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CROSS LAMINATED TIMBER: A SUSTAINABLE OPTION IN THE WORLD OF CONSTRUCTION

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ABSTRACT

The construction industry uses many energy-intensive, non-sustainable products like concrete and steel to construct high-rise buildings. While there are three main types of timber that can be used in modern construction, there is only one type that can be used to build high-rise buildings comparably to steel and concrete because of its high axial load and high dimensional stability. That type is cross laminated timber (CLT). There are many advantages to CLT because it is a sustainable material that requires less manual labor and time. However, it is not well known yet in the construction world and has some design drawbacks as well. Recent developments with seismic analyses by the American Wood Council, Jeena Jayamon, and Dr. Finley Charney led to a study done over the summer of 2016 in which CLT was compared to other wood-based designs. With more testing and reliably designed buildings, this sustainable, efficient material could be one of the forerunners in construction in years to come.

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Chapter 1

Introduction

Cross Laminated Timber (CLT) is a building material composed of lumber boards layered perpendicularly and bonded with adhesives to create a construction material with strength rivaling that of steel and concrete. Although not widely used in the United States, CLT is used in Europe and Canada as an environmentally-friendly alternative to traditional building materials. In 2010, the building sector (including designing, building, and operating buildings) was responsible for 44.6% of all USA CO_2 emissions ("Why the Building Sector?" 2017).

According to *MIT News*, worldwide steel production releases about 1.5 billion tons of carbon dioxide (CO_2) per year, which accounts for 5% of the world's total greenhouse gas emissions (Chandler, 2013). Global emissions from cement production were 2 billion tons in 2011, also around 5% of the world's total emissions ("Concrete, Cement, and CO2," 2015). Though research is being done to improve and reduce these emissions, the environment and the world of construction would greatly benefit from a viable, sustainable, and cost-effective alternative to steel and concrete such as CLT. Advantages to using CLT include sustainability, lower labor costs, and higher efficiency in production and construction. The disadvantages are that it is not yet well known in the construction world, and it lacks a large body of research data to support its viability as a material useful for the construction of larger buildings.

Chapter 2

Environmental Impacts of Wood

Wood has been a sustainable construction material throughout history. In sustainably managed forests, “trees can be grown, harvested, replenished, and then harvested again and again in an ongoing cycle of harvest, renewal, and growth (Howe and Fernholz, 2016).” Forests allow for diverse ecosystems with a wide variety of habitats for wildlife species. Timber also absorbs carbon dioxide, and it is estimated that 15% of total greenhouse gas emissions (955 tetragrams of carbon dioxide equivalent) were offset in 2012 (Oswalt et al, 2014). Another 270 Tg of carbon dioxide was sequestered by forest ecosystems and released during wildfires (Oswalt et al, 2014). According to “Building with Wood,” US forests contain 1 trillion cubic feet of wood and add about 26.5 billion cubic feet of new growth annually (Howe and Fernholz, 2016).

The US currently consumes more wood than any other country. The forestry and lumber industry employs about 900 thousand people and has a $50 billion payroll, US forests have a large impact on the US economy representing 4.5% of the US manufacturing GDP (Howe and Fernholz, 2016). The US consumes 28% of the earth’s industrial wood products (Oswalt et al., 2014). Manufacturing of lumber products and using wood in construction also generates little waste as compared to steel and concrete. Mass timber is easy to use as it requires fewer skilled construction laborers and has a rapid construction time (Cross Laminated Timber: The Hulk, 2016). Lumber is largely consumed in home construction.

In 2011, 88% of timber harvested in the USA came from private forests (Oswalt et al., 2014). In recent years, harvesting has moved from public lands in the West to private lands in the East, particularly in the South (Oswalt et al, 2014). This can be an issue because the impact of wood extraction can be detrimental to the environment if not done responsibly. All timber farms on public property are regulated by the US Department of Agriculture (USDA) and the US Forest Service (USFS) (“Laws and Regulations,” 2017). While only 8% of all family or individual forests that are harvested have a written management plan, these owners account for upwards of 24% of total forest land (Oswalt et al, 2014).

The top three types of wood-based systems used in load-bearing construction are Nail Laminated Timber (NLT), Glued Laminated Timber (Glulam), and CLT (Cross Laminated Timber). The main types of wood used in each is shown in Table 2-1. Wood is used both in load-bearing structures as well as decorative components designed to increase the aesthetic appeal of buildings all over the world. According to ReThink Wood, a representative of the softwood lumber industry, mass timber products such as NLT, Glulam, and CLT are "cost-competitive, carbon efficient, sustainable, reliable, [and] suitable candidates for some construction applications that currently use concrete, masonry, and steel (Tall Wood/Mass Timber, 2016)."

Table 2-1: Types of Wood Used in Engineered Timber (Tall Wood/Mass Timber, 2016)

	Main Types of Wood Used				
Type of Engineered Timber	Spruce-Pine-Fir	Douglas Fir	Black Spruce	Alaska Yellow Cedar	Port Orford Cedar
Nail Laminated Timber (NLT)	X	X		X	X
Glued Laminated Timber (Glulam)	X	X	X		
Cross Laminated Timber (CLT)	X	X			

Studies show that the three main types of construction materials account for a significant amount of carbon dioxide sequestered by the three main types of construction materials made with timber (See Table 2). This information has provided many researchers with the data to say that building with timber not only reduces the amount of carbon dioxide released into the air compared to concrete and steel, it also sequesters it.

Table 2-2: Amount of CO_2 Sequestered in Engineered Timber (ReThink Wood (NLT), 2016)

Type of Engineered Timber	Amount of CO_2 Sequestered
Nail Laminated Timber (NLT)	1655 kg per tonne
Glued Laminated Timber (Glulam)	1640 kg per tonne
Cross Laminated Timber (CLT)	1643 kg per tonne

Several studies give insight into the environmental impact of producing lumber for use in buildings. One such study looks at producing hardwood lumber for use in flooring, furniture, and other typical uses. According to Bergman and Bowe of the University of Wisconsin, the US produced 882 million ft^3 of hardwood lumber in 2005 (Bergman and Bowe, 2008). Though most of this was used domestically, there was also a large amount exported (112 million ft^3). As “green building” has increased in popularity in the US, more lumber has been utilized in mid-rise residential buildings to increase the percentage of green buildings.

While not directly correlated to softwood lumber, one study examines the Life-Cycle Inventory (LCI) of hardwood lumber to set a baseline for hardwood lumber production. The researchers studied each component with energy-consuming properties such as sawing, drying, fuel consumption, wood-fuel consumption, and thermal energy in the lumber. They found that increasing the sawing efficiency, where most of the energy for lumber production arises, would reduce the amount of electricity consumed; increasing the on-site wood fuel consumption would reduce GHGs but increase the particulate emissions; and the energy required in the drying process could be reduced by increasing the amount of air-drying vs kiln-drying (Bergman and Bowe, 2008). All of these positive changes in the processing of hardwood lumber could increase the efficiency and lower the amount of energy needed, making it even more “green” (Bergman and Bowe, 2008).

Studies on Mass Timber Environmental Impacts

Another significant study conducted by WoodWorks on non-high-rise buildings compares wood to steel in a one-story retail facility. The layout of both buildings is the same, with columns evenly spaced at 30' to 45'by 30' to 64' as well as gross floor area, floor plan and layout, functions, location, orientation and operating energy performance (WoodWorks 2015). Coldstream Consulting undertook the life cycle assessment (LCA) cradle-to-grave analysis of the structure and envelope, and SSA Quantity Surveyors did a detailed cost comparison with the theoretical structures.

The LCA performed used 6 of 22 different environmental indicators from a European standards committee, including global warming potential, ozone depletion potential, acidification potential, eutrophication potential, smog potential, and non-renewable energy use (WoodWorks 2015). As shown in Figure 2-1, wood in the "big box" scenario performed better than steel in 5 out of the 6 categories. This was greatly influenced by wood's performance in the manufacturing, transportation, and the amount of materials utilized in design. The steel and wood designs have a 14% difference in the weight of their proposed building designs, 6,924 and 5,923 metric tonnes respectively (WoodWorks, 2015). WoodWorks describes other differences in the proposed buildings' use of products, including a 66% reduction in steel products, 26% less concrete products, 1,125% more wood, and 36% more gypsum in the wood design.

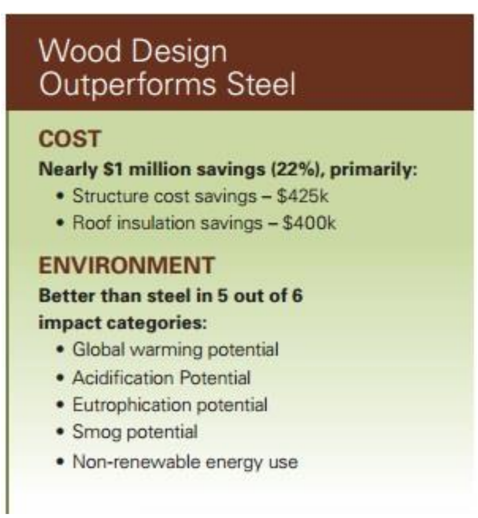


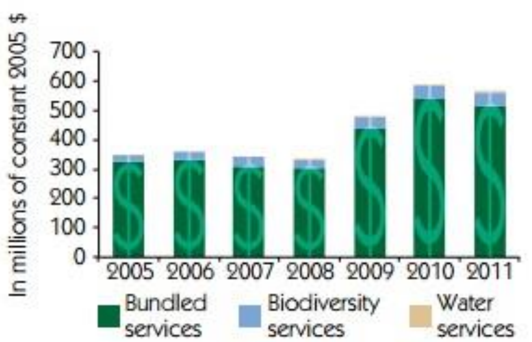
Figure 2-1. Wood Design Compared to Steel (WoodWorks, 2015)

The highlights from the LCA reports were that the proposed wood building as compared to the steel building had reductions in the global warming potential, non-renewable energy use, raw materials and manufacturing, and the end-of-life transport (WoodWorks, 2015). WoodWorks postulated that the LCA proves that wood could be used in “big box” wood design for structures such as grocery stores, home improvement stores, warehouses, malls, restaurants, and department stores.

