Cross-Laminated Timber: A Renewable Structural System

by

Joshua Strahm

B.S., Kansas State University, 2019

A REPORT

submitted in partial fulfillment of the requirements for the degree

MASTER OF SCIENCE

Department of Architectural Engineering and Construction Science
College of Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2019

Approved by:

Major Professor
Bill Zhang, Ph.D., P.E., S.E., LEED AP

Copyright

Abstract

Developed in Europe in the early 1990's, cross-laminated timber (CLT) is beginning to make its way into the North American building construction market. Similar to other types of engineered wood products, such as Glulam, CLT is an efficient and economical way to use natural wood resources. This report introduces the product with its structural characteristics, advantages and disadvantages, manufacturing, and construction. ANSI/APA PRG 320 *Standard for Performance-Rated Cross-Laminated Timber* published by APA – The Engineered Wood Association is the manufacturing standard for CLT in the United States. Manufacturers will supply reference design values for design engineers to check the strength of CLT members. Methods used to determine reference design values include experimental and analytical studies. CLT has many benefits in construction but also has challenges due to architects', engineers', and contractors' unfamiliarity with the product. A few projects have been built using CLT in the United States including a building at Oregon State University and one at the University of Arkansas.

Table of Contents

List of Figures v
List of Tables vi
Chapter 1 - Introduction 1
Chapter 2 - Cross Laminated Timber 3
Manufacturing 3
Classification 5
Advantages 6
Disadvantages 8
Chapter 3 - Design and Strength 9
Modeling CLT 12
Design 18
Chapter 4 - Construction 20
Connections 20
Lifting and Handling 22
Advantages and Disadvantages 27
Transportation 27
Chapter 5 - CLT Building Projects 28
Oregon State University 28
University of Arkansas 30
Curtain Place 31
Chapter 6 - Conclusion 33
References 35

List of Figures

Figure 2-1: CLT Panel Layup ... 4
Figure 2-2: Finger Jointing ... 4
Figure 2-3: Wood vs. Steel Loss of Strength in Fire (Waugh, 2018) ... 7
Figure 3-1: Diagram of Shear Analogy ... 15
Figure 3-2: Bending and Shear Stresses in Beam A (Karacabevli, 2013) ... 16
Figure 3-3: Bending and Shear Stresses of Beam B (Karacabevli, 2013) ... 17
Figure 3-4: Combined Stresses of Beam A and B (Karacabevli, 2013) ... 17
Figure 4-1: Self-Tapping Screw Wall Connections ... 20
Figure 4-2: Wall Connections With Metal Brackets ... 21
Figure 4-3: CLT Floor Connections ... 22
Figure 4-8: Inserted Rod With Soft Sling (Karacabevli, 2013) ... 25
Figure 5-1: Artist Rendering of Peavy Hall (Oregon Forest Science Complex, 2018) ... 28
Figure 5-2: Peavy Hall Under Construction (Oregon State University, 2018) ... 29
Figure 5-3: Artist Rendering of Stadium Drive Residence Halls (Williams, 2018) ... 30
Figure 5-4: Stadium Drive Residence Hall (University of Arkansas, 2018) ... 31
Figure 5-5: Curtain Place (Waugh, 2018) ... 32
Figure 5-6: Curtain Place Interior (Waugh, 2018) ... 32

List of Tables

Table 2-1: Required Characteristic Test Values for Laminations (APA, 2018)............................ 5

Table 3-1: CLT Applicable Adjustment Factors (NDS, 2015).. 1

Table 3-2: Sawn Lumber Applicable Adjustment Factors (NDS, 2015)....................................... 2

Table 3-3: Equations in CLT Handbook... 13

Chapter 1 - Introduction

Utilizing natural materials in structures has been around since man began building. Wood is one of those ancient materials. In recent decades engineered wood products have been brought to the market and used in structures. Engineered wood products utilize wood components with relatively small dimensions which are otherwise not very useful practically, and bond them together to create a larger size composite member and to enhance the structural characteristics. In this way it makes better use of forest resources. Early examples of manufactured timber products have been found by archeologists in the tombs of the Egyptian pharaohs (History, 2018). The Chinese glued wood shavings together for furniture use about a thousand years ago (History, 2018). Early plywood was typically made from decorative hardwoods for use in household items (History, 2018). The first patent for what could be called plywood was issued in 1865 to a man in New York City, but history does not record that he ever capitalized on his invention (History, 2018).

The manufactured wood products industry was born when the 1905 World's Fair was hosted in Portland, Oregon. A company in Portland decided to laminate wood panels for a display (History, 2018). The product created considerable interest and orders were placed for the product. By 1907, the Portland company had installed an automatic glue spreader, and production soared (History, 2018).

Since the beginning of plywood many other engineered wood products have become available such as oriented strand board (OSB), I-joists, glue laminated timber (glulam), laminated veneer lumber (LVL), and oriented strand lumber (OSL), etc. Glue laminated timber, or glulam, made its entrance into wood construction around 1900 in Switzerland (History, 2018). It could be considered the direct predecessor to cross-laminated timber.

Cross-laminated timber, or CLT, was developed in Europe in the early 1990's with the first technical approvals in 1998 (Brandner, 2016). It is similar to glulam in that it is composed of several layers of thinner timber members, but different in that adjacent layers are perpendicular to each other as opposed to all layers being parallel as in glulam. Most commonly the layers are made of sawn lumber but could also be of another engineered wood product such as OSB, LVL, or plywood. The layers could be connected together in a variety of fashions including nails, dowels, or adhesives. This report focuses on sawn lumber cross-laminated timber bonded with adhesives. Chapter 2 introduces more detail on the manufacturing, advantages, and disadvantages of cross-laminated timber.

Manufacturers will provide reference design values for engineers to use in order to find the allowable capacity of a panel. Chapter 3 presents an analytical method for determining reference design values and how engineers can take that data and use it in structural design.

Cross-laminated timber provides a challenge to contractors tasked with erecting the structure. It is a new product in the United States so construction methods and techniques are not well developed. Since cross-laminated timber is a wood product, connections are similar to other types of wood construction. Many techniques for handling the panels have been borrowed from the precast concrete construction industry because it is more developed. Chapter 4 presents different types of connections and handling techniques.

Many projects have utilized cross-laminated timber in Europe since it is more developed but few projects have been built with cross-laminated timber in the United States. Chapter 5 discusses two projects using CLT currently under construction in the United States and one completed CLT project in the United Kingdom.

Chapter 2 - Cross Laminated Timber

Cross-laminated timber (CLT) is a prefabricated, solid engineered wood panel consisting of several layers of lumber stacked in alternating directions and bonded together. CLT products are rectangular panels 2 ft. to 10 ft. wide, up to 60 ft. long, and up to 20 in. thick (Cross-Laminated Timber, 2018). Panels can be up to 18 ft. wide and 98 ft. long, but are uncommon. In reality, transportation of the panels or the manufacturers equipment is the limiting factor for size. Common applications for CLT are long span panels in walls, floors, and roofs. The lamination in CLT may be achieved by several different methods such as nails, dowels, or adhesives. This report focuses on CLT bonded with adhesives, which is the most common method in today's CLT.

