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Introduction: a story of building with wood

The story of wood buildings is a tumultuous one. As a construction material, it has gone from near ubiquity to marginalization to a contemporary resurgence. Its versatility is unmatched: able to span large distances and create dizzying towers as well as humble homes and sheds. It can be used as structure, cladding, interior finish, and furniture alike. The warmth and patterning of its grain as well as its texture and aromatic scent affect us as few materials can. Wood is alive, which makes it special but also creates unique problems, from splitting and shrinkage to combustibility and rot. The material properties of wood spell out its story of failure and success.

Wood is among the oldest of all building materials, most likely predating even stone construction. Because wood decays, however, the historic role of this material in our world is more difficult to trace than stone and masonry construction. When nomads of the Stone Age could not find suitable shelter in caves, historians believe that they constructed tent-like huts from trees, branches, and twigs and covered the walls and roof with animal hides. For nomad hunter-gatherers, erecting these lightweight structures was surely preferred over strenuous and time-consuming stone wall construction. It was probably not until man settled from a nomadic lifestyle that more permanent housing and different forms of construction evolved. Archeological excavations in Holstein (northern Germany) dated from the twelfth millennium BC indicate circles of stone that may have been used to weight tent walls during reindeer hunts. This suggests man's first wood buildings. Similar buildings are thought to have existed in Neolithic Egypt as well. As nomadic people settled, the tradition of building wood tent structures evolved and took the form of more permanent wood frame buildings used by chieftains and kings.[1]

In Egypt, wood framing and solid mud brick construction developed side by side and led to some of the first examples of construction hybridization. From the dawn of historical time, Egyptians used wood frame construction with solid infill. Greek civilizations also used wood construction, with archeological evidence from Minoan and Mycenaean wood columns or combination of masonry walls and timber roof framing.[2] The first Doric columns in Greek architecture may have been constructed from wood, and several ancient buildings indicate, although contested, that the iconic Greek temple's origin is of wood not stone.[3] Parts of the Doric order found in classic temples, such as the triglyph, frieza, and architrave, are thought to be recreations of early wood construction tectonics.[4]

In the first century BC, Vitruvius placed the origin of architecture with trees and branches in the forest. Forests themselves create a type of architectural enclosure that has long inspired thinkers and designers. Spurred by new ideas from the Enlightenment starting in the 17th century, Marc-Antoine Laugier turned to the origins of architecture with his concept of the primitive hut: a dwelling constructed from four live trees with a simple roof of branches and leaves.[5] While not based on archeological evidence, the idea presents a primal intuition that wood and man have been intrinsically linked for millennia.

From Europe's northern boreal forests to more southerly deciduous forests, rich traditions in timber architecture have flourished. The Norwegians during their numerous Viking invasions are thought to have seen and copied their wood architecture from examples in Western Europe and translated it into stave churches, similar to wood construction developments in northern Russia. The alpine regions of Europe, because of their geography, developed heavy timber log structures, while inhabitants of central Europe preferred timber frame construction of oak with wattle and daub infill.[6] When Europeans immigrated to America, they brought traditional wood construction with them but adapted to their new environment. From its origins, wood architecture has been regional and highly place-based, emphasizing a region's particular character, creativity and unique way of engaging the land.

A CRAFT

Historically, our cities—especially in timbered regions and in places that could easily import timber—were built from wood. Before Europe's forests were logged, wood was accessible, plentiful, and nearly ready-made for structural applications. With builders passing down traditional knowledge and intuition of craft and carpentry, wood has long provided a type of local independence in construction. No other material offers the same ease of use coupled with strength and flexibility. Wood is light enough for large pieces to be lifted by hand, strong enough to support great weight, yet supple enough to easily carve for joinery or ornamentation.

While pre-industrial multi-family structures still stand, many wood buildings have endured for far longer. Built over 950 years ago, the 67 m tall Sakyamuni Pagoda in China is one of the tallest multi-story wood structures in the world. Constructed entirely from wood, the pagoda has survived an estimated 40 earthquakes without the use of steel or modern seismic bracing.[7] Many examples of ancient timber construction still stand today, testaments of the material's durability and longevity when cared for. Timber framed buildings were in fact the model on which subsequent steel and concrete construction was based.[8]

Prior to the 19th century, wood was the common building material in most of central and northern Europe and North America. Cities like London and New York contained as many wood or timber buildings as stone or masonry ones and the carpenter was the craftsman of highest standing in the building trade.[9] At this time, other cities such as Moscow, Tokyo, Bangkok, and Beijing actually contained far more wood buildings than masonry.[10] Hundreds of years of use had established a strong vernacular knowledge in the ways of building with wood.

Some of the earliest wood buildings drove posts directly into the ground for stabilization. Contact with the earth caused these structural elements to rot, and later the posts were lifted on to stone or masonry pedestals or set on sills to protect the structure from moisture and lengthen its life. Wood was often combined with other materials for infill or exterior walls. Wood joints, fastening, spanning, and building stabilization all advanced over time, creating more ambitious rural and urban buildings that rose taller in residences or spanned farther in great halls. It was common to see multi-story wood buildings in urban centers up to the end of the 19th century. In some cases these buildings rose six stories or higher.[11]

DECLINE

Quests for material permanence, taller heights, structural innovation, and new architectural styles conspired to stem advancements in wood craftsmanship during the last 200 years. Steel and concrete rose to new heights in European and North American cultural centers during the 19th and 20th centuries. Meanwhile, wood became associated with lower-grade and lower-cost construction—buildings of lesser stature, safety, and durability. There are several primary reasons for this rapid and remarkable change in our urban building culture.

The first major factor in wood's decline was extensive deforestation, particularly in western Europe where as much as 70 percent of the continent's original forests were converted to other uses.[12] Where forests once covered more than 90 percent of central Europe, by the 19th century this amount had shrunk to around 10 percent with old-growth forests essentially gone.[13] For some, contemporary discussions of wood construction still conjure images of ravaged forests and clear-cut land.

The second major factor in wood's decline was fire. Severe and often recurring fires in cities around the world created catastrophic destruction. The Chicago fire of 1871 killed hundreds, left 100,000 homeless and destroyed three square miles of the city. As a consequence, non-combustible materials such as brick and stone became the norm for urban construction and new regulations were often enacted to limit the use of wood in construction.

In addition to fire, the rise of industrialization and new construction methods using iron, steel, concrete, glass, and plastics eroded the use of wood. Many of these new products had properties that could be clearly verified and did not possesses the natural inconsistencies of solid sawn wood. Some scholars believe that Joseph Paxton's groundbreaking Crystal Palace erected for London's Great Exhibition in 1851 marked the turning point away from wood as a building material.[14] Made largely of glass and cast iron, and designed to showcase technological and industrial innovation, the Crystal Palace was nevertheless destroyed by fire in the early 20th century. The first steel skyscrapers, erected in US cities in the late 1800s, also pointed toward what would come to define the future of urban architecture.

Architectural doctrines like those promulgated in Le Corbusier's 1923 *Vers Une Architecture* called for a new modern and hygienic era of steel, glass, and concrete – an architecture founded on industrial mass-production and the machine. As "modern" architectural styles were promulgated and exported globally as an *International Style*, the use of wood, which thrives in place-based design, was further denuded. Along with the spread of these ideas across borders, advances in manufacturing and transportation opened new markets and cut off traditional building techniques and craftsmanship.

Following the world wars, with a need for fast and inexpensive housing to rebuild Europe, architects and builders turned to concrete and steel. Today these "modern" materials are ubiquitous and wood is often viewed as outdated and inadequate for commercial buildings. The widespread adoption of concrete and steel coupled with the enormous manufacturing infrastructure for these materials and building codes that now favored non-combustible construction led to their dominance, and a general lack of investigation of other materials.

