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An Exploration of Structural Timber Innovation

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An Exploration of Structural Timber Innovation

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An Exploration of Structural Timber Innovation

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Table of Contents

About This Report

In many undergraduate programs of study, civil and structural engineering students are exposed to introductory material regarding timber construction. The information received in the undergraduate experience typically consists of a brief summary of the basic mechanical properties of wood but does not significantly cover timber design. Much greater emphasis is placed on design practices involving steel and concrete, likely due to their prominence in contemporary building trends in civil engineering. While it is true that wood is one of the older materials in terms of its utilization in structural and architectural design, it is certainly not an antiquated choice. Wood offers unique properties not found in steel and concrete, and new practices in timber construction are continually being introduced to the industry. Wood has the potential to be combined with other building materials, and the continued push for sustainable design practice is increasing its appeal. As such, it would be remiss to discard wood in the design process.

This report serves to provide its reader with an understanding of wood's unique properties and explain why it is a viable choice for projects in the twenty-first century. Topics presented include an overview of wood's material properties, contemporary engineered wood products, and its benefits as a green building material. Also included is a selection of recent projects showcasing innovative uses of timber materials. The projects are demonstrative of the range of possibilities when working with wood and represent forward-thinking design practices. While the report does not delve too deeply into any single topic, it offers a foundation for those interested in timber construction and its recent advancements. As will be shown, wood is not limited to single-family residences and other lightweight structures.

1. A Brief History of Wood's Importance

Wood has played a significant role in the lives of humans from prehistoric times to the modern era. It is abundantly found in a variety of natural settings and easily retrievable in its raw form. As such, it is an attractive resource for those with simple tools as well as those seeking large-scale harvest operations. Its desirable properties and versatility remain appealing for multiple applications. Since its adoption as a resource, the scope of wood's capabilities has expanded to meet new challenges faced by the human race.

The use of wood as a building material has been traced back to the early Paleolithic Era, roughly two-and-a-half million years ago [1]. Prior to this time, lumber was utilized as a heat source for fires. Its combustible nature was uncovered shortly after the discovery of fire, and wooden coals have the advantage of burning significantly longer than smaller plants. With the ability to create a sustained source of warmth, early humans began to explore the building properties of wood. The ability to easily shape wooden forms led to the creation of tools, weapons, and even early furniture by Paleolithic humans. As the use of wooden items increased, humans began to learn about the different types and species of wood. A basic knowledge of the advantages and disadvantages associated with different types of wood was established, and the desirable properties were exploited. Due to the tendency of wooden artifacts to decay completely and therefore become irretrievable, it is difficult to find intact examples of primitive tools and other wooden items; even so, the importance of wood to early humans is undeniable.

Along with earthen materials, wood was a prominent component in primitive man-made shelters [1]. Different methods of construction were utilized depending upon the type of wood available, the tools at hand, and the climate of the region. Simple shelters made of branches and mud gave way to hardier structures composed of logs and processed lumber. Where an abundance of straight-trunked trees was found, the concept of horizontally stacking logs emerged, producing the first "log cabins." Neolithic humans in what is now Europe created structures by anchoring logs vertically in the ground, forming tall barrier walls. In areas of more temperate climates, lighter structures were created with boards and poles, such as those used by Native American tribes.

The use of wood increased with advancements in technology and early engineering. Shelters became more sophisticated, durable, and weatherproof. Humans began to apply their knowledge of wood construction to new desires and goals, including efficient transportation endeavors. Primitive sledges and other such devices were constructed with wood [1]. As more capable tools were produced, the manipulation of timber resources became easier and quicker. The development of copper tools around 5,000 B.C.E. allowed for much sharper cutting edges and increased precision for joinery. The invention of the wheel around 3,500 B.C.E. brought about the prominence of wooden vehicles such as carts and chariots. Boats and other maritime vessels were developed with wood, and the later invention of the locomotive used wood as a fuel source as well as for vehicle and track components. Before the automobile and other metal-constructed vehicles took the world by storm, transportation was essentially dependent upon wood in various ways.

Although it has been virtually phased out of modern transportation methods, timber still plays a significant role in the building industry. Wood became the primary building material in Europe around the tenth century, and it remains a popular material choice for lightweight structures, especially in North America [1]. The desire for wood as a building material led to the emergence of the lumber industry that exists today. Wood products constitute approximately half of the industrial raw materials sourced in the United States [2]. Common applications for traditional structural timber products include roof trusses and framing for small buildings and residences. New engineered wood products have improved the structural properties of traditional preparation methods, and advancements are continually being made to prove that wooden members can compete with steel and concrete. In addition, professionals use wood in conjunction with other building materials to reach new levels of structural and architectural design. Steel components are often combined with wooden boards to achieve aesthetic and structural results. Temporary support structures are built with stock lumber, prototypes and models are carved quickly out of wood, and concrete workers create complicated formwork using wooden boards to develop innovative concrete structures.

In many regards, the appeal of wood has not changed with time. Many homes and other small structures still use wood as a plentiful and reliable source of heat. Luthiers create the world's finest instruments using traditional timbers and construction methods, and concert halls and other such venues employ wood for its acoustic properties and warm ambience. Wood has always been the primary choice of material for furniture, and exotic veneers grace the tops of fine tables and the interiors of luxury automobiles.

One aspect of wood that has contributed to its resurgence in structural applications is its potential as a green building material. As professionals place greater emphasis on sustainable construction and eco-friendly design, the inherent value of wood increases significantly. Concern for climate change is growing along with the population, and today's engineers are applying the knowledge of wood's properties to modern engineering practices in order to create better products with structural timber.

2. Fundamental Properties of Wood

In order to use timber in an effective manner when engineering structures and wood products, an understanding of its fundamental properties is necessary. Many of the unique characteristics of wood present both challenges and opportunities for engineering professionals. In contrast with metals and concrete, wood is an organic and fully natural material. Furthermore, the features associated with different classes and species of wood can vary in important ways.

Hardwood vs. Softwood

The two botanical classes into which trees are divided are softwoods and hardwoods [3]. Softwood trees include conifers, which bear needles or leaves that are rigid and narrow. Most softwoods have green needles that remain on the tree year-round. Hardwood trees have broad leaves, and many hardwoods bear flowers and edible fruits or nuts. Most of these trees lose their leaves during the winter season and are thus referred to as deciduous trees. Although the two classes seem to give an obvious indication as to the hardness and density of the wood that constitutes them, the nomenclature is, in actuality, fairly ambiguous. The specific gravity values range from approximately 0.25 to 0.65 for softwoods and from 0.15 to values greater than 1.0 for hardwood species (the specific gravity values presented represent oven-dry values) [4]. While it is true that many hardwoods have density values greater than those of the densest softwoods, certain hardwood species are the softest and least dense woods in existence. Balsa, the lightest and softest wood available, is actually a species of hardwood [5].

Wood's Cellular Composition

Wood cells are tubular in geometry, ranging from 0.04 to 0.3 inches in length [4]. A cell's diameter is typically around one percent of its length, and the cells in proximity to one another are oriented in a similar longitudinal direction. As a tree grows, more cells are formed around the existing mass, causing the trunks and branches to grow in a radial manner in addition to gaining length. The radial growth pattern can often be observed in cross-sectional cuts of the tree, where rings are clearly visible.

The growth rings of deciduous trees are most clearly visible due to the delineation between springwood and summerwood [4]. Springwood, also known as earlywood, is the growth portion that occurs quickly in the spring. This rapid production results in large cells forming wide rings of relatively low density. Summerwood, also known as latewood, is the portion of growth that occurs more slowly. As a result, rings are narrower and darker, with smaller cells more densely packed together. The rings of softwood trees are often less pronounced due to the relatively stable growth experienced throughout the year, though delineation may still be visible. Since a layer of springwood and its adjacent layer of summerwood represent one year of growth, the age of a tree can be visually estimated upon its harvest. Together, the springwood and summerwood rings constitute the portion of the tree known as heartwood [5]. The two other portions of a tree's cross-section are sapwood and bark. Sapwood is a layer of lightly-colored wood just underneath the bark. Sapwood is more susceptible to decay, so it is most often removed with the bark, leaving the heartwood as the desirable portion for lumber.

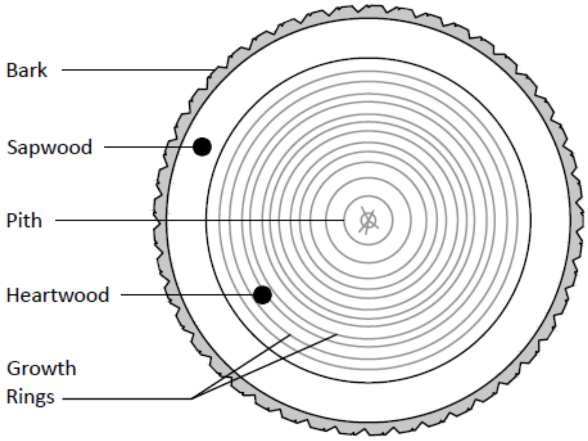


Figure 1: Cross-section of tree.

The cellular structure of wood contributes significantly to its unique properties, including its capacity for moisture retention and the geometric features of its mechanical properties [4]. The cellular structure is apparent even without technical knowledge, as the cells of some species are clearly visible and the splintering of wood products can be observed. In practice, the cells of wood are often referred to as fibers due to their shape and tendency for alignment in a common direction. This fibrous geometry leads to important mechanical characteristics.

Moisture Content and Specific Gravity

The specific gravity of a sample of wood is related to its moisture content at the time of measurement [4]. Water is taken in by tree roots and distributed upward throughout the height of the tree, and therefore all harvested lumber contains some amount of water. This water is stored both within the cell walls and in the cavities between cells. The moisture content value for a sample of wood is taken as the weight of water present in the sample expressed as a percentage of the kiln-dried weight of the sample. To determine the value, the mass of a sample is taken before and after being thoroughly dried in an oven, ensuring that no additional moisture can be removed in the drying process.

$$\text{Moisture Content (\%)} = \frac{\text{mass of moist sample} - \text{mass of dried sample}}{\text{mass of dried sample}}(100)$$

Since the amount of water in a sample of wood can vary based on environmental conditions and treatment processes, the specific gravity of the sample can vary as well [4]. Moisture content and specific gravity are directly related for a given piece of wood. As such, a comparison of specific gravity values among various species of wood requires a common ground. The simplest method of comparison is to examine the oven-dried specific gravity values for different species of wood. Since the lumber used in building projects is not typically oven-dried, however, it is common to compare the specific gravity values of different species using a common moisture content value. A typical basis for comparison is 12% moisture content. While the most common species of wood have specific gravity values below 1.0, it is possible to find species that surpass this value. Exotic species such as snakewood and various types of ebony are examples, highly valued for their striking aesthetics, tight grain patterns, and dense compositions [3].

Seasoning and Shrinkage

Wood that is harvested from living or freshly-felled trees is referred to as green wood [4]. Wood in this state has a very high moisture content, sometimes greater than 100% for species with low cellular densities. Once the wood is removed from the living tree, it becomes susceptible to moisture changes based on its environment. The wood will lose moisture as it acclimates to its surroundings. The moisture in the cavities between cells is lost first, and additional moisture is then lost from the cell walls. The moisture content will eventually reach an equilibrium state dependent upon the ambient temperature and humidity.

Wood with a high moisture content is not ideal for most uses, whether they be structural or aesthetic [4]. Similar to a sponge, moist wood shrinks and expands due to losing or gaining water, respectively. As wood tends to lose a significant amount of moisture early in its life, shrinkage is inevitable after harvesting and processing. Furthermore, the structural potential of a piece of lumber is enhanced when it is at a low moisture content. Drier wood is relatively stable dimensionally and exhibits a denser structure than wood with a higher moisture content.

The desire for these attributes is the motivation behind a process known as seasoning, in which the moisture content of lumber is allowed to drop until it reaches a desired level [4]. The procedure is typically performed on processed lumber. Seasoning can be done in a naturally-occurring process, where boards are set aside in an ideal environment to lose moisture over time, or through a process in which heat is applied [5]. Structural lumber and specialty pieces are often dried in a high-temperature kiln to quickly expel moisture and allow some control over shrinkage. The kiln-drying process also allows pieces to be dried to a specific moisture content. Lumber used for laminating is typically dried to an average moisture content of 12% [4]. Boards used for framing are typically seasoned to an average moisture content of 15%, as a slight decrease in dimensional stability is acceptable. For pieces requiring the highest level of stability, oven-drying may be ideal, removing all moisture possible. This is typically reserved for timbers utilized in high-precision joinery projects and decorative applications, such as musical instruments and high-end furniture [5]. In any drying application, it is important that the piece of lumber is allowed to dry evenly to reduce the chance of warping.

Even if a piece of wood is brought to a low moisture content or oven-dried, it still has the potential to absorb additional moisture [4]. This can cause swelling if the piece is exposed to an environment of high humidity. It is for this reason that the wood must be sealed if swelling is anticipated to cause problems. An acceptable weather-sealing finish is applied in such situations, typically adding a level of protection against abrasion as well.

Geometric Properties and Lumber Milling

The cellular composition of wood leads to its classification as an anisotropic material, meaning that its mechanical properties vary in different directions [4]. More specifically, it is an orthotropic material because it exhibits independent mechanical properties along three perpendicular axes [6]. Figure 2 displays the orientation of these axes with respect to a log's cross-section. The longitudinal axis runs along the length of the log, parallel to the wood's fibers. The radial axis is oriented perpendicular to the longitudinal axis, running perpendicular to the growth rings. The tangential axis runs tangential to the growth rings, perpendicular to the other two axes. The axis system is applied to boards as well, and a sample diagram is shown in Figure 3. Note that the orientation of the tangential and radial axes may differ depending on the orientation of the growth rings in the board's cross section.

