figure 11** (right) depicts the basic idea of designing CLT, in which lumber grades in its major strength axis are required to be at least 1200f-1.2E MSR or visually graded No. 2, where No. 3 is the minimum lumber grade required in the minor strength axis [20]. This design gives CLT two-way action capacities, suitable for floor uses.

Figure 12 further justifies the principles of engineering design in wood in terms of two basic veneer-based EWPs, namely plywood and LVL. Veneer can be, according to the size and number of defects (such as knots), sorted into three grades (high, mid, and low). In the construction of plywood and LVL, the best quality

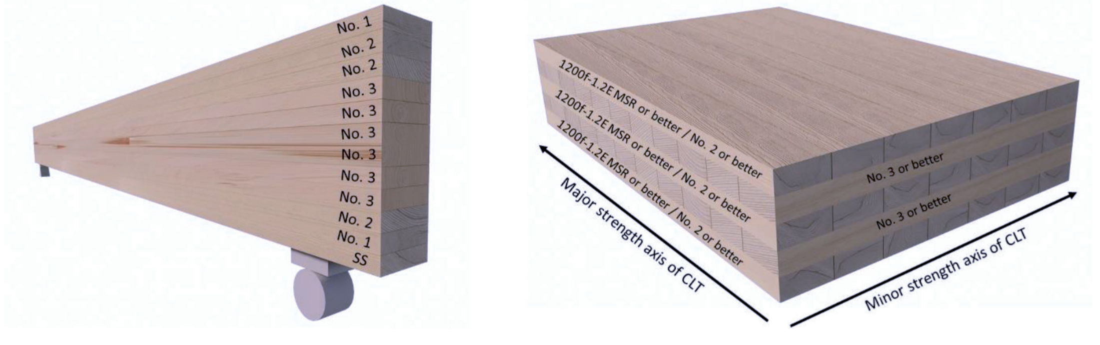

Figure 11.
Design of GLT (left) and CLT (right) [9].