A RESURGENCE

Today's interest in engineered wood buildings is driven by both technological advances and the growing concern for of ecology and sustainable construction practices. In many places, wood has caught up with concrete and steel in terms of industrialized manufacturing, prefabrication, and rapid site erection. In parts of Europe, according to the consulting engineer Josep Kolb, "the traditional carpentry shop has become a business with computer-assisted design processes and robotic controlled precision tools."[15] A growing group of architects and engineers from the sub-alpine regions of Austria, Germany, Switzerland, and Italy have adopted new wood building materials, connection systems, and fire protection techniques that have brought use of this material from an artisan craft to being part of modern practice. These alpine people, because of their challenging topography and limited natural resources, have established a self-dependency, resource efficiency, and durable craftsmanship in wood that is a model to follow. Designers and engineers from other regions have taken note and developed innovative timber buildings in their own right based on technology and resources available to them. With a new focus on high-tech production and speed, contemporary, engineered wood construction is able to compete with other materials on cost, but also offers the additional benefits of beauty, connection to craftsmanship, and a regional, ecologically-based architecture.

The reasons for wood's resurgence today are scientific rather than nostalgic, especially its environmental performance traits. Much international research has found that using wood in place of other construction materials can lead to a significant reduction in greenhouse gasses (GHG), while at the same time allowing for a net increase in the global forest cover if sustainable forestry practices are employed.[16]

SOLID WOOD AND WOODEN CITIES

After a century of decline, wood is findings its way back to the forefront of urban architecture. Cities are creative hubs where innovation, interaction, and discovery serve as the catalyst of change and progress. This kind of environment naturally fosters growth and creates the potential for a higher standard of living, as well as architectural innovation. Cities are also inherently more energy efficient than less dense communities. Urban dwellers require less heat in the winter, drive less, and require fewer miles of roads than their suburban counterparts. One study conducted at the University of California, Los Angeles found that a resident in Manhattan emits 14,127 fewer pounds of carbon dioxide per year than a suburban New Yorker.[17] If anywhere, it is in cities that we will find a sustainable way of living.

Using low embodied carbon materials for urban buildings can bring cities closer to goals of carbon neutrality. This is important because the UN estimates that by 2050 some 86 percent of the world's population will live in cities and population will have swelled an additional 2.3 billion.[18] To contain this kind of growth, planners and designers must build sustainably. Wood advocate and architect Michael Green, based in Vancouver, Canada, explains that with today's building culture, concrete will likely be used to house most of this growth, yet "concrete's large carbon footprint will continue to be a challenge without alternative structural solutions for the world's major environments."[19] Green goes on to say that "man can't compete with photosynthesis," meaning that materials generated naturally such as wood must be considered a real option to house future growth if we are to do this in a sustainable way.[20]

Recently, few countries have so intensely experimented with the use of solid wood in large institutional and multi-family residential applications as England. Alex de Rijke of London's architectural practice dRMM calls engineered wood "the new concrete" in a world of diminishing resources and growing environmental imperatives. He notes that:

> An abbreviated history of material technology as the main driver of architecture shows the best 17th century work to be characterized by stonework (e.g. Wren, Vanburgh, Hawksmoor), the 18C to be the refinement of brickwork (Georgian London & Dublin), the 19C to be the heyday of steel frame (Bessemer's mass production, Brunel's use of it), and the 20th century as the era of concrete (Nervi, Williams, Hadid). ... This leaves the 21st century open for the successor to concrete. My prediction is timber.[21]

Whether de Rijke's prophecy will come true remains to be seen. But interest in solid wood construction has grown considerably among architects, engineers, universities, industry, and government during the past few decades, as the twin forces of technology and ecology drive the development of larger, taller, mass timber buildings.

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2

Forests, forestry and carbon

We live on a blue-green planet: blue defined by our vast oceans and green by our forests, which today comprise around 31 percent of our planet's surface area. Distributed in horizontal bands around the Earth, forest composition and characteristics change with latitude. Starting in the Arctic, the world's great boreal forests account for about one-third of the planet's total woodland. These coniferous forests, made up largely of pine, stretch from Scandinavia through Russia, Canada, and Alaska. To the south, stretching across central Europe, Asia, and North America, are temperate forests of broadleaf deciduous trees and mixed conifers. Farther south, the subtropical and tropical forests contain an incredible diversity of species. Of the four billion hectares (10 billion acres) of forests on the planet today, about half is tropical, one-third boreal, and only one-sixth temperate. Two-thirds of this forest land has been degraded by human activity.[1] Stewardship of this land against competing human interests is one of the planet's greatest challenges.

Earth's early atmosphere contained little free oxygen. The air that we breathe today, and largely take for granted, is the result of organisms like trees capable of photosynthesis—a process in which plants use the energy from the sun to create food. In doing so, trees provide an essential lung for our planet, sequestering atmospheric carbon and releasing oxygen in exchange. Forests also provide habitat, regulate temperature, and generate materials and income for families across generations. From an economic point of view, trade in forest products was estimated at $460 billion in 2011 with over one billion people earning their livelihood from forests.[2] However, these numbers do not begin to capture the true value of our Earth's forests, which house 80 percent of our terrestrial biodiversity, purify our water,

2.1.1 Distribution of global forest canopy and canopy heights. Source: NASA and offer myriad other benefits interrelated and interconnected to the health of our planet on a global scale.[3]

THE DEFORESTATION TREND

Forests are changing ecosystems. Forests today are not the same as Earth's forests in the past because of geologic changes and fluctuations in the Earth's temperature over time. In addition to this continuing natural change, humankind has played a heavy hand in shaping today's forests. Over the last 8,000 years, man has reduced the planet's forest cover by about 50 percent, with a majority of this change occurring in the last 300 years.[4]

Prior to the 1950s, huge expanses of forests in the developed world were cleared for farmland, but this trend has reversed. Forests benefited as farms switched from animal power to mechanical powered tractors and other machines, which also brought about enormous gains in crop yields, development of such entities as the US Forest Service, and establishment of forestry as an area of professional study.[5] Consequently, in places like the United States, more farmland is being returned to forests than is created.[6] The forests of the United States, as well as forests of other countries, are key global carbon sinks.

Over the last 50 to 100 years, the pattern of deforestation has changed with the greatest rates of deforestation occurring in developing, tropical countries rather than temperate countries.[7] From 2000 to 2005 Brazil, Indonesia, Sudan, Myanmar, and Zambia were the five countries that experienced the largest annual net loss of forest area. Brazil, over the last 40 years, has seen approximately one-fifth of its forest cover converted to non-forest uses.[8] Conversely, over the same period Italy, Spain, China, Vietnam, and the United States reported the largest annual gains in forests. Countries that have recently changed from annual net losses to net gains include Chile, Costa Rica, India, and Vietnam, where the primary driver of deforestation had been war.[9] Despite the annual growth of forests in some countries, the planet is still suffering a net decrease in forests from year to year, indicating that more needs to be done to protect our remaining forests.[10]

BUILDING WITH WOOD IS SUSTAINABLE

Environmentalists have traditionally viewed logging and the increased use of wood for building as an unwarranted attack on nature, proof of humanity's inability to live in balance with our natural environment. This perspective is not without reason: logging releases large amounts of carbon into the atmosphere annually—some believe more than the entire transportation sector—and logging can create negative impacts on biodiversity, soil, and water quality.[11] However, forestry practices determine how detrimental logging actually is. Sustainable forestry practices balance the removal of trees with the growth of trees so that forests can be permanently sustained for future generations. Such practices have grown quickly in recent years to mitigate environmental degradation and to maintain sustained timber yields.

Chain of custody certificates ensure that wood can be tracked back to its source and that timber resources do not originate from areas with poor forestry management and regulatory practices. Already, a full quarter of all global roundwood used in wood building products comes from certified forests, and these forests are growing at a rate of about 10 percent per year.[12] Not all sustainable forestry certification systems are equal, however, and building professionals should research their local certification system before specifying wood to ensure that products are as environmentally sound as possible.

The United States and the European Union have seen a continuing trend of increased forest stock. In the United States forest carbon stocks have been increasing for the past 75 years and Sweden has experienced increasing forest stocks for at least the last 60 years.[13] Specifying wood as a construction material is not likely to harm the sustainability of forests. Currently, only 0.42 gigatonnes (Gt) of timber are removed from forests each year for roundwood use. From an environmental perspective, trees convert an estimated 25–30 Gt of carbon from the atmosphere into woody biomass every year.[14] With proper management and sustainable forestry practices, the Earth's forests are capable of sequestering large amounts of CO_2 while providing essential building materials at the same time.