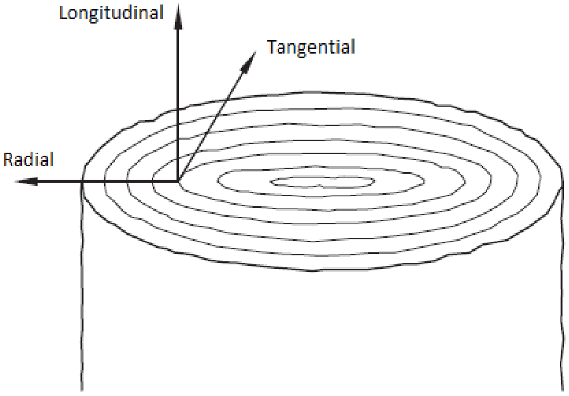


Figure 2: Axis system of log cross-section [4].

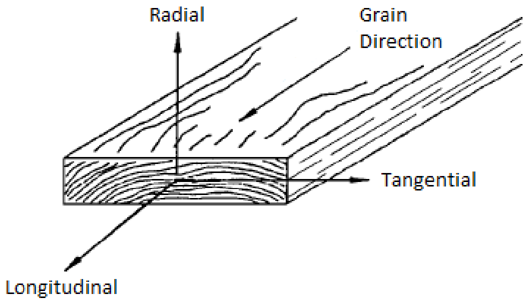


Figure 3: Axis system of sawn board [6].

When a log is processed into boards, the longitudinal axes of the boards produced coincide with the longitudinal axis of the original log. Lumber mills utilize a variety of cutting patterns to produce boards, each with certain advantages [5]. Figure 4 highlights common sawing patterns. Through-and-through sawing is the simplest method, but the center of the tree is left in at least one board. The center (or "pith") of the log is highly unstable and is not desirable for most lumber applications, so flat sawing may be used to remove it. A more advanced sawing pattern is known as quartersawing, two methods of which are presented in Figure 4. A board qualifies as quartersawn if its radial axis is approximately parallel to the longer side of the cross-section (i.e. the cuts in the board attempt to maximize perpendicularity to the ring pattern). In general, quartersawing produces more waste than through-and-through or flat sawing, but the boards produced are more stable.

The geometric properties and ring orientation of a board dictate the nature of shrinkage that the board will experience [4]. The dimensional changes of shrinking and swelling occur differently in the longitudinal, radial, and tangential directions. While the dimensional change in the longitudinal direction is negligible in virtually all cases, the largest dimensional change occurs in the tangential direction. This is the reason that quartersawn boards are the most stable, as flat-sawn lumber tends to experience greater changes in width [5].

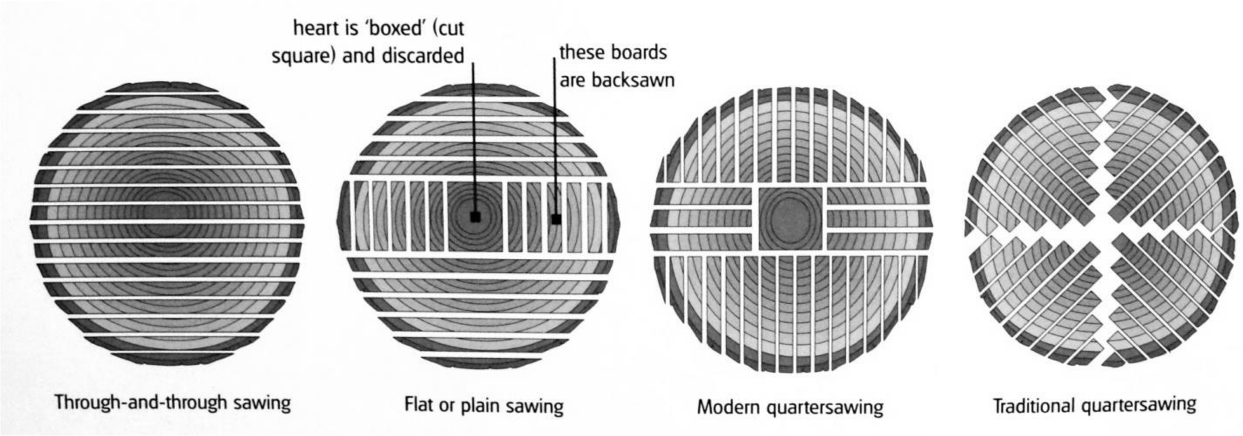


Figure 4: Common sawing patterns for dimensional lumber production [5].

Chemical Resistance

Wood is naturally resistant to chemical action, offering an advantage over other building materials in many situations [4]. Heartwood is significantly more resistant to chemical action than sapwood, so it is important that all sapwood is removed from lumber intended for use in chemical environments. Wood is not a material that is entirely resistant to chemical effects, however. In general, there are three ways in which wood can be adversely affected by chemicals, some more severe than others. The first involves swelling of wood cells when subjected to water, alcohol, and other organic liquids. This results in the weakening of the wood's structure, but the swelling and weakness are removed over time if the wood is allowed to dry. Second, acidic products may cause permanent changes in wood's structure, potentially weakening its mechanical properties. Third, contact with alkalis may permanently dissolve parts of the cells, leading to instability and poor performance.

Taking its shortcomings into account, wood is still superior to alternative choices in many chemical environments. Many species commonly used for structural applications are adequately resistant to acids, including Douglas fir, southern pine, redwood, maple, and white oak [5]. Wood is a common choice of material for the construction of chemical plants, where spills are anticipated, and for the vessels of chemicals that deteriorate other common materials.

Thermal Insulation

Wood functions as an efficient thermal insulator, although exact capacities for thermal conductivity and resistance are difficult to predict [4]. Specific thermal resistance values may vary from species to species and even between two boards of the same species. However, thermal conductivity and moisture content are directly related.

3. Engineering Considerations of Wood

The fundamental properties of timber provide a basis for the understanding of several important considerations regarding its use in engineering. The following are parameters and concepts that inform the design of engineered wood products. Where appropriate, reference values for the information presented may be found in Table 1 on Page 16.

Imperfections

As a natural material, wood can contain various irregularities and imperfections that may impede its performance as a building material [6]. Knots are a common imperfection in lumber, present where branches grew from a tree's trunk or from another branch. Knots tend to weaken the mechanical properties of wooden members, especially in tension, and often break free of the surrounding material to leave a void. Bark pockets and grain variations are other naturally-occurring irregularities that can affect mechanical properties. Wooden members may contain splits or checks that develop during the seasoning process, weakening the strength values. Portions of decaying material or sapwood may be included accidentally after sawing is performed.

Grading systems exist to indicate the quality of lumber [3]. A variety of visual inspection systems are in place to highlight the amount of imperfections in processed wood. While the systems vary by location, a high rating or a specification of "clear" indicates lumber that is free from visual defects. In addition, many distributors test batch specimens for bending strength and stiffness. Wood that performs well is set aside for structural purposes to take advantage of its properties.

Grain Slope

Ideally, the longitudinal axes of a wooden member and its fibers align [4]. This situation results in the best structural performance. In actuality, this is never the case due to variations in growth and the inaccuracies involved with sawing. In order to choose lumber that will perform well, the grain slope should be taken into account. Grain slope refers to the angle between the alignment of the fibers and the member's longitudinal axis. Grain slopes greater than 1/10 should generally be avoided for applications requiring high-grade lumber [3]. In addition, boards should be chosen with a low degree of variation in grain slope.

Implications of Specific Gravity

For clear wood, specific gravity can be an indicator of several useful parameters [4]. All wood fibers have a specific gravity of around 1.5, so the overall specific gravity value associated with a given sample of wood is indicative of its "substance" volume [6]. Strength and stiffness parameters are directly related to the specific gravity associated with a wood species. As a rule of thumb, the performance of a wood species in structural applications increases with specific gravity.

Modulus of Elasticity

Values for modulus of elasticity increase with specific gravity, representing increases in strength. Higher modulus values are associated with low grain slopes [6]. The elastic modulus for a given sample is determined in a laboratory by center-loading a beam specimen that is simply supported. The value varies with moisture content, and values are typically determined for green wood and specimens with a 12% moisture content. Because wood is an orthotropic material, there are three modulus values corresponding to the three axes. Engineers are typically only concerned with the value for the longitudinal axis, as that is the critical direction in design for bending stress. Thus, the reference values in Table 1 represent the modulus of elasticity for the longitudinal axis (E_L).

Dimension Change

The primary concern involving dimension change is shrinkage due to moisture loss [4]. Most of the moisture loss will occur during the seasoning process. Once the moisture content reaches a value of 30% or less, further shrinkage can be estimated with a simple equation:

$$\mathrm{S_m} = \mathrm{S_0}\left(\frac{\mathrm{m_i} - \mathrm{m_f}}{30\%}\right)$$

where:

$\mathrm{S_m}$ = shrinkage from initial moisture content to final moisture content (%)

S_0 = total shrinkage from green condition to oven-dry (see Table 1)

$\mathrm{m_i}$ = initial moisture content (30% maximum)

m_f = final moisture content (30% maximum)

The shrinkage equation may be applied to the tangential and radial directions through the use of separate total shrinkage coefficients for each direction. Longitudinal shrinkage is most often ignored, as the total percentage of longitudinal change is usually around 0.1% or less from green state to oven-dry. As engineered wood products are typically made of small wooden elements, shrinkage is a major production consideration.

Temperature Effects

Dimension change associated with temperature variation is far less significant than that associated with moisture content variation [4]. In the longitudinal direction, the effects of temperature change are ordinarily negligible. Shrinking and swelling due to temperature change is more noticeable for the tangential and radial directions. Although the value varies for different species and specific gravity values, an estimate for dimension change is approximately 0.003% per ˚F change. To account for minor changes in these directions, critical joints and connections may be designed with a small dimensional tolerance.

The structural performance of a wooden member is inversely related to its temperature [6]. At a constant moisture content, there is an observable linear relationship between mechanical properties and temperature. The relationship holds true until approximately 300˚F, but this temperature is not realistically experienced in the construction process. Prolonged exposure to temperatures above 150˚F may have a permanent weakening effect on some species. Under reasonable temperature conditions, the effect of rapid temperature change on wooden members is essentially reversible. For example, the quick heating of a board through sawing or abrasion will not have an adverse effect on its mechanical properties. In design practice, typical adjustment factors take reasonable high-temperature effects into account for conservativism [4].

Decay Prevention and Chemical Treatment

A number of preventative strategies may be considered to increase the longevity of wood products [4]. When properly used, wood can be a permanent construction material. For species that are more susceptible to decay, it is important that the wood is kept out of high-moisture environments after harvesting. Rain and snow should be directed away from structural timber members, and unfinished wood should not be in direct contact with concrete or masonry. Ideally, building envelopes should be installed around timber structures of substantial size. When exposure to the elements is desired, preservative chemical treatments or finishes should be utilized as required, or species which are naturally resistant to decay should be considered.

Depending upon the species of wood and the geographic area in which it will be installed, specific chemical treatment or surface finishing may be required for insect protection [4]. Termites, wood-boring beetles, wasps, and carpenter ants are common pests that have the ability to compromise the structural properties of wooden members. Chemical treatment is typically employed to prevent infestation in susceptible wood species. If the presence of insects is suspected or confirmed in a wooden element, the heating of the element to temperatures of 130˚F or greater results in the death of the insects. Such a process should only be considered for wooden members with geometries that have not been damaged by the infestation, and chemical treatment should follow. For subterranean wood use, such as in timber pile construction, species that are resistant to both decay and termite attack may strategically be employed.

Ease of Utility

Wood is easily manipulated with power and hand tools, along with being relatively gentle on tool edges. Concrete and metal prove more difficult to work, giving wood an advantage for field fabrication and on-site adjustments. Its lightweight nature provides additional advantages in the construction and transportation processes. Wood bonds very well with appropriate adhesives, and small wooden elements can be used to form massive timber members. Engineered wood products, especially those which are custom manufactured for a specific purpose, allow for a high level of prefabrication, which accelerates construction speed. In many applications, structural timber may be left exposed for aesthetic purposes, reducing or eliminating the need for cladding material and ultimately saving time and money.

Sustainability

As an organic, renewable, and recyclable resource, wood presents excellent potential for use as a sustainable material. Its unique capacity for carbon storage and its eco-friendly attributes are leading to increased value as green building accelerates. Further information regarding the sustainable advantages of wood is presented later in this report (Section 5).

