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Chapter

Lumber-Based Mass Timber Products in Construction

Meng Gong

Abstract

This chapter provides information related to commonly used wood construction methods (i.e., light-frame, post-and-beam, and mass timber) and mass timber products. It briefly discusses the manufacturing of four major lumber-based mass timber products (i.e., glue-laminated timber, nail-laminated timber, dowel-laminated timber, and cross-laminated timber), and their available dimensions and typical applications. The discussion also addresses primary lumber products, such as dimension lumber, machine stress-rated lumber, and finger-joined lumber, which are the building blocks from which mass timber products are manufactured. Advantages of using wood in construction are illustrated by examples largely from North American practices. The life cycle assessment concept is also introduced.

Keywords: building materials, cross-laminated timber, dowel-laminated timber, glue-laminated timber, life cycle assessment, lumber, mass timber products, nail-laminated timber, timber, wood construction

1. Introduction

Prior to the availability of rolled steel and reinforced concrete, wood was the primary structural material in North America and other timber-rich regions of the world [1]. However, the raw material resources keep changing in more recent times, e.g. log diameters become smaller and trees come from faster growing plantation species. As a result, traditional solid timber products have been supplemented by Engineered Wood Products (EWP) like glue-laminated timber (GLT or glulam), laminated veneer lumber (LVL), and oriented strand board (OSB). This has permitted economic construction of residential and nonresidential buildings, bridges, and industrial structures. Presently, using of traditional wood products and EWP is recognized as a "green" option, and is encouraged by governments as part of sustainable development and climate change mitigation strategies [2].

From a technical perspective, modern EWP commonly provide better and more predictable physical and mechanical properties than traditional wood products, such as more uniform structure, greater dimensional stability, greater strength, and stiffness. Initially, much development of EWP was focused on creating substitute products capable of replacing small dimension sawn lumber and boards as primary elements in light-frame building superstructures; but in recent decades, much attention has been switched to creation of mass timber products (MTP). The term MTP describes a family of EWP of large section size that offers the construction industry a viable alternative to use structural steel and reinforced concrete [3]. This

includes thick-panel products, such as cross-laminated timber (CLT) and structural composite lumber (SCL), as well as adhesively or mechanically laminated linear elements like GLT, nail-laminated timber (NLT), and dowel-laminated timber (DLT).

SCL refers to products manufactured by layering dried and graded wood veneers or strands bonded together by moisture-resistant adhesive into panel-like products of a width of up to 2.44 m, a thickness of 38 mm, or more. In principle, SCL is only limited in width and length by transportation considerations. SCL basically includes LVL, laminated strand lumber (LSL) and oriented strand lumber (OSL), which is usually sawn into lumber-like products. However, parallel stand lumber (PSL) is also deemed as a SCL product, which is commonly used as columns connected to other MTP. Use of terms in the literature can be colloquial, with timber-concrete composite (TCC) and other hybrid elements sometimes grouped into the meaning of MTP. Overall, MTP offers architects and builders many opportunities to express their concepts creatively, while satisfying various technical performance requirements applicable to engineered structures of many types [4]. This chapter places emphasis on the types of lumber-based MTP illustrated in **Figure 1**.

Figure 2 illustrates three types of wood construction methods, namely light-frame, post-and-beam, and mass timber. Light-frame construction consists of studs, joists, and other framing at spacings of 600 mm or less [6], **Figure 2**—top. Dimension lumber is used for framing members and plywood or OSB for sheathing materials. Light-frame construction is an economical choice for the construction of low- and mid-rise buildings, which makes use of dimension lumber in a range of grades and dimensions [7]. Light-frame wood structures can be also used for shopping centers, plazas, service and maintenance buildings, and institutional and municipal facilities. Prefabrication of components such as wall and roof panels, even complete homes or office units are efficient extensions of this framing technique [7]. However, the structural system of a light-frame building is not well-defined, resulting in much redundancy. Design of a light-frame building often only includes architects unless the building is large.

Post-and-beam construction is a skeletal framework of posts, beams, and decking supported on a foundation, in which the posts and beams are well spaced apart, more

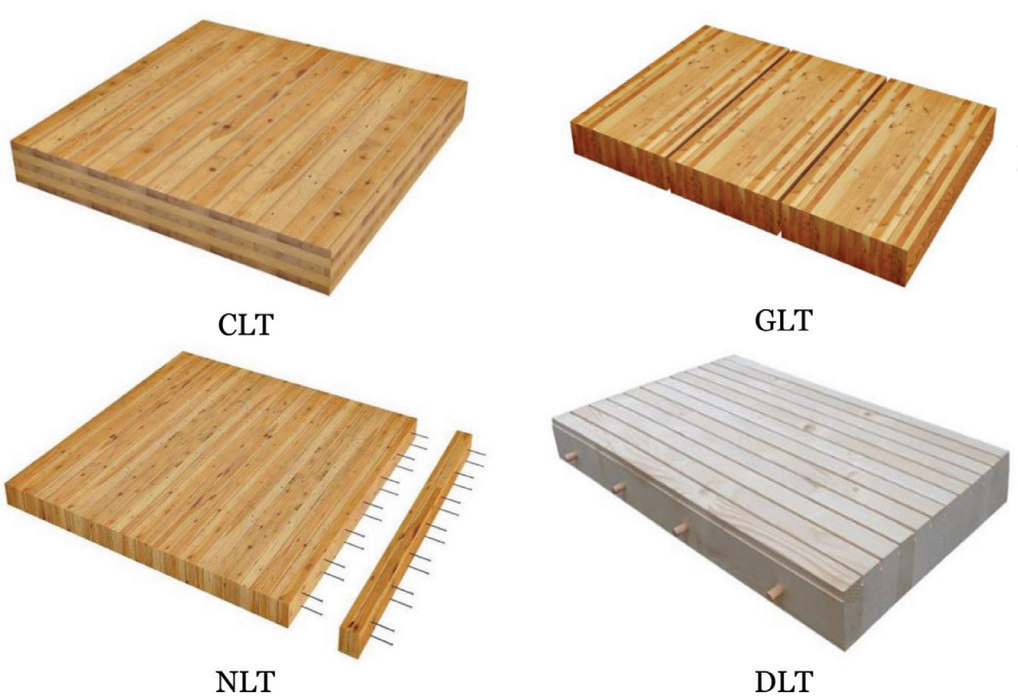


Figure 1.
Lumber-based MTP (Source: Images obtained from StructureCraft).