The development of tree plantations is another contentious issue among environmentalists because monoculture tree plantations reduce biodiversity and provide fewer ecological benefits for the land than natural forests. Forest certification systems seek to prevent the conversion of forests into plantations because of the potentially diminished quality of the land.[15] Since 1990, however, there has been an approximate 40 percent increase in the amount of forest plantations in the world, and this figure is expected to increase.[16] An advantage of plantations is their efficiency. While they account for only 5 percent of forest area globally, plantations produce around 35 percent of global roundwood, thus relieving development pressure on a much larger area of natural forest.[17] Moreover, planted forests are generally established on land that had previously been converted to agriculture or other uses. From 2000 to 2006, 90 percent of forest plantations were established on previously cleared areas, meaning that plantations actually provide better environmental benefits and carbon mitigation than would otherwise be the case.[18] Sustainably managed forests that contribute to the economy can also discourage the same land area from being converted into other uses, such as low-density suburban sprawl.

Old forests, while storing large amounts of carbon, are thought to sequester less carbon from the atmosphere on an ongoing basis than younger forests. Commercial forestry, which concentrates on young trees where growth is fast and rotations are short, not only maximizes profits but also maximizes the carbon captured by forests and subsequently stored in forest products before tree growth slows in later years. Forestry operations, however, do have other environmental impacts beyond carbon sequestration and understanding forest management practices is critical to assessing the overall sustainability of wood products.

In developed countries, there has also been a rapid advancement in utilization of wood during the manufacturing process; that is, wood converted to useful products versus wood that is wasted and sent to landfills during manufacturing. Today wood manufacturing can be categorized as a zero-waste industry with 99 percent of every tree being used at the mill.[19] Wood that is not captured as dimensional lumber is readily converted to other wood products or, using heat recovery boilers and cogeneration equipment at mills, converted to energy that fuels the plants. Sawmills are industry leaders in Combined Heat and Power (CPH) to produce electricity and reduce the amount of greenhouse gases emitted during manufacturing. The use of biomass for mill energy rather than fossil fuels creates a net-zero carbon emission strategy. Biomass provides more than 60 percent of the fuel energy used in the wood products industry, whereas iron, steel, and other materials use close to no biofuel.[20] In addition, for wood used in construction, at the end of a building's life, wood can be deconstructed and reused in other structures, composted, or burned for energy, thus potentially making it a zero waste product. Forests produce a structural building material without an industrialized process. The production process simply requires soil, sun, and water—and it generates no industrial waste. The process of photosynthesis is far more efficient and elegant than even the best photovoltaic cells.

THE CARBON PROBLEM

Forests are massive carbon sinks. While many plants are able to sequester carbon, trees have the unique ability to lock it up for long periods of time. During the growing season, all plants inhale some 120 billion tons of CO_2, but during the winter months most decay and emit this carbon back into the atmosphere.[21] Because trees can live for decades or centuries rather than just a few growing seasons, their carbon remains in storage. Wood traps huge amounts of carbon—roughly half of its dried weight—and a single tree can easily contain a ton or more of carbon, with each cubic foot (0.028 m^3) of wood holding between 11 and 20 pounds (5–9 kg).[22]

Forests make up one of the largest carbon pools on the planet and store over half of the carbon found in our terrestrial ecosystems. While other carbon pools (such as the oceans) are larger,[23] scientists believe that forests are able to absorb a full quarter of the total CO_2 emitted from human activity. In the context of global warming, this carbon-absorbing benefit provided by forests is perhaps more important today than ever before.

Forests are both sources of carbon and carbon sinks, participating in a two-way flow of carbon that can be measured with reasonable certainty.[24] They can also provide a source for carbon displacement, which occurs when the use of a fossil fuel-intensive material is replaced by a material of lower energy and fossil fuel intensity. Using today's innovative building systems, wood can displace other materials such as steel and concrete which are more carbon-intensive. Until recently, an obstacle to making recommendations on materials usage was the lack of carbon accounting for all stages of a material's life, from growth or extraction, to processing, reuse, and final end-use. A synthesis of 21 scientific studies has found that greater use of wood instead of non-wood products has the potential to displace large amounts of CO_2 and could potentially stabilize or even reduce atmospheric CO_2.[25] The use of wood in this case has a double benefit.

Most studies comparing the environmental impacts of wood to steel and concrete consider light wood frame construction, rather than massive, solid wood materials like cross-laminated timber (CLT) or glue-laminated timber. Because of the much greater amount of wood used in solid wood construction, it is important to take material volume into account when comparing it to other materials. A 2012 study compared a theoretical five-story commercial building made of CLT and glue-laminated timber with a similar five-story concrete-frame building. The study found that in 10 of 11 assessment categories the timber design offered a lower environmental impact.[26] A separate study completed in 2012 investigating the use of CLT in new construction compared with concrete found considerably lower CO_2 emissions using timber.[27]

Every product has a life cycle carbon footprint. Comparing carbon emissions between different products can improve decision-making about what products to use. A ton of cement takes five times as much energy to produce as a ton of wood, a ton of steel 24 times as much, and a ton of aluminum 126 times as much energy to produce.[28] In substitution studies, Sathre and O'Connor found that a "meta-average value for wood" to be approximately 3.9 tons of CO_2 reduced for every ton of oven-dry wood used as a substitute for other commonly used structural materials. Clearly one strategy to reduce greenhouse gases is to use materials that have the highest CO_2 displacement potential.[29]

In comparison to the carbon-storing benefits that forests provide, the total carbon emissions associated with forest management, harvesting, log transport, and wood processing are minimal—equivalent to about 6 percent of the total pre-harvest carbon storage (and lower if wood biofuels are used during production). The carbon stored in forest products minus processing emissions "rises on a sustainable trend" and produces a net growth to the overall carbon pool.[30] While carbon pools from managed forests producing wood products lead to an increasing carbon storage potential over time, this potential can be increased by material displacement. Combining the emission offsets from using wood instead of other materials such as concrete and steel creates a sustainable positive trend in carbon storage at a rate of increase greater than the maximum rate of growth in forests.[31] Using wood displaces carbon emissions from the production of other materials and sequesters carbon from the atmosphere—both strategies for mitigating climate change.

Although exploitation of forests can accelerate climate change, the intelligent, balanced use of forests can benefit the environment. As the field of life cycle analysis continues to mature, building professionals will have a more accurate picture of material impacts and benefits. Substituting wood in place of non-wood products appears to have the potential to provide benefits that no other common building material can offer in terms of mitigating against the dangerous release of greenhouse gases.

A large percentage of the total amount of material used in a building is attributed to its superstructure. Therefore, using wood as primary structure can make environmental sense, especially with the wide variety of solid wood/mass timber materials and structural systems available, highlighted in the following chapters.

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3

Solid wood materials and concepts

LIGHT WOOD/MASSIVE WOOD

Pre-industrial wood buildings were either constructed by horizontal logs stacked on top of each other—known as log construction or "blockwork"—or by using vertical posts to create a skeletal frame construction or palisade structure. The details of these systems vary by region and culture, and over time have changed with advances in knowledge, technology, and availability of forest resources. Because civilization in the past advanced, generally, in lock-step with a decline in forest resources, the use of small dimensioned lumber as opposed to log or timber frame buildings allowed a more efficient use of materials and labor and largely replaced earlier building methods.

3.1.1 Engineered wood products.
Source: MERK Timber, Aichach, Germany (www.merk.de)

By the late 1800s, a system of wood construction using small dimension sawn lumber, known as light frame construction, took hold in many places. Several primary drivers account for this shift in construction methods from massive wood to light wood. First, the availability of old growth timber was becoming increasingly rare and expensive, and technological advancements like steam powered mills and inexpensive metal nail fasteners also quickened the rate of change.[1]

Augustine Taylor's 1833 St. Mary's church in Chicago replaced old mortise and beam connections with 2x4s and 2x6 studs, all completely held together by nails. Incredulous carpenters at the time looked on during construction and declared that this method was no more substantial than a balloon and would surely blow over in a strong wind. Despite the disbelief of old-time carpenters, not only did the name "balloon framing" stick, but because of the simplicity of construction and the lack of skilled labor in American cities, the system proliferated and ushered in a new era of construction.[2] By the 20th century, except in the most remote areas of the world or in special construction circumstances (such as long-span roofs), technological advances had changed wood construction from large timbers to small dimension lumber.[3]

Light frame construction

Light wood frame systems are composed of small dimensioned wood elements that make building erection simple. Individual pieces can be lifted by hand and fastened with conventional nails. The system is low cost, and accessible to amateurs and professionals alike. Construction is generally fast, flexible, and adaptable to the prefabrication of wall, floor, and roof building components as well as modular construction. However, light frame construction is limited in strength and robustness when compared to solid wood or mass timber building components. It faces engineering limitations in height, area, fire resistance, and structural capacity.