Table 1. Properties of Common Structural Timber Species [4, 6]

Common Species Name	Clasification	Specific Gravity		Specific Weight (pcf)	Percent Shrinkage from Green to Oven-Dry $\{S_0\}$			Modulus of Elasticity $\{E_L\}$	Modulus of Rupture $\{E_R\}$
		Oven-Dry	12% MC	12% MC	Radial	Tangential	Volumetric	($x10^6$ lbf/in^2)	($x10^3$ lbf/in^2)
Alaska (Yellow) Cedar	Softwood	0.46	0.44	31	3	6	9	1.42	11.1
Aspen	Hardwood	0.39	0.37	26	3-4	7-8	11-12	1.18	8.4
Cottonwood	Hardwood	0.41	0.39	27	3-4	7-9	11-14	1.37	8.5
Douglas Fir	Softwood	0.50	0.47	33	4-5	7-9	11-14	1.79	13.1
Eastern (Red) Spruce	Softwood	0.41	0.39	27	4	7-8	11-12	1.61	10.8
Eastern White Pine	Softwood	0.36	0.35	24	2	6	8	1.24	8.6
Northern White Cedar	Softwood	0.31	0.30	21	2	5	7	0.80	6.5
Ponderosa Pine	Softwood	0.43	0.41	29	4	6	10	1.29	9.4
Port Orford Cedar	Softwood	0.46	0.44	31	5	7	10	1.70	12.7
Red Maple	Hardwood	0.58	0.55	38	4	8	13	1.64	13.4
Red Oak	Hardwood	0.67	0.63	44	4-5	9-11	14-19	1.82	14.3
Red Pine	Softwood	0.44	0.42	29	4	7	11	1.63	11.0
Redwood	Softwood	0.44	0.42	29	4	7	11	1.34	10.0
Southern (Loblolly) Pine	Softwood	0.55	0.52	36	5	7-8	12	1.79	12.8
Western Red Cedar	Softwood	0.36	0.35	24	2-5	5-7	7-10	1.11	7.5
Western Hemlock	Softwood	0.43	0.41	29	3-5	7-9	10-13	1.63	11.3
Western White Pine	Softwood	0.40	0.38	27	4	7	12	1.46	9.7
White Oak	Hardwood	0.73	0.68	47	4-7	9-13	13-16	1.78	15.2
Yellow Poplar	Hardwood	0.43	0.41	29	5	8	13	1.58	10.1

Notes:
1. The properties of wood may vary among samples of the same species. As such, the values presented serve as typical values for comparison and estimation.
2. Values for modulus of elasticity and modulus of rupture are representative of samples with 12% moisture content.

4. Innovative Engineered Wood Products

Lumber is easily sourced in standard sizes (2x4, 4x6, etc.) and engineered products such as plywood are also readily available all over the world. While these products have stood the test of time for the construction of lightweight structures, new products and manufacturing techniques are available for those wishing to push the conventional limits of timber construction. The following are critical innovations that are helping structural engineers and architects re-evaluate wood's potential and literally take wooden structures to new heights.

Glulam Construction

Structural glue-laminated timber, or "glulam" for short, is an engineered wood product that allows designers to transcend the dimensional limitations of stock lumber. Glulam members consist of a number of wood laminations (or "lams") that are bonded together through the use of an adhesive [4]. The boards are pressed with hydraulic equipment in the process to ensure tight bonds. Dimensional softwood lumber is commonly chosen for the laminations, and care is taken to ensure that the grain of the boards runs parallel to the longitudinal axis of the glulam member. Boards used in the lamination process may vary in size but typically do not exceed two inches in thickness. In addition to the advantages associated with large cross-sectional areas, lamination boards are often joined at the ends to produce glulam members that exceed traditional lengths of stock lumber. A number of manufacturers produce glulam members in standard sizes, offering a variety of choices for use in building projects. Other manufacturers specialize in producing custom glulam compositions, allowing for a wide range of strength and aesthetic possibilities.

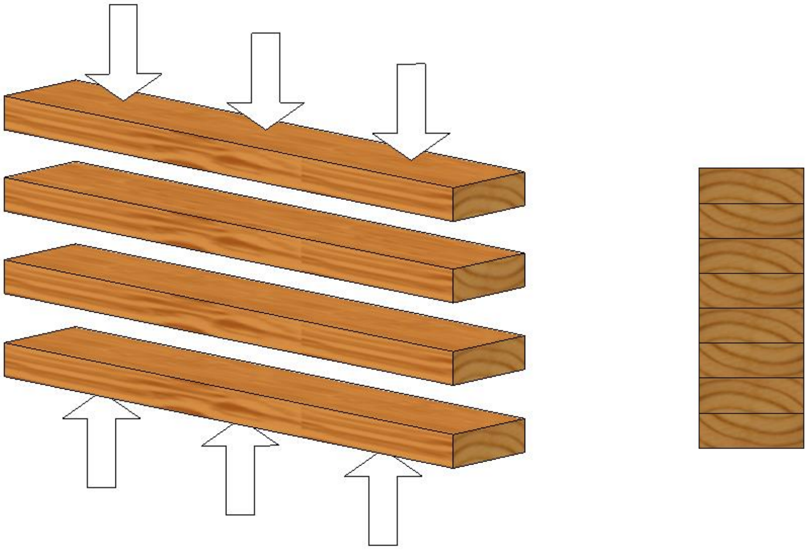


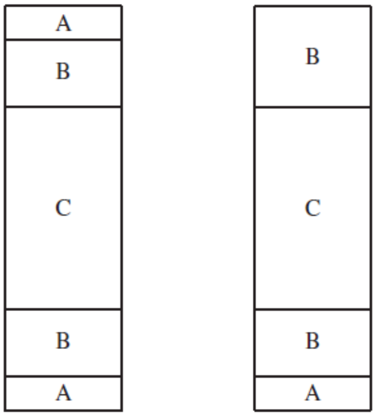
Figure 5: Glulam members are composed of wooden boards bonded in stacks.

Although the use of glulam members is gaining momentum in the contemporary building market, the glulam process is not entirely new. Experimentation with the lamination process began in Europe in the late 1800s, and the first relevant patent was filed by a Swiss company in 1901 [7]. The United States' first significant glulam structure was a building for the USDA Forest Products Laboratory in Wisconsin, completed in 1934. The first U.S. manufacturing standard regarding glulam production was established by the Department of Commerce in 1963 and has been updated periodically since its adoption.

Modern construction of glulam members involves a careful and controlled manufacturing process [4]. The quality and grading of the lumber used for laminations is monitored carefully to ensure that the strength parameters of the glulam beam will be consistent with the intended design. The moisture content of the laminations is controlled in order to minimize differential dimension change. Boards are planed with strict tolerances, joint faces are kept clean to allow for strong bonds, and adhesive joints are tested regularly to ensure proper strength. Commonly-used adhesives include polyurethane, melamine, and phenolic resin adhesives [8]. The American Institute of Timber Construction (AITC) provides accreditation to manufacturers who provide glulam products that meet code requirements and submit to routine product inspections.

The strength properties of wooden boards vary, and the lamination process allows low-strength and high-strength boards to be used in conjunction [4]. As glulam members often function as beams in structural systems, the laminate composition may be optimized for performance in bending. Since the largest stresses occur in the top or bottom of a beam in bending, the strongest laminations are placed at the top and bottom of the member. Lower-quality structural timber is placed towards the center of the beam, where stresses are less of a concern. The optimization concept is similar to that which informs I-beam geometry, where more material is placed in high-stress areas of the cross-section in order to increase section economy. The difference with glulam beams is that material is not removed from a section; weaker, less valuable material is utilized in the low-stress area.

Regarding the layup (or arrangement) of laminations, glulam beams are typically constructed in balanced or unbalanced configurations. Balanced layups are symmetric in lumber quality and laminate size about the beam's x-axis (as shown in Figure 6-a). Balanced beams can carry both positive and negative moments due to service load bending. They perform well when used in continuous spans or in cantilever applications. Unbalanced beams utilize lumber with the highest quality only in the outermost tension zone, placing lumber of lower grade in the anticipated compression zone. Unbalanced beams are commonly used for efficiency in simple-span applications; in the case of a top-loaded simple beam, high-quality lumber is commonly placed only in the tension zone on the bottom of the beam (as shown in Figure 6-b). When certified manufacturers produce unbalanced beams, the proper orientation of the beams is marked so that construction workers place them correctly.



(a) **(b)**

Figure 6: Balanced (a) and unbalanced (b) glulam beam layups with laminate grade designations [4].

As engineered products, all glulam members are created with design strength in mind [7]. To simplify the selection process for structural designers, mass-produced glulam beam members are grouped into stress classes. For bending members, the maximum allowable bending stress is indicated in the member's designated code. Other values such as shear design stresses and moduli of elasticity are provided with the manufacturer's reference material. When looking at the cross-section of a glulam beam, the member is most often installed with the glue lines perpendicular to the applied load so that the pressure of the loading is taken by the face of one board. If a designer intends to install the beam so that the glue lines are parallel to the applied load (i.e. rotate the beam 90˚ from the common installation orientation), the tabulated strength values associated with this orientation must be used in design calculations.

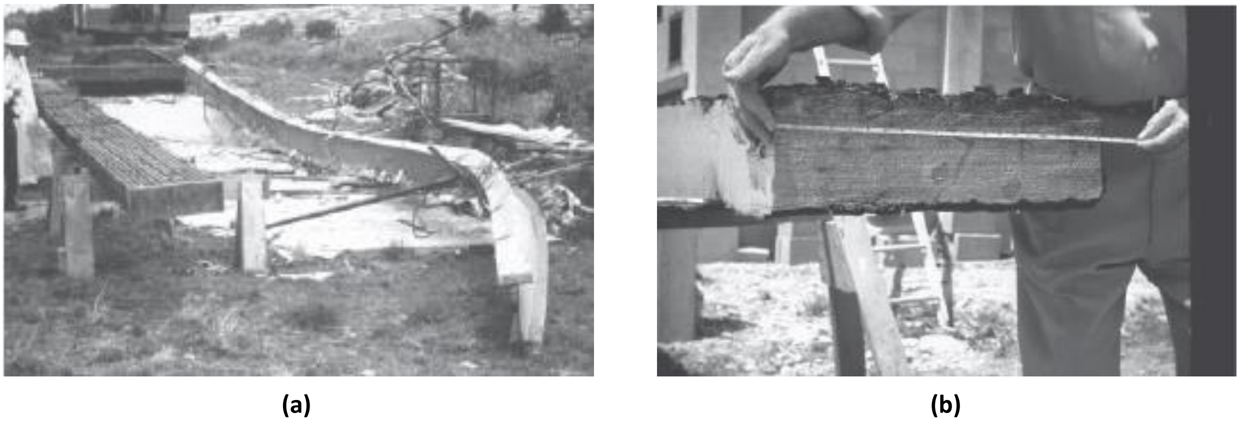
Mass-produced glulam members are available in a range of sizes [4]. The common timbers used in such products are Douglas fir and southern pine laminates. Available beam widths conform to common appearance grades, including 3-⅛, 5-⅛, and 6-¾ inches. Designers have the option of specifying straight members or members with a camber radius of 3,500 feet. In cases where dimensions are pre-determined for aesthetic purposes, the designer has the ability to choose among a variety of layup schemes to maximize efficiency. Some glulam products are sorted based upon aesthetic appeal, which is often a consideration for members that will remain exposed. Framing-classification members are intended to be concealed, whereas architectural or premium members meet strength requirements while exhibiting a desirable appearance.

The ability to create custom glulam members allows for nearly endless possibilities for structural designers. The simplest custom orders involve gluing multiple stock glulam members together to produce wider or deeper sections, but many more options are available. Beams may be designed with extra-long spans, custom cambers or tapers, and high-strength laminations [7]. Member lengths of over 100 feet can be produced [9]. Curved beams can be constructed, and even arches can be made with custom glulam members. Virtually any size and shape can be created if a manufacturer is willing to participate in the custom market. Engineers specializing in the construction of custom members work with lamination companies and are available to provide design services. If a certain shape, size, or strength is desired, it can likely be engineered and fabricated.

Figure 7: Truss with unbalanced glulam members [7].

Figure 8: Bridge with custom glulam members [9].

Appealing to architects and engineers alike, glulam products hold a great deal of potential for the building industry. On a pound-for-pound basis, glulam beams are stronger than steel [4]. The strength and stiffness achieved through the lamination process allows for greater spans with fewer columns. Members are very durable when kept dry, and preservative treatments are available for members that will be subject to high levels of moisture. Since the lamination boards are locked into place with adhesive, members retain a high level of dimensional stability. Glulam products are highly resistant to fire, with exposed members supporting loads for one to two hours when properly designed. In some cases, glulam members outperform steel in fire rating tests. Compared with steel and concrete, glulam products are much lighter, allowing for greater ease of construction and the possibility of smaller foundations. Glulam members can also be drilled, cut, and planed very easily in the field.



(a) **(b)**

Figure 9: In a fire rating test, steel beams warped and failed while comparable glulam beams held their load (a). The glulam beams retained their geometry and experienced ¾-inch char (b) [4].

Glulam products offer additional benefits besides those associated with structural performance [4]. Since they allow wood to be used in applications where traditional timber construction methods fall short, glulam members provide the building industry with more versatility for the renewable resource. The lumber processing and lamination procedures use very little energy compared to the production of concrete and steel, and formaldehyde emissions are extremely low. High-quality lumber is placed only where needed, reducing waste and eliminating the discard of lower-quality lumber. As wood is considered a beautiful and sophisticated material in many cultures, structural systems may be left exposed, eliminating the need for ceilings and other concealment cladding. Glulam members take stains and finishes well, allowing for a range of natural color options. The successful longevity of the glulam market is now serving as an inspiration for new engineered wood products.

Cross-Laminated Timber

The building industry is beginning to utilize new large-scale engineered wood products known as mass timber products. One such product showing a great deal of promise is cross-laminated timber (CLT). The fabrication of CLT utilizes a similar process to the production of glulam members but differs in board layout and product purpose. CLT products are large panels constructed through the lamination of multiple layers of structural-grade softwood boards [8]. In each layer, the boards are placed edge to edge with the longitudinal axes in one direction. The wide faces are glued to the adjacent layers under pressure, and the layers are stacked at 90˚ to each other. The products are finding use in building projects as floor slabs, load-bearing walls, and shear walls.