Figure 2.
Wood building construction methods. Top: Light-frame construction (Source: Photo obtained from Okoye et al. [5]). Center: Post-and-beam construction (Source: Photo obtained from Post & Beam Homes). Bottom: Mass timber construction (Source: Photo obtained from UBC Public Affairs).

than 600 mm, but commonly 1200 mm or more [6], **Figure 2**—center. Traditionally, posts and beams were made of large solid timbers, which were connected with mortise and tenon joints locked into place with hardwood pegs, with diagonal braces for stabilization of a structure [7]. Nowadays, many types of EWPs (such as GLT and LVL) and connectors (such as metal brackets, shear plates, and split rings with bolts) are very often used. The post-and-beam construction is commonly used to construct custom-designed homes, commercial buildings, recreation centers, and industrial structures, for reasons of ease of fabrication and consequent economy [7]. Unlike the light-frame construction, the structural system of a post-and-beam building is

well-defined and engineered, generating very limited or no redundancy. Design of a post-and-beam building is usually formal, involving both architects and engineers, especially if the building is relatively large. Hybrid post-and-beam and light-frame construction features the exposed heavy timber components, but allows insulation to be placed in the wall space, with finishes applied to both the inner and outer faces of the studs [7].

Mass timber construction complements traditional light-frame and post-and-beam construction methods due to emergence of various types of MTPs, **Figure 2**—bottom. It creates single or multiple material hybrid superstructures for building and other structures. Since beams are not always required, new technology and terminology, such as post-and-panel construction, have emerged. This demonstrates that MTPs have been developed into material options, where the only limits on their uses are limitations of the inventiveness of minds of architects and engineers within the scope of what applicable building/construction regulations permit [4]. What codes and standards permit architects and engineers to do is not yet uniform; but in the broad sense, construction codes and standards in various countries have transitioned, or are transitioning, away from prescriptive provisions to performance-based provisions in a manner that enables greater use of EWP, including MTP. Most important in this respect is the revision of fire performance provisions related to buildings [4, 6]. Mass timber systems are widely reported to be cost-competitive, carbon-efficient, sustainable and reliable, which stem from the scientific data generated from full-scale fire, seismic, durability, acoustic, and vibration tests being conducted internationally by researchers and engineers [3, 4]. It is now reasonable to claim that the use of EWP and MTP has the same level of supporting technical understanding as that underpinning any other major class of construction material. Latter sections of this chapter demonstrate the use of MTP as parts of high-performance buildings meeting needs of society and occupants.

2. Lumber and lumber-based MTP

2.1 Lumber

Lumber is a manufactured product derived from logs, including boards (elements with limited thickness), dimension lumber (elements with relatively small section dimensions), and timbers (elements with relatively large section dimensions). In North America, most lumber is softwood dimension lumber having thicknesses ranging from 38 to 89 mm, widths from 38 to 184 mm, and lengths of up to about 5 m [6]. Dimension lumber is widely used in light-frame construction, which is categorized into four groups in the Canadian practice: structural light framing, structural joists and planks, light framing, and studs. Dimension lumber is usually graded by visual inspection in terms of appearance characteristics, such as knots and slope of grain. For example, the grades of dimension lumber used for structural light framing construction are Select Structural (SS), No. 1, No. 2, and No. 3. It should be noted that there is not a strength difference between No. 1 and No. 2 Canadian dimension lumber albeit there exists an appearance difference [6]. Therefore, the product mix of No. 2 and Better is commonly used where the appearance of No. 1 grade lumber is not required. Alternatively, dimension lumber can be mechanically evaluated and sorted into grades using so-called machine stress-rated (MSR) lumber or machine-evaluated lumber (MEL) [6]. The MSR machine is widely used in wood industry to nondestructively test each piece of dimension lumber to determine its stiffness so that it can be assigned a permitted design stress based on the established relationship between the stiffness and bending

strength. In North America, grades of MSR lumber are assigned "f-E" values, such as 1950f-1.7E. The "f" value designates the predicted strength in pounds per square inch (psi), and the "E" value designates the average stiffness measured in millions of pounds per square inch (10^6 psi) [6].

Boards are lumber products having thicknesses of 32 mm or less, making them usable as decking and sheathing. When the smallest cross-sectional dimension of a lumber product reaches or exceeds 140 mm it is termed timber, which is graded based on visual inspection methods [6]. Uses of dimension lumber and timbers widely range with differences in whether the former or latter is suitable depending on the type of structural system, and performance requirements applicable to a structural system. In general, dimension lumber is used in systems where multiple parallelly arranged elements act together to resist effects of particular structural design loads. Timbers, on the other hand, can be used in situations where multiple elements or a single element is designed to resist effects of particular structural design loads. Another important difference is that dimension lumber elements must always be protected from effects of design fire situations; whereas, depending on specifics of a situation, timbers may not require such protection.

Finger-joints are commonly used to join short pieces of lumber together to make longer pieces. Meshing wedges known as "fingers" are made as either side of a joint, as illustrated in **Figure 3**, and bonded using structural adhesive. The joint profile governs the strength of a joint, and is defined by the finger length, tip thickness, tip gap, and finger pitch, slope, and depth. For example, a 29-mm-long finger joint is commonly used (**Figure 3**—left). However, reducing finger length to 13 mm with some modifications to the joint profile (**Figure 3**—right) not only helps to reduce material waste, but also keeps the same or slightly higher strength joints [8]. Also, it is noted that cutting out strength reducing features like large knots then finger joining lumber is a highly effective way of upgrading properties of dimension lumber, increasing value, and enabling higher value uses like creation of high-performance MTP [6]. Another advantage of finger joining lumber is that it increases dimensional stability under changing environmental conditions prior to or after installation of lumber in structures. Adhesives used in finger-joints are usually phenol-resorcinol formaldehyde for lumber products intended for general applications or incorporated in GLT elements, or polyvinyl acetate for lumber products used as studs [6].