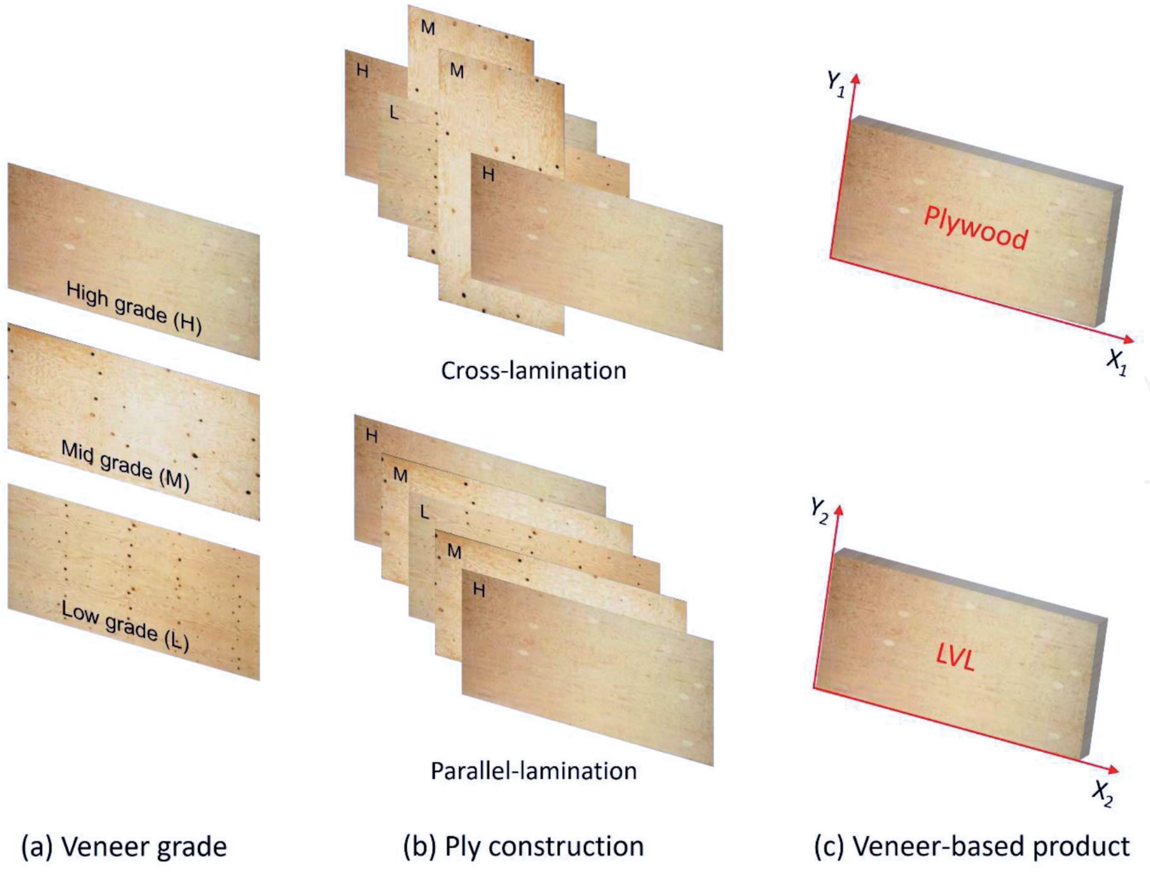

Figure 12.
Design of veneer-based products.

veneer is used as top and bottom laminations; however, the laminating approach differs. The cross-lamination of veneer enables plywood to be relatively strong in both the length (X1) and width (Y1) directions when loaded on its face, enabling it be widely used as sheathing materials. In LVL, the grain of each layer of veneer runs in the same direction, i.e., parallel-lamination. As a result, the strength in the length direction (X2) of LVL is much stronger than that in the width direction (Y2), making it a more suitable material for beam and column uses.

Assuming the same wood species, veneer quality, adhesive type, and other manufacturing parameters (except the laminating approach) are used in the fabrication of plywood and LVL, it can be reasonably predicted from **Figure 12** that the modulus of elasticity (MOE) and modulus of rupture (MOR) are the largest in the direction X_2, the second largest in X_1, the second smallest in Y_1, and the smallest in Y_2. This is verified by a group of undergraduate students at the University of New Brunswick, Canada, who made 5-layer poplar plywood and LVL panels in their laboratory using a phenol-formaldehyde adhesive at two levels of pressure. Each panel they made had a width of about 150 mm and a length of about 300 mm, from which small specimens were cut for bending tests. **Figure 13** summarizes their results indicating that there is a notable difference in MOE and MOR between plywood and LVL in either the major (X_1 or X_2) or minor (Y_1 or Y_2) direction. Plywood has fewer degrees of difference in MOR and MOE than LVL between the major and minor directions, suggesting a more uniform structure in plywood. However, LVL has a much higher MOR and MOE in the major direction (X_1) than that in the minor one (X_2), indicating its one-way strength capacities.

As discussed above, one of the advantages of EWPs over sawn lumber is that they can be engineering-designed. For instance, a cylindrical LVL was inspired by the hierarchical structure of a wood cell wall. A cell wall consists of three major layers in its secondary wall, and each layer has many lamellae containing microfibrils at

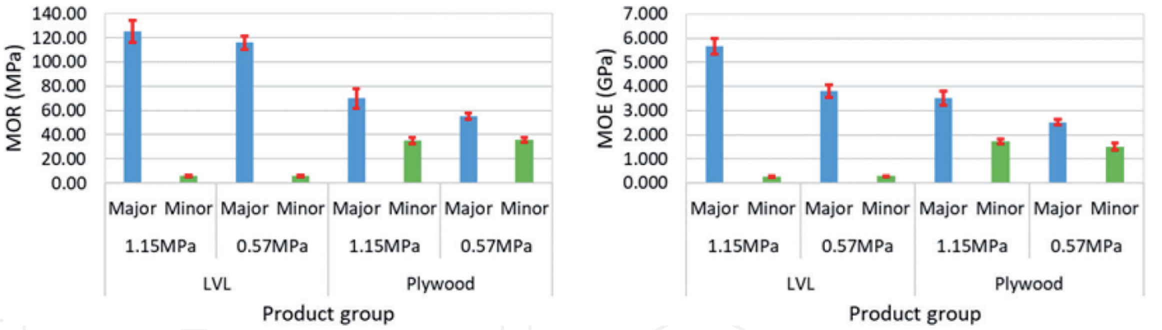

Figure 13.
The means and standard deviations of MOR and MOE of plywood and LVL.