Solid wood/mass timber

Solid wood construction, also commonly referred to as massive wood or mass timber construction, represents both a return to more traditional forms of timber construction and an advancement in wood

3.1.2 CLT panel being lifted into place at Earth Sciences Building (ESB). See case study for more information. Source: Structurlam building technology that exceeds the structural limits of light frame wood construction. While solid wood construction may include large dimension solid sawn timbers and logs, it more commonly consists of engineered wood building products such as glue-laminated timber posts, beams and panels, laminated strand lumber (LSL), parallel stand lumber (PSL), laminated veneer lumber (LVL), cross-laminated timber (CLT) and nail or dowel-laminated timber. Mass timber construction involves only large-sized engineered wood products, the two terms (mass timber and solid wood) are used interchangeably here. Whereas heavy timber and traditional wood systems are generally single directional loading, vertical force resisting only, and manufactured from large dimension timbers, solid wood systems today can be used for both vertical and lateral systems and are made from built-up small dimension lumber or other types of wood fiber like veneers, strips, or chips. In addition to walls, floors, and roofs, solid wood elements can be used as stair and elevator cores. Solid wood systems can hybridize with steel and concrete to expand design options and meet project goals. Building codes change over time, but often a combination of wood and non-wood building components can meet building codes and satisfy code officials when an all-wood building cannot. Within solid wood construction there are a wide variety of material and design options.

SOLID WOOD COMPONENTS

Solid timbers

Traditionally, solid timbers are used either in horizontal stacked log construction or as vertical and horizontal members in a frame system. Using the rough tree trunk and tree limbs to create an enclosure is a point of origin for all construction.

Building with logs is an ancient technique and early form of solid wood construction. In this system, horizontal logs are stacked directly on top of each other. Log construction in Europe is often referred to as block construction because the trunks are squared-off, but round logs are also used. Without the need of sawing or milling, log construction offers simplicity in building, requiring only hand tools to prepare and erect the structure. Simplicity is expressed in the load-bearing wall acting doubly as structure and enclosure, leaving joints exposed and expressive of the construction. Gravity and self-weight draws the alternating layers together and they are connected using simple grooves, internal splines, or dowels. Two adjacent walls of the building are erected together and interlock at the corner ends to brace the structure.

While log structures use large quantities of wood, an inherent benefit is that these massive wood walls provide good insulation, which is especially important in the heavily forested yet cold climates of the north hemisphere and alpine regions. Wood naturally creates a warmer environment than stone construction and has long been prized for this benefit in colder climates like Scandinavia and Russia. The warmth of wood is related to its thermal conductivity, which is significantly lower than stone, steel, or concrete. Steel, for example, is 20 times more thermally conductive than wood.[4]

Using vertical logs to create a skeletal load-bearing structure is one of the oldest forms of building and developed in parallel with blockwork construction. However, unlike blockwork construction, skeletal frame timber buildings do not rely on stacking and massive exterior walls to create stability. Rather than relying on gravity, these structures rely on sometimes exceedingly complex wood joinery for stabilization.

Historically, timber frame buildings are stabilized through a variety of diagonal timber bracing techniques. In addition to common diagonal braces, there are also cross-braces, double cross-braces, and diamond braces.[5] The different bracing styles provide detail and ornamentation, especially on half-timbered buildings where the structure can be viewed on the exterior as an artisan expression of the building culture.

Industrial solid timber construction in places like the United States focused on mill construction—an interior solid wood timber frame, solid wood timber floors (generally tongue and groove) and non-combustible exterior wall construction, usually of brick. This approach called slow-burning construction (also known as semi-fireproof or fire-resistive) was well understood and detailed in sources such as the 1899 *A Treatise on Architecture and Building Construction*, which describes slow-burning construction:

> The individual members, such as beams, columns, etc, are so proportioned that they retain strength enough to do the work required of them even after one-third of their bulk has been charred or burned. Instead of a large number of small pieces, as in balloon and braced frame construction, there is a small number of very large pieces in the slow-burning construction.[6]

This type of timber construction, modified but still in use today, allowed for greater safety and reduced risk of loss due to fires while affording large spaces between columns for flexible interior spaces, and ample grid dimensions.

For buildings that primarily utilize solid sawn timbers, see the H4 and H8 case studies (pp. 173–187).

Engineered wood

Large solid sawn timbers present a potential issue for both the environment and the builder. The size of timbers needed for large commercial buildings can take a hundred years to grow, whereas engineered wood products can utilize younger trees, lower grade lumber, and a wider variety of tree species. To manufacture engineered wood components, individual small dimension lumber sticks are reassembled using adhesive and pressure to create a manufactured product which can have higher design values and less variability than the sum of its parts. The maximum dimensions of engineered wood components are variable between manufacturers and subject to change over time. The specific engineered wood components a manufacturer makes as well as the dimensions of these components depend on a variety of factors such as individual choice, cost of equipment, material standards, access to raw materials, demand, and technical limitations of fabrication equipment, to name a few.

The biggest benefit of structural composite lumber is the product's consistency and reliable structural performance characteristics. Solid sawn lumber can have knots and inconsistencies that reduce strength. Because of the shrinkage (radial and tangential) of timber due to reduction of moisture content after being sawn, large sawn timbers may split, check, warp, twist, cup, and experience dimensional changes that can reduce their strength and usability. Engineered wood products remove defects in the wood to provide a more consistent, stronger, and predictable product. These wood products can be used as wall, floor, roof, column, beam, or bracing systems, providing a great amount of diversity and flexibility in design. The combination of high strength and dimensional stability opens the door for larger, taller wood construction and more daring architectural expressions.

Glue-laminated timber (glulam)

Softwood species like spruce, fir, hemlock, and Douglas fir are commonly used for glue-laminated timber products. Invented near the end of the 19th century, laminated timber construction offered new potential for wood structures going beyond the growth limits of trees. It is believed that Otto Hetzer of Switzerland is responsible for developing what we know today as glue-laminated beams with his 1909 patent. A short time later, Hetzer's material was being used as load-bearing elements in large halls and bridges.[7] Glue-laminated beams can be very deep and readily laid up board by board to create curved sections. The product is often used for both columns (used vertically in the strong-axis) and beams (laid flat in the weak axis). Glue-laminated elements can also be affixed side by side to create larger panels of timber or block glued for thicker beams. When glue-laminated beams are fixed together to form larger panels a layer of plywood can be added to transfer lateral loads.[8] Because of the price and environmental concerns of using old-growth large dimension sawn timber, above certain dimensions glue-laminated timber is almost always used instead and is common in post and beam and roof construction. Through the 20th century, post and beam-style construction has dominated timber construction and engineering. Glue-laminated timber hybridizes well with other forms of solid wood and other types of solid construction. At less than 10 percent the weight of steel and one-fifth the weight of concrete, glue-laminated timbers offer increased efficiencies in transportation and construction.

For buildings that primarily utilize glue-laminated timber, see the following case studies:

- Egenes Park (pp. 115–120)
- Vennesla Library (pp. 131–135)
- e_3 (pp. 155–166)
- H4 (pp. 173–178)
- LCT ONE (pp. 201–216)
- Salzburg University of Applied Sciences Kuchl Campus Extension (pp. 217–226)
- Mühlebach (pp. 227–230)
- Tamedia (pp. 231–242)
- Bullitt Center (pp. 245–256)
- Earth Sciences Building (ESB) (pp. 265–270)
- North Vancouver City Hall (pp. 271–280).