2.2 Glue-laminated timber (GLT or glulam)

GLT (also widely known as glulam) is a structural product composed of multiple pieces of finger-joined dimension lumber, or other types of EWP, adhesively face-to-face bonded to create a desired form. GLT was first used in Europe in the early 1890s. A 1901 patent from Switzerland signaled the true beginning of GLT construction [9]. A significant development in the GLT industry was the introduction of fully



Figure 3.
Two finger joint profiles (left: 29-mm long; right: 13-mm long) used for joining short pieces of lumber.

water-resistant phenol-resorcinol adhesives in 1942, which allowed GLT to be used in exposed exterior environments without concern of glueline degradation [9]. The manufacturing of GLT is deemed as a one-dimension additive process. The grain of all laminations runs parallel with the lengths of straight members, **Figure 4**. The dimension lumber laminations are not visually graded on the same rules as regular lumber, but follow the grading rules stipulated in Canadian Standard O122 "Structural Glued-Laminated Timber" [7]. Each lamination is visually inspected based on both faces of the piece, and then assigned one of four grades: B-F, B, D, or C [7], in which B-F indicates the highest grade and C the lowest grade. Laminations of higher grades are used in the top and bottom portions of a GLT beam, **Figure 5**, where bending stress is greatest. Specified laminations are also nondestructively graded by machine before assembly to meet both visual and stiffness requirements for particular grades of GLT. Sometimes layers of other materials, such as glass fibers, are incorporated among lumber laminations to add strength or stiffness or to locally reinforce GLT [10]. Moisture content of laminations ranges from 7 to 15% during fabrication. Durable cold-setting waterproof-structural adhesives are used, such as phenol formaldehyde and phenol-resorcinol formaldehyde [7]. Because finger-joined lumber is employed, dimensions of GLT members are in principle only limited by manufacturing and transportation capabilities of a manufacturer. Those capabilities are highly variable, with the most advanced involving fully automated manufacturing processes based on advanced integrated design and manufacturing methods. The automated processes can include robot handling of materials and elements from the arrival of logs at a manufacturing plant to installation of elements at a construction site. A typical GLT member ranges in depth from 114 to 2128 mm or more, in width from 80 to 365 mm, and in length of up to 40 m [7]. GLT is commonly used as beams and columns (**Figure 4**—left and middle), but can be also used as flexural members (**Figure 4**—right). In latter situation, the narrow faces of the laminations are normal to the direction of the load. The Canadian Standard O86 "Engineering Design in Wood" refers to this condition as "vertically glue-laminated" [11]. Usually, GLT is used in dry service conditions or is protected in some way if used under outdoor conditions.

Design stiffness and strength properties of GLT of a given grade are calculated based on engineering properties of the laminations using equivalent linear elastic mechanics theories. A wide range of GLT grades are available with some involving deliberate placements of laminations of different grades to achieve the design properties of GLT elements suited to their particular applications [11]. In general, there are two grade categories for GLT, stress grade and appearance grade [7]. The former defines specified strengths of a GLT member, and the latter the quality of



Figure 4.
GLT beam (left), column (middle), and panel (right).

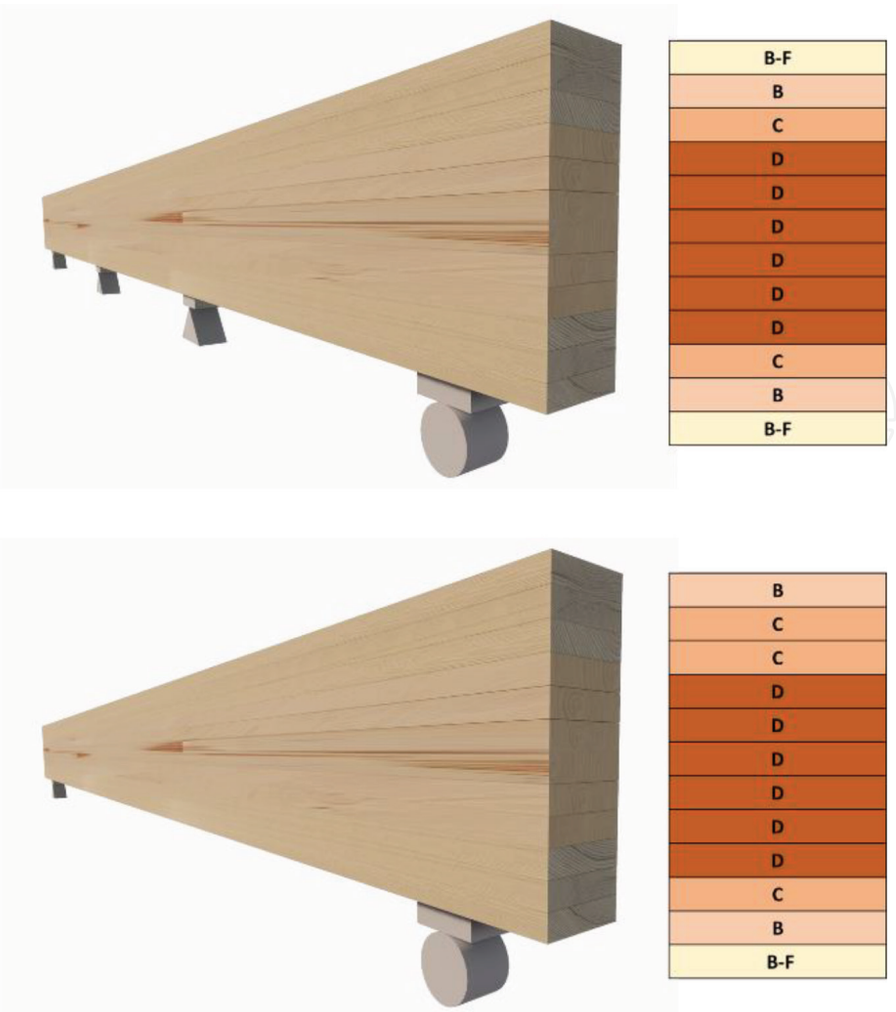


Figure 5.
GLT members with laminations suiting resistance of bending forces: Upper—Member with a balanced layup intended to maximize material use when the member is loaded in tension on both top and bottom faces (EX grade under Canadian system), and Lower—Member with an unbalanced layup intended to maximize material use when the member is loaded in tension on the bottom face (E grade under Canadian system).

finish on the exposed surfaces of the member. For example, some grades suit uses of GLT elements as beams, columns or tension members, **Figures 6–8**. Taking the Canadian Standard O86 "Engineering Design in Wood" as an example, that design standard specifies the grades of GLT bending elements as 20f-E, 20f-EX, 24f-E, and 24f-EX [11], **Figure 5**. Within those designations, numbers 20 and 24 are indicative of the associated specified design strength in bending. E indicates that associated grade properties apply to elements without an inflection in their deformed shapes, with the proviso faces intended to be stressed in tension are correctly oriented. EX indicates that associated grade properties apply to elements with inflections in their deformed shapes. Similar approaches are adopted by other international standards which define rules for engineering design of timber structures.