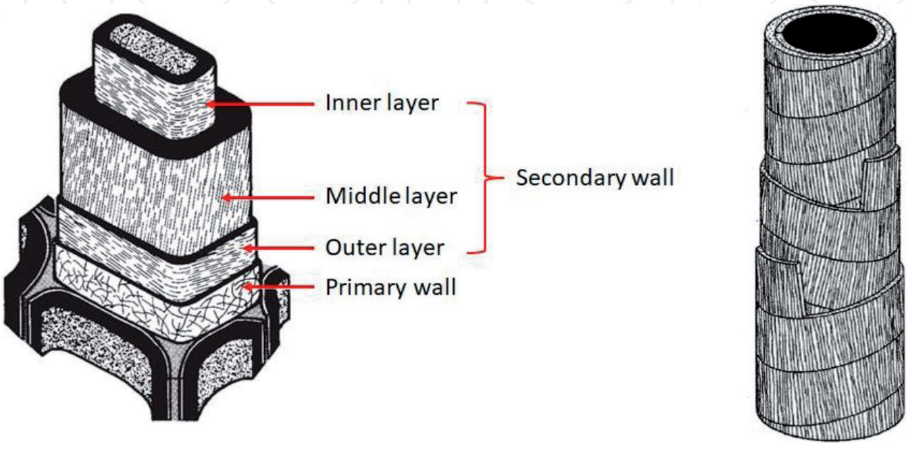

Figure 14.
The hierarchical structure of a mature cell wall (left) (adapted from [21]) and a cylindrical LVL (right) (adapted from [22]).

different angles [21], **Figure 14** (left). The middle layer in the secondary wall has 30–50 lamellae, occupying about 75% of the thickness of the cell wall. The microfibrillar angle in the middle layer ranges from 10 to 30 degrees relative to that of the longitudinal axis of the cell (almost parallel to the longitudinal direction of wood). Therefore, the middle layer governs the properties of the cell wall and furthermore the properties of wood, and provides considerably more strength and stiffness parallel to its axis than perpendicular. Yamauchi et al. used 2.5-mm-thick Japanese cedar veneer and a resorcinol resin to make cylindrical LVLs using the spiral-winding method, i.e., by laying neighboring veneer sheets at ±10 degrees to form an interlocked grain structure [22], **Figure 14** (right). The cylindrical LVL specimens they made were about 300 mm in the outer diameter, 25 mm in the wall thickness, and 3600 mm in the specimen length. They discovered that (1) the MOE of cylindrical LVLs was the same as that of solid lumber of the same species; and (2) as the number of veneer plies used in cylindrical LVLs increased from 6 to 10, its MOR increased; yet MOE remained almost unchanged. Yamauchi et al. concluded that the interlocked grain structure they applied could effectively prevent a decrease in MOE and indicated that cylindrical LVL was suitable for structural uses, especially for posts in construction [22].

3. Deformation

Wood and EWPs may undergo dimensional changes due to variation in ambient temperature and relative humidity, and stresses caused by external loads. The interaction of the surrounding atmosphere and loading conditions can create an enhanced level of deformation in wood. This section briefly explains how the change in moisture content of wood affects the shrinkage or swelling of wood and aims to increase the awareness of how the moisture-induced deformation impacts the structural performance of a timber building.

As a hygroscopic material, wood and its products can absorb and release moisture, resulting in dimensional changes. **Figure 15** illustrates the possible changes in moisture content (MC) of wood during the construction and use of wood buildings. The initial MC is the MC at the time of the manufacturing of a wood product, which is usually less than 19% for lumber and 4–15% for EWPs [10, 23]. The initial MC of strand-based or veneer-based EWPs, such as OSB and LVL, ranges from 4–6% [10]. However, the initial MC of lumber-based EWPs, such as GLT and CLT, varies from 11–15% [10]. The difference in initial MC between strand/veneer-based and lumber-based EWPs can be attributed to the dimension and shape of wood elements, amount and type of adhesive, and heat and pressure applied during manufacturing. The MC can significantly increase during construction if the wood components are not well protected from moisture/water, which can cause a large change in dimension and shape as well. Proper cautions and measures must be used to minimize such a large dimensional change. After a wood building is completed and occupied, its in-service MC may vary from 7–15% [23], depending on the surrounding temperature and relative humidity, before eventually reaching equilibrium moisture content (EMC). The EMC fluctuates between the low and high in-service MC, resulting in some dimensional changes in wood from time to time.