Manufacturing

ANSI/APA PRG 320 *Standard for Performance-Rated Cross-Laminated Timber* is the CLT manufacturing standard in the United States first completed in 2011 (Yeh, 2012). The first step of manufacturing CLT products is selecting the lumber. Each layer must be the same species or species combination to ensure uniform mechanical and physical properties, but need not be the same between layers (Yeh, 2012). Permitted lumber includes any species or species combination recognized by the American Lumber Standards Committee under PS 20 (APA, 2018). Additionally, the lumber must have a specific gravity of 0.35 or above as listed in the National Design Specification for Wood Construction (APA, 2018). The lower bound for specific gravity is intended for CLT connections (Yeh, 2012). The grade of lumber is required to be at least machine stress rated 1200f-1.2E or visually graded No. 2 in the parallel layers and at least visually graded No. 3 in the perpendicular layers (APA, 2018). Parallel layers are those parallel to the strength axis of the CLT panel and perpendicular layers are those perpendicular to the strength axis of the CLT panel. Figure 2-1 shows which layers are considered parallel and which are perpendicular.

Once the lumber has been selected, defects such as large knots and bark are removed and then the lumber is kiln dried. Moisture content is important to ensure proper bonding and dimensional stability. Proper moisture content is 12% with a 3% tolerance (APA, 2018). Boards

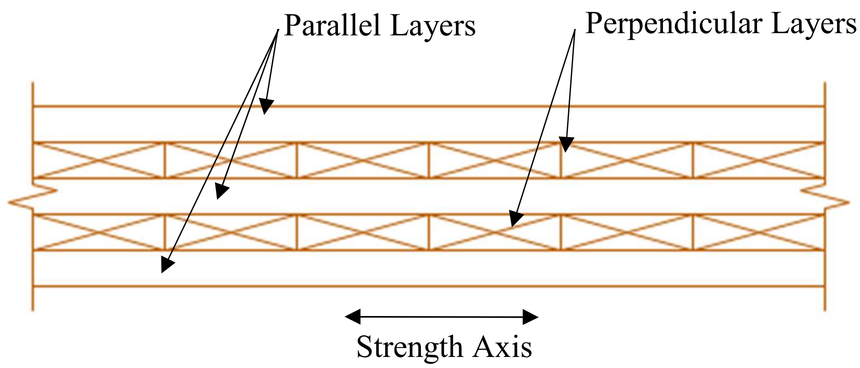

Figure 2-1: CLT Panel Layup

are then trimmed and finger jointed to achieve the desired length and quality. Finger jointing, as shown in figure 2-2, allows shorter boards to be connected to form longer boards which may be required for longer spans. Typically, the thickness of each layer is from 1 in. to 2 in. The NDS limits the layer thickness to between 5/8 in. and 2in.

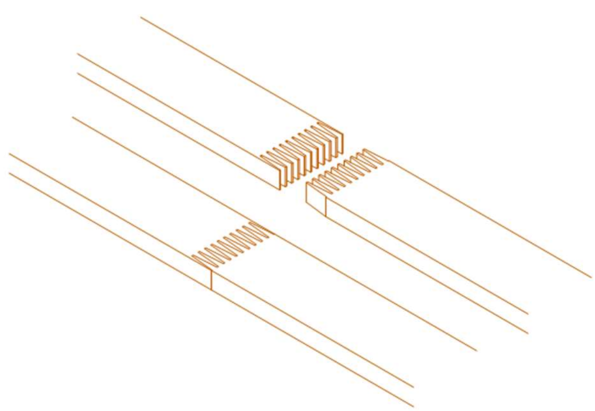

Figure 2-2: Finger Jointing

A CLT panel is then assembled by laying boards side by side to form solid wood layers. Each layer is laid perpendicular to the preceding layer to establish cross lamination. A bonding adhesive is applied between the layers and then the layers are pressed either hydraulically or by vacuum to bind the layers together. CLT adhesives must conform to ANSI-405 *Standard for Adhesives for Use in Structural Glued Laminated Timber* (APA, 2018). One difference between CLT and other glued laminated timber products is that there is no provision for wet-service conditions at this time. After assembly, all that remains is to cut the panel to size and mill to specifications.

Classification

Seven stress classes have been developed by PRG 320 based on prescriptive lumber species and grades available in North America. The classifications designated with an "E" are based on the use of E-rated or machine stress rated lumber in the longitudinal layers. The "V" designation represents classifications based on visually graded lumber in the longitudinal layers. All classifications are based on visually graded lumber in the transverse layers. Table 2-1 shows the test values required for each classification.

Table 2-1: Required Characteristic Test Values for Laminations (APA, 2018)

	Laminations Used in Major Strength Direction						Laminations Used in Minor Strength Direction					
CLT Layup	f_b (psi)	E (10^6 psi)	f_t (psi)	f_c (psi)	f_v (psi)	f_s (psi)	f_b (psi)	E (10^6 psi)	f_t (psi)	f_c (psi)	f_v (psi)	f_s (psi)
E1	4095	1.7	2885	3420	425	140	1050	1.2	525	1235	425	140
E2	3465	1.5	2140	3230	565	185	1100	1.4	680	1470	565	185
E3	2520	1.2	1260	2660	345	115	735	0.9	315	900	345	115
E4	4095	1.7	2885	3420	550	180	945	1.3	525	1375	550	180
V1	1890	1.6	1205	2565	565	185	1100	1.4	680	1470	565	185
V2	1835	1.4	945	2185	425	140	1050	1.2	525	1235	425	140
V3	1575	1.4	945	2375	550	180	945	1.3	525	1375	550	180

The standard does allow for manufacturers to create custom CLT layups when approved by an approved agency.

Advantages

As it is with any structural system, there are both advantages and disadvantages for CLT. Those depend on many different factors including material, availability, and the experience of architects, engineers, and contractors.

The primary advantage of CLT is that it is made of a renewable material. Properly managed forests can be an inexhaustible source of material by planting new trees for those harvested. For those who are concerned with the amount of carbon in the atmosphere, another advantage would be that CLT is a natural carbon storehouse. The movement of carbon between various states is known as the carbon cycle. Trees are part of that cycle. As the natural growth process progresses, trees absorb carbon dioxide from the atmosphere, hold the carbon in the wood, and release the oxygen. If not harvested, the tree will eventually die and then decay releasing the carbon back into the atmosphere. Harvesting the tree prior to the end of its life for products such as CLT traps the carbon for possibly centuries.

Another advantage of CLT is the reduced required size of structural foundations based on several factors. First, CLT has a high strength-to-weight ratio, reducing the weight of the structure itself. Second, a CLT panel can be used as the finished surface as well as a structural member reducing secondary structures and finishes. Because of these reasons, the overall structure will have less weight, reducing the required size for foundations.

Structures in areas that have high seismic activity must be designed to handle the energy input from an earthquake. CLT structures have connections that are more likely to deform in a ductile manner contrasted with connections in steel and concrete that are more likely to fracture. This flexibility allows the structure to dissipate energy without fracture leading to higher seismic resilience.

One fact that is not commonly known about CLT since it is made of a combustible material is the inherent fire resistance of CLT which is not intuitive to most people. When heat is applied to wood, a charred layer forms on the exposed surface. As the char layer grows, the cross sectional dimensions of the CLT panel decrease reducing its capacity, but the growing char layer also serves as an insulator protecting the uncharred portion of the panel from heat (Frangi, 2009). The charring rate of timber can be assumed to be constant (Frangi, 2009). Because of its mass, CLT panels char slowly. Once charred, combustion stops as the oxygen source is removed (Smartlam, 2019). Since CLT is a totally solid panel there are fewer concealed spaces in a CLT structure reducing the likelihood of a fire spreading undetected. Because of the unique charring feature of timber, there is often no additional requirement for fireproofing as is often the case for steel. Wood actually retains its strength longer in a fire than steel as shown in figure 2-3.