2.3 Nail-laminated timber

NLT is manufactured with dimension lumber laminations, stacked on edges, and fastened with nails, to create large-flat structural components, **Figure 9**. Spikes and screws are sometimes used as well. Since the beginning of the nineteenth century, NLT systems were utilized as floor elements in structures known as "mill construction" that originated from cotton mills and sawmills found in the North Eastern United States [7]. The prevalence of the industrial building systems led



Figure 6.
Conference room built with GLT beams and columns at the University of New Brunswick, Fredericton, Canada.

the National Lumber Manufacturers Association to publish a guide "Heavy Timber Mill Construction Buildings" in 1916 [7]. In addition, NLT has been used to create deck and diaphragm elements of bridges and buildings for centuries [6]. Like GLT, the manufacturing of NLT is a one-dimension additive process. In North America, individual laminations have a thickness of 38 mm or more and a depth of 64 mm or more, similar to plank decking [7]. The moisture content of laminations is usually 12–16% at time of manufacturing of NLT [14]. The visual or MSR grade of softwood laminations are widely used, such as SS and No. 2 and Better or 1650f-1.5E [7, 14]. Single laminations are commonly employed if the length of prefabricated panels is less than 6 m [14]. The spliced laminations of specific pattern [11, 14] or finger joined lumber laminations [14] are used if longer panels are required. The Canadian Standard O86 "Engineering Design in Wood" [11], for example, specifies connection requirements for fabricating NLT, requiring that nails be long enough to pass through two adjacent laminations and at least halfway through the third, **Figure 9**. For example, 102-mm-long nails should be used to fasten 38-mm-thick laminations, and 152-mm-long nails for 64-mm-thick laminations. Such requirements are based on practical experience and ensure integrity of NLT in various end use situations. NLT shall be spiked together with a staggered single row of nails at intervals of not

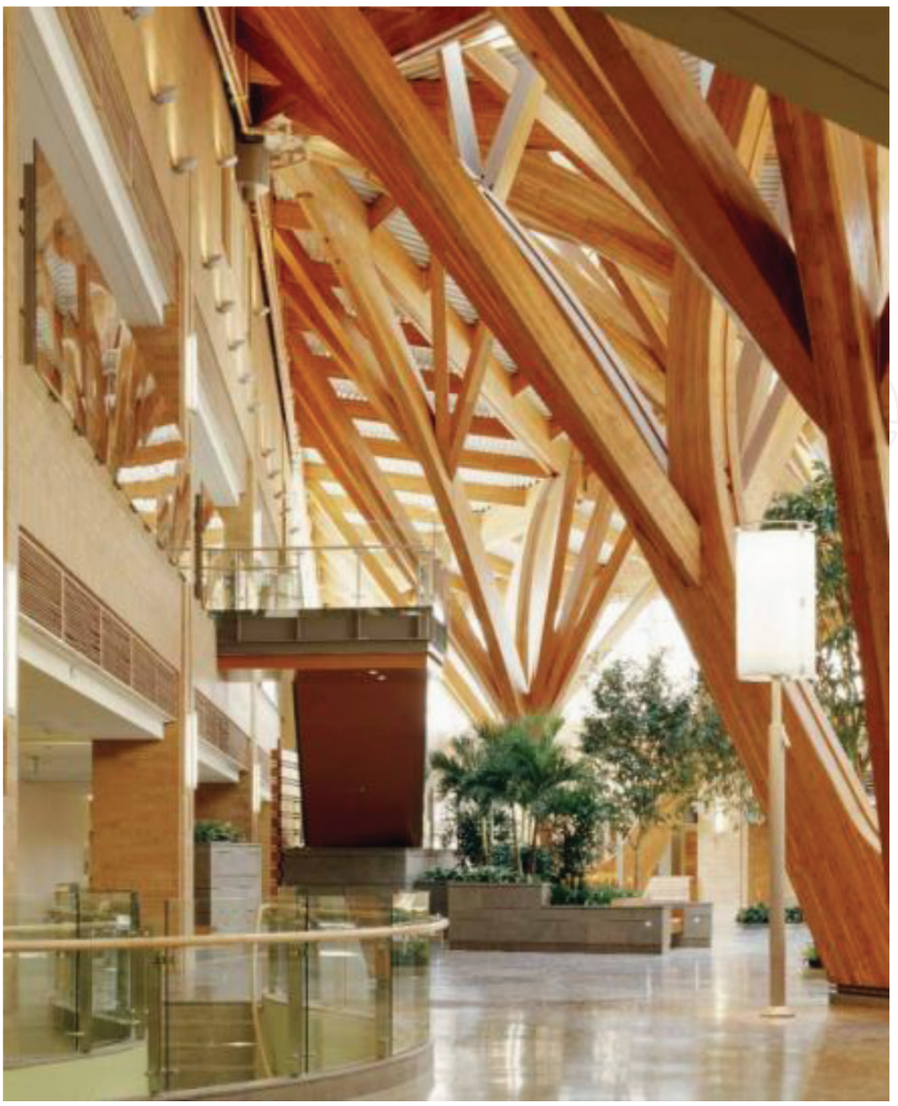


Figure 7.
A forest of intertwined GLT trees in the Carlo Fidani Peel Regional Cancer Centre, Mississauga, Canada (Source: Photos obtained from CWC [12]).

more than 450 mm [7]. The prefabricated NLT panels typically come in lengths of 3–8 m; however, the panel size is limited by transportation restriction [7]. The drawbacks of using NLT are its slow fabrication process and after-fabrication machining problem due to existence of nails.

In North America, many timber decks of rural bridges constructed from 1920s through the mid-1960s were made of NLT [15]. Mostly, the NLT was oriented so the lumber laminations were transverse to the bridge span and supported by bridge girders, but for short bridges lumber laminations were sometimes orientated parallel to the span [15], **Figure 10**. Another common traditional use of NLT is in floors of industrial and commercial buildings. The reasons for choosing NLT are as follows: it is well suited to onsite fabrication; it is capable because of the nails of absorbing energy damping vibrations caused by transient or sustained dynamic force (e.g., bridge wheel loads and reciprocating industrial equipment); and it has good fire performance. Disadvantages of NLT include that it is not particularly mechanically efficient if NLT elements are required to have high rigidity when loaded in-plane or as flexural elements, also there have been durability issues associated in particular with bridge applications. The disadvantages stem from the flexibility of nailed interconnections between laminations, and proneness to gaps to form at those interconnections (e.g., due to moisture movements in the laminations).



Figure 8.
160-m-long timber bridge with GLT deck structure in Mistissini, Canada. (Source: Photos obtained from Lefebvre and Richard [13]).