Figure 10: Five-ply CLT panels [8].

Austria and Germany undertook CLT research and development in the early 1990s [8]. Austrian scholars began to work with the nation’s construction industry several years later to instigate the production of CLT for use in new buildings. Interest in the material grew substantially in the early 2000s. By this time, the production of CLT was more efficient than earlier efforts and it was more widely known in the building industry. Manufacturers and proponents market the material as being a viable option for heavy structural systems, increasing interest in CLT and providing a green alternative to steel and concrete in many applications. Europe currently remains the global leader in CLT building construction with hundreds of successful projects. European production of CLT has increased more than tenfold since 2009, with annual outputs now surpassing 650,000 cubic yards [10].

The basic production steps of CLT are similar to those for glulam members [8]. Adequate lumber is selected and seasoned to the desired moisture content, which is typically 12%. Boards tend to fall within the thickness range of ⅝-inch to two inches. Board surfaces are planed and cleaned for the application of adhesive, and the boards are pressed in the desired configuration after the adhesive is applied. Strict quality control requirements are followed and mechanical tests are administered to ensure that the desired bond strengths are obtained.

CLT panel fabrication allows for a wide range of panel sizes and thicknesses. Production panels manufactured in Europe are available in typical metric widths of 0.6 meters (2.0 ft), 1.2 meters (4.0 ft), and 3 meters (9.8 ft), with some manufacturers producing panels up to 5 meters (16.5 ft) in width [8]. Panel lengths may reach 18 meters (60 ft), and thicknesses may be up to 20 inches. Where individual boards are not long enough to produce the desired panel dimensions, finger joints are commonly employed. In order to qualify as CLT, a panel must contain at least three layers of orthogonally alternating board orientation. Three layers is certainly not the limit, however; typical production panels may contain up to seven layers and panels with an even greater number have been produced for specific projects. In some cases, consecutive layers may be placed in the same orientation. The most common positions for double layers are the outermost layers of the panel or the central layer. Such layers provide increased thickness (and strength) for the corresponding grain orientation. When double layers are utilized, the integral layers are typically offset by one-half of the board width (as shown in Figure 11).

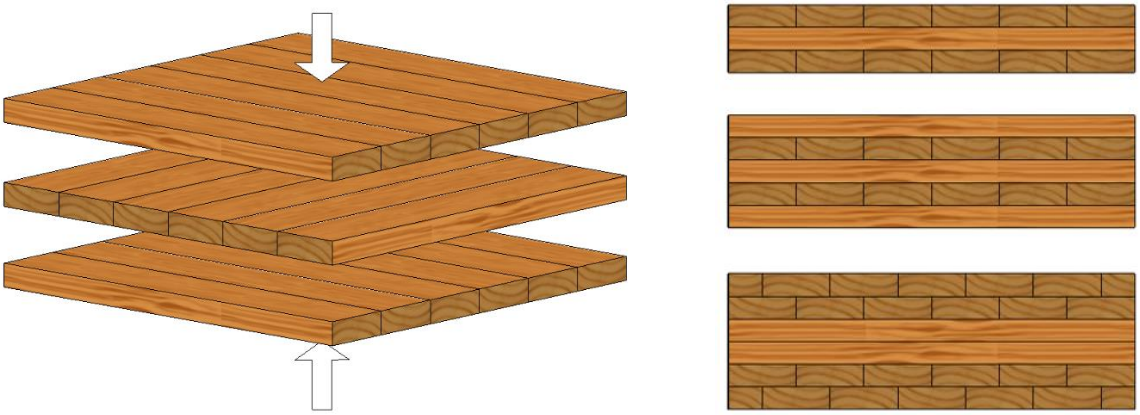


Figure 11: The CLT production process allows for a multitude of layer configurations.

The cross-lamination process offers a number of advantages over strict longitudinal lamination [8]. Since the lamination boards are restrained by other boards in both directions, the panels hold a very high level of dimensional stability. Very large panels can be fabricated with little anticipated dimension change in any direction. The orthogonal layering of the boards results in high in-plane and out-of-plane strength properties in addition to increased stiffness in both directions. As such, the panels become an attractive option for floor slabs. The cross-lamination functions similarly to a perpendicularly-reinforced concrete floor slab, providing bending resistance in both the major and minor span directions. Where connections are present, the lamination system decreases the chances of splitting and tear-out that often occur in large-scale, single-direction pieces of lumber.

The CLT manufacturing process encourages designers to work with a high level of prefabrication in mind. Many manufacturers are willing to provide cutting and milling services in order to aid in the construction process [8]. Panels may be cut to the exact sizes needed, and voids may be provided for windows, doors, electrical fixtures, etc. Depending on the intended type of panel-to-panel connections, factory preparation may be considered for joints and connections as well. Coupled with the lightweight nature of the panels compared to alternative materials, factory-fabricated details may allow for improved construction times when designed properly.

Designers use CLT panels as load-bearing plate elements in structural projects, functioning as floor slabs, roofs, and walls [8]. Depending on the application, engineers take a number of considerations into account. Such considerations include strength and deflection behaviors, vibration performance, fire performance, and durability. In Europe, an analytic design approach has been adopted based on extensive product testing. The approach predicts the strength and stiffness properties of a specific CLT panel based on the structural properties of the boards used to fabricate the panel. The methodology has been implemented into several European building codes, the provisions of which have been used with success in many projects.

The heavy-duty nature of CLT and its impressive strength capacities provide the possibility for use in multi-story buildings [8]. Many projects (mainly in the residential sector) vindicate the product as a worthy competitor to concrete and steel for mid-rise buildings of around four to eight stories. Compared with concrete floor slabs, which often weigh more than 40 psf, typical CLT floor slabs do not exceed 30 psf. The panels allow for easy connections between slabs, commonly made with interior or exterior splines and lap joints with the use of screws. For aesthetic purposes, the undersides of CLT floor panels may be exposed, offering visual warmth and appealing acoustic properties. When intended for use in wall systems, CLT panels offer a variety of options. For load-bearing wall applications in multi-story structures, the product lends itself well to tight floor plans with many rooms. Where large open spaces are desired on lower floors, CLT panels may be combined with a steel column-and-beam structure. In such a case, the panels may function as shear walls due to CLT’s ability to resist lateral loading.

The seismic performance of CLT has been under investigation by many professionals around the world. The product’s effective lateral load resistance indicates desirable performance under earthquake loading [8]. A 2009 study conducted in Japan by the Trees and Timber Institute of Italy involved shake table testing of two CLT structures. The seven-story buildings were subject to small- and large-scale seismic simulations, providing satisfactory results. Results from testing of CLT shear walls support the belief that the product is an adequate choice for seismic zones if builders ensure that the connections between elements allow for ductile failure in extreme circumstances.

Figure 12: London's 52 Whitmore Road, designed by Waugh Thistleton with KHL UK, is a six-story CLT building [10].

Fire testing of CLT panels indicates a satisfactory level of heat and fire resistance [8]. The massive assemblies are able to maintain structural capacity for long durations under fire. The thickness of the timber contributes to a slow and predictable rate of char, providing fire ratings of up to two hours when following traditional fire design codes. On the other hand, CLT is not intended for use in areas exposed to the environment. The thickness of the panels results in a slow drying process when exposed to high levels of moisture. Whereas some glulam products may be used for external or partially exposed applications, the durability of CLT may be compromised in high-moisture situations. Care must be taken when designing CLT wall systems to protect them from rain, commonly achieved through the use of insulated cladding, adequate overhangs, or building envelopes. In addition, care should be taken in the delivery process of CLT. European delivery services pay special attention to the products, ensuring that the panels are not exposed to precipitation en route to construction sites.

While Europe has shown the great potential of CLT as a heavy building material, North America is relatively far behind. There are only a few North American manufacturers producing CLT products, although additional companies are in the stage of pilot production [8]. FPInnovations, a Canadian organization, launched a CLT research program in 2005 and has since contributed a significant portion of the product's technical investigation. As the demand for alternative wood-based building products increases, it is likely that CLT use will become more common and more widespread. Further integration into localized and international building codes will provide standard design procedures and greater acceptance of the material, and the adoption of further code specification is in progress.

Laminated Veneer Lumber

While glulam members and CLT panels are comprised of wooden boards, a number of engineered products are made with wood veneer. A veneer is a very thin sheet of wood, sometimes as little as 1/32 of an inch thick [3]. Perhaps the most well-known building material constructed with veneer is plywood, a common sheet material. Plywood is used for many light-duty building applications and furniture components. It is easily sourced from all over the world and has demonstrated successful use for many years. In fact, the use of plywood-like products can be traced back to the pre-Christian Egyptian empire. A newer product takes its cues from plywood but applies veneer-based construction in a different manner. Known as laminated veneer lumber (LVL), the composite wood product optimizes veneer composition for structural use.

LVL products are dimensional members comprised of laminated sheets of veneer [11]. While plywood is only available as a sheet material, LVL members are available in similar sizes to traditional sawn boards. Additional differences between the two products are present in the veneer layouts. LVL is constructed with the grain directions of all veneer laminates oriented in the longitudinal direction of the members. Plywood is constructed so that the grain orientation of adjacent layers is orthogonal. A plywood panel contains an odd number of layers (typically five) to ensure that the top and bottom layers have similar grain direction, and wood of lesser quality may be used for central layers. An LVL member is made of veneer with similar quality throughout, and the number of layers depends upon the intended thickness of the member.

Produced since the 1980s, LVL members are finding increased use as an alternative to stock lumber [12]. The production of LVL begins with the production of veneer, most often from softwood trees. Typical species include Douglas fir and southern pine, although some relatively soft hardwood species such as poplar and aspen are used. Long, straight logs of the desired species are sent to veneer mills where all bark is removed. Lathe machines peel the logs by turning them against flat blades, producing large sheets of veneer. Typical veneer sheets do not exceed ⅛-inch when intended for use in LVL [13]. The veneer is carefully dried to a moisture content around 3-6% to eliminate virtually all further shrinkage potential. The material is transported to an LVL manufacturing facility if not produced in such a location.

LVL is manufactured in large billets, with members cut to size after the adhesive has been allowed to cure [13]. Veneer sheets are arranged in stacks of desired heights with adhesive applied between each sheet. The adhesives utilized are similar to those found in glulam and CLT products, with phenolic resins most commonly applied. The prepared billets are pressed and heated, allowing a strong bond to form between layers. Wood material comprises 97% or more of the laminated product [14]. Final billet thicknesses typically range from ¾-inch to 3-½ inches, and members are cut in a variety of widths [13]. Member lengths may exceed traditional lumber constraints because veneer sheets may be lap-jointed as desired. The entire step-by-step process of LVL production is shown in Figure 15.

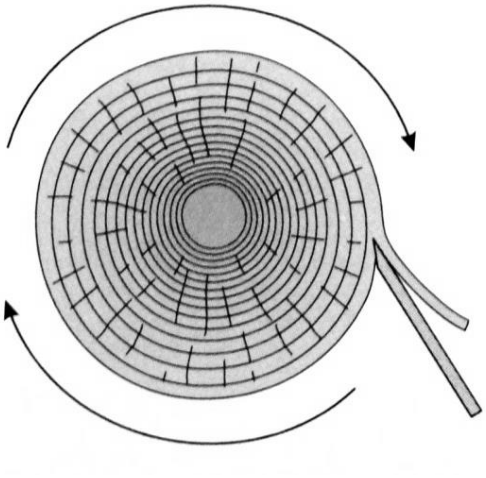


Figure 13: Lathe production of veneer [5].

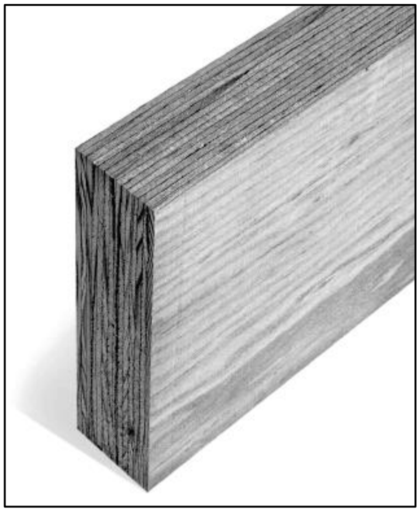


Figure 14: LVL member with visible glue lines [14].

The lamination of veneer results in products with exceptionally high levels of dimensional stability [12]. The low moisture content of the veneer reduces shrinkage potential, and the high number of adhesive bonds holds each element in check. As a result, LVL members experience little to no shrinking, splitting, or warping when used in building projects. Since the veneer is dried before billets are created, the resultant LVL members are consistent in size. Comparable stock lumber tends to differ slightly in size, as the boards are dried to the final moisture level after sawing. The production of veneer through the peeling of logs results in very little waste, and trees of small diameter may be used for this process [5].

The glue lines of LVL run parallel with the depth of the cross-section. This differs from glulam member construction, where glue lines run perpendicular to the depth. Comparison of strength properties between the two products is difficult, as glulam members vary greatly in composition and tend to be larger than common LVL sizes. Nevertheless, LVL members exhibit superior performance when compressed perpendicular to the grain and perform exceptionally well in tension [11]. The bending performance of glulam members varies greatly with composition, so members are designed for different circumstances; LVL production, however, results in members with consistently high performance in bending. In any case, LVL results in better structural performance than stock dimensional lumber.

Since LVL is available in similar sizes to dimensional lumber, it can be used for many structural elements in traditional framing design. Beams, headers, studs, truss members, and columns are examples of building elements for which LVL may be utilized. Due to the material's superior structural properties, projects may be designed with less material if traditional framing is used. Conventional board length limitations are no longer an issue when working with LVL. Due to its differences, it is beginning to find use in unconventional building applications and high-performance situations.