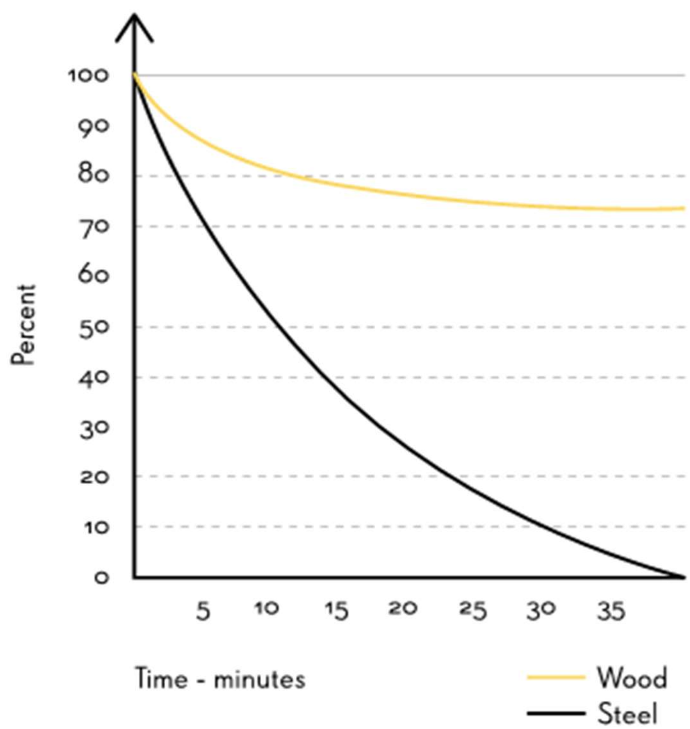

Figure 2-3: Wood vs. Steel Loss of Strength in Fire (Waugh, 2018)

Disadvantages

CLT is a relatively new product in North America. Because of its infancy, architects, engineers, and contractors are unfamiliar with the product. There are also few manufacturers in North America.

A second disadvantage of CLT is its inflexibility with regard to design. All design issues need to be determined ahead of panel fabrication as it is difficult to adjust the design once the panels are fabricated. Any variations on site are difficult and expensive to resolve. Future transformation of the building is difficult as well. And, services such as electrical and HVAC need careful consideration ahead of time if exposed CLT is used as a finish with services also being difficult to relocate later.

The final disadvantage of CLT is the material cost. A CLT building has a 30-40% higher cost by building volume compared to other materials (Waugh, 2018). A possible contributing factor to this is the rarity of CLT. With few manufacturers and few contractors, competition is limited. As CLT grows in popularity and availability, competition will surely drive the price down.

Chapter 3 - Design and Strength

Codes and standards for CLT design are still under development in both Europe and North America. Eurocode 5, the timber design standard in Europe, does not currently include provisions for CLT but some national annexes do. In the United States, provisions for CLT were first included in the 2015 National Design Specification for Wood Construction in the United States on a limited basis.

The National Design Specification for Wood Construction (NDS) is the design code for wood structures in the United States. In order to determine strength of a wood structural member the first step is retrieving reference design values and then applying the adjustment factors. The adjustment factors depend on several factors including loading condition, grain orientation, service conditions, etc. One difference with CLT compared with sawn lumber is that reference design values are dependent upon the section as a whole instead of only the section material properties. This contributes to the fact that there are fewer adjustment factors for CLT, shown in table 3-1, than for sawn lumber, shown in table 3-2. The manufacturer will provide the reference design values based on the analysis procedure introduced in the next chapter.

Table 3-1: CLT Applicable Adjustment Factors (NDS, 2015)

		ASD only	ASD and LRFD					LRFD only		
		Load Duration Factor	Wet Service Factor	Temperature Factor	Beam Stability Factor	Column Stability Factor	Bearing Area Factor	Format Conversion Factor	Resistance Factor	Time Effect Factor
								K_F	φ	
Bending	$F_b'S_{eff}=F_bS_{eff}$ X	C_D	C_M	C_t	C_L	-	-	2.54	0.85	λ
Tension	$F_t'A_{parallel}=F_tA_{parallel}$ X	C_D	C_M	C_t	-	-	-	2.70	0.80	λ
In-plane Shear	$F_v(t_v)'=F_v(t_v)$ X	C_D	C_M	C_t	-	-	-			
Out-of-plane Shear	$F_v'(lb/Q)_{eff}=F_v(lb/Q)_{eff}$ X	C_D	C_M	C_t	-	-	-	2.88	0.75	λ
Parallel Compression	$F_c'A_{parallel}=F_cA_{parallel}$ X	C_D	C_M	C_t	-	C_P	-	2.40	0.90	λ
Perpendicular Compression	$F_{c\perp}'A=F_{c\perp}A$ X	-	C_M	C_t	-	-	C_b	1.67	0.90	-
Apparent Stiffness	$EI'_{app}=EI_{app}$ X	-	C_M	C_t	-	-	-	-	-	-
Minimum Apparent Stiffness	$EI'_{app\text{-}min}=EI_{app\text{-}min}$ X	-	C_M	C_t	-	-	-	1.76	0.85	-

Table 3-2: Sawn Lumber Applicable Adjustment Factors (NDS, 2015)

		ASD only	ASD and LRFD										LRFD only		
		Load Duration Factor	Wet Service Factor	Temperature Factor	Beam Stability Factor	Size Factor	Flat Use Factor	Incising Factor	Repetitive Member Factor	Column Stability Factor	Buckling Stiffness Factor	Bearing Area Factor	Format Conversion Factor	Resistance Factor	Time Effect Factor
													K_F	φ	
Bending	$F_b' = F_b$ X	C_D	C_M	C_t	C_L	C_F	C_{fu}	C_i	C_r	-	-	-	2.54	0.85	λ
Tension	$F_t' = F_t$ X	C_D	C_M	C_t	-	C_F	-	C_i	-	-	-	-	2.70	0.80	λ
Shear	$F_v' = F_v$ X	C_D	C_M	C_t	-	-	-	C_i	-	-	-	-	2.88	0.75	λ
Parallel Compression	$F_c' = F_c$ X	C_D	C_M	C_t	-	C_F	-	C_i	-	-	-	-	2.40	0.90	λ
Perpendicular Compression	$F_{c\perp}' = F_{c\perp}$ X	-	C_M	C_t	-	-	-	C_i	-	C_P	-	C_b	1.67	0.90	-
Modulus of Elasticity	$E' = E$ X	-	C_M	C_t	-	-	-	C_i	-	-	-	-	-	-	-
Minimum Modulus of Elasticity	$E_{min}' = E_{min}$ X	-	C_M	C_t	-	-	-	C_i	-	-	C_T	-	1.76	0.85	-

Load duration factor is applicable only for ASD design methodology. Wood has a greater strength for short duration loads than for long duration loads. This factor takes that property into account. The wet service factor adjusts the strength properties in the presence of extra moisture. Currently PRG 320 does not allow CLT products for wet service conditions so this factor is one. The temperature factor takes into account the effect of sustained temperatures above 100°F. The beam stability factor adjusts for buckling of a beam and the column stability factor adjusts for buckling of a column. The time effect factor is the LRFD counterpart to load duration factor in ASD. The resistance factor is dependent on the limit state. The format conversion factor adjusts the reference design value for LRFD.