Figure 9.
NLT with linear (left) and staggered (right) nailing patterns.

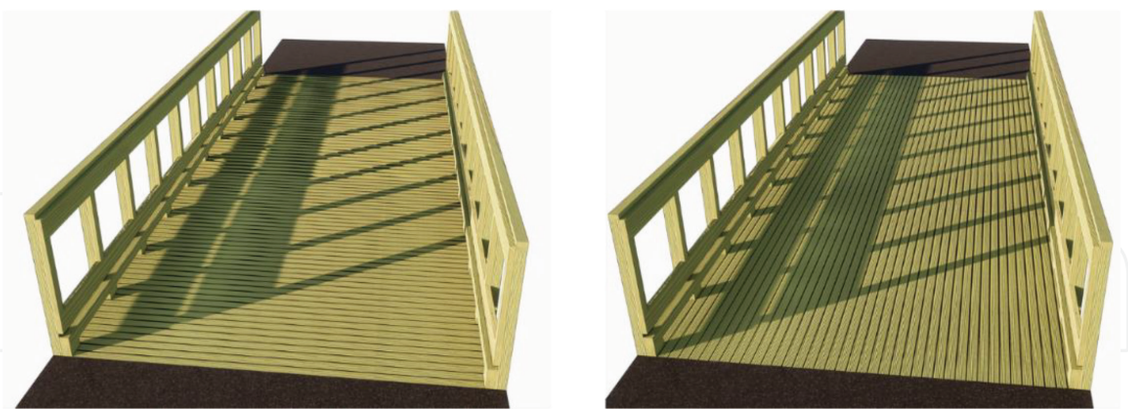


Figure 10.
Transverse (left) and longitudinal (right) oriented NLT bridge decks.

Recently, use of NLT has undergone resurgence as part of the modern mass timber movement in buildings [3, 4], **Figure 11**. This, in some cases, supports adoption of complicated architectural forms, **Figure 12**, supported by creation of hybrid NLT products which combine lumber laminations with layers of sheathing materials such as plywood and OSB to reinforce the system [14, 17]. Sheathing adequately nailed to NLT can create a diaphragm of the capability to resist lateral forces, and can also help keep the system dry if exposed to moisture [7]. In any such case, it is required to consider the system as an individually designed engineering project.

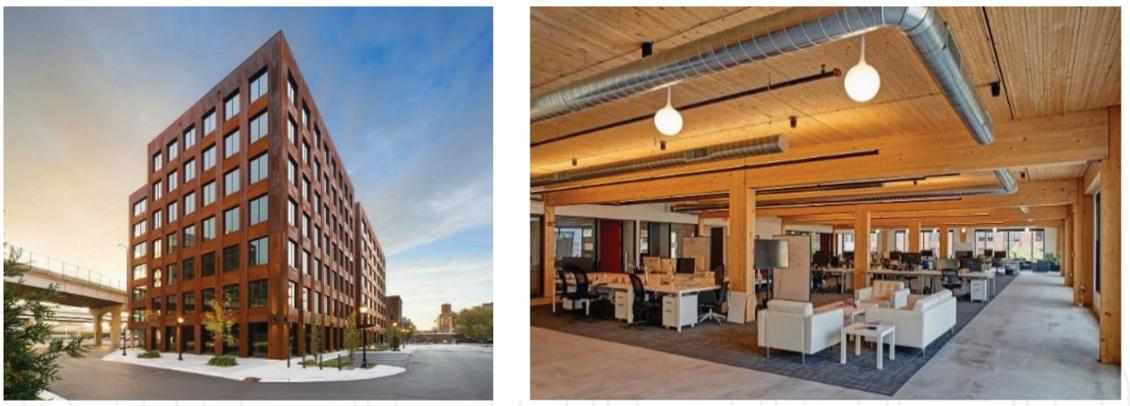


Figure 11.
Seven-story T3 Minneapolis building made of NLT floors and GLT beams and columns in USA (Source: Photos obtained from StructureCraft [16]).



Figure 12.
Qingdao Pearl Visitor Centre of exposed NLT roof in China (Source: Photo obtained from StructureCraft [16]).

2.4 Dowel-laminated timber

Dowel-laminated timber (DLT) is another member of MTP family. DLT is similar to NLT regarding laminations, but different in fasteners. Instead of nails, DLT uses hardwood dowels to join laminations, **Figure 13**. The manufacturing of DLT is another example of one-dimension additive process. DLT was developed in the early 1990s in Switzerland [7]. DLT is manufactured with softwood lumber of a thickness of 38 mm and a depth of 89, 140, or 184 mm, stacked on edges just like NLT, and fastened face-to-face with wooden dowels. Unlike NLT, finger-joined lumber is typically used in manufacturing of DLT. The moisture content of laminations is 19% or less at time of manufacturing [7]. The visual or MSR grade of laminations is, if spruce-pine-fir lumber is used for example, SS and No. 2 and Better or 2100f-1.8E [18]. The wooden dowels, which are usually made of high-density hardwood species (such as oak), have typically a diameter of 19 mm and a moisture content of approximately 6–8% [7]. The predrilled holes of a diameter being about the same as dowels are required prior to driving dowels into laminations [18]. The dowels can then be hydraulically pressed in a linear or staggered way with spacing of 300 mm [7], the latter of which could offer additional stiffness DLT panels, **Figure 13**. Dowels

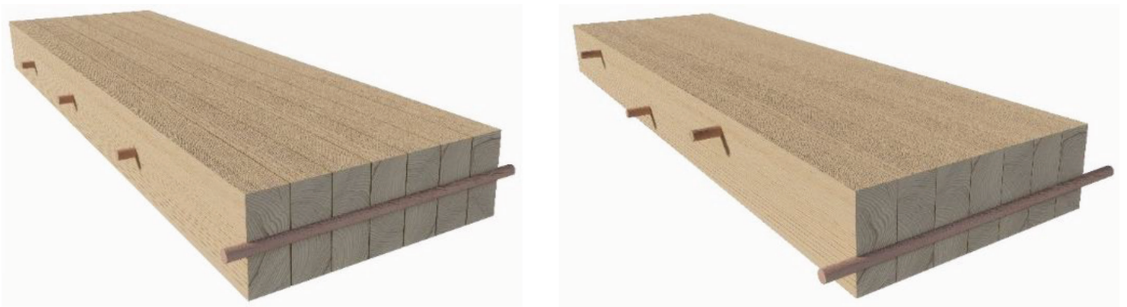


Figure 13.
DLT with linear (left) and staggered (right) fastening patterns.

are commonly penetrated through 7–10 laminations, resulting in a more efficient process of manufacturing DLT than NLT. As the moisture content of both materials used in DLT equilibrate after fabrication, the dowels swell and the lumber shrinks, which forms a strong friction-fit joint between the lumber and the dowels, resulting in a panel that does not require glue or nails [7]. DLT has been gaining interest in both Europe and North America since it is almost made of 100% wood, except those of finger-joined laminations that contains very limited amount adhesive. DLT is ease of being manufactured using computer numerical controlled (CNC) machinery, such as lathes, routers, and mills. The prefabricated DLT panels typically have a length up to 18 m, a width up to 4.3 m in any increment, and a thickness ranging from 76 to 349 mm [18]; however, the panel size is usually limited by transportation restrictions.

