

CLT Handbook

CROSS-LAMINATED TIMBER

U.S.  EDITION

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FC Handbook

CROSS-LAMINATED TIMBER

U.S.  EDITION

Edited by
Erol Karacabeyli, P.Eng., FPInnovations
Brad Douglas, P.E., AWC

FPInnovations
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PREFACE

Expansion into mid-rise, high-rise and non-residential applications presents one of the most promising avenues for the North American wood industry to diversify its end use markets. This may be achieved by:

- Designing to new building heights with **Light Frame Wood Construction**
- Revival of **Heavy Timber Frame Construction**
- Adoption of **Cross-laminated Timber (CLT)**
- Facilitating **Hybrid Construction**

There are concerted efforts both in Canada and in the United States towards realizing that goal. In fact, the Canadian provinces of British Columbia and Quebec went even further and created specific initiatives to support the use of wood in those applications.

This Handbook is focused on one of these options – adoption of cross-laminated timber (CLT). CLT is an innovative wood product that was introduced in the early 1990s in Austria and Germany and has been gaining popularity in residential and non-residential applications in Europe. The Research and Standards Subcommittee of the industry’s CLT Steering Committee identified CLT as a great addition to the “**wood product toolbox**” and expects CLT to enhance the re-introduction of wood-based systems in applications such as 5- to 10-story buildings where heavy timber systems were used a century ago. Several manufacturers have started to produce CLT in North America, and their products have already been used in the construction of a number of buildings.

CLT, like other structural wood-based products, lends itself well to prefabrication, resulting in very rapid construction, and dismantling at the end of its service life. The added benefit of being made from a renewable resource makes all wood-based systems desirable from a sustainability point of view.

In Canada, in order to facilitate the adoption of CLT, FPInnovations published the Canadian edition of the CLT Handbook in 2011 under the Transformative Technologies Program of Natural Resources Canada. The broad acceptance of the Canadian CLT Handbook in Canada encouraged this project, to develop a U.S. Edition of the CLT Handbook. Funding for this project was received from the Binational Softwood Lumber Council, Forestry Innovation Investment in British Columbia, and three CLT manufacturers, and was spearheaded by a Working Group from FPInnovations, the American Wood Council (AWC), the U.S. Forest Products Laboratory, APA-The Engineered Wood Association and U.S. WoodWorks. The U.S. CLT Handbook was developed by a team of over 40 experts from all over the world.

Both CLT handbooks serve two objectives:

- Provide immediate support for the design and construction of CLT systems under the alternative or innovative solutions path in design standards and building codes;
- Provide technical information that can be used for implementation of CLT systems as acceptable solutions in building codes and design standards to achieve broader acceptance.

The implementation of CLT in North America marks a new opportunity for cross-border cooperation, as five organizations worked together with the design and construction community, industry, universities, and regulatory officials in the development of this Handbook. This multi-disciplinary, peer-reviewed CLT Handbook is designed to facilitate the adoption of an innovative wood product to enhance the selection of wood-based solutions in non-residential and multi-storey construction.

Credible design teams in different parts of the world are advocating for larger and taller wood structures, as high as 30 stories. When asked, they identified the technical information compiled in this Handbook as what was needed for those applications.

A Renaissance in wood construction is underway; stay connected.

ACKNOWLEDGEMENTS

The great challenge with this U.S. Edition of the CLT Handbook was to gather experts from the United States, Canada and Europe to bring together their expertise and knowledge into a state-of-the-art reference document. The realization of this Handbook was made possible with the contribution of many people and numerous national and international organizations.

Such a piece of work would not be possible without the support from financing partners and, as such, we would like to express our special thanks to Binational Softwood Lumber Council, Forestry Innovation Investment (FII), Nordic Engineered Wood, Structurlam, and CLT Canada for their financial contribution to this project.

First and most of all, we would like to express our gratitude to AWC, APA, USFPL, FPIInnovations, U.S. WoodWorks and their staff for providing the effort and expertise needed to prepare this work. We would also like to express our special thanks to all chapter authors, co-authors, and reviewers who shared their precious time and expertise in improving this manual.

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Erol Karacabeyli, P.Eng. and Brad Douglas, P.E.