Laminated veneer lumber (LVL)

Laminated veneer lumber (LVL), patented in the late 1960s, uses thin layers of softwood veneer, usually about 3–4 mm thick, that are glued together to make large format panels or billets. Generally, LVL plies are all oriented in the same direction, but the product can also be made with some interior plies oriented at 90 degrees to the main direction, providing two-way structural capacity. LVL can be incredibly strong in the longitudinal direction parallel to wood fibers, especially when the plies are all oriented in the same direction. Although manufacturers produce different-size panels, LVL billets can be over 18 m long, 1.5 m wide, and 275 mm thick. In solid wood

3.1.3 Glue-laminated timber panel during construction of Kuchl Campus Extension Building. See case study for more information on project. Source: Salzburg University of Applied Sciences

3.1.4 LVL columns, beams and floor components during construction. Source: Brisco Manufacturing Ltd.

3.1.5 LVL-glulam floor cessettes for Kuchl Campus Extension Building. See case study for more information on project. Source: Dietrich I Untertrifaller Architekten

3.1.6 Laminated Strand Lumber used for ceiling at North Vancouver City Hall. See case study for more information. Source: Michael Green Architects

systems, LVL can be utilized as large dimension panels for floors, roofs, and walls, or as columns and beams. Another benefit of LVL is that the product can use small dimension, rapidly renewable tree species.

To take advantage of LVL's strength and efficiency, it can be combined with other panel products (like CLT) or used in hollow box floor and roof cassettes. These cassette elements are constructed from two (top and bottom) panels that sandwich wood ribs (generally glue laminated) to create a structural cross-section with good spanning characteristics.

For buildings that primarily utilize LVL, see the following case studies:

- Salzburg University of Applied Sciences Kuchl Campus Extension (pp. 217–226)
- Mühlebach (pp. 227–230)
- NMIT Arts Building (pp. 293–304)
- Te Ara Hihiko (pp. 305–320).

Laminated strand lumber (LSL)

Laminated strand lumber (LSL) is similar to LVL in many ways, but instead of layering thin veneers it is made from layering flakes of wood pressed together with adhesive. Recent advancements have allowed flakes for LSL to be taken from notably small diameter tree branches. LSL is usually lower in strength than LVL but greater than laminated lumber products. These panels are able to take high stresses and can have bending and shear design values up to 2.5 times higher than cross-laminated timber panels.[9] Like LVL, LSL can come in large format sizes.

For buildings that primarily utilize LSL, see the following case studies:

- Earth Sciences Building (ESB) (pp. 265–270)
- North Vancouver City Hall (pp. 271–280).

Parallel strand timber (PSL)

Parallel stand lumber (PSL) is manufactured from wood strands/strips (longer than those used in LSL) oriented in the same direction and combined with adhesive to form large format billets. PSLs are used in applications where high bending and/or compression stress is needed, such as long-span beams, columns, and header applications. As an engineered wood product, PSL can be manufactured in long lengths, however, PSL billets are generally limited to about 20 m and found only in North American markets. They can range up to around 265 mm thick and widths of around 460 mm.[10]

For a buildings that utilize PSL, see the North Vancouver City Hall case study (pp. 271–280).

Cross-laminated timber (CLT)

Cross-laminated timber (CLT) was first patented in France in the mid-1980s, but development of the product was driven in southern Germany and Austria in the 1990s. CLT was developed originally as

3.1.7 CLT production shop. Source: KLH

3.1.8 Modular CLT housing for 2005 Olympic Games in Torino. Source: KLH

3.1.9 CLT panels being prepared for lifting. See BioEnergy Research and Demonstration Project for more information. Source: McFarland Marceau Architects a way to reduce waste in saw mills as side cuts from dimensional lumber and glue-laminated timber were unutilized or went into a less valued production stream. Not only does CLT capture a commonly wasted resource, but it is also capable of utilizing wood of smaller dimensions and lower grade, while at the same time yielding a high-value structural grade panel.

CLT can be explained as a massive plywood panel replacing thin layers of veneers, typical in plywood, with dimensional finger-jointed lumber (like glulams) oriented with the wide face in the plane of the glue line. Each layer of planed lumber is arranged at 90 degrees to the following layer and then glued together in an odd number of layers, either three, five, seven, nine, or more layers with outer fibers parallel to the principal loading direction. In vertical applications the outer layers should be oriented with the grain running vertically, and in horizontal applications the grain of the outer layers should run parallel to the longest span direction.[11] After gluing, the panels are pressed in either a vacuum press or mechanical press and pressed in multiple directions where they set and achieve final strength. High-pressure mechanical presses are able to suppress natural tendencies in the wood to warp, and consequently produce a more stable and robust panel. Press type can also affect delamination tendencies in fire scenarios.[12] After curing of the panel, it is sanded and cut to exact dimensions (with openings such as door and windows also factory cut) with a multi-axis computer numerical controlled (CNC) machine. Early production of CLT was characterized by vacuum press technology and phenol-resorcinol formaldehyde (PRF) adhesive, but CLT production has shifted to mechanical presses and the use of formaldehyde-free emulsion polymer isocyanate (EPI) adhesives like one-component polyurethane (PUR).

The cross-banded orientation and attachment of layers translates into panels that are monolithic and experience very little shrinkage in either the vertical or horizontal directions. This stability can result in very precise tolerances for prefabricated construction applications. Air infiltration is also greatly reduced by the cross-banded orientation of the layers, especially when the manufacture includes edge gluing, which is when the narrow edge of the lamella are glued within the lamination layer. However, the panels do experience a small amount of shrinkage perpendicular to the grain, which should always be considered in multi-story applications.

The first CLT project was executed in 1993 and in 1998 the first multi-story residential CLT building was completed in Styria, Austria. A major moment for CLT occurred in 2005 at the Olympic Games in Torino where a four-story modular CLT building to house journalists was completed.[13]

For buildings that primarily utilize CLT, see the following case studies:

- Graphite Apartments (pp. 47–56)
- The Hive (pp. 91–100)
- Woodland Trust (pp. 83–90)
- City Academy (pp. 61–74)
- Bridport House (pp. 75–82)
- Svartlamoen Housing (pp. 105–110)
- Svalbard Housing (pp. 111–114)
- Egenes Park (pp. 115–120)
- Limnologen (pp. 141–150)
- H8 (pp. 178–188)
- Alpenhotel (pp. 191–200)
- Salzburg University of Applied Sciences Kuchl Campus Extension (pp. 217–226)
- Forté (pp. 321–332).

Adhesives

The manufacture of engineered wood products relies heavily on adhesives. There are many different adhesives (also called resins) available with different bonding characteristics, durability and chemical make-up. The wood species also affects adhesive performance. A crucial issue for structural composite lumber is the adhesive's ability to transfer loads between laminations. All suitable adhesives for structural wood products create bonds stronger than the wood itself. Durability in the presence of water is also critical for adhesive laminated structural elements.

Formaldehyde, produced naturally by many plants and animals, is a carcinogenic binder commonly found in wood resins such as phenol-resorcinol formaldehyde and can cause health concerns. In addition, the production of resin is energy intensive. Resins for LVL may account for around 16 percent of total cradle to gate energy use, 19 percent for plywood, and 8 percent for glulam, depending on the area and manufacturing process.[14] The contribution of the resin production to the overall environmental footprint of the product varies. Energy use and the chemical properties of resins influence cost and also are an important component in the overall "green" assessment of modern engineered wood products. Different wood products use different adhesives. Some common adhesives used for structural applications for engineered wood products include, but are not limited to, phenol-resorcinol formaldehyde, emulsion polymer isocyanate, and one-component polyurethane.

Non-adhesive-based solid wood

In addition to the use of adhesives to manufacture solid wood elements, a variety of fabrication methods exist that do not rely on adhesives. Sometimes referred to as brettstapel, these non-adhesive-based solid wood systems have been used for over 100 years, and new types are being developed and refined to improve performance and durability. As adhesives are largely petroleum-based and contribute to the environmental footprint of a mass timber element, eliminating adhesives reduces the overall embodied energy in the production of timber elements, and also eliminates chemicals that can off-gas and pose end-of-life disposal questions.