DLT panels can readily be milled and routed for preintegrated electrical and other service conduits, which offers a unique feature to DLT, i.e., the flexible design, **Figure 14**. This also allows designers to improve the acoustic performance and visual appeals of a building by making kerfs and curves. For example, acoustical strips can be integrated into the bottom surface of a DLT panel, helping designers reduce sound while keeping the wood exposed and also allowing for a variety of surface finishes [18]. DLT can be also recognized as a type of MTP that can be used in exterior exposure, allowing itself to be used for decks, balconies, and canopies.

DLT performs similarly, in terms of structural performance, to GLT and NLT, because its grains run in one direction. DLT allows a significant flexibility in architectural design, which is well suited for floor and roof applications, but can be used as wall panels as well [18], **Figure 15**. Two-way spans can be achieved with the use of reinforcement such as adding multiple layers of plywood atop the DLT panels [18]. In addition, DLT panels can be used as structural bearing or shear walls, and elevator and stair shafts. The design requirements for DLT may be considered the same as those used for NLT, if the hardwood dowels can adequately connect the laminations [7]. In reality, there is almost nothing that can be referenced in the

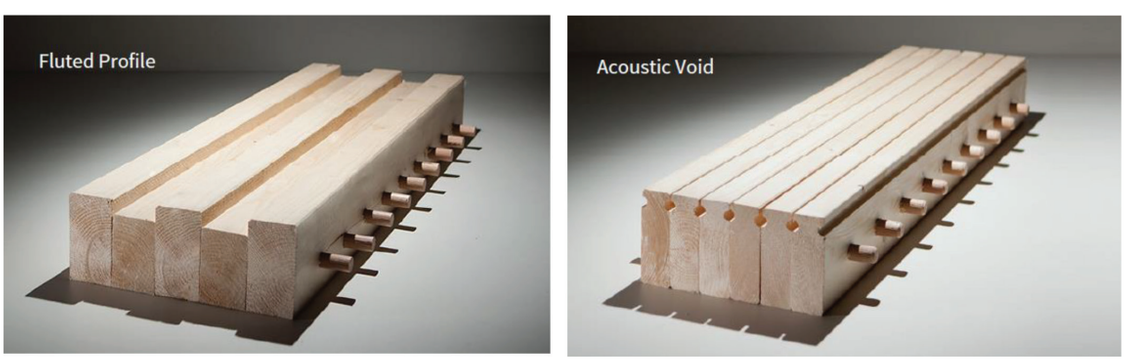


Figure 14.
Two sample profiles of DLT (Source: Pictures obtained from StructureCraft [18]).



Figure 15.
Seven-story T3 Atlanta building comprising DLT floor and roof panels in USA (Source: Photos obtained from StructureCraft [18]).

codes worldwide, except that a few manufacturers provide published design values for their own DLT products [4]. Thus, use of DLT would require approval by the building authority on a case-by-case basis.

2.5 Cross-laminated timber

Cross-laminated timber (CLT) is a new-generation engineered large-size structural panel product, which consists of layers of dimension/MSR lumber (typically three, five, or seven) oriented at right angles to one another and then bonded using adhesives, **Figure 16**—upper. CLT was originally invented in the 1970s in Europe [6] and introduced as an innovative wood product in the early 1990s in Austria and Germany [19]. In the mid-1990s, Austria undertook an industry-academia joint research effort that resulted in the development of modern CLT [19]. In the last 2 decades, the use of CLT has gained interest to both construction and wood industries in North America, featured with the publication of two editions of CLT Handbook [20, 21] and erection of 18-stories CLT building "Brock Commons Tallwood House" in 2017 in Canada. Unlike GLT, NLT, and DLT, the manufacturing of CLT is a kind of three-dimension additive process. The species of wood used depends on the location of a manufacturing plant. For example, black spruce is widely used in Eastern Canada. The commonly used lumber products in manufacturing of CLT are dimension lumber of a grade of No. 1/No. 2 or MSR lumber of a grade of 1200f-1.2E or better in its major strength direction, and dimension lumber of a minimum grade of No. 3 in its minor strength direction [7]. In the major strength direction, the minimum net width of a lamination shall be 1.75 times its thickness, and in the minor strength direction, the net width of a lamination shall not be less than 3.5 times its thickness if the laminations are not edge-glued [7]. The moisture content of lumber at fabrication of CLT is about 12% [7]. The cold-set structural adhesives are preferred to increase the productivity of manufacturing CLT panels, which include emulsion polymer isocyanate (EPI), polyurethane (PUR), and phenol-resorcinol formaldehyde (PRF) [7]. In Canada, the adhesives used in manufacturing process of CLT must comply with the Canadian Standard O112.10 "Evaluation of Adhesives for Structural Wood Products (Limited Moisture Exposure)" and ASTM D7247 "Standard Test Method for Evaluating the Shear Strength of Adhesive Bonds in Laminated Wood Products at Elevated Temperatures" [7]. The finger- or scarf-joined lumber is used to face-to-face and/or edge-by-edge laminating as two-dimension components. Use of edge-gluing or not slightly differs in the manufacturing of CLT between North America and Europe. In North America, edge-gluing of lumber is not a common practice due