A symposium in 1997 called Wood in Our Future: The Role of Life-Cycle Analysis and held at Battelle Memorial Institute examined wood as a raw material and its environmental impacts.

As a raw material, wood uses resources such as the soil, minerals, air, and water. In the information presented at the symposium, many conclusions were drawn, including the following: forests can be sustainably managed and thereby have less of an effect on the forested environment; after wood is used, it can be recycled multiple times before it is finally disposed of; since it absorbs CO_2 and converts it into organic carbon, it allows for a reduction in overall carbon use [when used for building material]; and wood can represent a large degree of sustainability due to its effect on the carbon cycle (Augood, 1997).

Forests provide critical services to humans such as jobs, carbon sequestration, habitats, and water purification, but only recently have there been incentives introduced to continue sustainable timber harvesting (Oswalt et al, 2014). These incentives come from both public and private proposals to provide payments to land owners in order to protect the ecosystem services mentioned above (Oswalt et al, 2014).



Federal payments to private forest landowners for ecosystem services, 2005–2011.

Figure 2-2. Federal Payments to Private Forest Landowners for Ecosystem Services (Oswalt et al, 2014)

In 1985 and 1990, the Farm Bill created the Conservation Reserve Program, Wetlands Reserve Program, Forest Legacy Program, Forest Stewardship Program, and the Stewardship Incentives Program (Oswalt et al, 2014). From 2005 to 2011, the payments for ecosystem services increased as seen in Figure 2-2 (Oswalt et al, 2014).

Chapter 3

Types of Mass Timber

For thousands of years, timber has been used in everything from residential construction to small buildings to ships. Wood has stood the test of time in places such as China with the Wooden Pagoda of Yingxian built in 1056 with 9 stories of wood (Mortice, 2016). However, mass timber, or composite wood that combines multiple pieces of wood to increase their compressive and tensioned strength, has only been a recent advent in the age of increasingly sustainable construction (Mortice, 2016). These systems are increasingly all-wood and have paved the way for an increase in the allowable height of wood structures to 10 to 12-story buildings. There are multiple types of mass timber, but the three main types used today are nail laminated timber, glue laminated timber, and cross laminated timber.

Nail Laminated Timber

Figure 3-1. Nail Laminated Timber (ReThink Wood, 2016)

Nail Laminated Timber (NLT) is created by "fastening individual dimensional lumber, stacked on edge, into one structural element with nails (NLT, ReThink Wood, 2016)." Nail-laminated assemblies have been used for more than a century in buildings that need particularly solid, sturdy floors, and NLT has recently been recognized as a "valid substitute" for concrete slabs and steel decking in commercial and institutional buildings as well as residential buildings (NLT Panels, 2016). Created from dimensional lumber stacked on edge, the 2x4, 2x6, 2x8, 2x10, or 2x12 boards are fastened together with nails, hence "nail-laminated" (See Figure 3-1) (NLT Panels, 2016). Currently, there is a 7-story building project in Minneapolis, Minnesota, (Figure 3-2) using NLT as its primary building material because of "aesthetics, structural advantages, lower cost, and faster procurement times (T3 Minneapolis, 2016)."

Figure 3-2. NLT as the Primary Building Material in T3 Minneapolis (T3 Minneapolis, 2016)

Glued Laminated Timber

Figure 3-3. Glulam in: Left - A railway station roof; Centre - A Visitor Centre at a vineyard; Right - A Lifeboat Station (AITC Glulam, 2015)

Glued Laminated Timber, otherwise known as Glulam, is manufactured by "bonding assemblies of high-strength, kiln-dried lumber, with waterproof adhesives (AITC Glulam, 2015)." Glulam is well known in the wood construction world for its versatility, beauty, strength, and dependability. Due to its versatile laminating process, Glulam is often used to build irregular designs such as arches, tapered shapes, and curved shapes as seen in Figure 3-3 (More About Glulam, 2016). Glulam is also cost effective, as it is easily adaptable to changes in plans and can be fabricated on-site. This allows the minimization of waste and labor costs during installation. Though this product has been used for more than 70 years successfully in the US, it is mostly used in roofing and shaped-wood projects due to its high resistance to corrosive and exposed environments as well as its ability to be formed into beautiful structures that are not feasible with steel and concrete (More About Glulam, 2016).

Chapter 4

Cross Laminated Timber History

CLT was created in Lausanne and Zurich, Switzerland, in the early 1990s. In 1996, research was conducted by several universities in conjunction with industry, including one in Austria that resulted in the development of modern CLT (Crespell and Gagnon, 2015). Cross Laminated Timber is "composed of multiple lumber boards layered crosswise at 90-degree angles and bonded together using structural adhesives (Nordic Structures, 2015) (See Figure 4-1)." Wide faces are typically laminated together, and CLT is further defined to have between three and seven laminated layers of board. The standard adhesives used are polyurethane products that are formaldehyde and solvent free. The boards are pressed together with a hydraulic or vacuum press to form an interlocked panel that limits expansion and shrinkage.

Figure 4-1. Cross Laminated Timber (Nordic Structures, 2015)

Many buildings that have been built in the last 20 years with CLT demonstrate the versatility of CLT panels. The most recent development in the use of CLT is in mid- to high-rise buildings. In the past 5 years, 17 tall wood buildings (7 stories or taller) have been completed in Australia, Norway, United Kingdom, Italy, Sweden, France, Finland, Canada, Spain, Austria, Germany (Looking Up, ReThink Wood, 2015). There are many more buildings that are still being constructed. Since its design causes structural qualities that are on par with steel and concrete, it has been used to replace non-sustainable building materials with this more sustainable option. CLT has also been shown to save time and the number of workers needed as it is a modular material.

Chapter 5

The Physics and Types of CLT

The internal designs for each placement of the CLT panel is different, as the panels are used for walls need very different load distributions than those for floor or roof systems. However, the positive building performance aspects are high axial load capacity for walls due to the large bearing area, high shear strength against horizontal loads, dimensional stability and static strength in all directions, and high buckling capacity. According to FP Innovations, CLT has been found to have high dimensional stability in practice as well as in the lab (Crespell and Gagnon, 2015). Building types that have recently used CLT include educational facilities and mid- to high-rise apartment buildings.

Each type of CLT is designed to the specifications of different countries, which means each type of CLT has different specifications that vary by the developer.

Structural

Each structural property of CLT requires details about specific conditions for the design of the building. These include the load duration, wet service, temperature, beam stability, column stability, and time effect factors. There are specific methods for designing CLT bending members, compression members, tension members, bending and axially loaded members, and bearing of members (Karavabeyli and Douglas, 2013). All of the equations that describe each component as well as a detailed example are detailed in the CLT Handbook (Karavabevli and Douglas, 2013) and will not be discussed in depth in this paper.

Lateral

Lateral loads from wind and earthquakes in CLT structures are critical to take into account when designing buildings. The resistances are achieved through wall and floor panels that are designed as shear walls and diaphragms (Karavabeyli and Douglas, 2013). CLT design shear strength is determined by engineering mechanics from the National Design Specification for Wood Construction (Karavabeyli and Douglas, 2013). Shear strength varies by fastener size, spacing, and location as well as the shear strength of the panel. Moreover, design should account for all deflection sources (Karavabeyli and Douglas, 2013). This will be discussed further in Chapter 6 and 13.

Chapter 6

Tests and Codes for Design

Fire Loads

A concern raised in many studies and articles is the resistance that wood structures have to fire. Fire resistance is "the period of time a building element, component, or assembly maintains the ability to perform its separating function, continues to perform a given loadbearing function, or both" (Karavabeyli and Douglas, 2013). As seen in Figure 6-1, parts a-c, the a) structural resistance, b) integrity, and c) insulation are the criteria by which fire resistance is measured. Structural resistance is the applied load that must be supported for the duration of the test. Integrity is that there must be little to no passage of flame or gases that could light a cotton pad. Insulation requires that the temperature must be kept from rising above 325 degrees F at any location or an average of 250 degrees F at a number of specified locations (Karavabevli and Douglas, 2013).