Individual wood planks that make up these elements can be nailed, doweled, or dovetailed. While the elements were originally nailed, it is common now to see these elements joined into large

3.1.10 Dowel laminated panel being lifted into place. For more information see e_3 case study. Source: Kaden + Partner Architekten

panels by steel or wooden dowels from a variety of manufacturers. The ability for mechanically fastened solid wood elements to act as a single component when transferring loads is dependent on the connection type and the calculation of lateral capacity.

Nail-laminated elements

A traditional solid wood element involves the use of nails to fix timber planks into large homogeneous elements. Here light wood dimensional boards are fixed side by side using nails to bind the individual layers. Sometimes cross-laminated, these elements are usually stacked uniformly in the same orientation and built up to be a larger member. Traditional industrial heavy timber buildings often used nail-laminated floor construction to span between solid sawn timber post and beams. These wood elements, however, can be used as solid wood walls, floors, or roofs. The individual members can also be bent and assembled to create curved roofs or other custom structures. Because of the simplicity of this system, most timber manufacturing companies or carpenters have the ability to assemble these types of components. Nail-laminated elements can either be assembled on-site or pre-manufactured as panels for faster construction times. Due to the nature of their construction, nail-laminated elements are not airtight and will need additional layers to create an airtight, smoke-proof assembly that also meets acoustic standards. To deal with lateral loads, a layer of plywood sheathing can be added over the top of the nail-laminated timber elements.

For buildings that primarily utilize nail-laminated elements, see the following case studies:

- e_3 (pp. 155–166)
- Ilmasi (pp. 167–172)
- Bullitt Center (pp. 245–256)
- CIRS (pp. 257-264).

Dowel-laminated elements

A second common form of non-adhesive solid wood elements uses dowels to bind laminations together. The dowels can either be metal or wood. The use of threaded metal rods bolted at each end can lock stacked wood planks together into a solid element. The use of wood dowels, however, does not rely on nuts and bolts to lock the layers together. Instead, wood dowels work by controlling the moisture content of both the planks and the dowels during manufacture. Dried softwood planks, typically of fir or spruce, have a moisture content between 12 and 15 percent, while the hardwood dowels, often made of beech, are dried to a lower moisture content of around 8 percent. This moisture differential locks the elements together because the hardwood dowels, seeking moisture equilibrium, will swell and expand after manufacture. Continual swelling and shrinking due to changes in relative humidity can potentially cause separation of the planks over time, but good manufacturing can alleviate this.

3.1.11 Thoma Holz100 cross-banded doweled wood element used for Woodcube project. Source: IBA/Martin Kunze

Dowel-laminated elements can be either stacked on edge or cross-banded. Cross-banded doweled timber elements are similar to CLT but use wooden dowels in place of adhesive resins to create a 100 percent timber element. The arrangement of wood layers can also be different than CLT. Solid wood doweled elements generally consist of one vertically oriented central layer and several layers of horizontally oriented or diagonally oriented layers.[15] Semi-rigid wood fiber insulation can even be incorporated into the final build-up. Each layer does not necessarily have a 90 degree orientation from the last, and the exact build-up and orientation of layers is project specific, depending on the engineering requirements. Although generally used as walls, cross-banded doweled elements can also be used for floor and roof constructions with panels from 12 to 40 cm thick. The panels are generally thicker than CLT elements, and because each layer is not locked by adhesive, doweled layers may experience movement and exhibit less strength than CLT. Cross-banded dowelled timber elements can offer some degree of airtightness where elements stacked on edge cannot.[16]

In contrast to dowels, wood screws can also be used to bind together multiple layers of wood panels. Interlocking-laminated elements that use dovetail joints to lock individual boards into large format panels is another option under development.

For buildings that primarily utilize dowel-laminated solid wood elements, see the following case studies:

- Pulpit Mountain Lodge (pp. 121–130)
- Woodcube (pp. 153–154)
- Mühlebach (pp. 227–230).

Hybrid and composite construction

Using wood in buildings can take a variety of different forms. A building can be completely wood, or else parts of the building can be constructed from non-combustible materials in combination with wood to meet certain code or project requirements. Often wood buildings may sit on non-combustible podiums or have non-combustible vertical egress cores. Some buildings, however, are primarily built from non-combustible materials but have a wood façade system for better energy performance. Other materials may be introduced into the structure for better spanning, acoustic, or bracing capabilities. Solid wood buildings that also use concrete, structural steel, load-bearing masonry, or other structural materials are known as hybrid buildings. While hybrid buildings may impact the structure's environmental footprint, introducing other materials can allow more options in design. The incorporation of steel can provide longer spans and allow for large, open column-free spaces. Structural steel can provide shallower headers, beams, and columns if space is restricted on the site or more area is needed for heating ventilation and air conditioning (HVAC) coordination. Concrete, when used at the first levels of a building, protects wood elements from moisture, insects, and potential damage from unforeseen impacts. Concrete can also provide improved acoustics and fire safety. It is often used for stair and elevator shafts and can provide lateral resistance for multi-story projects when used as shear walls. Other hybrid applications may include the use of sand or other aggregate in floor construction for better acoustic performance.

When using hybrid construction, differential movement between materials must be accounted for. Because wood has different thermal and moisture expansion properties than concrete and steel, it is essential to account for movement between the elements at the interfaces. Hybrid construction, rather than all-wood construction, may complicate the design, and inaccuracies in concrete and steel construction during on-site erection can cause installation problems with highly accurate prefabricated timber components.

Post-tensioned timber

Pres-Lam is a composite system of wood and internal steel post-tensioned strands that allows for long column-free spans, excellent seismic resistance, and multi-story applications. The post-tensioned timber system, similar in theory to well-established post-tensioned concrete systems, was developed by a research consortium of academics and timber industry representatives from New Zealand, and is a prefabricated system of structural beams, columns, floor joists, and walls. The Pres-Lam system can theoretically be built to 10 stories or more, although the first commercial buildings range from three to five stories.[17]

Typically the system uses fabricated LVL billets for the main structural wood elements, but glue-laminated timber and CLT are also suitable. Unlike traditional CLT design, which relies on many internal load-bearing shear walls for stabilization, Pres-Lam allows open interior spaces by using a hybrid/composite wood moment frame design. This makes the Pres-Lam system ideal for commercial buildings in seismic zones or areas of high wind loading and where considerations of low-embodied energy of building components are important.

Structural elements in the Pres-Lam system are constructed hollow with full-length ducts that allow for the placement of post-tensioning steel tendons inside of the structural elements. Lateral load resistance is carried either by moment frames or by cantilever shear walls. Many buildings will use walls in one direction and frames in the other for stability. Using moment frames, the beam-to-column connections are made by horizontal tendons running inside the full length of the beams and passing through the columns. Structural walls have internal vertical tendons anchored to the foundation and stressed from the top of the wall.

During construction, the steel tendons are tensioned, tying the building together both horizontally through the beams and vertically from the foundation to the top of the column or wall structure if large hold-down forces are required. Load-bearing partition walls can be spaced at greater intervals or eliminated depending on the spatial organization. Post-tensioning also allows for more slender structural wood elements which are typically stressed only parallel to the wood grain, creating an efficient, strong system. This has the double benefit of resource efficiency and the creation of interior spaces less encumbered by deep beams and thick floor assemblies. The timber beams and columns are approximately the same size as

3.1.12 Tensioning steel cables in post-tensioned timber frame. Source: Professor Andy Buchanan, University of Canterbury

a similar concrete design, yet have only one-quarter the weight. This lightweight nature reduces dead load and helps contribute to long spans. The Pres-Lam system typically uses hybrid LVL and concrete floors with composite action created by either notches in the LVL joists or screwed shear fasteners.

The University of Canterbury in New Zealand has subjected a full-scale prototype building to earthquake forces measuring up to eight on the Richter scale with no permanent structural damage. Because the system is a kit of parts, at the end of the building's life cycle it can be disassembled and reassembled in a different application. The Expan building on New Zealand's University of Canterbury campus is an example. Following months of seismic lab testing, the undamaged structure was dismantled and re-erected as an office building on the campus.