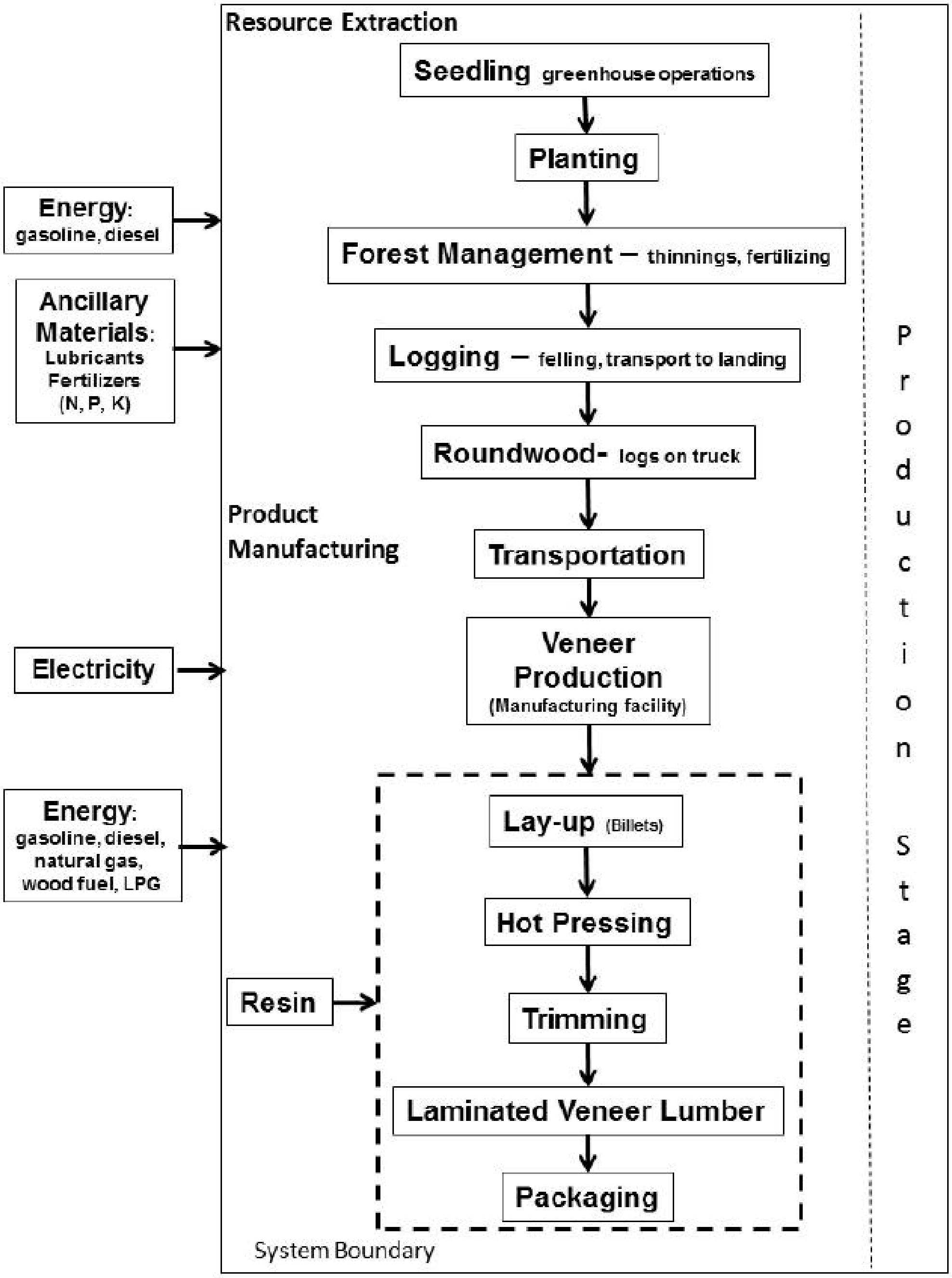


Figure 15: Cradle-to-gate process of LVL production [13].

A particular high-performance use of LVL lies in the construction of I-joists [9]. Used in floor and roof systems, I-joists are geometrically similar to steel I-beams. Narrow flanges of high-grade solid or composite lumber are glued to webs of lower-grade wood products to produce efficient sections. Typical flange widths vary from 1-½ inches to 3-½ inches, with depths of up to 16 inches available. To increase bending capacity of the joists, LVL is often used as the flange material. Some manufacturers specifically cut LVL for various I-joist flange sizes. The use of I-joists allows for greater joist spacing, long spans, and increased loading. When LVL is utilized for flanges in place of dimensional lumber, the performance of the joist can be significantly improved [11].

Figure 16: I-joists utilized in combination with glulam beams [9].

While LVL differs greatly from glulam and CLT, a number of similar products are available that should not be confused with LVL. Belonging to a family of products known as structural composite lumber, LVL and similar products are composed of thin pieces of wood layered through the use of an adhesive [15]. The most common alternative to LVL is parallel strand lumber (PSL), in which the veneer sheets are sliced into ribbons of ½-inch or narrower widths. Grain is still oriented in the longitudinal direction, and similar member sizes are available. Although it offers competitive performance values, LVL is more cost-effective and is therefore utilized more often. The remaining two products are laminated strand lumber and oriented strand lumber. Both are sheet products made from flaked wood strands, with the grain of each flake of the latter product roughly running in the same direction. These products offer advantages over dimensional lumber in some applications but fail to outperform LVL and PSL [11]. As such, they are often used for the webs of I-joists. Where performance and economy are desired, LVL is the product of choice when considering structural composite lumber.

The attractive properties and widespread use of LVL boards have led to a recent interest in LVL's potential as a structural sheet material. MetsäWood is a Finnish company currently offering such a product [16]. Its new LVL sheet material is marketed as Kerto-Q (the company adopted the name Kerto for its laminated veneer product line) and is available in a variety of sizes. Widths of up to eight feet and thicknesses of up to three inches are offered. The substantial dimensions allow for the possibility of using sheets as milling blanks, out of which unique beam elements may be cut. The product differs slightly from normal LVL construction in that approximately one fifth of the veneers are glued crosswise, forming symmetrically stacked patterns dependent upon the total number of sheets. MetsäWood claims that such construction results in higher shear strength values and less humidity-induced dimension change. The company supplies mechanical performance values for its products that may be used in the design process. Kerto-Q and generic LVL sheet products are still very new concepts, and the level of market success held by these products has yet to be realized.

CNC Production

While not an engineered wood product, the CNC machine has been instrumental in the creation of innovative timber structures. An acronym standing for “computer numerical control,” CNC technology was developed in the early 1970s [17]. Computers running control programs were added to numerically-controlled manufacturing machinery in an attempt to reach higher levels of automation and efficiency. The success of the technology has resulted in the proliferation of CNC manufacturing machines. The machines have become ubiquitous for high-tech manufacturing facilities performing cutting, milling, and other subtractive methods of machining. Modern CNC machines are integrated with CAD software, allowing technicians to convert digital models to machine movements in order to manufacture products extremely quickly and with a high level of precision. The tolerances within which CNC machines work are unmatchable with manual production methods.

CNC machines are produced or custom-made in a variety of setups able to perform a multitude of machining tasks. These machines vary in appearance and function, each with a set of specialized abilities. The common machines employed for woodwork include CNC milling machines, lathes, and laser cutting machines [17]. CNC routers and milling machines utilize rotating drives, incorporating router bits, drill bits, and blades. These machines work in at least three axes (x, y, and z), and some models are available with up to five working axes for advanced machining. Tasks include carving complex shapes as well as boring holes and voids. CNC lathes perform similar work to traditional lathes but incorporate automated cutting heads. Veneer for LVL as well as many furniture components is produced with CNC lathes. Both milling machines and lathes typically utilize a variety of cutting heads, and many of the machines are able to automatically switch between dozens of options throughout a production program. Laser cutting CNC machines are used less frequently for woodwork, employing high-powered lasers to precisely carve patterns into lumber.

As most CNC machines have the capacity to work with metals and synthetic materials, they work very well with wood of all species. Wood is relatively easy on cutter heads, and vacuum systems are employed to remove wood dust during the cutting process [3]. With automated programs and closed working systems, injury may be less of a concern in many applications. CNC production may also produce less waste in many instances, as digital preparation allows for optimization of material.

Utilization of CNC machines for woodwork creates new possibilities for designers. For prefabrication of structural timber members, CNC technology offers a major advantage. CNC machines excel for replication in manufacturing. Once a successful machining program is established, it can be run repeatedly with extremely high precision. This allows for the creation of custom connections for timber members as well as unique geometries for wooden elements. When connections are prefabricated, there may be less fit-up problems on site, saving construction time. Traditional joinery is easily performed in the automated process. In addition, unusual or nontraditional connections are an option (as shown in the Tamedia expansion in the Notable Building Projects section of this report). Custom members may be milled to the exact specifications of the designer, allowing for predictable performance and uniform appearance. CLT may be prepared with CNC machines carving doors, windows, and other voids in wall and floor panels. In this case, CLT building frames can be constructed very quickly. Further advancement in CNC technology will likely expand the current scope of possibility while also making custom manufacture more economical.

5. Wood Products and Green Building

Topics such as climate change, the environment, and the overall health of the planet are current issues garnering worldwide attention. Architects and engineers have taken interest in a concept known as green building in an effort to address such concerns. In essence, green building is the practice of increasing the level of efficiency with which buildings consume resources [2]. In addition, proponents of green building wish to reduce the negative impacts that buildings have on their inhabitants and the environment. The practice involves a holistic approach to building design, taking into account everything from building size and construction practices to site layout and choice of appliances. One of the major focal points in the design process is the choice of building material. With many attractive properties and a variety of applications, wood remains a top contender for incorporation into many projects in the green building realm.

Sustainability

Wood is a renewable resource, meaning that timber can be harvested indefinitely as long as forests are properly maintained [2]. This is a significant advantage over metals and fossil fuel-based products, which are produced using materials that exist in limited supply. Linked to sustainability is the non-intrusive nature of wood on the environment. When wooden building materials are no longer needed, they may be burned or discarded with little to no harmful impact on the surrounding area. Essentially, wooden products are always recycled. When reused, they serve a second purpose in a new structure; when burned, they provide thermal energy; and when they are allowed to decompose, they are converted to nutrient-rich organic soil.

It must be stressed that the forest is considered to be renewable only in the case that it is managed in an effective manner [2]. Overharvesting has the potential to decimate forest resources, destroy habitats, and reduce levels of biodiversity on a grand scale. Forest products play a major economic role for many areas of the world, including the United States, and the exhaustion of forest resources would be detrimental. In the past, responsible harvesting of forests was not practiced. The adoption of forest certification programs has helped to regulate areas of timber harvest in order to ensure the longevity of the resource. Today, there are more than fifty different certification systems in place for land management and forest protection. In total, there are over 700 million acres of certified forestland across the world. More than one-third of North America’s forests have been certified, and more than half of the forest area in Europe is under certification.

The two major certification systems in North America are the Forest Stewardship Council’s certification program and the Sustainable Forest Initiative [2]. The Forest Stewardship Council (FSC) is the most well-known certification program worldwide, with approximately 300 million acres of certified land. The FSC provides standards of responsible forest management and offers certification for products produced in areas that are managed in compliance with its standards. Products from such areas are marked with an FSC label and can be traced back to the certified forest from which they were harvested. The Sustainable Forest Initiative (SFI) takes a slightly different approach, promoting efficient use of wood materials and the conservation of resources. Whereas the FSC focuses on preserving natural environments, the SFI focuses on industry. Certifications provided by the SFI account for harvest planning and procedures along with wood processing techniques to discourage wasteful practices. In the selection of timber products, architects and engineers can easily make sustainable choices by selecting products bearing the stamps of these or any other certification organizations. Wood is currently the only structural material with third-party sustainability certification [18].

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Efficient Use of Wood Material

Engineered wood production techniques allow for the creation of massive members with the use of small wooden entities. It is difficult to produce solid dimensional lumber of very large cross-section [4]. Large-diameter logs are required, and the logs must be free from defects throughout the entire intended geometry of the board. Trees of the required size may only be found in old-growth forests, and the harvesting of such trees is likely not a sustainable practice. Producing large timber products with smaller elements allows for the utilization of younger trees. In the manufacture of veneer, lathe production results in virtually no waste and allows for the use of logs of all sizes [5]. In addition, structural composite lumber products are typically stronger than dimensional lumber of equivalent geometry, potentially decreasing the amount of material required [11].

Energy Consideration

Wood has a low level of embodied energy when compared with other building materials [2]. Embodied energy refers to the amount of input energy required for a material to be converted from unharvested or raw form into a final product. The sun supplies the production energy for raw timber, and the harvesting of wood is much less energy intensive than the acquisition of steel and concrete ingredients. Fossil fuels provide the primary energy source for the production of steel and concrete. In the United States, over one half of the energy consumed for lumber manufacturing is from biomass. Tree bark, sawdust, and wood chips are the typical components of the biomass utilized. Thus, the by-products of lumber production contribute significantly to the manufacture of new wood products. The wood product industry is both the leading producer and consumer of bioenergy in the United States.

The amount of energy required to manufacture a wood product varies depending on the production methods utilized and the complexity of the product itself [2]. For example, kiln-drying lumber consumes more energy than the natural seasoning process, and engineered wood products require more input energy than dimensional lumber. Even the most energy-intensive wood products, such as LVL and its similars, have significantly lower levels of embodied energy than steel and concrete products.