Modeling CLT

In order to determine the reference design values, CLT can be modeled in two ways, analytically and experimentally. An analytical approach generally predicts the strength and stiffness properties based on the material properties of the laminations of a CLT panel. An experimental approach requires testing full-size panels or sections of panels. Every time the lay-up, type of materials, or any of the manufacturing parameters change, more testing is required to find the properties of the member. Once confirmed by testing, an analytical approach is less costly in terms of time and money, compared to experimental approach.

One analytical approach, named the Gamma Method, has been adopted for CLT in Europe and can be found in Annex B of Eurocode 5. More recently, the "Shear Analogy" method has been developed and adopted by the product standard PRG 320. It is applicable for solid panels with cross layers where the load is applied perpendicular to the panel. In-plane loading of the panel such as that in shear walls requires a different method of analysis to determine the panel properties.

Table 3-3: Equations in CLT Handbook

Equation	CLT Handbook Chapter 3 Equation Number (Karacabevli, 2013)
Equation 3.1	13
Equation 3.2	14
Equation 3.3	15
Equation 3.4	16
Equation 3.5	17
Equation 3.6	18
Equation 3.7	19
Equation 3.8	20
Equation 3.9	21
Equation 3.10	22
Equation 3.11	24
Equation 3.12	25
Equation 3.13	23
Equation 3.14	28
Equation 3.15	31
Equation 3.16	33

The shear analogy method is used to consider the different properties of single layers for nearly any system configuration. The following is an introduction of this method from the CLT Handbook. Table 3-3 shows the equation match in the CLT Handbook. To begin, panel characteristics are separated into two virtual beams, A and B. The sum of the inherent bending stiffnesses of the individual layers along their own centers is given to Beam A as shown in equation 3.1.

$$B_A = \sum_{i=1}^{n} E_i I_i = \sum_{i=1}^{n} E_i b_i \frac{h_i^3}{12} \qquad \text{(Equation 3.1)}$$

where:

$B_A = (EI)_A$

E_i = Modulus of elasticity of each individual layer

b_i = Width of each individual layer, usually taken as a unit width (e.g. 1 ft.) for CLT panels

h_i = Thickness of each individual layer

Beam B represents the increased moment of inertia for the bending stiffness due to the distances from the neutral axis of the section to the neutral axes of the layers using the parallel axis theorem as shown in equation 3.2.

$$B_B = \sum_{i=1}^{n} E_i A_i z_i^2 \qquad \text{(Equation 3.2)}$$

where:

$B_B = (EI)_B$

z_i = the distance between the neutral axis of layer i and the neutral axis of the section

A_i = Area of each individual layer

Beam B also contains the shear stiffness, S_B, which can be calculated using equation 3.3.

$$\frac{1}{S_B} = \frac{1}{a^2}\left[\frac{h_1}{2G_1 b_1} + \sum_{i=2}^{n-1} \frac{h_n}{G_i b_i} + \frac{h_n}{2G_n b_n}\right] \qquad \text{(Equation 3.3)}$$

G_i = Shear modulus of each individual layer

a = Distance between the neutral axes of the top and bottom layers

The two beams are then connected with infinitely rigid web members. Figure 3-1 shown a visual representation of the model.

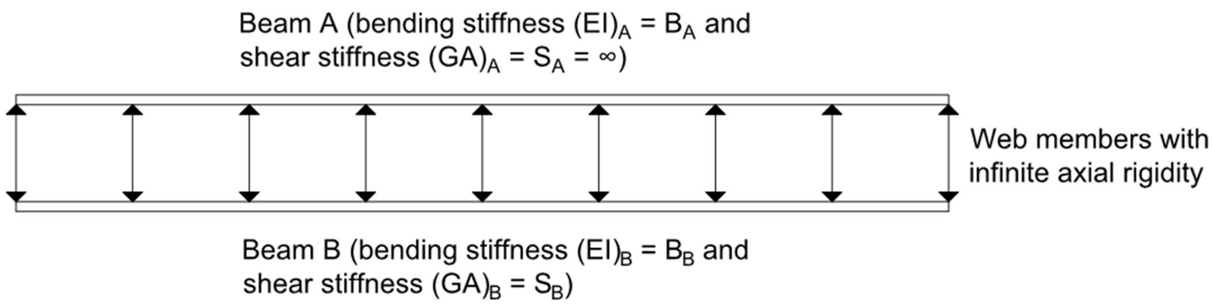

Figure 3-1: Diagram of Shear Analogy

In the above equations, elastic and shear moduli for longitudinal layers should use E_0 (E parallel to the grain) and G, while those for perpendicular layers should use E_{90}=E_0/30 (E perpendicular to the grain) and G_R=G/10 (rolling shear). It is assumed that G = E/16 in PRG 320.

The deflections of beams A and B must be equal at every point. Virtual section sizes of beams A and B and the values for M_A, M_B, V_A, and V_B are produced numerically, often using a spreadsheet (Karacabeyli, 2013). The bending moments and shear forces of each layer can then be found using equations 3.4 and 3.5.

$$M_{A,i} = \frac{E_i I_i}{B_A} M_A \qquad \text{(Equation 3.4)}$$

$$V_{A,i} = \frac{E_i I_i}{B_A} V_A \qquad \text{(Equation 3.5)}$$

where M_A and V_A are the bending and shear forces on beam A and B_A is from equation 3.1.

Equations 3.6 and 3.7 can be used to obtain the bending stresses, σ_A, and shear stresses, τ_A, of individual layers.

$$\sigma_{A,i} = \pm \frac{M_{A,i}}{I_i} \frac{h_i}{2} \qquad \text{(Equation 3.6)}$$

$$\tau_{A,i} = \frac{E_i I_i}{B_A} * 1.5 * \frac{V_A}{b h_i} \quad \text{(Equation 3.7)}$$

Figure 3-2 shows the bending and shear stresses in beam A.

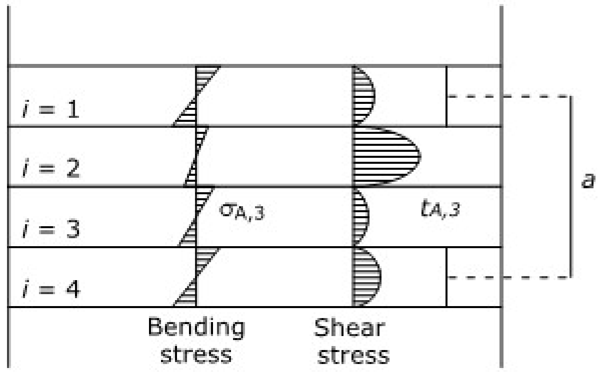

Figure 3-2: Bending and Shear Stresses in Beam A (Karacabevli, 2013)

Axial forces, N_B, and normal stresses, σ_B, of each individual layer of beam B can be found using equations 3.8 and 3.9.

$$N_{B,i} = \frac{E_i A_i z_i}{B_B} M_B \quad \text{(Equation 3.8)}$$

$$\sigma_{B,i} = \frac{N_{B,i}}{b_i h_i} = \frac{E_i z_i}{B_B} M_B \quad \text{(Equation 3.9)}$$

Shear stresses at the interface of each layer can be found using equation 3.10.

$$\tau_{Bi,i+1} = \frac{V_B}{B_B} \sum_{j=i+1}^{n} E_j A_j z_j \quad \text{(Equation 3.10)}$$

Figure 3-3 shows the bending and shear stresses for beam B.