As discussed above, the wood components of a low *MC* at the time of delivery may get wet on a construction site, generating a swelling value that cannot be ignored. **Figure 16** illustrates a floor joist that is supported by a wood frame wall on the right end and by a masonry block on the left [10]. During the service of the floor joist, differential wood movements may occur between the two ends, **Figure 16** (upper). To ensure that the floor is at a horizontal level, the movements at the two ends must be the same. To address this, a wooden sill beam, just like the interior beam, can be added to the concrete wall, as shown in **Figure 16** (lower), which provides an equal amount of wood movement in the vertical direction. This example provides a hint to designers, i.e., it is important to identify, in the course of designing a wood building, the locations where potential differential wood movements could affect structural integrity and serviceability.

Wood is indeed an anisotropic material. Thus, its dimensional change varies from one direction to another. The dimensional change in the longitudinal direction is as low as 0.1–0.2% for mature wood [13]; thus, it can be ignored. However, the dimensional change in the transverse (i.e., radial, tangential or in-between) direction can reach as high as 12% or so [13]; therefore, it must be taken into account during the design of wood buildings. However, it is not practical and sometimes

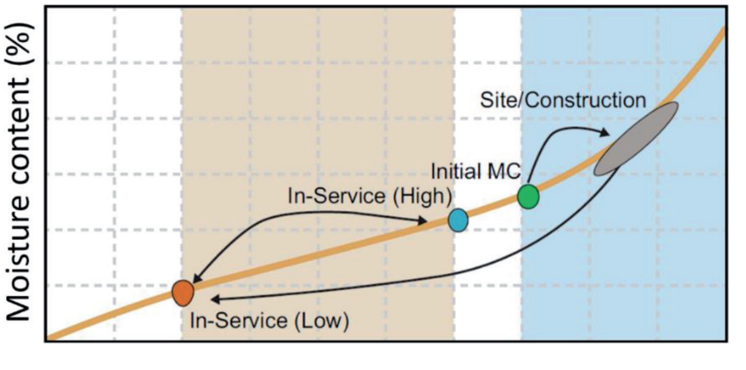

Figure 15.
Variation of moisture content of wood during the construction and use of wood buildings [23].

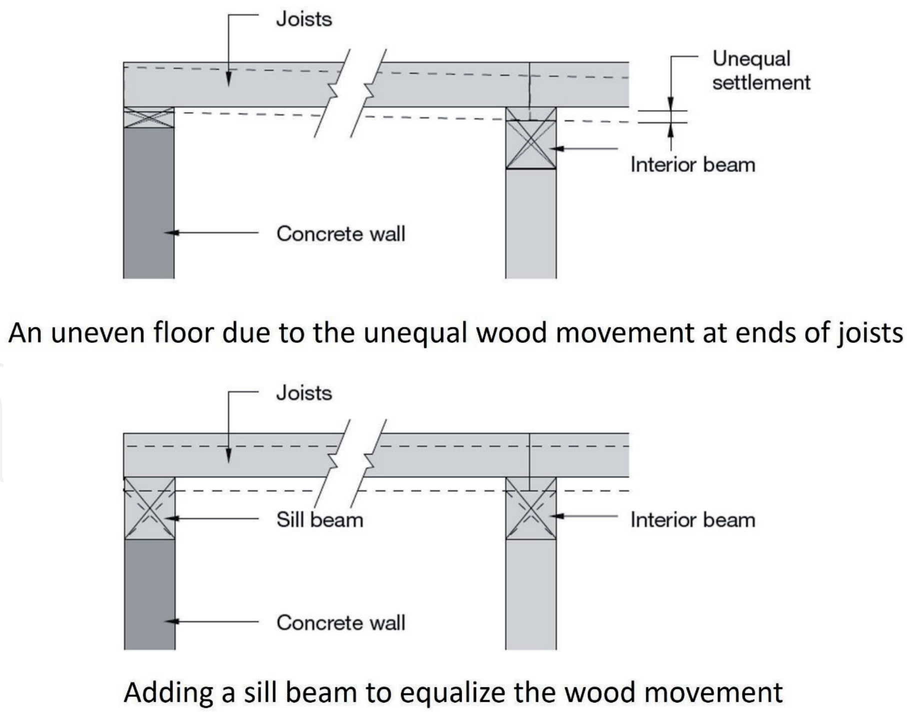

Figure 16.
Detailing to account for vertical movement due to the change in moisture content [10].