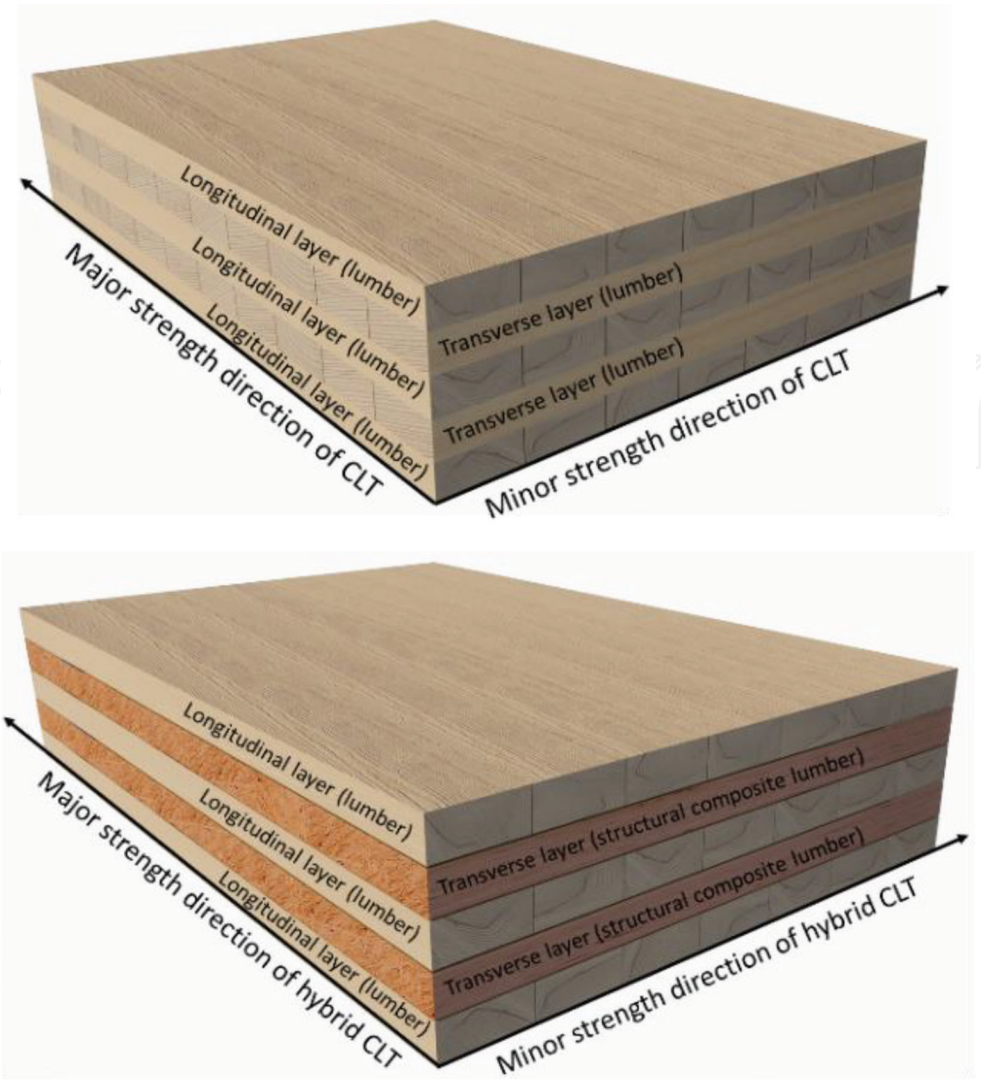


Figure 16.
CLT products (Upper: a generic CLT made of lumber only; lower: a hybrid CLT made of dimension lumber in the major strength direction and structural composite lumber in the minor strength direction).

to the added manufacturing costs. The gaps between lumber could provide some tolerances for wood movement due to the change in moisture in service. However, the European practice appears to widely apply edge-gluing with an aim to offer good stiffness and strength of a CLT panel. Anyhow, as a trade-off between cost and improved panel performance, edge-gluing of selected layers as needed could be adopted [6]. CNC routers are often employed to precisely cut CLT panels to size and openings for windows, doors, connections, ducts, and service channels. A CLT product can be produced in large sizes of a width ranging from 1.2 to 3 m, a length from 5 to 19.5 m, and a thickness from 100 to 500 mm [7]. CLT can be also manufactured in custom dimensions, with panel sizes varying by a manufacturer.

Despite the availability of commercial machines to manufacture construction size CLT using dimension lumber, there are challenges with the existing systems, such as the need to apply pressure to all four sides of a panel to ensure adequate edge-glue bond quality, as well as the out-of-plane pressing. From a product performance perspective, CLT is known to be prone to the so-called rolling shear failure and excessive deflection when subjected to out-of-plane loading. This is particularly critical where the lumber layers are not edge-glued. These performance issues could be addressed by replacing one or more of the layers in a CLT panel with SCL, such as LSL and OSL. Such an innovative hybrid CLT can offer many advantages over the

generic one that is made of 100% dimension lumber, **Figure 16**—lower. The hybrid CLT products could reduce the production cost because of the reduced efforts to layup of individual lumber pieces and the possible elimination of the need to press the panel on all four sides simultaneously, improve the rolling shear strength and stiffness properties of generic CLT since SCL has relatively high shear strength and rigidity, and improve the fire resistance of CLT due to the elimination of gaps present in generic CLT made with non-edge-glued dimension lumber. The research on three- and five-layer hybrid CLT, recently conducted in the Wood Science and Technology Centre, the University of New Brunswick, Canada, showed that the bending stiffness, moment capacity, and shear capacity of hybrid CLT were increased to a large degree in comparison to generic one [22–24].

Cross laminating technology provides CLT panels with improved stable dimensions, and relatively high in-plane and out-of-plane stiffness and strength properties in both directions, giving these panels a two-way action capability [6]. It is well-suited to floors, walls, and roofs, and may be left exposed on the interior for esthetics. The light weight of CLT directly helps reduce the size and cost of foundation. As a prefabricated building component, CLT offers shorter onsite construction time than traditional platform frame construction or steel and concrete construction, minimizes waste and noise during construction, and provides a very competitive cost in comparison to concrete and steel [19]. CLT has also been used to fabricate bridge decks, heavy equipment mats, and platforms for oil rigs, and to construct mid-rise and tall wood buildings of over seven stories, and large industrial structures [4]. In addition, CLT exhibits good seismic and fire performance. The 2015 International Building Code (IBC) and 2015 International Residential Code recognize CLT products manufactured according to the ANSI/APA PRG-320 "Standard for Performance Rated Cross-Laminated Timber." Under the 2015 IBC, CLT at the required size is specifically stated for prescribed use in Type IV buildings, i.e., heavy timber buildings, which hold well under fire conditions due to formation of char layer. However, CLT can be used in all types of combustible construction, i.e., wherever combustible framing or heavy timber materials are allowed [4].