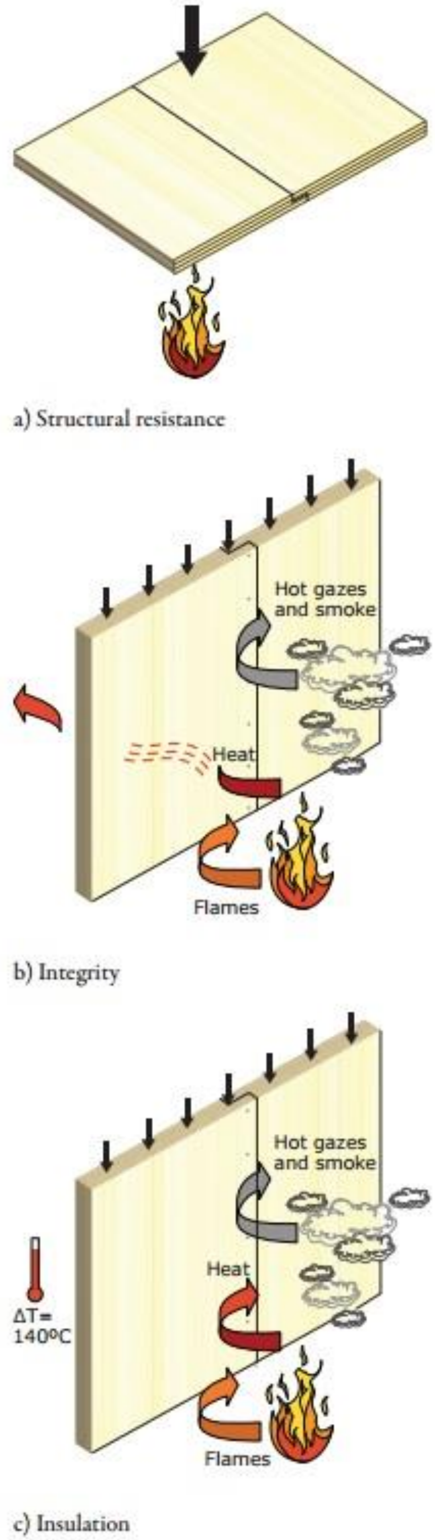


Figure 6-1. Fire Resistance [see Appendix A for a larger image] (Karavabeyli and Douglas, 2013)

CLT has been tested by many different companies and was found to have strength and fire-resistant tendencies inherent in mass timber products (Karavabeyli and Douglas, 2013) (Mohammad et al, 2011). According to FPInnovations in their CLT Handbook, since CLT panels char slowly at a well-known predictable rate while maintaining their strength, it gives occupants more time to leave the building.

The American Wood Council (AWC) conducted a test that was run on a wall system at NGC Testing Services in Buffalo, NY in 2012 (See Figure 6-2). The 5-ply CLT wall was "covered on each side with a single layer of 5/8-inch Type X gypsum wallboard (Showalter, 2016)," a system that most building designs include. The wall was loaded to the maximum load available through the testing equipment, and the specimen lasted 3 hours, 5 minutes, and 57 seconds before failure.

Figure 6-2. Cross Laminated Timber (Nordic Structures, 2015)

In Europe, three tall wood buildings' cross laminated timber beams, 3XGRÜN, Bridport House, and Limnologen, were tested, and each surpassed the fire requirements as shown in Figure 6-3. Each matched or surpassed the one-hour fire requirements with Limnologen more than doubling the minimum requirement (Taller Wood, 2016).

Figure 6-3. Cross Laminated Timber (Nordic Structures, 2015)

Seismic Loads

Figure 6-4. Seismic Testing at the Shaking Table Facility in Mika, Japan (Wind & Seismic, 2016)

IVALSA (Trees and Timber Research Institute of Italy) ran a test on a CLT building on the Shaking Table Facility in Miki, Japan. A seven-story CLT building (Figure 6-4) passed with flying colors after it was subjected to the severe earthquake motion “like that of the devastating Kobe earthquake (magnitude 7.2 and accelerations of 0.8 to 1.2g) (Wind & Seismic, 2016).” There was “no residual deformation after the test[,] the maximum story drift was 1.5 inches, [and] the maximum lateral deformation at the top of the building was just 11.3 inches (Frequently Asked, 2014).” It is easier to design earthquake resistant building due to the CLT panels “lightweight and … excellent shear resistance (Wind & Seismic, 2016),” as well as the hierarchy of strength characteristics such as by adding ductile and weak-link connections to allow for the desired failure mechanism.

Seismic simulation programs are currently being developed to better aid the standards committees in their evaluation of mass timber products in each country. See Chapter 13 for more details.

Chapter 7

Codes

Codes in UK, Europe, and Australia

The United Kingdom, Europe, and Australia have building codes that have been updated for the purpose of using Cross-Laminated Timber. Under the Eurocode basis of structural design, actions on structures, and Design of Timber Structures as well as the General and Structural Fire design, CLT is a compliant building material (Forte-Building, 2013). In Australia, the Building Code of Australia does not directly approve of high-rise buildings made out of timber, so a "fire engineered solution is required for CLT buildings above [3 stories] (Forte-Building, 2013)." The Australian codes for design are AS 1170-Structural Design and Actions and AS 1720-Timber Structures-Design Method.

Codes in the US

Though Europe has the majority of regulations, US building codes are able to accommodate well-tested, new materials and are constantly being updated and revised. Recently, the American Wood Council (AWC) code approved a change to include the use of CLT under the "heavy timber construction classification (Type IV)…in the 2015 International Building Code (IBC) (Showalter, 2016)," which will allow the use of CLT in non-residential buildings.

In order to be accepted in North America as a new construction material, all prospective construction materials must have a consensus-based product standard for designers and regulatory bodies to use (Karavabeyli and Douglas, 2013). APA-The Engineered Wood Association of the United States and FPInnovations in Canada saw the potential of CLT and created a development process in 2010. This goal was to develop an American National Standards Institute accredited standard for Canada and the US (Karavabeyli and Douglas, 2013). It took 22 months, but in December of 2011, a new product standard had been developed, ANSI/APA PRG 320-2011 *Standard for Performance-Rated Cross-Laminated Timber*, and it was referenced in the 2015 International Building Code (IBC). These codes were developed from typical manufacturing techniques in Europe and other places around the world. Chapter 9, Manufacturing discusses the manufacturing details for this standard.

Chapter 8

Economics of CLT

Cross Laminated Timber is used in many different capacities including the construction of tall buildings, residential structures, and office buildings. Over the past five years, very few studies have been published. However, several studies are forthcoming that will explore the economics of CLT work in the US market (USDA, 2017).

In Chapter 2, “Environmental Impacts of Wood,” a study by WoodWorks compared steel to mass timber panels to steel “Big Box” building, which are large-scale buildings often used for bulk retail stores (WoodWorks 2015). In addition to the environmental impact portion of the study, there was a study on the economics of using timber instead of steel. This comparison was done by the company SSA Quantity Surveyors and included costs due to the structure, roof insulation, contractor’s fees, and other related potential costs. Each building had a hard cost that was associated with the structure and envelope. This included the slab-on-grade, roofing, wall finishes, and exterior windows and doors (WoodWorks, 2015).

The results show a savings of about $1 million when using the wood building instead of the steel building (WoodWorks, 2015). Additional economic analysis would benefit the CLT industry and the use of wood structures in place of steel structures.

In the CLT Handbook, the costs of assembly, construction, and the shell were calculated in-house (Karavabeyli and Douglas, 2013). The average costs of production were approximated at $19.20 per cubic foot for a 300-mile radius of delivery as well as connection and erection costs at $0.70 and $1.24 per square feet (Karavabeyli and Douglas, 2013). For walls and floors, the assembly costs included a $1.00/square foot additional charge for CAD work and engineering by the manufacturer were $12 and $19 per square foot (Karavabeyli and Douglas, 2013).

The costs of constructing 14 different buildings using 86 combinations of building type, story class, and frame material were used to compare CLT’s cost competitiveness as seen in Figure 8-1 (Karavabeyli and Douglas, 2013). From Costworks, the square footage of each individual assembly and shell was assessed. In Figure 8-1, it is clear to see that as the buildings height increased in the simulated units (the top row 3, 5, and 8 tell the number of stories), CLT became more economically viable. While the estimates in Figure 8-1 are simply estimates per square foot, and each building cost varies by the types of materials and locations, it still suggests that CLT would be a viable option in high-rise building scenarios.

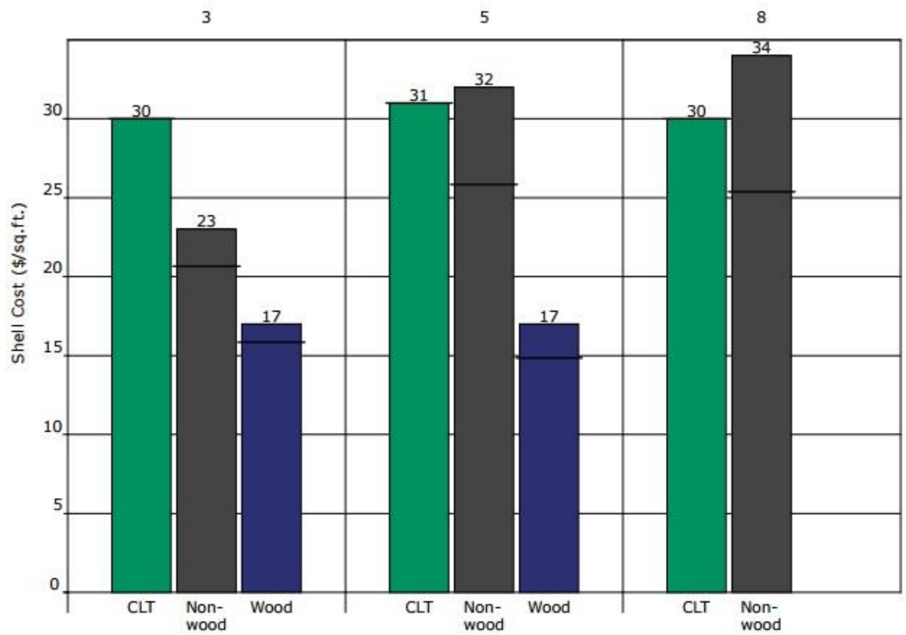


Figure 8-1. "Unit shell cost by story class and frame material apartments" from the CLT Handbook (Karavabeyli and Douglas, 2013)

Chapter 9

Manufacturing

CLT has been engineered and manufactured in Europe for 15 years, but has only recently begun to be manufactured in North America. For example, several manufacturers in the United States produce mass timber: Nordic Engineered Wood Products, SmartLAM, Structurlam Wood Products, StructureCraft, Cross Lam Timber Solutions, KLH U.S., DR Johnson Lumber, Stora Enso Wood Products (ReThink Wood, 2017). CLT thicknesses are limited to 20 inches due to practical manufacturing requirements. Further, they follow the requirements in ANSI/APA PRG 320-2011 Standard for CLT which specifies the type of lamination, adhesives, joints tolerances, stress, appearance, selection of lumber, and many more (the history of the standard is discussed in Chapter 7: Codes) (Karavabeyli and Douglas, 2013).