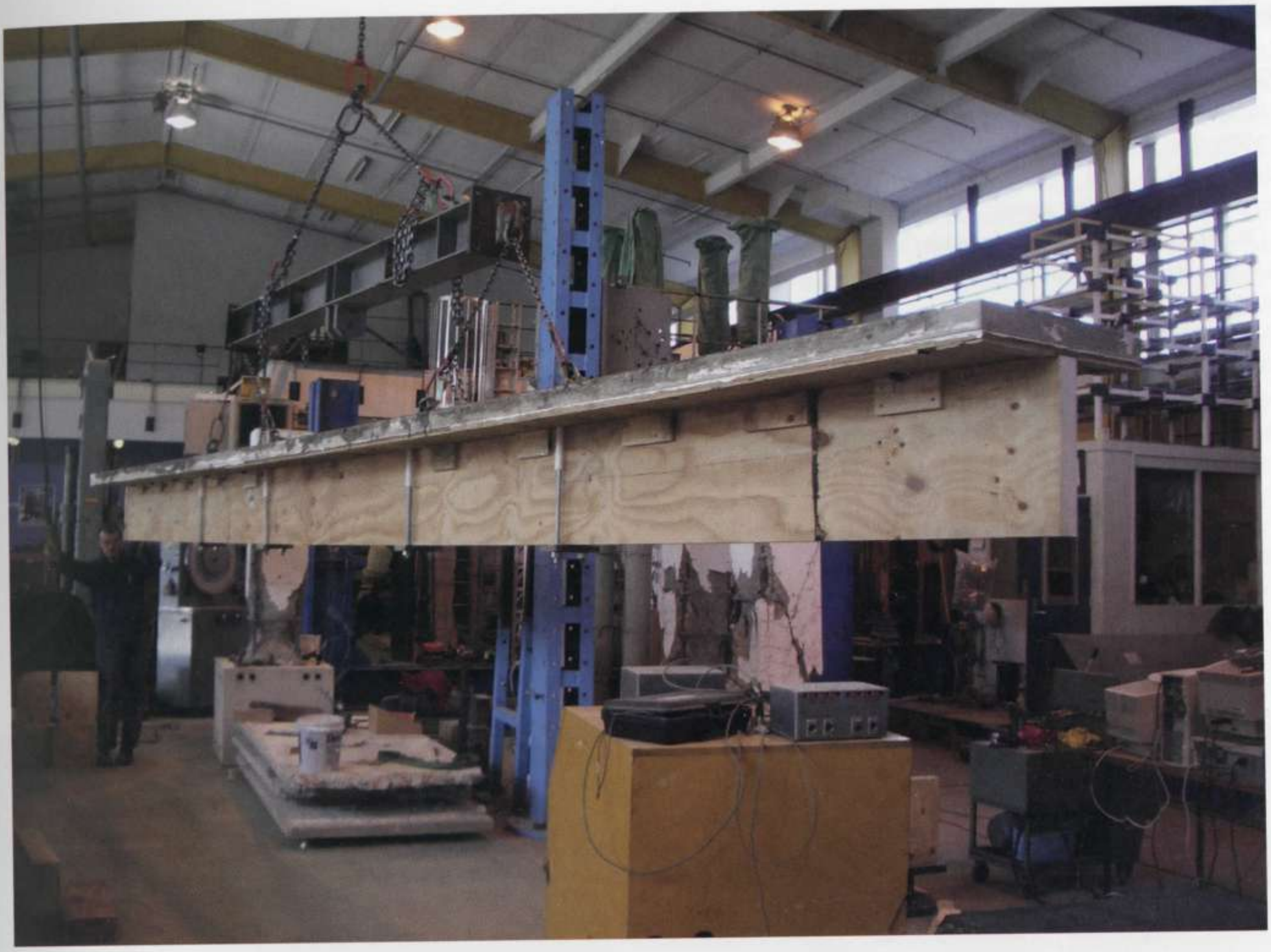
Compared to traditional light wood frame construction that relies on hundreds of nail or screw connections, Pres-Lam's ductile, moment-resisting connections and shear wall connections can be made in one post-stressing operation—a major benefit for time and economy of construction.[18]

For buildings that primarily utilize post-tensioned solid wood systems, see the following case studies:

- NMIT Arts Building (pp. 293–304)
- Te Ara Hihiko (pp. 305–320).

Wood and concrete composite floors

As opposed to thin topping slabs, composite timber and concrete floors act in unison with each other through the combination of a variety of shear connectors. Composite timber and concrete action offers special advantages in floor systems. In these systems, the concrete acts in compression and the timber acts in tension, thereby using each material's inherent strength. For longer spans



3.1.13 Composite LVL-concrete floor panel. Source: Professor Andy Buchanan, University of Canterbury

3.1.14 Steel mesh epoxied into CLT floor panels before pouring concrete slab. Source: Structurlam or heavier loads, a composite floor provides added stiffness and the ability to handle increased live loads. Composite floors also minimize deflection in the floor system as wood floors have the tendency to sag (creep) over time especially at mid-span areas. Vibration due to human-induced footfall excitation is often the limiting factor in solid wood floor design rather than span, and concrete can improve this aspect. The concrete topping slab can be used to improve acoustics, but also adds thermal mass and provides a rigid diaphragm to distribute lateral forces while allowing longer floor spans.

A variety of wood products can be used in composite floors, including glue-laminated timbers, solid timber, and solid timber panel elements like CLT and LVL. For the two materials to work in unison, shear connection must be established between them. This can be accomplished through either interlocking shear connection or the use of shear connector hardware.[19]

Proprietary screws are a common connector specifically developed for timber–concrete composites. A variety of other hardware shear connectors exist, such as lag screws, punched metal plates, steel brackets, and mesh. When using steel mesh, long narrow grooves are routed out for the insertion of the steel elements which are held in the wood by an adhesive bond. Concrete is poured over the top creating a mechanical interlock and the steel mesh plates create composite action between the wood and the concrete. These systems can be further improved by using troughs or dado joints in the wood surface, thus combining shear connection hardware with interlocking shear connection.

For buildings that primarily utilize composite timber–concrete floors, see the following case studies:

- Woodland Trust (pp. 83–90)
- e_3 (pp. 155–166)
- LCT ONE (pp. 201–216)
- Mühlebach (pp. 227–230)
- Earth Sciences Building (ESB (pp. 265–270)
- North Vancouver City Hall (pp. 271–280)
- NMIT (pp. 293–304)
- Te Ara Hihiko (pp. 305–320)

WOOD TECHNOLOGY AND MANUFACTURING

Computer numerical controlled (CNC) machines integrated with digital design and fabrication software have transformed wood manufacturing into a high-tech industry. First seen in the 1980s, digital joinery machines can now cut timber in virtually any form with a variety of tools from circular saws, to chain saws, drills, routers, and more. Interest in five-axis CNC machines has grown as they allow the possibility of full 3D contouring and integration with 3D-modeling software.[20] While CNC machines that cut on three- and five-axes are common, some CNC machines that resemble robotic arms (industrial robots) from the car manufacturing industry can cut on as many as eight or more different axes.

Three-axis CNC machines, as the name implies, are able to move and cut along the X, Y, and Z axis. A five-axis machine allows timber to be cut on a slant to the horizontal plane and moves like a human wrist along the two additional axes.[21] High-tech machining allows highly crafted, unique, or repeatable wood elements to be quickly manufactured at accuracy rates in the range of 0.05 to 0.10 mm.[22] The Metropol Parasol in Seville, Spain for example, consists of 3,400 unique individually CNC-milled raw LVL panels up to 311 mm thick, 3.5 m wide, and 16.5 m long, assembled to form one of the largest wood structures in the world. Macro-scripting allowed for a semi-automatic process for the detailed calculation and fabrication of the individual timber elements and connections based on architect Jürgen Mayer H and engineers at Arup, leading to a seamless digital design to fabrication process. The use of digital tools ensured absolute precision for the timber parasols, and enabled all components and the erection process to be carried out with minimal tolerances. Cutting of the individual LVL panels was optimized by nesting pieces of the same thickness to minimize waste. The elements were precisely cut down to the millimeter by a CNC-controlled trimming robot, and were milled and notched at the same time.[23]

3.1.15 CNC fabricating wood building component. See Tamedia case study for more information. Source: Blumer Lehmann AG

3.1.16 Manufacturing wood components using a robotic arm CNC machine. Source: MERK Timber, Aichach, Germany (www.merk.de)

Solid wood manufacturing process is usually based on individual orders so plants do not keep stockpiles of products like CLT on hand. Modern wood manufacturing is a bespoke product manufactured under industrial conditions using advanced and expensive manufacturing equipment. Timber manufacturers may take jobs from other companies to keep their machines running and avoid downtime. To increase productivity, timber manufacturers often employ a kind of nesting strategy, wherein they run several jobs at the same time in order to get the most efficient use of materials, cutting time, and energy. The combination of industrial and digital technologies enable fast construction times, high-performance prefabrication, modular design and extremely tight precision and tolerances in manufacturing and construction on-site. While curved and intricately cut timber elements are mechanically machined, humans still assemble these pieces into final prefabricated elements in the warehouse and bring them together on-site. Technology, while vitally important, still depends on the human hand.