A study conducted in 2004 by the Consortium for Research on Renewable Industrial Materials illustrates the energy benefits of structural timber when compared with steel [2]. The study examines the energy required to produce above-grade structural wall systems in two different environments, with Minneapolis and Atlanta chosen for the locations. The production of the building materials and the construction processes were evaluated for energy consumption as well as other parameters, including greenhouse gas emission and total mass of waste (as shown in Table 2). In both locations, the utilization of wood products resulted in lower levels of embodied energy as well as other advantages over comparable steel construction. Note that the researchers did not consider the use of biomass in the wood production process; fossil fuels were considered for both the wood and steel wall structures to compare the intensity of material production and efficiency of construction. Further research indicated that the steel structures utilize at least 280% more non-bioenergy than the wooden structures.

Table 2. Environmental Performance Indices for Above-Grade Residential Wall Designs [2]

	Wood	Steel	% Difference*
Minneapolis Wall Design			
Embodied Energy (GJ)	250	296	+18
Global Warming Potential (kg CO_2)	13,009	17,262	+33
Air Emission Index	3,820	4,222	+11
Water Emission Index	3	29	+867
Solid Waste (kg)	3,496	3,181	-0.9
Atlanta Wall Design			
Embodied Energy (GJ)	168	231	+38
Global Warming Potential (kg CO_2)	8,345	14,982	+80
Air Emission Index	2,313	3,373	+46
Water Emission Index	2	2	0
Solid Waste (kg)	2,325	6,152	+164

*Value represents the percentage increase associated with steel wall construction.

Carbon Footprint

Timber building materials hold a major advantage when examining carbon impact. The measurement of carbon emissions is one of the most direct methods for the determination of a project's environmental impact [2]. Carbon footprint is associated with climate change and holds a high level of importance to the environmentally-conscious public. Wood products have the unique advantage of carbon storage, resulting from the chemical process of photosynthesis:

$$\text{Sunlight Energy} + 6H_2O + 6CO_2 \rightarrow C_6H_{12}O_6 + 6O_2$$

As a tree respires, it utilizes solar energy to take in water and carbon dioxide, producing glucose for growth with oxygen as a byproduct [2]. The carbon that is absorbed is stored in the tree's mass. Trees play a significant role in the planet's natural carbon cycle, reducing the level of carbon dioxide present in the atmosphere. It is estimated that 26 billion metric tons of carbon are stored in forests while an additional 28.7 billion metric tons are stored in fresh forest soils. When a tree dies, a portion of the carbon is released back into the atmosphere very slowly during decomposition. The release of carbon can be accelerated through a number of processes, including incineration, insect attack, and rapid decomposition due to disease.

When trees are harvested for lumber, the resultant wood products retain the carbon stored in the wood's mass [2]. This phenomenon is known as carbon storage or carbon sequestration, associated with all wood products, including paper. Products made from wood are approximately half carbon by weight. Wood products retain their carbon supply for the life of their use, which is often longer than the life of the structure due to wood's high reuse potential. New plants take the place of those that were harvested, serving as new sources of carbon absorption.

In addition to storing carbon, wood products are associated with low levels of carbon emission during manufacturing [2]. As mentioned previously, the natural growth of forests and the ease with which wood products are produced lends to very little burning of fossil fuels. Concrete and steel require more energy to produce and therefore have significantly higher carbon footprints. Compared to the production of a ton of dimensional lumber, a ton of concrete emits 8 times as much carbon and a ton of steel emits 21 times as much. Wood products that utilize processes requiring higher levels of energy input (e.g. veneer cutting, adhesive application, heat pressing) are associated with higher levels of carbon emission than dimensional lumber. Once again, the negative effects associated with the production of these products are negligible compared to those associated with steel and concrete.

Wood's carbon storage ability and low-emission production make it a standout choice for green building efforts. CLT is a particularly enticing product, offering a low carbon footprint for heavy construction applications. In some cases, wood products may be carbon neutral or even carbon negative (when associated with a very low level of embodied energy, the carbon storage consideration of a product may be greater than the level of emissions required to manufacture the product). Bioenergy plays a major role in the emissions calculation, as the use of biomass for fuel is considered to be a carbon-neutral undertaking [2].

Environmental Ratings

The use of wood in building projects is encouraged throughout the various green building rating systems currently in place [18]. For those seeking LEED certification, the use of wood products (especially those which are certified or recycled) can provide substantial benefit in the certification process. Many high-profile building projects involving structural and aesthetic timber have achieved excellent LEED ratings, including the LEED Platinum designation. Credits are offered for a wide range of timber properties and qualities. As the scope of consideration for certification is constantly increasing, those interested in LEED awards should verify the current credits available during the design process.

6. Timber High-Rise Studies

Tall buildings are typically associated with large carbon footprints, and the structural support of a building plays a significant role in its assessment. High-rise buildings are commonly supported with structural systems utilizing concrete or steel as the primary material. In recent years, designers have begun to examine the suitability of wood for use in high-rise structural systems. The carbon storage properties of wood and its sustainable nature are characteristics that may help to reduce some negative aspects associated with tall buildings.

The following two studies were conducted by design firms interested in increasing the use of wood as a heavy building material. Both studies represent the growing interest in mass timber, its role in green building, and the possibilities of wood products when used in tandem with other materials. While there is more work that must be done before structural timber systems will be utilized in new skyscraper projects, these studies help demonstrate what is possible and hint at the future of timber construction.

SOM – Timber Tower Research Project

The designers at Skidmore, Owings & Merrill (SOM) are responsible for some of the most iconic and successful high-rise projects around the world. The renowned architecture and engineering firm has completed projects such as Lever House, the Willis Tower (formerly Sears Tower), and the Burj Khalifa, currently the tallest building in the world. Recognizing the need for greener high-rise construction, the firm completed an experimental project in 2013 evaluating the use of mass timber in a tall building.

The goal of the project was to design a high-rise building using mass timber as the primary structural material in an effort to minimize the building's carbon footprint [19]. Compared to low-rise buildings, high-rises have higher carbon footprints per square foot of floor area due to heavy structures of concrete and/or steel. The Softwood Lumber Board sponsored SOM's efforts to evaluate the feasibility of reducing this discrepancy through the use of a timber structure. The new design was to be as sustainable as possible while remaining cost-competitive with typical contemporary building techniques. Although the new design was not to be built, it was approached with the same considerations that accompany a commissioned building project. The structural system needed to be applicable for many floor plan layouts, the building's mechanical systems needed to be considered in the design, and the construction process needed to be analyzed, among other appropriate considerations.

In order to inform the geometric design of the new building and serve as a comparison for study, a benchmark building was selected [19]. The chosen benchmark was the Dewitt-Chestnut Apartment building, a 42-story, 395-foot-tall complex in Chicago that was designed by SOM and completed in 1965. The building remains a successful and marketable high-rise, utilizing an efficient structure of reinforced concrete (0.98 cubic feet of concrete per square foot of floor area). The new design incorporates similar floor plans for its residential program, matching the number of stories of the benchmark.

Figure 17: The Dewitt-Chestnut high-rise [19].

The design team's chosen structural system is referred to as a concrete jointed timber frame [19]. In this system, the majority of the structural elements are made of mass timber, including columns, floor slabs and shear walls. For structural connections and areas where wood was deemed inadequate, reinforced concrete was specified to provide proper strength. The resultant structural system of a typical floor is approximately 80% timber and 20% reinforced concrete by volume (as shown in Figure 18). Concrete elements include spandrel beams around the building's perimeter and interior link beams. The beams serve as connection areas for the main timber elements, with the spandrel beams providing column/floor connections and the link beams connecting floor/wall intersections. In the intended construction process, rebar would be threaded into holes drilled in the timber elements and secured with epoxy before the concrete is formed. Modeling of timber alternatives for the link and spandrel beams led SOM to conclude that wood is not ideal for the resistance of large loads at such critical locations. The concrete jointed timber frame concept utilizes the strengths of steel, concrete, and wood while still allowing for an extensive use of timber products.

The design's specified timber products are all readily available or can be acquired through common production processes in the timber market [19]. The mass timber product utilized most in the design is CLT, which is incorporated as the material for floor slabs and shear walls. The floor panels are 5-ply CLT with a double layer at the center (essentially a stacked pair of 3-ply panels), measuring 8 inches in total thickness. The product was chosen for strength properties as well as dimensional stability under variable humidity conditions. The two-way behavior of the panels also aids in vibration control. Typical shear wall panels are constructed in a similar way, utilizing a triad of 3-ply sheets to produce a total thickness of 12 inches. These panels are placed around the building's service core, providing lateral and torsion resistance. Additional wall panels run from the core toward the building's perimeter, helping to resist uplift forces caused by wind hitting the building's broad faces. Columns are glulam elements, utilizing 2x12 milled lumber to produce square cross-sections measuring 2 feet per side. In addition to the aforementioned timber products, the designers provided alternatives that could further increase the building's level of sustainability. The alternative wood solutions incorporate air-dried lumber, heavy timber, and smaller amounts of adhesive but ultimately cost more and complicate the fabrication process.

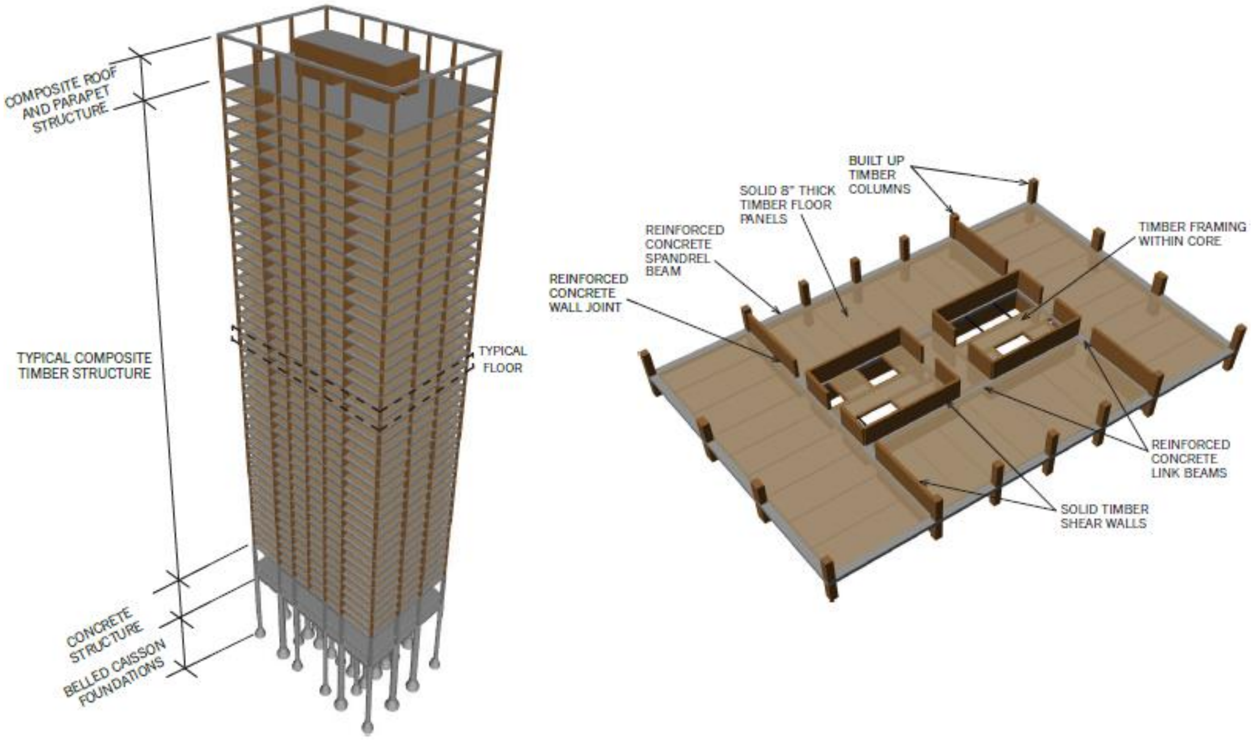
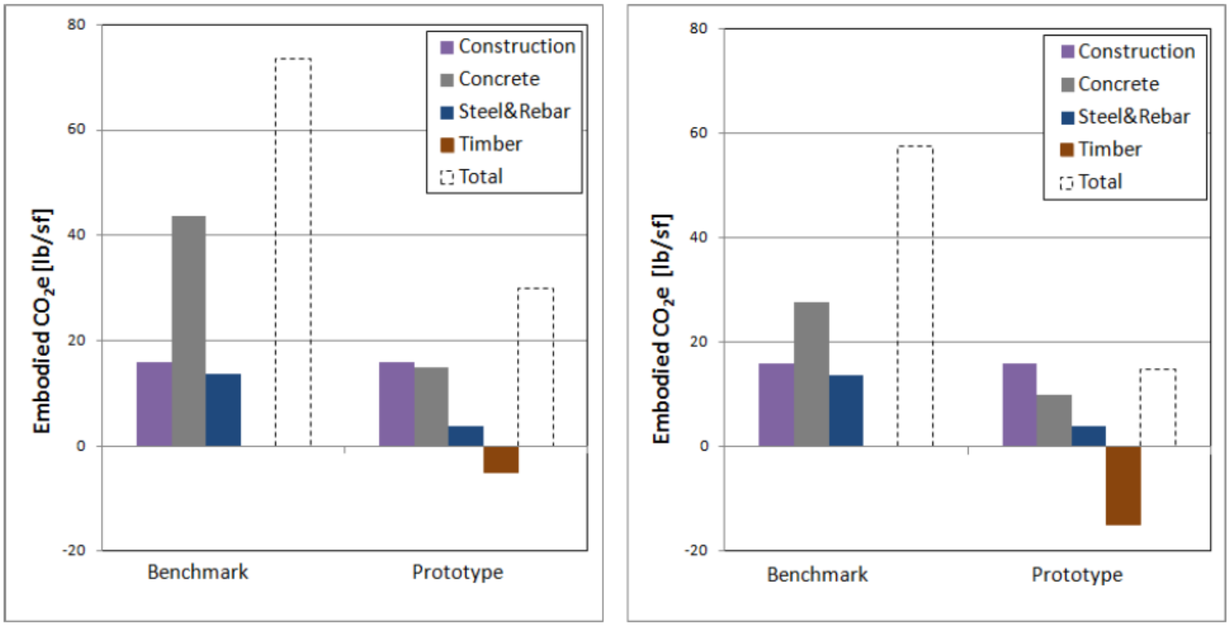


Figure 18: Rendering of overall structural system and typical floor [19].