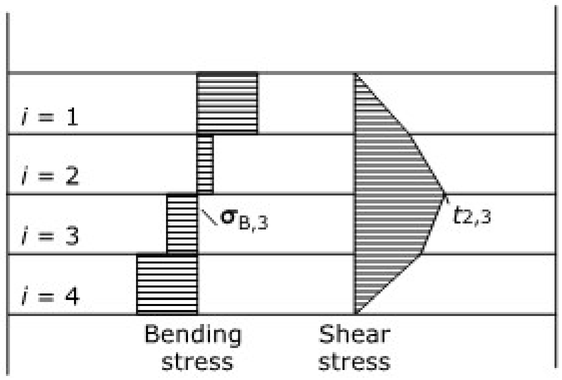

Figure 3-3: Bending and Shear Stresses of Beam B (Karacabevli, 2013)

The resulting stresses from beam A and B can be combined by superposition as shown in figure 3-4.

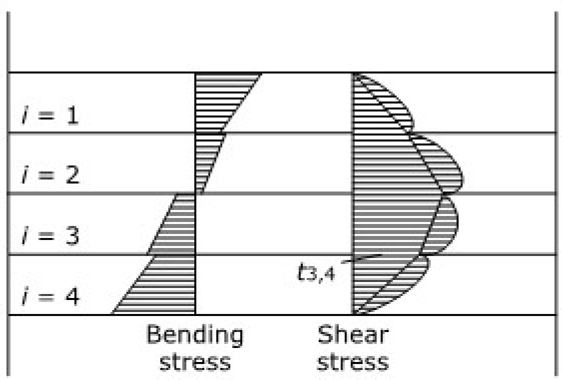

Figure 3-4: Combined Stresses of Beam A and B (Karacabevli, 2013)

The effective bending stiffness and effective shear stiffness of the composite section can be obtained using equations 3.11 and 3.12 respectively.

$$EI_{eff} = \sum_{i=1}^{n} E_i b_i \frac{h_i^3}{12} + \sum_{i=1}^{n} E_i A_i z_i^2 \qquad \text{(Equation 3.11)}$$

$$GA_{eff} = \frac{a^2}{\left[\left(\frac{h_1}{2G_1 b}\right)+\left(\sum_{i=2}^{n-1}\frac{h_i}{G_i b_i}\right)+\left(\frac{h_n}{2G_n b}\right)\right]} \quad \text{(Equation 3.12)}$$

The maximum deflection in the middle of a CLT slab under a uniformly distributed load is the sum of the deflections due to bending and shear. Shear needs to be included because shear deformations can be significant in CLT. Equation 3.13 describes this deflection.

$$\Delta_{max} = \frac{5}{384}\frac{wL^4}{EI_{eff}} + \frac{1}{8}\frac{wL^2 k}{GA_{eff}} \quad \text{(Equation 3.13)}$$

where k is a constant dependent on loading and end fixity. The deflection equation is simpler if the apparent bending stiffness is used instead of the effective bending stiffness. The apparent bending stiffness can be found using equation 3.14

$$EI_{app} = \frac{EI_{eff}}{1 + \frac{K_s EI_{eff}}{GA_{eff} L^2}} \quad \text{(Equation 3.14)}$$

where K_s is dependent on the loading and end fixity. All these equations are only valid for out-of-plane loading. A different method is required for in-plane loading in-plane.

Design

The simplified method is used to determine reference design values. For flexure the effective section modulus is first calculated using equation 3.15.

$$S_{eff} = \frac{2EI_{eff}}{E_1 h} \quad \text{(Equation 3.15)}$$

where E_1 is the modulus of elasticity of the outermost layer and h is the entire thickness of the panel.

PRG 320 stipulates that this value is multiplied by a reduction factor of 0.85 for conservatism. The effective section modulus is then multiplied by the fiber bending stress of the outer most layer to find F_bS_{eff}.

For shear the simplified method can also be used. An effective $(lb/Q)_{eff}$ can be calculated using equation 3.16.

$$(lb/Q)_{eff} = \frac{EI_{eff}}{\sum_{i=1}^{\frac{n}{2}} E_i h_i z_i} \qquad \text{(Equation 3.16)}$$

This is then multiplied by the rolling shear strength to obtain the reference design value $F_s(lb/Q)_{eff}$.

Axial load is considered to be carried only by the layers in which the wood fibers are parallel to the applied load. Therefore, $A_{parallel}$ is the area of layers with fibers parallel to the direction of the load. $F_cA_{parallel}$ is then found by multiplying $A_{parallel}$ by the allowable compression stress and $F_tA_{parallel}$ is found by multiplying $A_{parallel}$ by the allowable tension stress. These reference design values can then be adjusted to determine the design strength of the CLT panel.

Chapter 4 - Construction

CLT is a wood product used in structural systems that has its unique features. There are aspects of wood construction such as connections that are similar. When it comes to lifting and handling the panel, techniques are borrowed from the precast concrete industry.

Connections

Connections are critical to the functionality of a structure and CLT members can be connected utilizing a variety of fasteners and joint details. Long self-tapping screws are typically recommended by CLT manufacturers and are commonly used for connecting panels to panels in floors and floor-to-wall assemblies such as shown in figure 4-1 (Karacabevli, 2013). The left side of figure 4-1 shows a connection with only two walls intersecting at a location. With two walls intersecting a third at a location the same method can only be used to connect one side. The other side must use a different method such as driving a screw at an angle as shown on the right side of figure 4-1. More methods of using self-tapping screws are available. Compared to traditional wood or lag screws, self-tapping screws can be installed easily, and have a high withdrawal capacity making them popular among builders.

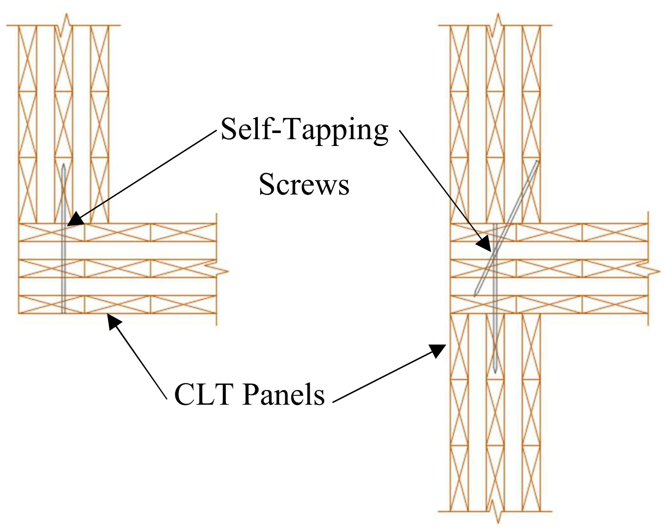

Figure 4-1: Self-Tapping Screw Wall Connections

Screws could also be used in conjunction with metal brackets. The brackets could either be attached on the exterior of the panel or concealed within the panel. The left side of figure 4-2 demonstrates a bracket fastened on the exterior of a panel, while the right side of figure 4-2 shows a bracket concealed within the panel. In the latter case, holes are drilled through the panel and bracket for dowels or bolts.