impossible to estimate the dimensional change in the transverse direction because the grain orientation in the cross-section of lumber cannot be predicted in the construction of a wood building. To resolve this problem, the Canadian standard CSA O86 "Engineering design in wood" specifies Eq. (1) to estimate the dimensional change of a member made of sawn lumber or lumber-based EWPs such as GLT and CLT [11]:

$$S = D \times \left(M_i - M_f\right) \times c \tag{1}$$

where, S is the dimensional change (mm) due to moisture; D is the actual dressed dimension (mm) (i.e., thickness, width, or length); M_i is the lesser of the initial moisture content of the fiber saturation point (28%); M_f is the final moisture content; and c is a coefficient. As for lumber, c = 0.002 or 0.00005 for the dimensional change perpendicular to the grain (i.e., the transverse direction) or parallel to grain (i.e., the longitudinal direction), respectively.

Scientists at FPInnovations, Canada, conducted a study by monitoring the vertical movement in a 4-storey wood-frame building over 22 months [24]. The floors consist of 38 mm by 240 mm "S-Dry" dimension lumber joists with a concrete topping. The walls consist of 38 mm by 140 mm "S-Dry" solid sawn plates and studs. Double top plates and double bottom plates are used in all storeys. The stud length of all storeys is 2.44 m. The joist spacing is 400 mm; joist spans are 3.75 m; and stud spacing is 400 mm. The scientists calculated the vertical wood movement including shrinkage from an initial *MC* of 19% to the final *MC* of 8%, using the above equation and deformation by assuming the specified roof and floor dead loads to be 0.5 kPa and 1.3 kPa, respectively. Deformation generated by stress includes instantaneous deformation and creep deformation. The equations for calculating these deformations are provided in the report by Doudak et al. [24]. **Figure 17** summarizes the estimated vertical movement values at each storey, indicating that the accumulated shrinkage over 4 stories accounts for about 90% of the total vertical movement. This suggests the vertical deformation generated due to the change in the moisture content of wood is critical and must be considered in the design of a wood building. The actual vertical movement measured in this 4-storey building

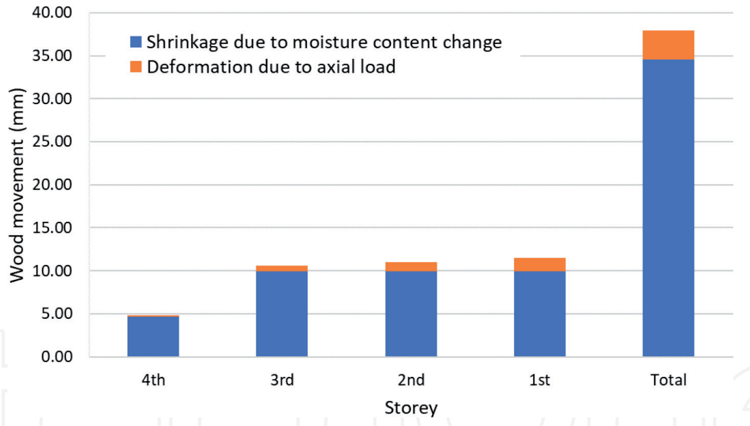

Figure 17.
Estimated vertical movement due to changes in MC and axial compressive load (source: data from [24]).

was about 40 mm, which is in good agreement with the estimated value (about 38 mm). They concluded that it was possible to make a good estimation of vertical movement to avoid the potential problems of structural integrity, serviceability, and building envelope over the lifespan of this wood building. The scientists also found that the use of EWPs could reduce the accumulated shrinkage to about 80% of the total vertical movement, based on their monitoring of another 5-storey building with floor joists