For a reliable and consistent product, ANSI/APA PRG 320 takes into account available wood resources and end-use expectations that will enable each country to meet the requirements of other countries (Karavabeyli and Douglas, 2013). An example used in the CLT Handbook is the softwood lumber species or a composite softwood material permits a minimum specific gravity of 0.35. In addition, each individual layer of CLT must be the same type of wood in order to avoid differing mechanical or physical properties (Karavabeyli and Douglas, 2013). The standard also specifies that the net lamination thickness for CLT layers at the time of gluing is between 5/8 inches and 2 inches, and it must not vary outside of ± 0.008 inches for the width and ± 0.012 inches within the same layers (Karavabeyli and Douglas, 2013). More information can be found in the CLT Handbook about lamination specifications.

Adhesives are also regulated, and the standard requires adhesives to be heat resistant and able to resist changing moisture contents (Karavabeyli and Douglas, 2013). Many adhesives have been used before in CLT production, including phenolic types such as phenol-resorcinol formaldehyde (PRF); emulsion polymer isocyanate (EPI); and one-component polyurethane (PUR) (Karavabeyli and Douglas, 2013). However, certain mixtures of these adhesives have yet to be approved until potentially different properties of the mix are known. The lamination joints do not necessarily have to be in accordance with ANSI/APA PRG 320 unless they are part of the fire or structural performance section (Karavabeyli and Douglas, 2013).

The dimensional tolerances are that the CLT is limited to 20 inches thick with additional tolerances at the time of manufacturing for ± 1/16 inch for thickness, 1/8 inch of the CLT width, and 1/4 inch for the length of the CLT (Karavabeyli and Douglas, 2013). The strength must remain the same or any loss of strength must be compensated for if the designers decide to do a textured finish (Karavabeyli and Douglas, 2013). Stress Classes were developed to organize the lumber species and grades that are available in North America. They follow structural properties such as bending strength, bending stiffness, and shear rigidity (Karavabeyli and Douglas, 2013). The CLT Handbook has multiple tables for the modulus of elasticity of the lumber for individual species as well as the stress classes and design capacities for CLT in the USA (Karavabeyli and Douglas, 2013). The appearance of lumber is not specified in ANSI/APA PRG 320 and is left to the buyer and seller to agree upon.

Figure 9-1 shows the manufacturing process in the following sequential steps (Karavabeyli and Douglas, 2013):

1) Primary lumber selection,
2) Lumber grouping,
3) Lumber planing,
4) Lumber or layers cutting to length,
5) Adhesive application,
6) CLT panel lay-up,
7) Assembly pressing,
8) CLT on-line quality control, machining, and cutting, and
9) Product marking, packaging, and shipping.

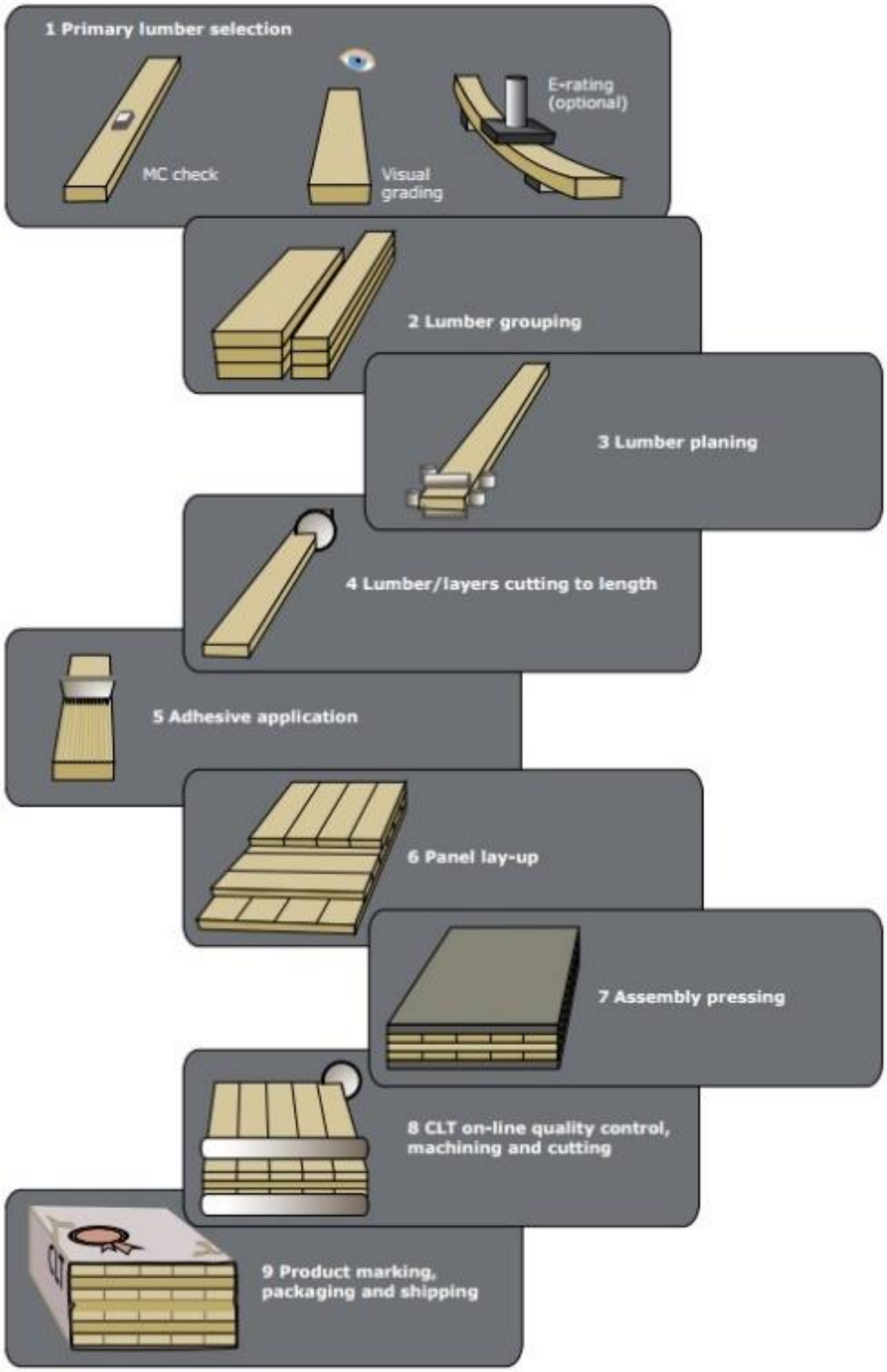


Figure 9-1. Cross Laminated Timber Manufacturing Process [for a larger picture see Appendix A] (Karavabeyli and Douglas, 2013)

CLT is manufactured using three or more layers of the same or variable thicknesses up to 2 inches laid across each other in a 90° crisscross pattern (Karavabeyli and Douglas, 2013). Each step in the process can include substeps. For example, in Step 1, Primary Lumber Selection, includes moisture content (MC), quality control (QC), and appearance if necessary (Karavabeyli and Douglas, 2013). Most lumber moisture is dried to a MC of 19% or less, but CLT requires that the lumber have a lower MC, 12 ± 3%, to enable bonding to occur properly (Karavabeyli and Douglas, 2013).

For lumber grouping, Step 2, the MC level and visual characteristics are taken into consideration and used to put similar types of lumber together for each individual layer to ensure that the properties are as strong as possible (Karavabeyli and Douglas, 2013). For lumber planing, a thin surface layer is removed to reduce oxidation so the bonding of the layers can be optimal (Karavabeyli and Douglas, 2013). Step 4 consists of cutting and laying the pieces before the adhesive is applied, and Step 5 is the application of adhesive onto each individual layer. Step 6 is the CLT panel lay-up step that aligns the panels perpendicular to each other, and step 7 those layers together with a hydraulic press (Karavabeyli and Douglas, 2013). The CLT is then quality control checked to make sure it matches the correct specifications and does not delaminate. Next, the CLT is cut to fit the requirements (Step 8), then marked, packaged, and shipped to the proper locations (Step 9) (Karavabeyli and Douglas, 2013).

Chapter 10

Typical Connections

Each design of CLT buildings is highly variable and depends largely on the designer's vision and execution of their ideas. For this reason, this paper will not present "typical" CLT designs, but will present some of the typical connections for connecting CLT panels associated with CLT designs.

Connections

It is essential while using CLT in building design to accurately use connections to increase the strength, stiffness, stability, and ductility in the structure (Karavabeyli and Douglas, 2013). CLT connections can include mechanical connections, such as metal hardware or fasteners, or prefabricated joints cut in the manufacturer's warehouse. The proper installation of both of these types of connections is essential to the success of the building (Karavabeyli and Douglas, 2013). Wood screws, self-tapping screws, and bolts and dowels are also utilized in CLT connections when building mass timber buildings. Internal splines such as that in Figure 10-1 can be used to connect CLT floor panels together because they resist normal and out-of-plane loading, but splines are not used frequently due to the difficulty in installing them on site (Karavabeyli and Douglas, 2013). Other types of splines can work for CLT connections as well, but they do not necessarily positively affect the time for erection as well as the on-site installation (Karavabeyli and Douglas, 2013).