While wood makes up the majority of the building's structure, concrete was used for several additional features [19]. The benchmark's foundation design was used for the prototype, which consists of bell-bottom concrete caissons bearing approximately 75 feet below ground level. Due to the reduction in weight associated with the timber structure, the designers were able to reduce the number of caissons by 35%. However, the lighter structure is more susceptible to uplift, so the design had to account for this. In addition to the foundation elements, the substructure, plaza and roof incorporate concrete. The design for the plaza, which refers to the lobby level and second floor of the building, utilizes reinforced concrete as the sole building material for a number of reasons. Weather durability was a major concern, and the high-strength design allows for the support of construction equipment during erection. In addition, the capacity of the concrete shear walls allows for a greater open area, providing flexibility for the use of the lobby. The roof utilizes a composite system, with CLT panels supporting a concrete slab. The concrete slab aids in the distribution of equipment loads while providing acoustic dampening. Considering the entire project including the foundation design, timber products constitute 70% of the total material by volume.

Evaluation of the carbon footprint associated with the project provides favorable results [19]. SOM's designers evaluated the carbon impact related to the wood, concrete, and steel materials in addition to the estimated impact of the building's construction. The carbon emissions for the construction process were estimated on a per-square-foot basis, with the value obtained from previous research and estimation standards. For both the benchmark and prototype buildings, a value of 16 lb CO_2/sf was utilized. While the composite timber structure would likely result in lower construction emissions due to greater ease of construction, the lack of data for this type of structure coupled with the desire for a conservative comparison prompted the value's adoption. The team analyzed two scenarios for carbon comparison: the use of standard building materials and the use of sustainable materials. In the standard materials scenario, the primary CLT and glulam members are specified and all wood is assumed to be kiln-dried. In the sustainable materials scenario, the alternative wood solutions are considered, all wood is assumed to be air-dried, and 60% of the cement for concrete is replaced with fly ash and GGBS. A cradle-to-gate investigation was utilized for the material evaluation in both cases. Whether considering standard or sustainable materials, the embodied carbon footprint of the prototype design is significantly reduced from the benchmark (as shown in Figure 19). The designers estimated that the carbon footprint of the timber building would be 60 to 75% smaller than that of the benchmark structure upon completion.



Standard Materials **Sustainable Materials**

Figure 19: Embodied CO_2 emissions comparison between the benchmark and prototype high-rise designs [19].

Based on the information obtained through the project, SOM contends that mass timber is capable for use in high-rise structural applications [19]. While timber is not ideal for use in all the load-bearing applications required in tall buildings, composite systems play to the strengths of other materials while still allowing for prolific use of wood products. Based on the study, the team believes that all-timber structural systems pose critical strength problems after approximately fifteen stories.

Composite systems allow for greater heights and greener buildings. The incorporation of timber can lead to more economical projects and greater ease of construction in addition to its clear benefits to carbon emission reduction. Compared with other structural materials, typical floor plans and building service designs need not be altered when considering a timber structure. The idiosyncrasies of wood products can be incorporated into the structural design, such as compensation for the differential shrinkage potential of columns or additional tie-down measures for uplift forces.

In addition to the favorable findings, the published report acknowledges areas where further research is needed [19]. A cost estimate was not provided, as predicting the construction costs associated with the prototype's construction proved difficult due to a lack of data. The designers believe that performance-based design criteria should be developed for fire performance, with physical testing recommended. While timber structures have been approved for fire performance in high-rise buildings overseas, SOM recommends further study to ensure compliance with applicable US design codes. In addition to fire testing, physical testing of the structural connections is suggested, including seismic testing to study the suitability of the design for areas prone to earthquakes. Regarding architectural study, acoustic performance, durability, and detailing techniques could benefit from further investigation. SOM is beginning to look deeper into several of these concerns and has published an in-depth follow-up study, analyzing performance characteristics of the gravity framing components for the prototype building [20]. The company's work will likely serve as a catalyst for additional outside investigation of timber high-rise construction in North America and elsewhere.

MGA and Equilibrium – Empire State Building

In an effort to truly showcase the potential of engineered wood products, a conceptual project was undertaken by a Canadian team with rather lofty goals. In a collaborative effort, Michael Green Architects (MGA) and the engineers of Equilibrium Consulting, both from the Vancouver area, redesigned New York's Empire State Building with wood as the primary structural material [21]. The two firms are highly involved in the mass timber building industry: Michael Green is a leading proponent of innovative green building and Equilibrium is recognized internationally for its design work with engineered wood products. The Empire State Building project was commissioned by MetsäWood as part of its Plan B program, in which large-scale icons of architecture are redesigned with timber. The other projects currently underway include the Colosseum and the German Reichstag. The intent of the conceptual program is to change the public's perception of wood as a construction material.

MGA and Equilibrium were faithful to the design of Shreve Lamb & Harmon's skyscraper [22]. Like the famous steel and masonry tower, the timber design contains 102 stories and reaches a spire height of 1,454 feet. The building's dimensions, column spacings, and floor-to-floor heights match those of the original. The team's structural solution relies heavily on the use of LVL, both in board and panel form. Elevator shafts and core structures consist of LVL walls forming large rectangular tube-like structures. The dense rectangular columns are built with multiple laminated sheets to achieve the required dimensions. Columns are as long as 6 stories in some locations. Moment connections are employed at splices, causing the columns to be structurally continuous for a maximum of 86 stories. Floor slabs are thick LVL panels, which are also used for shear walls to resist wind loading.

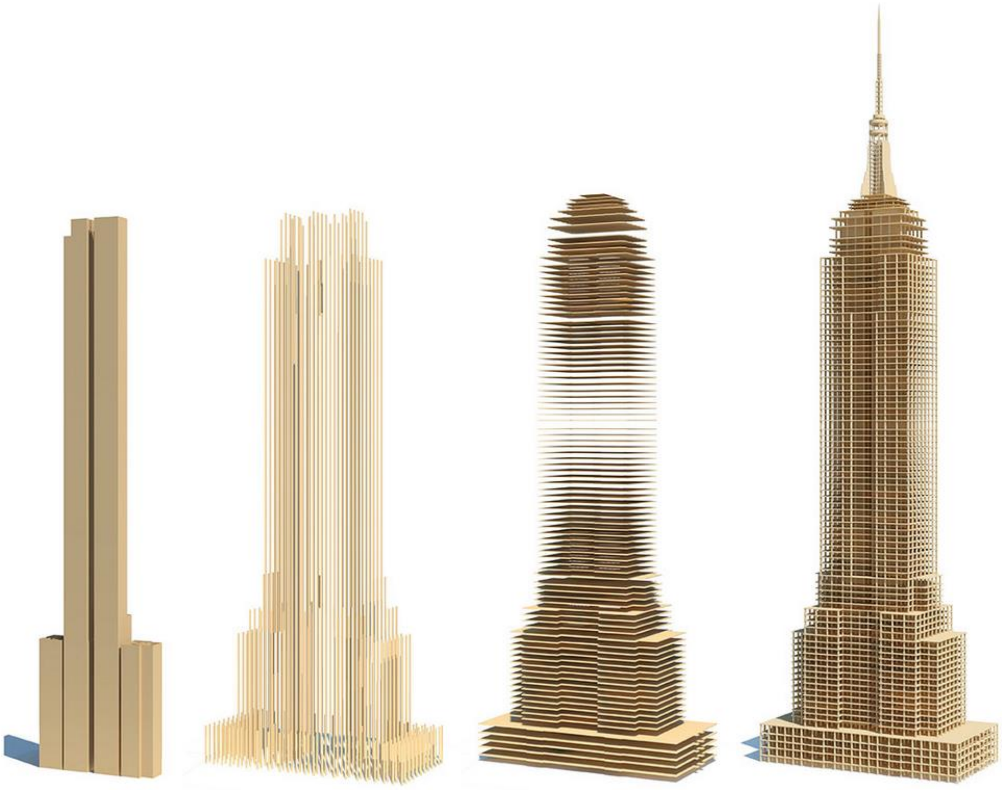


Figure 20: The timber redesign features LVL core units, columns, floor slabs and shear walls [21].

Similar to SOM, the team found deficiencies in various beam applications when considering an all-timber design. MGA and Equilibrium decided to utilize a composite beam system of wood and steel [22]. The system involves the use of LVL box beams working in tandem with post-tensioned steel cables. The beams are rectangular U-shapes in cross-section and span from column to column along the short axis of the building's floor plan. Four steel cables run through the central void of each beam, anchored in the columns and tensioned to a specified design force. The floor slabs rest on the LVL beams, closing the cross-sections and completing the moment frames.

Compared with the original design, the materials involved with the "plyscraper" cost significantly less and are more economical to transport [22]. A large number of the building elements were designed for prefabrication, contributing to construction efficiency and allowing for quality control measures to be in effect. The structure has obvious carbon benefits, and the LVL material may be sourced from sustainable forests, some of which are replenished at a greater rate than they are harvested. The design utilizes over 100,000 cubic yards of LVL, which is estimated to store approximately 78,000 tons of carbon dioxide [21]. In case of fire, the timber products used in the design burn in a predictable and relatively controlled manner. Nevertheless, additional fire protection is necessary, including drywall and a sprinkler system, but wooden elements may remain exposed in many locations. Steel members, on the other hand, must be fully protected.

Figure 21: Structural detail including proposed drywall, flooring, and curtain wall [21].

Based on the project's progression, both MGA and Equilibrium contend that such a skysraper is technically feasible [21]. The team admits that timber high-rises as tall as the Empire State Building will not be built in the near future. Just as early steel skyscrapers caused a recognizable level of public unrest, wood high-rises are associated with skepticism. Currently, the level of skepticism is relatively high in North America. MGA associates hope that the study provides further incentive toward the construction of wood buildings of 30 or 40 stories. The team is currently preparing a technical design report to provide further information about the skyscraper's detailing and implications, which will soon be published by MetsäWood [22].

7. Notable Building Projects

Tamedia Headquarters Expansion – Zurich, Switzerland

Engineer / Architect: Blumer-Lehmann / Shigeru Ban Architects

Completion Date: March 2013

Figure 22: Façade of the Tamedia Headquarters expansion [23].

Swiss newspaper group Tamedia was looking to expand its Zurich headquarters, seeking a distinct design for its height-limited building project. The company hired the firm of Shigeru Ban, a Japanese architect and Pritzker-Prize laureate, to handle the project's planning and design. Known for using conventional materials in unexpected ways, Ban presented a seven-story building supported primarily with custom mass timber elements. Both the Swiss and Japanese are associated with fine wood building and joinery, and the design capitalizes on the use of modern technology and engineering know-how with dramatic effect.

The building's wooden structure was intended to be the prevailing aesthetic element in the project [23]. Working alongside Swiss engineer Hermann Blumer, a specialist in timber design, Ban and his team devised a novel system of large beams and columns. These members are spruce glulam elements with unique geometries, prefabricated with the use of CNC laser cutting machines. Columns are 17-inch squares in cross-section, each with a length of just over 65 feet to reach the full height of the structure. Columns are placed around the periphery of the building in two rows, and large crossbeams connect the lines of columns by running along the plan's minor axis. The beams are rectangular in cross-section with large, rounded geometry at column connection locations. Each column is sandwiched between two beams, which traverse a 32-foot main span. Orthogonal to the main beams, spacer beams with oval-shaped cross-sections span between the connections. As a design choice, the members were over-dimensioned by 2 inches all around in order to provide excellent fire resistance.

Figure 23: Timber structure prior to curtain wall installation [23].

The three unique types of members converge in a connection that was meticulously designed to perform without the use of any metal fasteners [23]. The columns contain integral notches into which the rounded portions of the main crossbeams are fitted. Both the column and its adjacent crossbeams have large holes at each point of convergence to house a hidden connection element formed with beech plywood. The oval-shaped spacer beams fit into the holes in the crossbeams and attach to the connection element, securing the crossbeams to the column. The plywood infill is fully concealed, providing a snug connection with the spacer beams and reinforcing the joint. The system was constructed one bay at a time, and the connections were hammered into place with the use of large, soft-headed mallets. The precision of the members resulted in a working tolerance of only 5 millimeters (approximately 3/16 inch).

Figure 24: Joint detail with exposed plywood connection element [23].