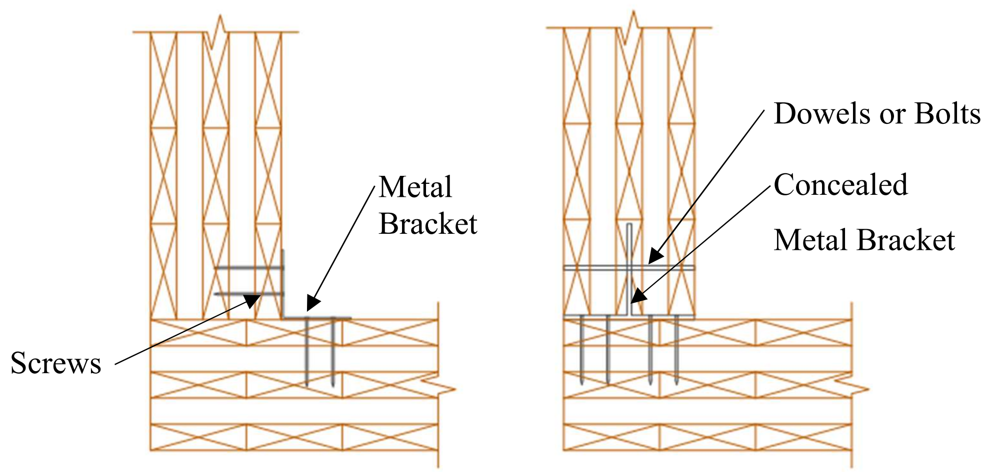

Figure 4-2: Wall Connections With Metal Brackets

The same fasteners can also be applied to floor joints albeit in a different manner. Splines can be placed in a groove cut into each panel and then screwed together. The spline could be placed at the top middle or bottom of the panel. Another method is to lap the panels and then screw the panels together. These methods are shown on the top and bottom of figure 4-3 respectively.

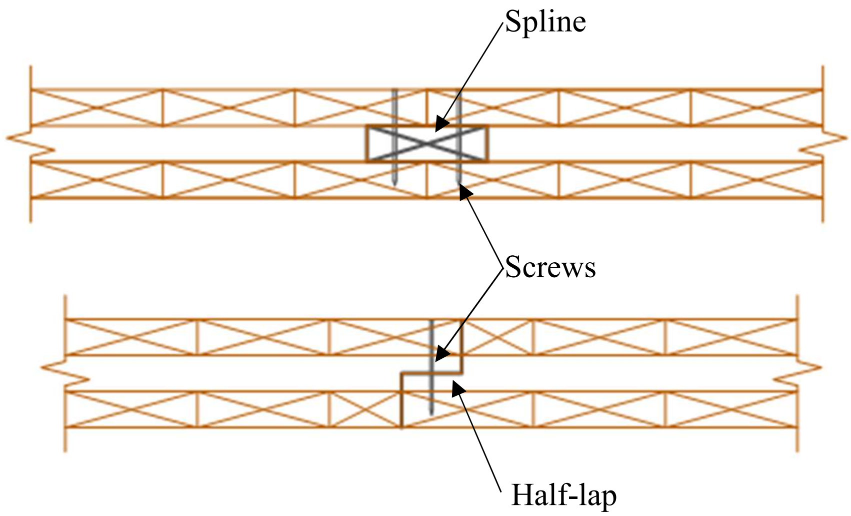

Figure 4-3: CLT Floor Connections

Lifting and Handling

Since CLT is a relatively new product, construction techniques have not been well developed. Precast concrete construction using large slabs is similar to CLT construction since both are utilizing large panels. Because the precast concrete industry is more developed, most techniques that are currently used for CLT have been borrowed from it.

Care must be taken when moving large panels around. While many techniques have been used, the complexity or location of a building often dictates which technique will be used (Karacabevli, 2013). In remote or inaccessible construction sites CLT elements may be lifted using a cableway or even a helicopter. On most job sites CLT elements would be lifted using a crane.

Several different methods could be used to connect lifting apparatuses to the panels. The first are contact lifting systems. These systems take advantage of the efficient compressive strength of wood perpendicular to the grain by utilizing compressive resistance on the underside of a panel. Figure 4-4 shows examples of a steel plate fastened to a threaded socket or a bolt. Here the steel plate imposes a compressive bearing force on the underside of the panel. Caution must be taken once the panel is in place as the steel plates are not secured once the system is removed. This type of system is considered to be the safest CLT panel handling method (Karacabevli, 2013). Another example of a contact lifting method is using a soft sling inserted through holes in the panel as shown in figure 4-5. Both lifting methods discussed thus far require holes to be drilled in the panel. These holes do need to be plugged to ensure proper air tightness and to prevent the spread of sound, smoke, and fire (Karacabevli, 2013).

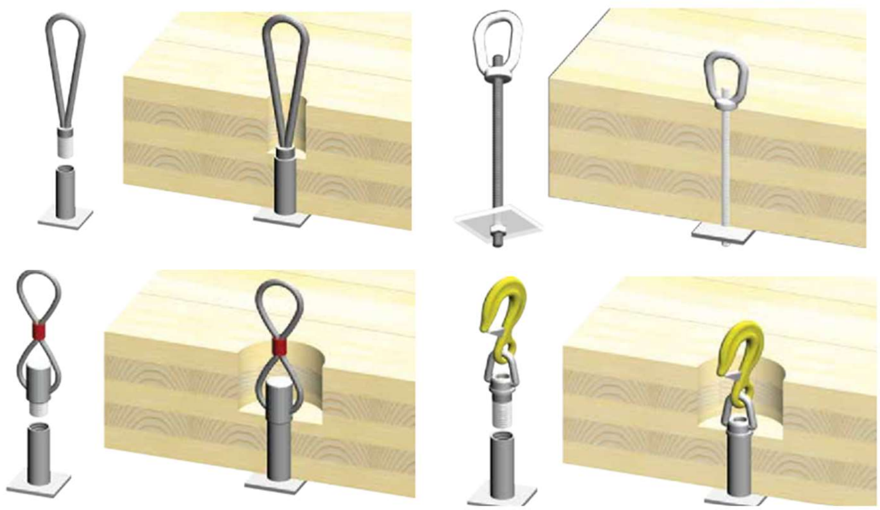

Figure 4-4: Steel Bearing Lifting Systems (Karacabevli, 2013)

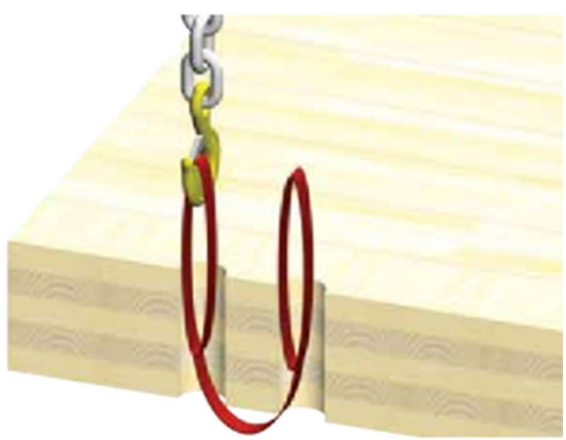

Figure 4-5: Lifting Sling With Holes (Karacabevli, 2013)

The second method to lift CLT panels are screw hoist systems. These systems rely on the withdrawal resistance of the fasteners. While simple and effective, they require a careful design analysis for loads and strict control during installation and use (Karacabevli, 2013). An advantage of this system is that the appearance of only one side of the panel is affected. A screwed anchor as shown in figure 4-6 is based on an anchor used in precast concrete construction. In precast concrete an anchor is embedded in the concrete with a protruding head to which a lifting ring is attached. In CLT a self-tapping screw provides the connection of a lifting ring to the panel. Another type of screw connector is a screwed plate and lifting ring as shown in figure 4-7. Figure 4-7 shows the plate attached with four screws but could accommodate up to 12 screws. This allows the same plate to be reused in multiple situations adding flexibility.