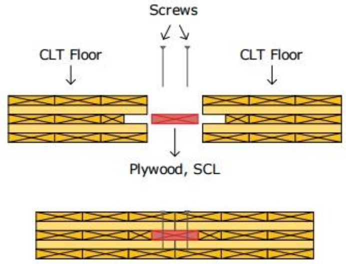


Figure 10-1. Single Internal Spline Panel-to-Panel Example (Karavabeyli and Douglas, 2013)

For most wall to wall designs and perpendicular walls, self-tapping screws are used from the exterior or at an angle. Metal brackets and wooden profiles can be used as well, with metal brackets being the most efficient and easy to install on the construction site. For wall to floor designs, metal brackets and self-tapping screws are also utilized (Karavabeyli and Douglas, 2013). Figures 10-1, 10-2, 10-3, 10-4, and 10-5 show the techniques that are used to connect panels-to-panel, wall-to-wall, wall-to-floor, roof-to-wall, and wall-to-foundation (Karavabeyli and Douglas, 2013).

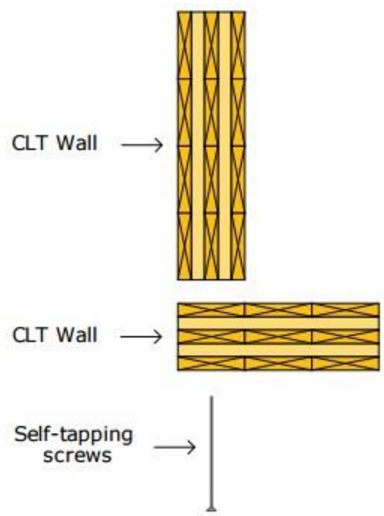


Figure 10-2. Wall-to-Wall Example (Karavabeyli and Douglas, 2013)

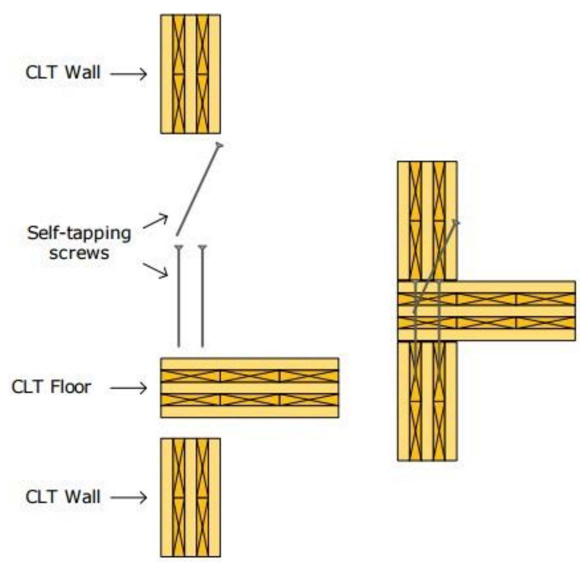


Figure 10-3. Wall-to-Floor Example (Karavabeyli and Douglas, 2013)

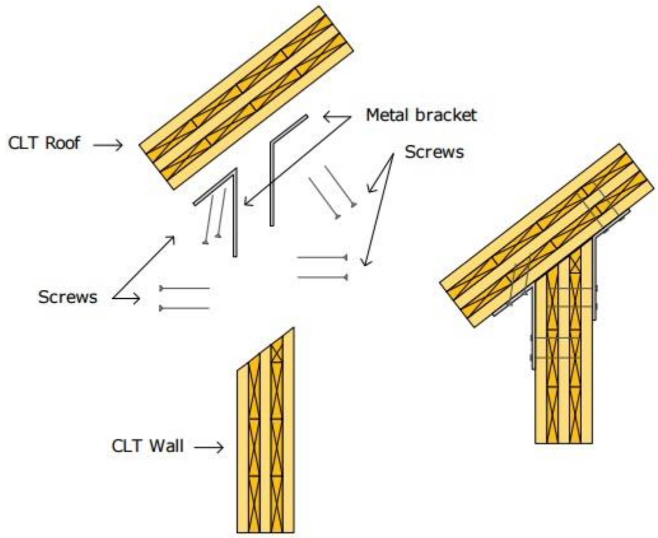


Figure 10-4. Roof-to-Wall Example (Karavabeyli and Douglas, 2013)

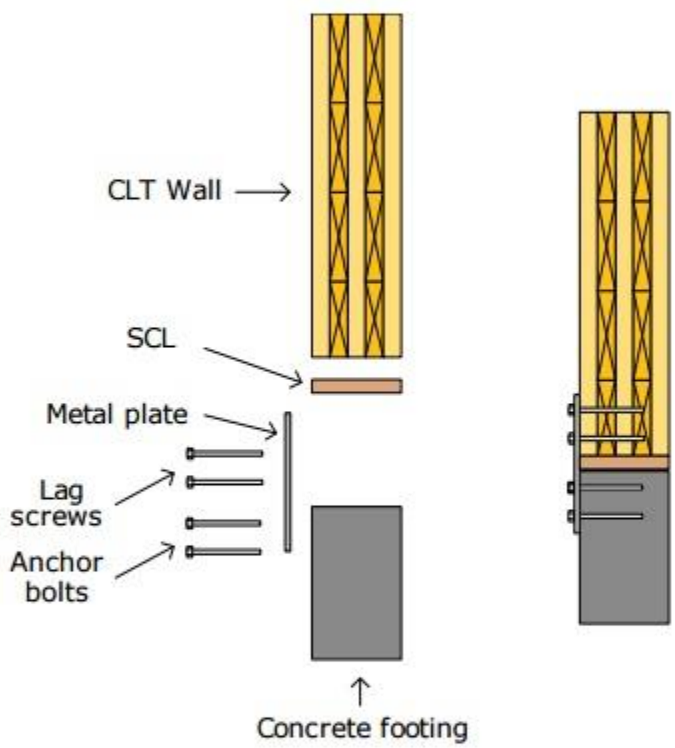


Figure 10-5. Wall-to-Foundation Example (Karavabeyli and Douglas, 2013)

The CLT Handbook has many other detailed descriptions and diagrams of all of the methods mentioned as well as roof to wall and wall to roof designs (Karavabeyli and Douglas, 2013).

Chapter 11

Case Studies

Throughout many parts of the world, countries have used CLT in new building construction bringing CLT and other timber products into the forefront of sustainably-minded construction projects. In this chapter, case studies from Europe, USA, Canada, and Australia will be discussed, including Stadthaus, the Crossroads at the Feynman Center, the Earth Sciences Building at the University of British Columbia, and the Forte building. Each building is a unique case study with different requirements and designs, but all were inspired by the desire to construct sustainable buildings.

European Case Study

Stadthaus: London, U.K.

On the corner of Provost Street and Murray Grove in Hackney, London, Stadthaus stands nine stories tall with white and gray tiles (Figure 11-1). The client, Telford Homes PLC and the Metropolitan Housing Trust, employed Waugh Thistleton Architects, Telford Homes (main contractor), Techniker (structural engineer), and KLH UK (timber supplier and erector) to design and build a wood building above the UK building requirements. One of the tallest wood residential buildings in the world, the top eight stories are constructed of laminated spruce panels that are 30 feet long and up to a half of a foot thick (Fountain, 2012). In 2009, Stadthaus, also known as Murray Grove, was completed with sustainability as a priority.

Figure 11-1. Stadthaus Murray Grove (Trada, 2009)

architects and engineers had worked with timber in low-rise buildings, industrial projects, and educational projects previously and attempted to make wood structures more acceptable in the UK. They did this by of the building with photovoltaic (PV) panels on the roof, a green-wall wrapping for local plants to grow, and an ecologically-minded mini-park. The design also includes CLT panels for load-bearing walls and floors (Trada, 2009). In Trada's discussion of the CLT panels used in the building, they state that dried spruce boards are used in CLT for large wall, floor, and roof elements in the design to improve aesthetics (Trada, 2009). Finally, recognizing mass timber's natural fire resistance, the structural engineer, Techniker, wanted to go beyond the one-hour fire resistance requirements and added plasterboard to increase that number to 90 minutes (Trada, 2009).

Using a pre-fabricated technique for the structure of the building, they were able to reduce the time of construction from 72 weeks for a concrete building to 49 weeks for pre-fabricated CLT (Trada, 2009). It was calculated that using concrete would have incurred an extra 124 tons of carbon generated during construction, and the timber sequestered 188 ton of carbon in 31,783 ft^3 of timber used in the structure. There was also money and energy saved due to the high thermal resistance of wood. This meant that they only needed to add 3.94 inches of insulation to the 5.04 inches wall to meet the thermal resistance requirement of $U=0.13\ W/m^2/K$ (Trada, 2009). Overall, nearly every aspect of this project exceeded expectations according to Trada including acoustic performance, construction time, thermal resistance, and generated or offset carbon.

United States Case Study

The Crossroads in the Feynman Center: Madison, Wisconsin

The Crossroads is part of a building called the Feynman Center constructed for the Promega Corporation, which is known for advances in the biotechnology field, see Figure 11-2 (WoodWorks, 2013). Completed in 2014 with a 260,000 ft^2 footprint, the Feynman Center contains 14,133 ft^3 of cross laminated timber that the architects claim stores 302 metric tons of carbon and prevents 391 metric tons of CO_2. It has an indoor plant facility that is situated on a living wall with 7,000 plants of 42 varieties. Though the building uses 14,000 ft^3 of CLT, it also incorporates a combination of concrete, rebar, structural steel, brick, and concrete masonry (Promega, 2014). The Crossroads is a 52,000 ft^2 meeting area for client and staff, purposefully designed to offer a relaxed ambiance than the highly-regulated, strictly clean Feynman Good Manufacturing Practices facility.