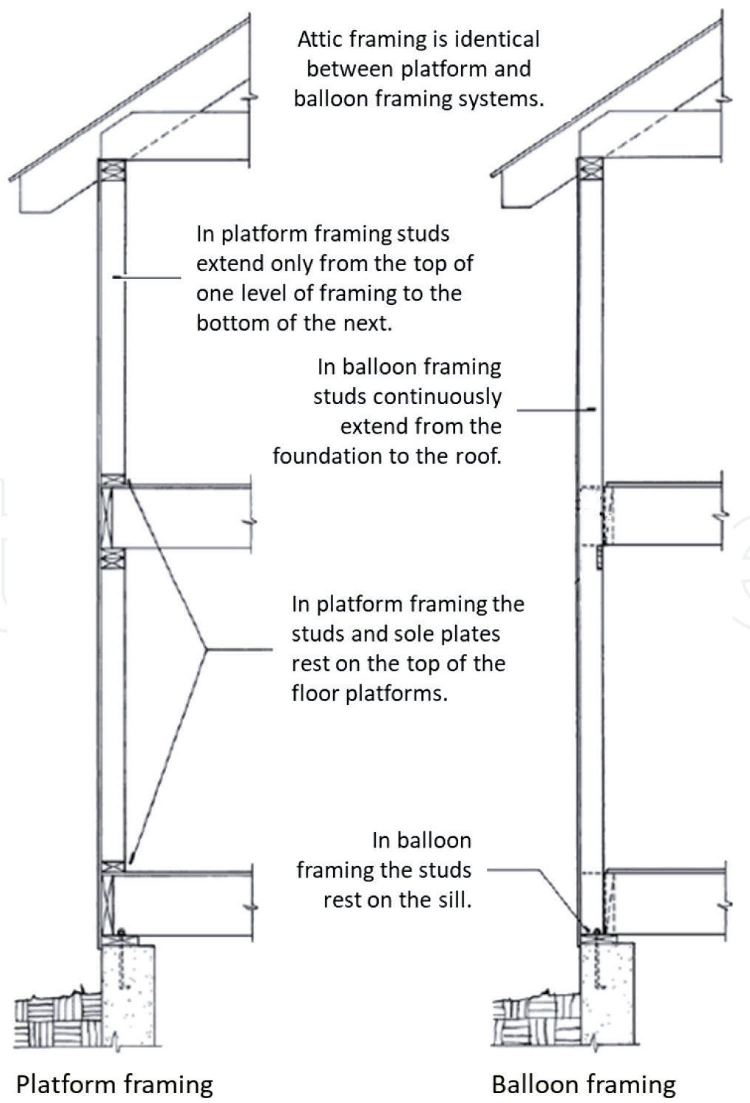

Figure 18.
Light frame construction methods: platform framing and balloon framing (modified from [25]).

made of LVL flanges and OSB webs. The total vertical movement of this 5-storey building was about 30 mm, which was 75% of that of the 4-storey building they studied.

There are two basic wood framing construction methods, notably platform framing and balloon framing [25], **Figure 18**. In the platform framing, all vertical structural elements of the exterior bearing walls and partitions consist of single studs extending the full height of the frame. Meanwhile, in the balloon framing, the studs of the exterior walls and some of the interior walls are continuous from the foundation sill plate to the top plate below the roof framing. In comparison to balloon framing, platform framing is more commonly used for modern structures due to its simplicity and ease of erection; but its vertical movement due to MC changes is much larger. Balloon framing is rarely used nowadays since the length of sawn lumber available is not sufficient due to changes in forest resources with the production of smaller trees compared to older times. However, with advancing technologies, many modern EWPs have been invented and manufactured, providing sufficiently sized materials with less moisture-induced wood movements. This gives an opportunity for people to rethink the use of the balloon framing method in building construction.