Figure 4-6: Screwed Ring Connector (Karacabevli, 2013)

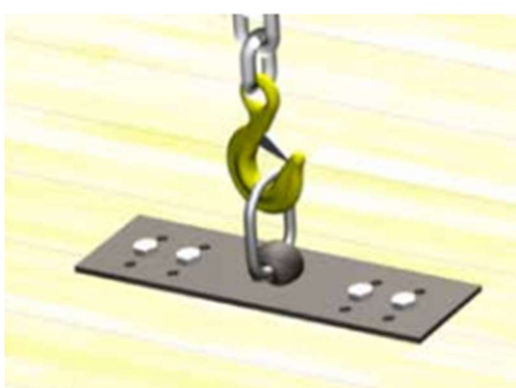

Figure 4-7: Screwed Plate and Lifting Ring (Karacabevli, 2013)

A third type of lifting system is an integrated lifting system. In this system a hole is drilled at the manufacturing plant near the edge of the panel and part way through the panel. A small hole is then drilled in the side of the panel perpendicular to and intersecting the first hole. A steel rod is then inserted in the small hole. At the time of erection, a soft sling can then be placed around the rod as shown in figure 4-8. This system takes advantage of manufacturing support to speed up erection on the jobsite. A metal hook could be connected to the rod as well. Holes should be filled once the panel is in place with this type of system as with contact lifting systems.

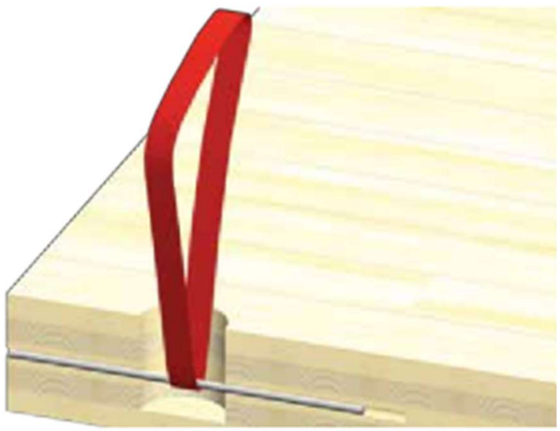

Figure 4-4: Inserted Rod With Soft Sling (Karacabevli, 2013)

A system that does not require any alteration to the panel can be seen in figure 4-9. A disadvantage of this system is the absence of a positive connection. The only thing keeping the panel in the sling is gravity. Winds in general provide complications with lifting large panels, but is more dangerous with this system because the wind could lift one end of the panel and lift it off the sling.

Panels that are placed vertical need additional shoring to be placed at the correct angle. Adjustable steel shoring can be used to accomplish such as shown figure 4-10.

Figure 4-9: Soft Lifting Sling Without Holes (Karacabevli, 2013)

Figure 4-10: Adjustable Steel Shoring (Karacabevli, 2013)

Advantages and Disadvantages

CLT has several advantages when it comes to construction. The first is speed. It is 20% faster than reinforced concrete (Waugh, 2018). Building with CLT is safer than other materials because the material weighs less. This reduces the hazards of moving heavy things as well as reducing the size of equipment necessary to move the panels around. Wood also absorbs airborne vibration leading to a quieter jobsite. Due to the high degree of prefabrication, less waste is produced on the jobsite.

The primary disadvantage of CLT is the tight tolerances required. This makes it challenging to contractors because a high degree of accuracy requires more time to erect.

Transportation

It is important that the CLT panels can be transported from the manufacturing facility to the jobsite. The size of panels must fit on the truck and be within the limits of local regulations on size and weight. The truck must also be able to travel to the site as could be a problem in either remote locations or very crowded locations. Faster erection can occur if the panels are stacked in the reverse order in which they will be installed. Once the panels arrive on the jobsite it is important to keep moisture away from the panels as much as possible.

Chapter 5 - CLT Building Projects

CLT is a new product in the United States so few projects have been built with it. A couple of universities, Oregon State University and University of Arkansas, are located in regions with abundant timber resources. These universities are pushing mass timber as a viable structural system as a way to enhance their respective states economy. Both universities have projects under construction built with CLT to demonstrate the viability of mass timber.

Oregon State University

Oregon State University is currently constructing a new Forest Science Complex to serve its expanding College of Forestry. A stated purpose of the project is to "showcase innovative uses of wood in building design" (Brown, 2015). The university also wants to demonstrate how Oregon's natural resource of timber can be used to improve the economy of the state. One way of doing that is by using CLT.

Peavy Hall is part of the Forest Science Complex and a three-story 80,000 square feet building constructed using CLT. Figure 5-1 shows an artist rendering of the building. The project incurred setbacks before construction even began. The contractor originally selected to build the project had concerns about the experience of the supplier of CLT panels. When the

Figure 5-1: Artist Rendering of Peavy Hall (Oregon Forest Science Complex, 2018)

university would not allow a different supplier the contractor asked for more money. The university refused and hired a different contractor.

Construction began in 2017. Figure 5-2 is an image of Peavy Hall's construction progress in February 2018. In March 2018 a section of the third floor fell to the floor below. This failure was traced to the delamination of a panel. Further investigation revealed that a change in the manufacturing process caused the adhesive to cure before proper bonding could occur. The manufacturer corrected the issue but testing of the panels to determine if more needed replacing delayed construction. The expected completion date is now fall 2019 (Manning, 2018)

Figure 5-2: Peavy Hall Under Construction (Oregon State University, 2018)

Disagreement exists over the effect this incident will have on the CLT industry. Skeptics say this is an "opportunity to stop the zoning and building code changes and reconsider its safety and soundness." Others say this is just a "manufacturing blip" and will have no effect moving forward (Manning, 2018).

University of Arkansas

As with Oregon, Arkansas also has timber as a natural resource. Similarly, the University of Arkansas has buildings built with CLT to demonstrate the potential of timber products to improve the economy of the state. The University of Arkansas has multiple buildings built with CLT. The first is a library storage facility completed in 2018 which is the first building built with CLT in the state. The second is a five story 200,000 square feet residence hall, shown in figure 5-3, which is the largest building built with CLT in the United States.

Figure 5-3: Artist Rendering of Stadium Drive Residence Halls (Williams, 2018)

A big advantage of CLT in construction is its short erection time. The estimated time to erect the structure of the residence hall is 12 to 15 weeks compared to the 18 to 20 weeks it took to construct a similar sized project with steel and concrete (Williams, 2018). The CLT panels are manufactured in Austria and shipped to Fayetteville, Arkansas. The 142,000 cubic feet of timber being used in the project can be grown in Arkansas forests in hours demonstrating the sustainability of CLT (Williams, 2018). Figure 5-4 shows a portion of the residence hall under construction.

Figure 5-4: Stadium Drive Residence Hall (University of Arkansas, 2018)

Curtain Place

Curtain Place in London is a mixed-use six story building completed in 2015. An image of the exterior is shown in figure 5-5. The structure of the building is a combination of CLT and steel. Floor slabs, roof slabs, and external walls are constructed with CLT panels reducing its weight while the beams and columns steel as shown in figure 5-6. The structure is exposed to give the building a "contemporary, stripped down feel" (Waugh, 2018). CLT was primarily chosen to overcome planning restrictions on building heights and to assist with access to the site. The accelerated speed of construction was an additional benefit (Waugh, 2018).