Figure 11-2. Feynman Center by Promega ("Feynman Center," 2013)

With the goal of creating a warm environment, three firms collaborated to design this portion of the building: Uihlein/Wilson, EwingCole, and Archemy Consulting (WoodWorks, 2013). A column superstructure of glulam and CLT in conjunction with a CLT roof provided increased deck span due to the strength of the CLT panels. CLT also enabled the curved roof from the architects' designs to become a reality. Using *ANSI/APA PRG 320-2011 Standard for Performance-Rated Cross-Laminated Timber,* the building team submitted the information under the International Building Code (IBC) section 104.11 and developed the design to meet the criteria of the including minimum roof snow loads of 30 psf, maximum snow drift load of 132 psf, basic wind speeds of 90 mph, and seismic design category B.

By showing that the wood had equal or better fire performance, it was classified as a Type II-B steel frame structure (WoodWorks, 2013). CLT also has a two-direction geometry, allowing curves to be easily incorporated and lateral frames to be spaced farther apart. The USDA Forest Service installed sensors to relay data about moisture and temperature while the building is in operation to show that CLT can effectively control heat, air, and moisture in a well-designed project, which directly tied in with the sustainability goals for the project (WoodWorks, 2013).

Canadian Case Study

Earth Sciences Building at University of British Columbia, Canada

On the Vancouver campus of the University of British Columbia (UBC), a new building houses the Earth, Ocean, and Atmospheric Sciences, Statistics, and the Pacific Institute of the Mathematical Sciences (Figure 11-3). The main portion of the building is the north wing offices and lecture halls, which uses 1,317 cubic meters of wood (Perkins and Will, 2013). The reasons for using wood in this project were the added environmental benefits including carbon sequestration (1,094 tons of carbon), a CLT canopy for the protection of pedestrians, and the belief that wood provides an environment conducive to being welcomed into the building (Perkins and Will, 2013). An additional goal of the project was also to show the aesthetic and structural capabilities of engineered timber and the CLT canopy and Glulam staircase met this goal (Karsh, 2013).

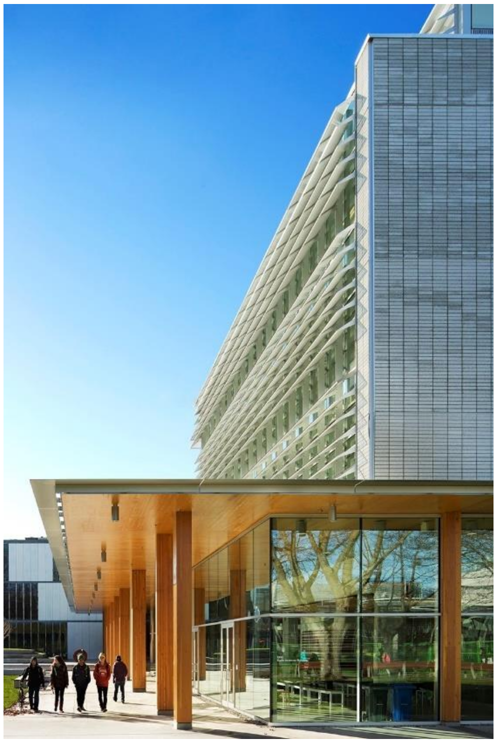


Figure 11-3. Earth Sciences Building Exterior (Perkins and Will, 2013)

Due to the "Building Code Alternative Solution" in the *British Columbia Building Code* (*BCBC*), the use of wood as the main structural element was assessed and peer-reviewed (Karsh, 2013). Unfortunately, the project used less timber than originally planned due to problems convincing the British Columbian Buildings and Safety Standards Branch that the fire safety requirements in the *BCBC* will be met (Karsh, 2013).

Vibration testing was also an important part of the solid wood construction process due to the differences from cast-in-place concrete. This analysis was conducted by a third party. Additional structural elements were included in the innovative portion of the project, including a wood-concrete composite floor system, post and beam structure and connections, transfer trusses over the lecture theaters, exposed CLT roof and canopy, ductile chevron braces, and the cantilevered atrium staircase (Karsh, 2013). Overall, though not used extensively in the building, the CLT portions of the building met the sustainability goals and exceeded the requirements established by the building designers.

Australia Case Study

Forté -Australia

Designed by Lend Lease Design and the Robert Bird Group, the Forté Building in Australia is a 10-story CLT apartment building, which made it the tallest timber apartment complex in the world when it was built in 2012 (Figure 11-4). The TREET building, completed in 2016, only recently surpassed Forté as the tallest wood building in the world, but TREET consisted mostly of glulam structures (see Chapter 3 for more about glulam) for its load-bearing system, so it will not be discussed in this paper. Since CLT has structural qualities that are on par with steel and concrete, it was used to replace non-sustainable building materials. Lend Lease's design involved three years of research, one year of design, and 10 months of construction (Evans, 2017). Lend Lease's goal was to demonstrate that sustainability can be cost effective in large commercial development, and the building got a "5 Star Green Star As-Built" rating which is equivalent to LEED's Platinum rating (Evans, 2017). They also reached a near net-zero-carbon rating and calculated that the building kept 1,450 metric tons of carbon dioxide (equivalent) out of the air as well as sequestering 761 tons of CO_2 (Evans, 2017) ("Featured Project," 2017).

Figure 11-4. Forté building in Melbourne, Australia photo by Lend Lease (Evans, 2017)

Weighing in at 485 tons, 759 CLT panels of European spruce reach a height of 10 stories to make up the Forté building (“Featured Project,” 2017). While the majority of the building is constructed from CLT, the first floor and ground floor slabs were constructed out of concrete to keep the wood off the ground, allow for retail space in the bottom of the building, and prevent termites from entering the building (“Featured Project,” 2017). To meet the fire resistance and durability requirements, Lend Lease collaborated with the Melbourne Metropolitan Fire Brigade to ensure that the appropriate measures of fire protection were in place (“Featured Project,” 2017). The project also passed the fire code requirements due to the 5.04 inches thick CLT walls with 0.51 inches of plasterboard on both sides as well as 5.75-inch CLT floors with 2 layers of 0.63-inch plasterboard (“Featured Project,” 2017). Overall, the Forté building satisfied all building code requirements, and the people living in the apartments are estimated to save up to $300 per year on energy and water bills due to the efficient building and appliance design (“Featured Project,” 2017).

Chapter 12

Advantages and Disadvantages of Mass Timber Construction

Advantages

CLT has many advantages including that it is a renewable material comparatively to steel and concrete and has been shown to be quicker and more efficient with less expense during construction.

Renewable Material

A major advantage of CLT is that timber is a renewable material. Not only can forests be sustainably managed and harvested, but they are also a great resource in providing a carbon sink for the earth in removing carbon dioxide from the atmosphere. Many companies and proponents of wood product use claim that CLT is a cost-effective material that doubles as a renewable resource (Wood Grows Naturally, 2015). According to reThink Wood, the construction industry consumed “nearly half of all energy produced in the United States, 75 percent of the electricity produced is used to operate buildings, and…was responsible for nearly half of U.S. carbon dioxide (CO_2) emissions (Frequently Asked Questions, 2014).”

In the UK, the architect of a CLT apartment building estimated that “between the carbon stored in the panels and emissions avoided by not using concrete, he kept about 300 metric tons of carbon out of the atmosphere (Frequently Asked Questions, 2014).” Using Cross-Laminated Timber would allow a sustainable material in the construction field that could revolutionize the industry.

Quick, Efficient, and Less-Expensive Construction

Another advantage is that CLT can be constructed quickly and efficiently with fewer workers than a typical construction site. According to Cross Laminated Timber-A Primer, the average CLT construction site uses crews of 2, 4, or 8 carpenters plus one crane operator, and outputs of 1,000 to 8,000 SF/day can be achieved. This leads to "lower capital cost, faster project turnaround, and potential insurance benefits due to fast and safe erection (Cross Laminated Timber: A Primer, 2010)."

Disadvantages

With any new material introduced to the construction world, barriers must be overcome, such as the building community's disinclination to use materials that are less familiar and have not been tested as stringently. Though CLT is praised as a sustainable option, the drying process and installation must be considered as well in order for it to be reasonably compared with steel and concrete production.

Accepting New Things

The major disadvantage to CLT is that the building and design communities are slow to accept CLT as a viable resource. One of the main reasons that CLT is not used as much in the US is the lack of public knowledge on the subject. Misinformation about how mass timber reacts in fires has led to all wood being classified as a combustible building material despite it being less susceptible to fire due to charring (Karavabeyli and Douglas, 2013). It also takes a large amount of time to design wood high-rise structures due to the restrictions place on wood construction. Codes are being adapted to include CLT, but the process is slow, so the building community has been reluctant to use it as a viable option.

Timber in Construction

While there are a lot of positive outcomes based on the sustainability of wood in construction, the environmental benefits of timber are not straightforward (Ramage et al, 2017). Timber must be dried in order to be used in construction due to its susceptibility to rot and potential for fungal degradation. Dry timber also allows for easier transportation and gluing (Ramage et al, 2017). This causes most standards for timber to have an upper limit of 20% moisture content and to account for the fact that timber adjusts according to the environmental moisture content (Ramage et al, 2017). The use of a kiln or other drying mechanism is necessary and is the most energy-intensive aspect of the manufacturing process, consuming up to 92% of the total manufacturing energy (Ramage et al, 2017). Figure 12-1 shows the amount of energy consumed in MegaJoules (MJ) per cubic meter.