The structure's column system functions as a line of vertical trusses, with the outer columns performing in tension and the inner columns in compression [23]. Two concrete cores, one new and one from the adjacent structure, offer lateral resistance. To protect the timber system from the elements, a curtain wall of glass and metal surrounds the building. A second building envelope hangs from the inner layer of columns. The zone between the two envelopes acts as a thermal buffer region, also containing circulation pathways and lounge space. Since the structure is fully concealed by the outer envelope, all of the wooden elements have been left exposed. The floor assembly includes wooden joists, CLT panels and cement boards. The building provides approximately 109,000 square feet of floor area.

The collaboration between Blumer-Lehmann and Shigeru Ban Architects resulted in a one-of-a-kind structural system. The seven-story structure adequately supports the building, has a strong resistance to fire, and provides green benefits. The exposure of the wooden elements and their unique geometries contribute to a dramatic architectural aesthetic, visual both inside and outside the building.

Treet Residential Building – Bergen, Norway

Engineer / Architect: Sweco / ARTEC

Completion Date: October 2015

Figure 25: View of Treet from the adjacent harbor [24].

The current record holder for the world's tallest timber building is the 14-story Treet, an apartment high-rise located in Bergen, Norway [21]. With an architectural height of 163 feet, it surpassed the previous record holder – Melbourne's Forté apartment building – by four stories and more than 55 feet. "Treet" translates to "the tree" from the Norwegian language, and its name resonates with the designers' specific intentions to employ structural timber in an ambitious, high-reaching application [24].

Designed by Switzerland-based engineering firm Sweco and Norwegian architcture firm ARTEC, the building's structure consists of a glulam truss system supporting 62 modular apartment units [24]. The glulam frame takes cues from modern timber bridge construction to provide the building with its required stiffness. The staircases and elevator shafts are constructed with CLT panels, offering additional lateral stiffness. Both the glulam and CLT elements were produced in Norway by Moelven Limtre, a manufacturer that uses locally-sourced spruce and pine. Rectangular columns measure 16 x 25-½ inches in cross section, and square columns with side lengths of 19-½ inches are utilized as well. The column bracing members measure 16 inches square in cross-section. All elements were slightly oversized, leading to a satisfactory fire rating of more than 90 minutes for the truss structure. The glulam elements are connected with steel plates and dowels, producing high-strength joints. At ground level, the load-bearing frame achors into a concrete parking garage to resist uplift forces due to wind loading. Bedrock is located approximately 16 feet below the floor of the garage, and over 100 vertical and tilted steel core piles comprise the foundation.

Figure 26: Rendering of Treet's structural system [24].

The modular apartment units were constructed off site with CLT panels [21]. The assembly was undertaken in a controlled factory setting in order to minimize their exposure to moisture. Plumbing fixtures and appliances were installed during the prefabrication process, and surface finishing was completed before the modules were transported to the site. Installation of the modules was accomplished by crane, with the units placed in stacks up to four stories high. Levels one through four comprise the first stack, which rests upon the concrete garage without tying into the framing structure

[24]. The fifth floor is denoted as a "power story," in which the truss structure is reinforced with additional bracing members. The floor's apartment modules are tied into the structure to elevate them above the units below. At the top of the power story is a precast concrete slab, supported by the structure's beams. This slab serves as a support for the next stack of prefabricated living units (stories six through nine), which are independent from the frame. A second power story is located on the tenth floor, with the final four units stacked above. Additional concrete slabs are utilized for the roof of the building, and the added mass from these and the power story slabs adds a significant level of mass to the building. The additional mass reduces wind sway, increasing the occupant comfort level [21].

ARTEC and Sweco took a number of measures to ensure safe structural performance. The glass and metal building envelope hung from the structure protects the timber from Norway's wet climate, increasing durability and reducing maintenance [24]. The structure was overdesigned in order to prevent collapse due to the failure of a truss member. Located in a seismically-active region, the building is adequately designed for earthquake loading, although wind loads were the prevailing design consideration. In addition to the over-sizing of members for fire performance, the building incorporates fire-retardant paint in escape routes, a sprinkler system, and pressurized stairwells. The individual apartment units prevent the spread of fire throughout the inside of the building.

The completion of Treet has helped bring positive publicity to mass timber construction. While reducing the level of production emissions, the extensive use of wood also contributed to a highly efficient construction process. Coupled with the prefabrication of the housing units, the use of wood reduced the total construction time by three months, according to comparitive estimates provided by Sweco [21]. The company is currently involved in the design of another timber high-rise near Oslo that is slated to reach 216 feet with 17 stories. Several other proposals for timber high-rises have surfaced from a variety of design firms, with one such proposal detailing a 24-story tower in Vienna. Just as Forté influenced Treet, the current height champion is paving the way for even taller high-rises.

Grandview Heights Aquatics Centre – Surrey, British Columbia

Engineer / Architect: Fast + Epp / HCMA

Completion Date: Expected Spring 2016

Figure 27: Longitudinal section of the Grandview Heights Aquatics Centre [25].

Timber buildings pushing the envelope in terms of height receive a great deal of publicity, but engineered wood products can also help designers clear very large spans. The Grandview Heights Aquatics Centre in western Canada takes advantage of wood's flexural ability, exhibiting a virtuosic use of continuous glulam beams. Currently approaching completion, the 86,000-square-foot complex was designed by Hughes Condon Marler Architects (HCMA) with structural engineers from Fast + Epp, two Vancouver-based firms [25]. The collaboration resulted in a building design in which form and function interact with striking effect.

The building required a roof that would clear a tower of diving platforms [25]. The architects placed the platforms at one edge of the floor plan and developed a roof with a curved profile, highest above the diving boards. The maximum height of the roof was deemed unnecessary for the rest of the complex, informing the unorthodox shape. For aesthetic interest, the roof was designed with an undulating form, descending from the extents of the building's major axis and culminating in a gentle crest near the center. Traveling along the length of the roof, its maximum height of 72 feet is reduced to a minimum height of 29 feet. The wave-like form is slightly torqued about the major axis and reflects the spirit of the aquatics complex.

To realize the ambitious design of the roof, the engineers devised a system of glulam beams with concrete supports. The glulam elements supporting the roof are of relatively small cross-section, measuring 5 inches wide and 10-½ inches deep [25]. Anchoring the beams on both ends of the building are post-tensioned concrete buttress structures, furnished with steel fasteners. The beams are connected to the fasteners in pairs, with 30 inches of clearance between the center of each pair. The total span between the buttresses is 425 feet. The only intermediate connection is near the center of the building, where the beams converge with a curved concrete platform supported by V-shaped concrete columns. The wooden beams perform in tension similar to cables, forming catenary curves between the supports with the help of custom cambering.

Figure 28: Interior rendering showcasing roof beams [25].

The glulam members offer a number of advantages for this specific application [25]. The engineers examined the possibility of utilizing steel trusses, but the required depth approached 10 feet per truss. The trusses would also be less flexible in terms of height change along the roof, likely leading to a larger building volume and increased energy costs. The use of steel cable was considered, but the material did not have the required bending stiffness to match the intended appearance of the roof. Timber was deemed the best solution for the beam structure, providing adequate support while not imposing upon the swooping form. The use of wood helped to reduce construction energy and emissions, and the finished material is well suited for the humid and corrosive pool environment.

Metropol Parasol – Seville, Spain

Engineer / Architect: Arup / J. MAYER H. Architects

Completion Date: March 2011

Figure 29: Aerial view of the Metropol Parasol (photo courtesy of J. Mayer H. Architects).

One of the world's largest timber buildings is also one of its most unconventional. The Metropol Parasol, an urban center located in the Spanish city of Seville, is an architectural attraction created with structural composite lumber. The design competition for the project was won by Berlin-based firm J. Mayer H. Architects, and the designers worked extensively with renowned structural engineering group Arup to develop the complex wooden system.

The Parasol takes its name from six umbrella-shaped timber forms that cover a footprint of approximately 120,000 square feet [26]. The mushroom-like masses rise from sinuous concrete plinths and are joined together at the top of the structure, reaching a height of about 92 feet. Beneath the timber structure is an archaeological museum, formed with reinforced concrete. The roof of the museum serves as a raised public plaza, which is shaded by the wooden forms. The timber structure supports a restaurant and a public promenade, both offering views of the city and the complex itself.

The unorthodox wooden structure is comprised of nearly 3,300 cubic yards of Kerto-Q LVL sheet material [26]. The entire structural plan conforms to an orthogonal grid with units measuring 1.5 x 1.5 meters (4.9 x 4.9 feet). Engineers from Arup worked closely with the architects, converting 3D renderings into analytical models in order to create the geometries of individual LVL panels. The intensive process resulted in a structure composed of approximately 3,400 wooden pieces, each tailored for its load-bearing requirements. The largest panel reaches a length of 54 feet, and the thickest exceeds

12 inches. The sheet material was produced by Finnforest in Germany and the pieces were precision-milled with CNC machines. Since the entire structure is exposed to the elements, a new weather protection system was employed. Each panel was sealed with a 2-3 millimeter coat of polyurethane. The coating results in waterproof yet diffusion-permeable components with adequate fire performance.

Arup's structural connections incorporate threaded steel rods anchored into the LVL panels [26]. Cutouts and connection details were included in the CNC production process, but the holes for the steel rods were drilled manually. The rods are bonded to the panels with tempered epoxy, ensuring structural integrity at high temperatures. The threaded rods secure the panels to steel connection assemblies, and the system allowed the structure's joints (more than 3,000 in total) to be constructed in an efficient manner. The completed project displays the ability of LVL sheet material and showcases a satisfactory method for weather protection of structural composite lumber.

Figure 30: Two of the Metropol's parasol-shaped forms (photo courtesy of Arup).

Arcus Center – Kalamazoo, Michigan

Engineer / Architect: Thornton Tomasetti / Studio Gang

Completion Date: September 2014

Figure 31: Cantilevered portion of the Arcus Center [27].

While not as ambitious as the projects previously discussed, a campus building in Michigan utilizes wood in an unexpected way. A new addition to Kalamazoo College, the Arcus Center for Social Justice Leadership is a modern building defined by masonry walls. Instead of bricks, stones, or concrete blocks, the masonry units are logs of various diameter. The wall construction technique, known as cordwood masonry, is a building method that is centuries old but relatively unknown in the contemporary industry [25]. Principal architect Jeanne Gang, who begins each project with research into location and materiality, studied the concept [27]. Early settlers of the area built houses with cordwood masonry walls, and the Arcus Center provides a historical connection through its use of timber.

The wood chosen for the walls is decay-resistant white cedar, harvested from forests in northern Michigan [25]. The straight logs were cut to be 11 inches in length, with diameters ranging from 4 to 14 inches [27]. The logs are stacked horizontally, and the variation in size results in a balanced, tightly-packed configuration. Cordwood masonry experts from the Earthwood Building School in New York were consulted for the design of the mortar mix [25]. The specific design provides a mortar with a relatively slow curing time, helping to avoid the pull of moisture from the logs and resultant cracking. The Arcus Center's wall construction is similar to that of a brick cavity wall. A gap of 1-½ inches remains between the wood masonry units and the backing stud wall, with weep holes providing drainage. The backing wall contains air barriers, waterproofing, and insulation. The walls curve with the Y-shaped floor plan, converging at large steel-framed windows. The masonry follows the sculptural form of the façade in several locations, such as at the main entrance and around a protruding ellipse-shaped window. The inside of the building features a modern aesthetic with an exposed steel structure, curving glass partitions and a large contemporary fireplace.

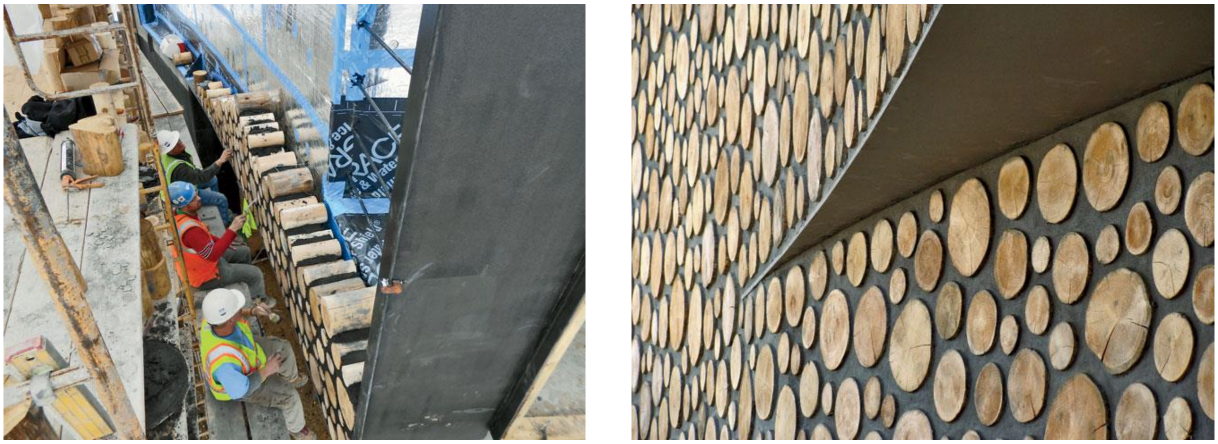


Figure 32: Logs of various diameter were carefully placed to provide even distribution [25].

The project's incorporation of cordwood masonry results in a thermal resistance value well above that required for insulation, even in an area which experiences very cold winters [25]. The masonry materials and building processes proved cost-effective and environmentally friendly, utilizing local labor and materials. The design team's work has demonstrated that the masonry technique is viable for use in modern pressurized buildings, and the project has introduced the concept to other designers. Cordwood masonry does not push the limits of structural timber, but it can be incorporated into projects for greener performance and visual impact.

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