CLT panels can, attributed by their inherent two-way spanning capabilities, eliminate the necessity of placing beams underneath the panels, as with other MTPs. This facilitates the emergence and application of a post-and-panel mass timber construction system [9]. Therefore, this system significantly reduces the building height and construction time, as well as overall costs [26]. In this type of modern construction system, the CLT floor plates are point-supported by GLT and PSL columns. This may cause two potential issues, i.e., excessive vertical wood

Figure 19.
Column-to-column connection used in the Brock Commons Tallwood House in the University of British Columbia, Vancouver, Canada (upper: on-site installation of columns connected to CLT panels (source: www.fastepp.com); lower: HSS steel connectors [26]).

movement because of MC change and crushing of CLT panels due to axial loads, if there are no proper connectors joining CLT plates and columns. These issues occur because the vertical direction of the building is the thickness direction of CLT (i.e., the transverse direction of lumber), along which larger accumulated wood movements and lower compressive strengths exist in CLT. To address these issues, a so-called HSS steel connector was developed and employed, **Figure 19** (lower), which can directly transfer load from upper columns to lower columns and provide some tolerance for dimensional change. The development of various types of metal connectors is of great importance in the design and construction of wood buildings with EWPs.

4. Endnotes

With climate change being an inevitable and urgent global challenge, it is essential to address such issues with real-life content, for instance, the global warming impacts caused by buildings and constructions. The World Green Building Council reports that building construction and operation account for 39% of greenhouse gas (GHG) emissions annually [27]. Among this 39%, 11% is from embodied carbon and 28% from operational carbon. The embodied carbon of a building is defined as the amount of carbon emitted during its construction. Whereas, operational carbon is defined as the amount of carbon emitted during the operation of a building. As innovative building technologies continue to develop, operational carbon will be significantly reduced, and embodied carbon can be responsible for almost 50% of total new construction emissions from now to 2050 [28]. In the next 40 years, with a doubled urban population, a building area of 2.48 trillion square feet is required to fit the needs of urban population growth [29]. The combination of considerable global CO_2 emissions from the building sector and the increasing demand on buildings reveals that actions should be taken immediately to mitigate emissions from the embodied carbon. One of the answers to this global challenge is to increase the use of wood and wood-based products in the construction sector. As a biomaterial, wood possesses its natural ability to mitigate carbon dioxide (CO_2). During the growth of trees, wood is produced, sequestering carbon. After trees are harvested, wood can be processed into various products. These products can be therefore used in construction of buildings, which store carbon over their lifespan. The recently released report "The state of mass timber in Canada 2021" from the Government of Canada [30] indicates "As high-value wood products, mass timber can play an instrumental role in the circular economy by providing a renewable source of building materials and contributing to a lower carbon footprint for the construction sector." In the last two decades, the development of mass timber was rapid in Canada, which can be viewed through the number of completed mass timber projects, **Figure 20**, with 10 projects in 2007 and upwards of 60 projects in 2018. It should be noted that each project listed in this figure must meet two criteria, i.e., a minimum floor area of 300 m^2 and structural use of MTPs.

Figure 21 illustrates the percentage share of each EWP in major markets over a time horizon [31]. The data in this figure are outdated, only depicting the status of EWPs in 2006, but it still provides some insight into the market shares of each EWP. The sheathing and industry plywood markets are in the stages of "decline" and "maturity", respectively. This is mainly due to the decreasing volume of veneer quality logs and the rapid development of OSB. Sheathing OSB is in "rapid growth", which has taken a big market share from plywood because of its high yield of using raw wood materials. Framing lumber takes 90% or more market shares since SCL is still much more expansive than sawn lumber, resulting in its failure to completely

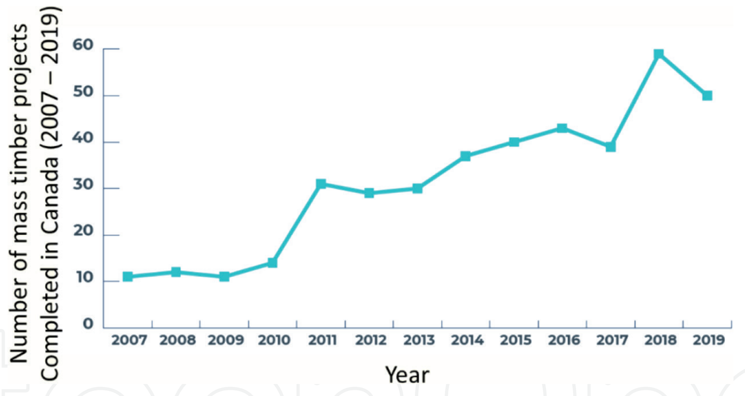

Figure 20.
The number of completed mass timber projects per year in Canada [30].