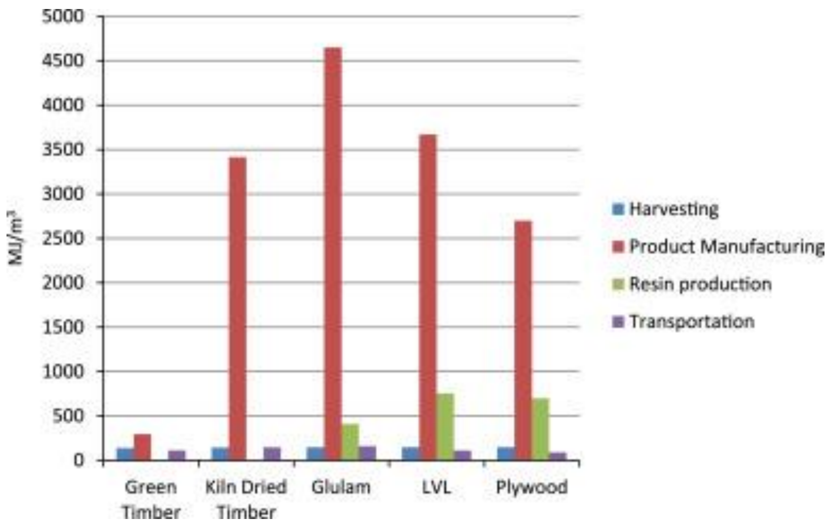


Figure 12-1. Typical Amounts of Energy Used in Construction Timber Products (Ramage et al, 2017)

The values from Figure 12-1 can be compared to the values of steel and concrete using the University of Bath's Inventory of Carbon and Energy found in Table 12-1. While the values represented are typical, it does not mean that they are all necessarily accurate for different types of steel, concrete, or lumber. The embodied energy of glue laminated timber, while lower than that of typical steel, is still double that of the average concrete, as seen in Table 12-1. There are many other aspects to compare among of these materials, but in some cases, glue laminated timber uses more energy than concrete. Mindfulness of the type of energy used or the type of timber or concrete in question is important because these values and the amount of CO_2 released while producing the material vary significantly, depending on which specific materials compared. It is also important to consider that energy required during construction could even out the playing field between timber and concrete, so it is important to look at the whole picture. However, even with these embodied energy requirements, timber still sequesters carbon as mentioned in previous chapters.

Table 12-1. Embodied Energy of the Production of Different Building Materials (Values from Inventory of Carbon & Energy, 2017) Density of CLT from Byle, 2012

Materials	**Embodied Energy (MJ/kg)**	**Density (kg/m^3)**	**Embodied Energy (MJ/m^3)**
Concrete (Average)	1.11	2400	2664
Steel (Average)	20.10	7800	156,780
Timber (Average)	10.00 (not including carbon sequestration)	720	7200
Glue Laminated Timber (Average)	9.5 (not including carbon sequestration)	561 (CLT)	5330

Chapter 13

FEMA P-695 Seismic Performance

Seismic Performance of CLT

The most commonly used procedure for the designing of buildings that need good seismic performance is the equivalent lateral force (ELF) method. Using R, C_d, and Ω_O, seismic design coefficients, the seismic loads are calculated to determine whether the structure or material meets the associated design requirements (Karavabeyli and Douglas, 2013). CLT designs follow mostly performance-based design procedures that follow the ASCE 7-10 Minimum Design Loads for Buildings and Other Structures with guidance from FEMA P695 and FEMA P795. While seismic design guidelines for CLT systems are not yet widely available, it is expected that ongoing efforts will lead to more guidelines for simulation of seismic performance of CLT. Currently, Phil Line, P.E. of the American Wood Council (AWC) is developing a software with Jayamon and Charney to evaluate seismic design of wood shear wall structures, which will be used to designing wood structures that will meet seismic standards.

FEMA P695 outlines the model building code specifications for all seismic designs with a specification of less than a 10% probability of a partial or total collapse of the building with the maximum considered earthquake (MCE) (Karavabeyli and Douglas, 2013). The key factors of the P695 analysis are with ground motions, analysis methods, test data, design, and peer reviews with different configurations (Karavabeyli and Douglas, 2013). The FEMA P795 method does not meet the compliance needed in FEMA P695 of less than a 10% probability of partial or total collapse. It uses a direct comparison of a proposed component and a reference component of a recognized component that resists seismic forces (Karavabeyli and Douglas, 2013).

Research and Conclusions

PhD candidate Jayamon and Dr. Charney of Virginia Tech University in conjunction with Philip Line of the American Wood Council (AWC) recently conducted research into modeling seismic performance of wood-based buildings. Their research focuses on using FEMA P695 to describe how 16 different models of wood building shear walls will react to 44 different defined ground motions.

In addition, PhD candidate Amini is determining seismic performance factors for CLT shear wall systems at Colorado State University. Amini finds the strength of CLT shear walls by using FEMA P695 methodology to design the walls and test their seismic performance under certain circumstances. This section focuses on how the tools from these research projects enable engineers to apply the modeling of wood buildings using 10 parameters to CLT buildings. It also looks at broad potential applications of this proprietary software tool in seismic design.

Previous papers written by Jayamon and Charney focus on replicating 16 FEMA P695 examples from Chapter 9 to investigate the influence of varying load-displacement shape on the FEMA P695 seismic performance metrics including the Collapse Margin Ratio (CMR). The purpose of these papers was to evaluate the damping in wood-frame shear wall buildings, determine the influence of wall load-displacement shape on seismic performance of wood-frame shear wall structures, and determine the seismic design factors for CLT shear wall analysis.

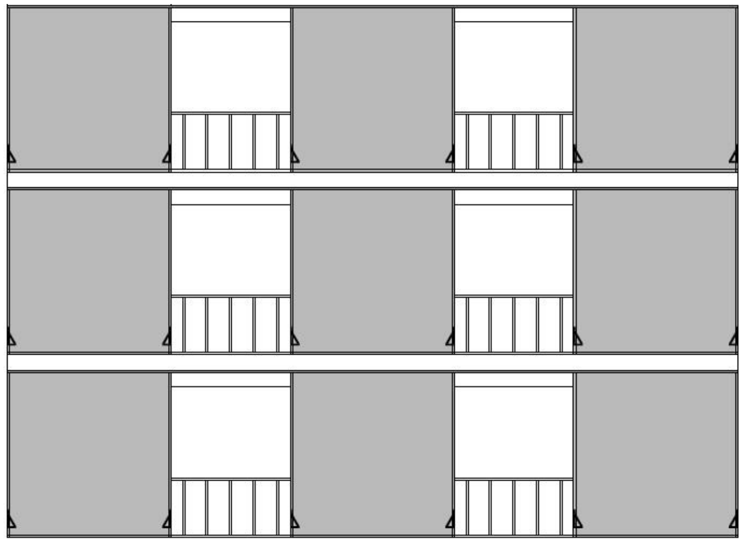


Figure 13-1. IM9: 3-Story Model, 16 Wood-Frame Structures from AWC

Sixteen different wall models are listed and tested in the FEMA P695 document. Of the 16 different shear wall models, IM 9 (see Figure 13-1) was chosen to compare CLT and a wood-frame structure because it is 3 story structure and is expected to perform similarly to the test walls. In this case, the reference is a wood-frame structure often used in current wood building design with an R-factor of 6. The CLT building uses a modified version of a 10-parameter hysteretic system developed by Folz and Filiatrault as part of their CUREE California Tech Wood-frame Project (Jayamon et al, 2016). These parameters are used to "define wood shear wall load-displacement hysteretic response (Jayamon et al, 2016)." The model is meant to replicate load-deformation responses of wood panels in certain building designs as shown in Figure 13-2.

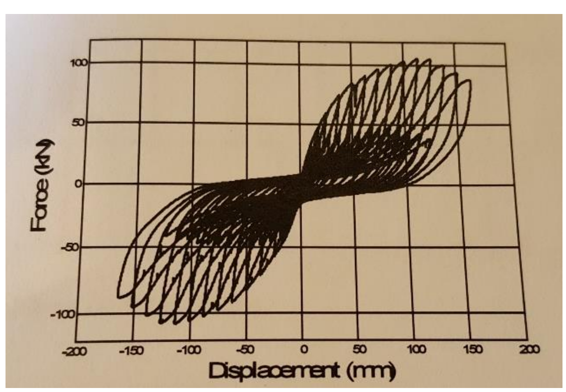


Figure 13-2. Hysteresis Model for a CLT Test (Amini, et al, 2016)

The comparison between the CLT shear wall and the typical wood wall looks at the Collapse Margin Ratio (CMR) using assumed stiffness and strength properties to assess whether CLT shear walls perform better or worse than wood structural panel walls. CMR is defined in FEMA P695 as the ratio between median collapse intensity and Maximum Considered Earthquake (MCE) intensity (see Equation). The median collapse intensity is obtained by scaling all the records in the Far-Field record set to the MCE intensity. It is not necessarily a representation that should be used for comparing CMRs of other types of shear walls not using this system, but CLT shear walls are assumed to react similarly.

$$Equation:$$

$$CMR = \frac{\hat{S}_{CT}}{S_{MT}}$$

The baseline case for a regular wood wall with 44 ground movements (GM) produced a CMR=1.4596. When the same test with the modified values for the parameters was conducted under the same 44 GM, the result was CMR=2.1321. This was a 46.1% increase from the original CMR value, showing that it performed better in this ground movement scenario. While this does not mean that every model will turn out the same way, it is certainly a step in the right direction for CLT's seismic performance comparatively to other wood structures. In the future, experimental studies will test CLT buildings up to 12 stories tall and beyond, and standards that encompass all of the needed material will be created.