CLT is sometimes deemed as a standalone building material and construction system. A kind of post-and-panel construction has emerged, accompanied with many innovative connections. The tallest wood building as of the year of 2018,



Figure 17.
Brock Commons Tallwood House, Vancouver, Canada (Source: Photo obtained from UBC Public Affairs).

Brock Commons Tallwood House (**Figure 17**), stands in Vancouver, Canada. This building includes 17 stories of CLT floors supported on GLT columns atop a concrete base with two 18-stroy concrete cores. This 53-m-high building is used as student residence providing 404 bed units. Its unique designed column-to-column metal connector makes a column-panel-column connection, minimizing the accumulation of deformations (i.e., the transverse wood movement) generated from each CLT floor. It was reported that 80% of the work for this tall building was prefabricated and 70% alone was gaining code approval [25].

3. Endnotes

Environmental awareness coupled with sustainable design and construction practices are increasingly becoming a requirement for many building projects throughout North America and around the world [7]. Sustainable design aspires to use less energy and material resources in conjunction with lowering the environmental impacts on a building from its cradle to grave [7]. The reasons for using wood in construction are attributed to its environmentally friendly attributes, ease of assembly, reduced noise and waste during construction, natural beauty, and cost-effectiveness. Increasing use of renewable and sustainable building materials in construction, such as wood, is a worldwide move. Wood-based materials, such as MTP, consume less energy and emit fewer greenhouse gasses (GHG) and pollutants over their life cycle than traditional energy-intensive construction materials such as steel and concrete [2]. To spur innovation and certify the performance of wood as a construction material, many countries have made a great effort to support the research and development of wood products such as MTP. In Canada, for example, the 2015 Edition of its National Building Code of Canada (NBC) allows to construct wood frame buildings up to six stories. The Canadian have been working hard to the code revisions with an aim at the 2020 Edition of the NBC to permit tall wood buildings up to 12 stories [2]. Their long-term objective is to establish the performance-based codes for the 2025 Edition of the NBC and beyond, which will eliminate the distinction between building materials. This will give architects and developers freedom of choice in their materials. Ramage et al. illustrated the selection of structural systems for multi-story buildings in terms of the number of stories and their use of wood [26], **Figure 18**. For buildings up to about six stories, CLT uses substantially more wood to achieve the same function as a light-wood frame building. For buildings over six stories, the use of CLT together with light-wood frame may use less wood than CLT alone. As for buildings taller than 10 stories, the mass timber construction method is employed by using GLT megaframe to support CLT walls, floors, and roofs [26].

The life cycle of a product is defined in the standard ISO 14040 as "consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal" [27]. This has led to the use of the life cycle assessment (LCA), which is defined as "the compilation and evaluation of the inputs and outputs and the potential environmental impacts of a product system throughout its life cycle" [27]. LCA is a performance-based approach to assessing impacts that building products or systems have on the environment over their lifetime [7], including all activities from raw material extraction/harvesting, materials processing/products manufacturing, transportation, distribution, installation, use, repair and maintenance, and final disposal or recycling [7]. LCA is deemed as the best available tool to compare sustainability of building materials, which includes four main phases, i.e., goal and scope definition, inventory analysis, impact assessment, and interpretation.

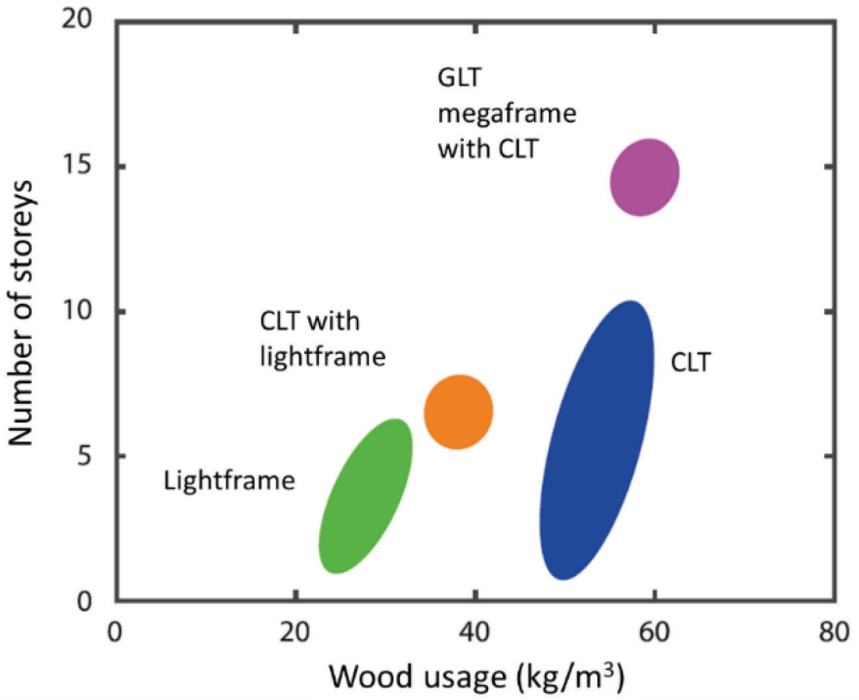


Figure 18.
Use of structural lumber and mass timber products for various structural systems (Adapted from Ramage et al. [26]).

LCA studies on wood buildings are rooted in the assumption of the same life span for wood as other structural materials. Ramage et al. summarized, after conducting a comprehensive review on use of wood in construction, that the buildings are really demolished due to degradation of their main structure, whatever the structural materials [26]. However, some wood components in a building may have a design life shorter than that of the building as a whole, or may require maintenance during the life of the building. There are many factors impacting the lifespan of wood components, including fire and natural degradation. In comparison to other building materials such as steel and concrete, wood is combustible. However, large cross-section wood components, such as those made of GLT and CLT, may perform well in case of catching a fire due to the formation of char layer that can act to insulate the material inside. The burnt wood can still keep large, enough strength to support the integrity of a building. As for small cross-section of wood components, they must be encapsulated in noncombustible material such as gypsum boards or concrete. Steel connectors are widely used in modern wood buildings, thus heat can be quickly conducted through the connectors, degrading the strength and stiffness of the wood connections and materials around them [26]. Caution must be used at time of using steel connectors in construction of wood buildings.

In a summary, mass timber building systems make it feasible to use wood in construction of mid-rise and tall buildings, industrial structures, and bridges. However, mass timber products and building systems behave in a fundamentally different way in fire than steel or concrete buildings in structural and spatial layout. More research is required to increase use of wood in construction.

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Conflict of interest

I confirm there are no conflicts of interest.

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