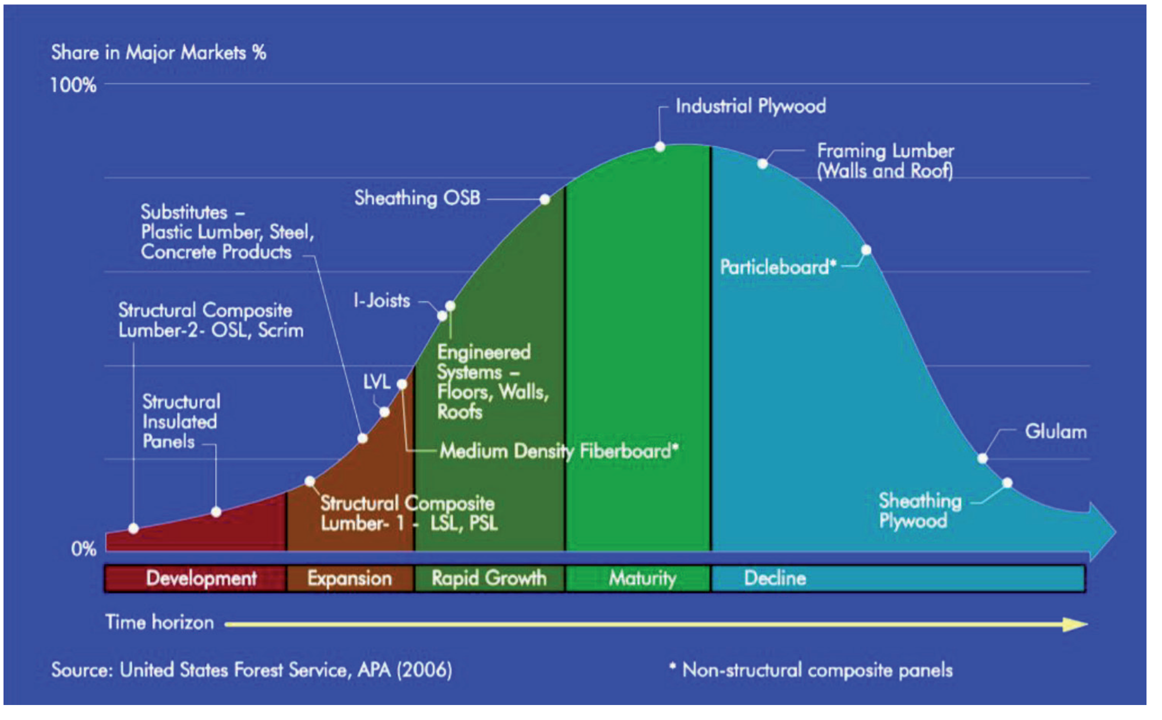

Figure 21.
Percentage share in major markets of EWPs over time horizon (source: photos obtained from [31]).

replace lumber [6]. Glulam, a commonly used name for GLT, has passed its plateau of market demand, moving into the "decline" stage. The main reason for this decline could be the emergence of other EWPs such as LVL, LSL, and PSL. Albeit LVL stays at the end of the "expansion", it could have reached its maximum market share. This implies that the cost of producing LVL will, just like manufacturing plywood, definitely increase, since premium logs for producing veneer are becoming scarce [6]. LSL and PSL are in "expansion" due to their high raw material yield from logs to the final products. **Figure 21** does not show the market shares of CLT, NLT, and DLT, but it can be reasonably speculated that these lumber-based EWPs are in the "development" and "expansion phase", and will enter "rapid growth" quickly, particularly for CLT. As technologies advance, the cost of manufacturing EWPs will be further reduced. For example, adoption of the artificial intelligence in production can lead to an increased yield of raw material usage from logs and reduced labor costs. Therefore, EWPs will be more competitive to sawn lumber and make inroads into more market shares.

It can be well foreseen that EWPs will have a bright future in construction because (1) EWPs are designable, producing an optimal structural performance

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for construction; (2) EWPs have more uniform strength properties and fewer changes in dimensions and shape, making them more suitable building materials; (3) EWPs provide a wide selection of dimensions, allowing designers and builders to design and build tall timber, wood-concrete, and wood-steel hybrid structures; and (4) EWPs fall into the category of environmentally friendly and recyclable products, contributing to a lower carbon footprint for the construction sector.

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