Chapter 14

Concluding Remarks

When compared to the baseline case for the CMR value, there is a 46.1% increase in the CMR value. This suggests that in the 44 ground movement scenario that was tested, the CLT seismic performance was greater than the typical wood shear wall tested as the baseline.

In the future, more testing will be done to determine the seismic capabilities of CLT, and equations and standards will be developed similar to those for steel and concrete. However, all aspects of the CLT system must be considered, including the amount of energy used to dry the timber, the amount of energy used to press the panels together, and other aspects as well.

As more design professionals learn about CLT and the advantages that it offers the construction industry and the environment, more research and development will be devoted to minimizing CLT's limited effect on the environment. In addition, the public will become more comfortable with the idea of using CLT more widely in the US. Research is also needed to assess the embodied energy of a CLT system, and the people who have the potential to live in CLT buildings must be informed of this alternative to steel and concrete. The advantages of CLT will become more widespread as the use of CLT becomes more mainstream, and in the coming years, the construction industry has the potential to be more environmentally friendly than ever before.

Appendix A

Enlarged Pictures

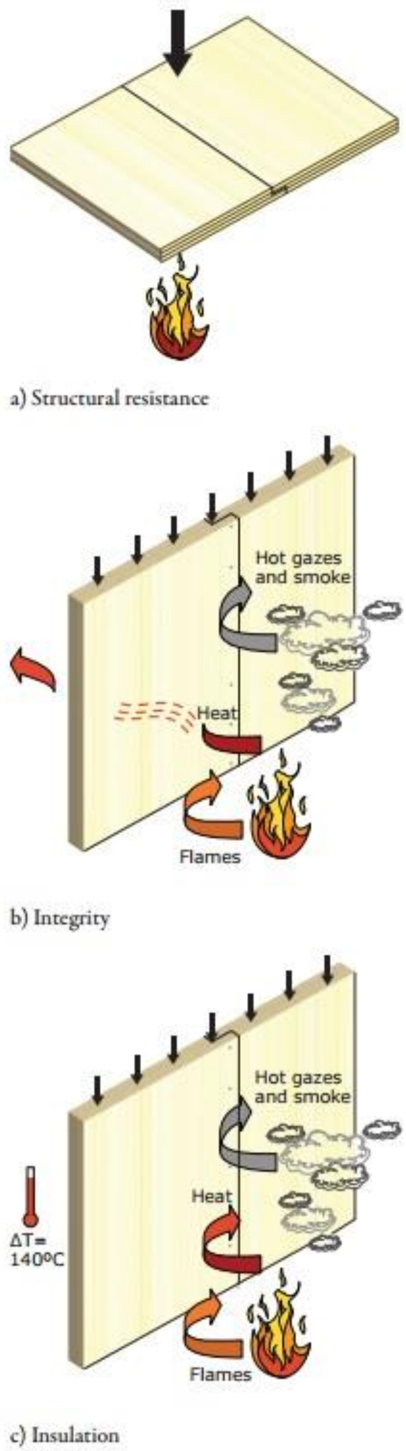


Figure 6-1-A Fire Resistance

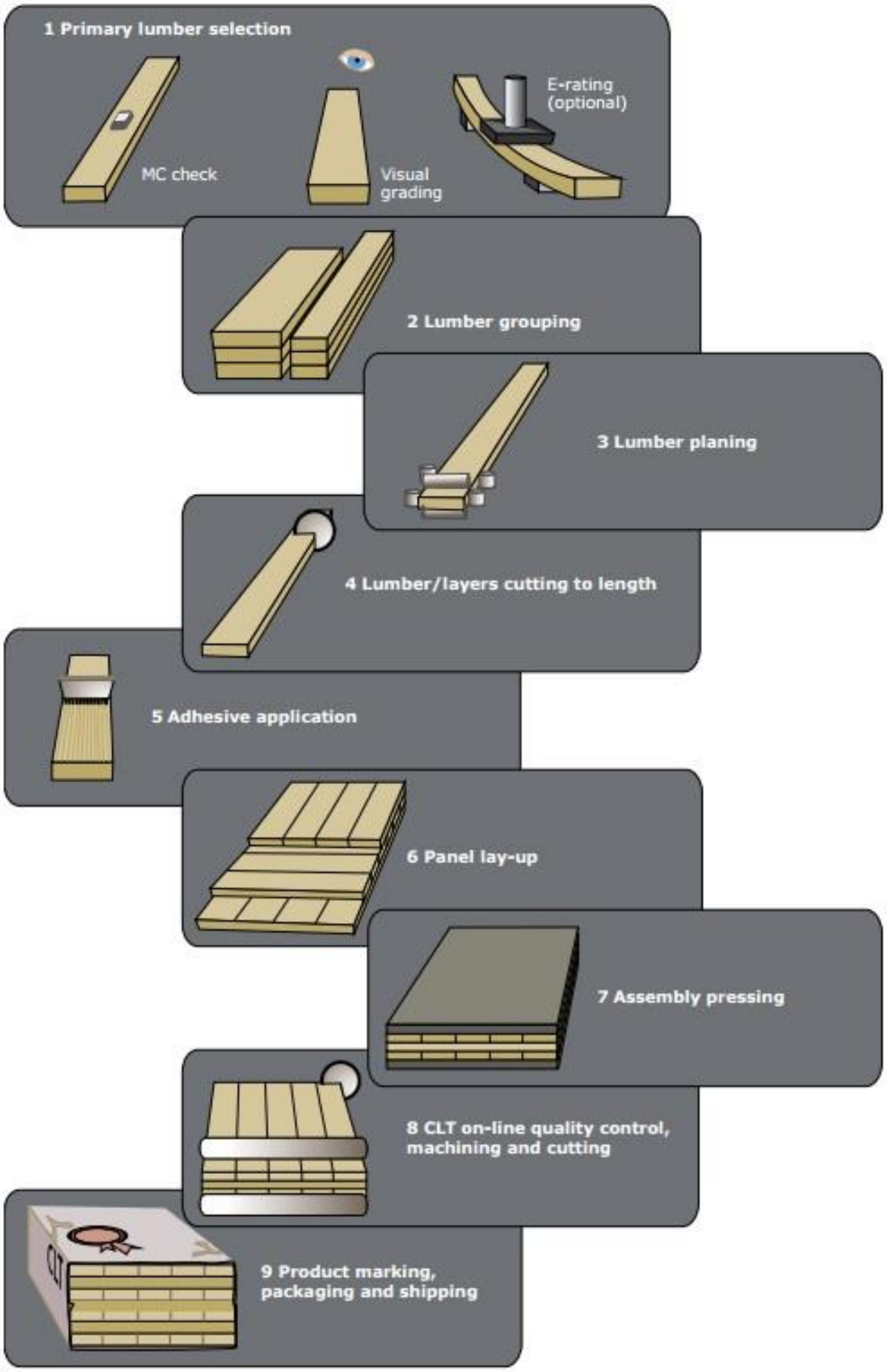


Figure 9-1-A Manufacturing process for CLT

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ACADEMIC VITA

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Education

Major(s) and Minor(s): B.S. Civil Engineering and Masters of Engineering in Environmental Engineering.

Minors: Environmental Engineering and Watersheds and Water Resources

Honors: Civil Engineering

Thesis Title: "Cross-Laminated Timber: A Sustainable Option in the World of Construction"

Thesis Supervisor: Dr. Ali Memari, PhD, PE

Work Experience:

US Army Corps of Engineers (Baltimore, MD)
Supervisor: Mark Chalecki
Summer Intern in the Capital Planning Division (June 2015-Aug. 2015)

- Internship with the USACE working on projects in the Chesapeake Bay watershed
- Analyzed chemical data of nutrients in the Chesapeake Bay for the Baltimore Harbor Navigation Project
- Documented findings for different types of fish and wildlife for the Anacostia, Prince George's County Ecosystem Restoration Project
- Collected GPS floodplain data at Andrews Air Force Base and Annapolis, MD

American Wood Council (Leesburg, VA)

Supervisor: Phil Line

Summer Intern for the Engineering Division (June 2016-Aug. 2016)

- Analyzed data for head-pull-through project and created user manual for P695 Seismic Design Analyses
- Developed and organized green building standards and for Cross Laminated Timber
- Designed AutoCAD drawings as specified by the project supervisor for P695 Analysis Project

Grants Received *[whether from Schreyer Honors College (e.g., Schreyer Ambassador Awards) or from other sources; please specify]*: N/A

Awards:

- Landis Memorial Scholarship for Excellence in Engineering (Fall 2016-Spring 2017)
- Chi Epsilon Dexter C. Jameson, Jr. National Scholarship (Spring 2016)
- Izaak Walton League Thomas W. Fisher Conservation Scholarship (Spring 2016)

- ASCE Central Pennsylvania Chapter Award for Excellence (Fall 2015)
- Dean's List, all semesters at PSU and Montgomery College, MD (Spring 2012-Fall 2016)
- Frank Holzer Memorial Scholarship-PSU Civil Eng. (Fall 2015-Spring 2016)
- Penn State University Schreyer Honors Academic Excellence Scholarship (Fall 2013-Spring 2017)
- Penn State Provost's Scholarship (Fall 2013-Spring 2017)

Professional Memberships: American Society of Civil Engineers, Chi Epsilon, Engineer In Training (Fundamentals of Engineering Exam)

Publications: N/A

Presentations: N/A

Community Service Involvement: Incarnation Fellowship

International Education (including service-learning abroad):

Mercy Ships (Aboard the Africa Mercy)
Full-Time Volunteer Dining Room Worker on the Africa Mercy Ship (May 2014-August 2014)

- Supervised the dining room for 3 weeks while the regular manager was on leave
- Stationed in the Republic of Congo and sailed to the Canary Islands for dry dock

Language Proficiency: N/A