Figure 5-5: Curtain Place (Waugh, 2018)

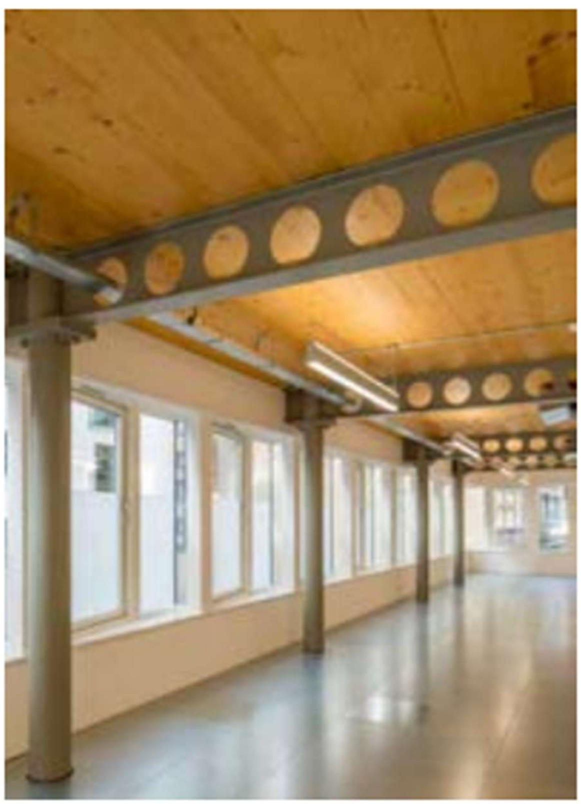

Figure 5-6: Curtain Place Interior (Waugh, 2018)

Chapter 6 - Conclusion

Wood has been used for building structures for many centuries. Engineered wood products take wood as a natural resource and use it in a more efficient manner leading to a sustainable building solution. Cross laminated timber (CLT) is one of those products, was developed in Europe in the 1990's and is now beginning to make its way to the United States.

Structural CLT in the United States must be manufactured and classified in accordance with ANSI/APA PRG 320 *Standard for Performance-Rated Cross-Laminated Timber*. Advantages of CLT include a high strength-to-weight ratio and a high seismic resilience. It also has inherent fire resistance due to the charring of wood. Disadvantages include the infancy of CLT in the United States which lead to its unfamiliarity with architects, engineers, and contractors and its inflexibility with regard to design.

Reference design values for CLT panels are based on the section as a whole contrasted with sawn lumber whose reference design values are based on material properties. The manufacturer determines the referenced design values using either an experimental or an analytical approach. An analytical approach is preferred due to the time and cost needed to conduct an experimental analysis every time the properties of a CLT panel change. Engineers then apply adjustment factors to the reference design values to find the allowable loading of the panel.

CLT has some unique features when it comes to construction. Due to a high degree of prefabrication erection can proceed quickly and little jobsite waste is produced. Prefabrication also means that potential issues need to be addressed before the panel makes its way to the field as it is then expensive to make changes. Self-tapping screws are the most popular method of connecting panels together due to their ease of installation and high withdrawal capacity.

Handling methods for CLT have been borrowed from the precast concrete industry since it is more developed.

Places that have timber as an abundant resource are promoting wood building products to enhance the local economy. This can be seen with CLT buildings being constructed in forested areas like Oregon and Arkansas. More research needs to be done on how to construct buildings with CLT. The product itself is fairly well developed, especially in Europe, but the construction industry is unfamiliar with how to use it. Advancements in codes and education of architects, engineers, and contractors would be a big contributor to bringing CLT to the mainstream construction in the United States.

References

2015 National design specification for wood construction. (2015). Leesburg, VA: American Wood Council.

APA—The Engineered Wood Association. (2018). *Standard for performance-rated cross-laminated timber*. (ANSI/APA PRG 320). Retrieved from https://www.apawood.org/ansi-apa-prg-320

American National Stantards Institute—ANSI. (2018). *Standard for adhesives for use in structural glued laminated timber.* (ANSI 405). Retrieved from https://www.apawood.org/ansi-405

BENEFITS & ADVANTAGES OF CLT. (2019). Retrieved January 25, 2019, from http://www.smartlam.com/about/benefits/

Brandner, R., Flatscher, G., Ringhofer, A., Schickhofer, G., & Thiel, A. (2016). Cross laminated timber (CLT): Overview and development. *European Journal of Wood and Wood Products,74*(3), 331-351. doi:10.1007/s00107-015-0999-5

Brown, Molly. "OSU Begins Initiative for Forest Science Complex." *Newsroom*, 6 Jan. 2015, today.oregonstate.edu/archives/2015/jan/osu-launches-initiative-forest-science-complex.

CrossLam CLT: Technical Design Guide. (2018). Structurlam.

Cross-Laminated Timber (CLT). (2018). Retrieved from https://www.apawood.org/cross-laminated-timber

Frangi, A., Fontana, M., Hugi, E., & Jübstl, R. (2009). Experimental analysis of cross-laminated timber panels in fire. *Fire Safety Journal,44*(8), 1078-1087. doi:10.1016/j.firesaf.2009.07.007

History of APA, Plywood, and Engineered Wood. (2018). Retrieved January 28, 2019, from https://www.apawood.org/apas-history

Horx-Strathern, O., Varga, C., & Guntschnig, G. (2017). *The future of Timber Construction: CLT-Cross Laminated Timber*(F. Mayer, Ed.). Zukunftsinstitut Osterreich GmbH.

Jacob, M., Harrington, J., Robinson, B. 2018. The Structural Use of Timber - Handbook for Eurocode 5: Part 1-1. COFORD, Department of Agriculture, Food and the Marine, Dublin

Jelec, M., Varevac, D., & Rajcic, V. (2018). Cross-laminated timber (CLT) – a state of the art report. *Journal of the Croatian Association of Civil Engineers,70*(02), 75-95. doi:10.14256/jce.2071.2017

Karacabeyli, E., & Douglas, B. (2013). *CLT handbook: Cross-laminated timber*. Pointe-Claire, QC: FPInnovations.

Manning, Jeff. *Problems at Peavy: Faulty Timber Panels Raise Stakes for Promising New Oregon Market*. OregonLive.com, 12 Aug. 2018, expo.oregonlive.com/news/erry-2018/08/4965f0c7df3495/problems-at-peavy-faulty-timbe.html.

Massey, Richard. “Ozarks Bound.” *Civil Structural Engineer Magazine*, 1 July 2018, csengineermag.com/article/ozarks-bound/.

“Oregon Forest Science Complex Construction Project.” *Finance and Administration*, 13 Aug. 2018, fa.oregonstate.edu/project-delivery/oregon-forest-science-complex-construction-project.

Oregon State University. (Producer). (2018, February). *Forest Science Complex 1* [Video file]. Retrieved from http://webcam.oregonstate.edu/cam/fsc1/timelapse/fsc1-full.mp4

University of Arkansas. (Producer). (2018, August). *Stadium Drive Residence Hall #2* [Video file]. Retrieved from https://app.oxblue.com/open/universityofarkansas

Waugh, Andrew, and Anthony Thistleton. *100 Projects: UK CLT*. Waugh Thistleton Architects, 2018.

Williams, Hannah. “Largest Cross-Laminated Timber Project in US Constructed by Nabholz.” *Nabholz Corporation*, 27 Feb. 2018, www.nabholz.com/cross-laminated-timber-project-america-nabholz/.

Yeh, B., Ph.D., P.E., Gagnon, S., Eng., Williamson, T., P.E., Pirvu, C., Ph.D., P.Eng., Lum, C., P. Eng., & Kretschmann, D., P.E. (2012). The North American Product Standard for Cross-Laminated Timber. *Wood Design Focus,22*(2), 13-21.