3.1.17 The Metropol Parasol in Seville, Spain during construction. Source: Jan-Peter Koppitz, Associate at Arup

The integration of technology and availability of a wide array of wood building products and systems has created a fertile field for advances in prefabrication and modular design. Wood, because it is easy to craft and lightweight for easy transportation and lifting (wood weighs around 560kg/m^3 (35 pounds per cubic foot (pcf)), concrete and steel weigh 2,403kg/m^3 (150 pcf) and 7,849kg/m^3 (490 pcf), respectively), is the most accessible material for prefabrication.[24]

Solid wood and prefabrication

Several different types of prefabrication exist. The simplest type of prefabrication involves individual structural pieces cut to size and delivered to site. For example, wood studs for frame wall construction can arrive pre-cut; glue-laminated columns and beams are usually pre-cut and numbered for easy installation in the field.

The next step in prefabrication includes constructing entire wall or floor components in a factory and shipping them to site, known as panelized construction. The building enclosure is often the most common type of prefabricated unit. Both load-bearing and non-load-bearing exterior walls offer a range in extent for prefabrication in the multiple layers that make up the wall. More advanced prefabrication involves affixing insulation, air and weather barriers, windows, doors, services, and exterior cladding all in the factory. Similarly, wood floors are readily prefabricated, either as hollow box cassettes, CLT timber plates, or a combination of different wood elements with plumbing and services pre-installed in the factory. This level of prefabrication adds a level of oversight with inspections as covering wood structural elements may require inspectors to come to the factory.[25]

3.1.18 Prefabrication of solid wood wall panels. See H8 case study for more information. Source: Huber & Sohn

Proper sequencing is essential when prefabricated elements arrive on-site. These elements must be closely tracked and erected in the right order and correct orientation for this type of construction to be cost efficient. The designer should strive to limit the number of joints and connections in prefabricated buildings, as these are weak points for air and water infiltration, and can contain an inefficient doubling of structure at joint locations. To increase efficiency, the building can be rigorously designed to the maximum dimensions of panels and wood components to eliminate waste, reduce costs, minimize joints, and speed up construction.

When floors/ceilings and walls are combined, modular prefabricated box units are an additional option for on-site efficiency. Modular units can be attractive in building types that have a high degree of repetition and do not require large open spaces. Building types such as multi-family housing and hotels present themselves well to modular construction. One of the most important attributes of CLT modular unit construction is that the boxes are in themselves stable and can be stacked on top of each other without requiring a second independent frame.

In general, the more prefabrication or modular construction that takes place in a factory, the more savings that can be achieved on-site. However, transportation costs, sequencing, on-site storage and labor costs all must be accounted for. Furthermore, all design issues must be well resolved before construction starts when utilizing prefabricated components. Solid wood elements or full building components are not easily field modified and waiting for replacement panels or modules can hinder construction schedules. Prefabrication requires aggressive building coordination in the design phases. In many countries there is development in complete prefabricated wood building systems, designed for speed of erection and high-quality craftsmanship—two characteristics that without hi-tech manufacturing facilities are not generally equated with one another. Repetition is a general prerequisite for prefabricated design. The more repetition in a design, the more effective prefabrication becomes. This presents a problem for architects who often desire each building to be a unique work unto itself. Finding a good balance between repetition and uniqueness is necessary for architects to adopt prefabrication and architecture to remain expressive yet cost effective.

While technology is the future of wood design and construction, there are obstacles. Design software and manufacturing software are distinct: the digital software (computer aided design or CAD) tools used by building designers do not necessarily communicate seamlessly with the (computer aided manufacturing or CAM)

3.1.19 Solid wood wall prior to factory installation of gypsum board, insulation and exterior cladding. See H8 case study for more information. Source: Huber & Sohn

3.1.20 Installing gypsum board cladding to prefabricated wall in the factory. Source: Huber & Sohn software used by manufacturers. CNC machines, for example, cut elements along predefined paths and movements which is data not supplied by the designer. A building often has to be designed twice, once by the designers and once by the manufacturer.

SIMPLICITY AND MASS CUSTOMIZATION

Even after years of use in some areas, mass timber systems like CLT are still referred to as an "alternative" building material and may be perceived as risky by clients and designers. In addition, wood engineering is often poorly covered in university curriculum, creating gaps of knowledge and serving to restrict wood use by professionals. High-technology solid wood systems, however, offer the potential for simplified, efficient construction, reducing the perceived risk of wood and opening channels for its use. To simplify design, the architect, engineer, and contractor must all be comfortable with using the material, which can be a problem due to lack of experience. Unfortunately, because of this lack of experience wood may often never make it to the table, yet it can be as simple to use as concrete and steel. To create real efficiencies, wood should be conceptualized very early in the planning and design process and outside expertise, if necessary, should be sought early.[26]

As well as having fewer trades on-site and fast erection, simplicity in detailing can be another advantage of solid wood building. Solid timber panels can be erected in standard platform style construction and fastened with a minimum of simple components. Even for multi-story buildings, the structure can be constructed using only panels, brackets, and screws. The prefabrication of wood elements or modules also simplifies on-site construction as much of the detailed work has occurred in the factory (because of their prefabrication, this causes a shift in cost as solid wood components may be higher in material cost, but on-site construction costs may be less, depending on the particulars of the project) and the building can be erected as a kit of parts.

Simplicity also means that the building can be detailed easily with minimum transitions and fussy material interactions. Such construction speeds up erection time and reduces the risk of mistakes. Simplicity can make a solid timber structure, especially large panelized construction, inherently low risk in terms of building performance due to the lack of material interfaces. Increased component interfaces not only pose problems for moisture intrusion, but also make airtightness problematic, as each connection point must be properly sealed. The inherent mass of a solid timber structure can also provide more thermal stability than lightweight construction, which in turn can contribute to energy savings. With energy performance requirements increasing, the risk of non-compliance can pose a serious cost to any project. Solid wood construction offers a reliable path to compliance.

Not all mass timber buildings, however, are simple. Program requirements and projects with ambitious span, acoustic, or height goals, as well as buildings using multiple materials or in areas with high wind loading or seismic activity can add complexity. However, wind and seismic activity is largely a building code issue, not a "physics" issue because solid wood lends itself well for high wind and seismic activity. Smart design, engineering, and early coordination and detailing can help meet design criteria. When looking at the entire mix of benefits, solid wood can be the right choice in terms of breathability, sustainability, durability, structural performance, and ease of construction.[27]

Wood also allows for mass customization. When each piece in a building can be cut and machined uniquely, rather than relying on pre-manufactured stock components, designers are empowered and possibilities for responsive architecture expanded. In this way highly individualized buildings with complex geometries can be manufactured in the factory as they are drawn in the architect's office, and erected quickly on-site.[28]

Despite the advances in technology and fabrication, the majority of wood buildings are still erected piecemeal on-site in a process that has changed little in the last hundred years. Solid wood materials and integration with design technology and prefabrication allow for an evolution of the construction site beyond better construction tolerances and improved craftsmanship. Such an evolution could produce less on-site waste, less noise, and faster construction while allowing for the use of simpler tools for assembly by workers who may not be greatly experienced in wood construction. Solid wood architecture and construction offers the possibility to modernize the design and construction field.

NOTES

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