Co-editors

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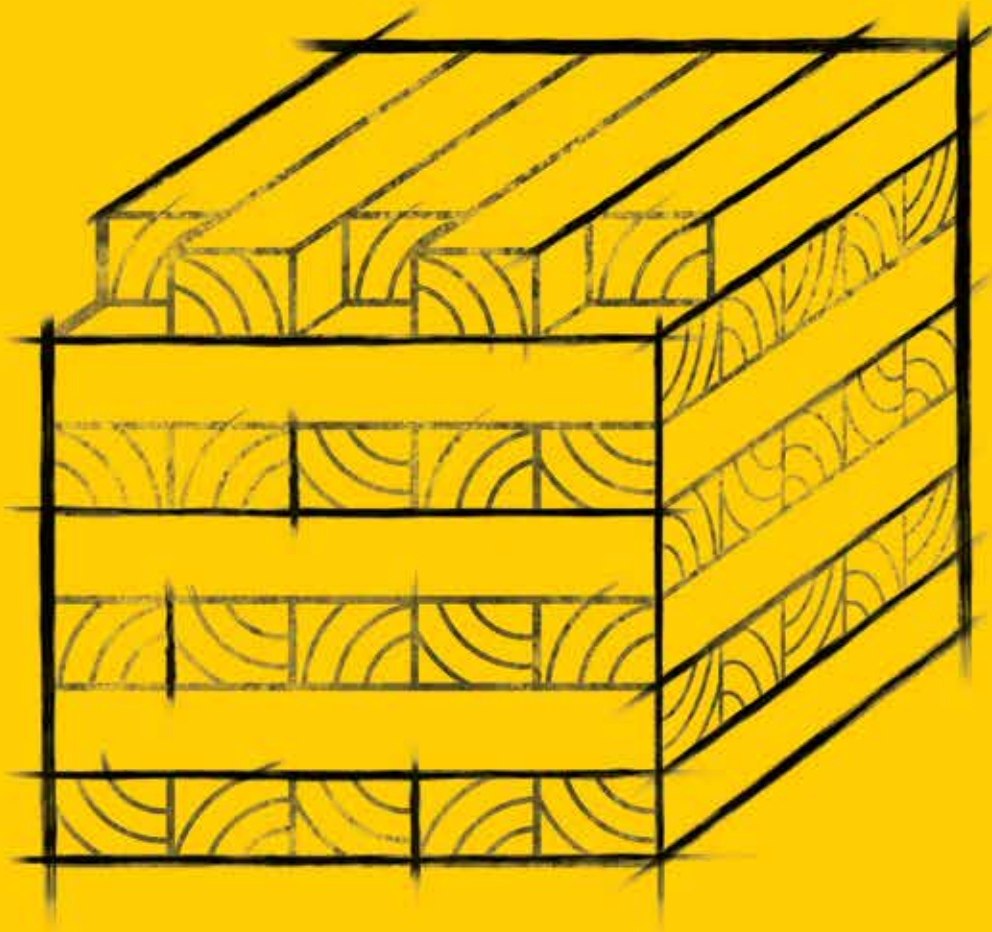
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The U.S. Edition of the CLT Handbook: *cross-laminated timber* combines the work and knowledge of American, Canadian and European specialists. The handbook is based on the original Canadian Edition of the CLT Handbook: *cross-laminated timber*, that was developed using a series of reports initially prepared by FPInnovations and collaborators to support the introduction of CLT in the North American market. A multi-disciplinary team revised, updated and implemented their know-how and technologies to adapt this document to U.S. standards.

The publication of this handbook was made possible with the special collaboration of the following partners:



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ABSTRACT

Cross-laminated timber (CLT), a new generation of engineered wood product developed initially in Europe, has been gaining increased popularity in residential and non-residential applications in several countries. Many impressive low- and mid-rise buildings built around the world using CLT showcase the many advantages this product has to offer to the construction sector.

In this Chapter, we put forward an introduction to CLT as a product and CLT construction in general, along with different examples of buildings and other types of structures made with CLT panels. CLT is now available in North America and several projects already built in Canada and the United States, using CLT, are presented in this Chapter. An assessment of market opportunity for CLT based on the latest construction statistics for the United States is also presented.

GENERAL NOTE: The information contained in this Handbook represents current research results and technical information made available from many sources, including researchers, manufacturers, and design professionals. The information has been reviewed by wood design professionals including professors, design engineers and architects, and wood product manufacturers. While every reasonable effort has been made to ensure the accuracy of the information presented, and special effort has been made to assure that the information reflects state of the art, neither of the participating parties assume any responsibility for the accuracy or completeness of the information or its fitness for any particular purpose. It is the responsibility of users to exercise professional knowledge and judgment in the use of the information.

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1

BRIEF HISTORY

Cross-laminated timber (CLT) is a relatively new building system of interest in the North American construction and is helping to define a new class of timber products known as massive or “mass” timber. It is a potentially cost-competitive, wood-based solution that complements the existing light frame and heavy timber options, and is a suitable candidate for some applications that currently use concrete, masonry and steel. CLT is an innovative wood product that was introduced in the early 1990s in Austria and Germany and has been gaining popularity in residential and non-residential applications in Europe.

In the mid-1990s, Austria undertook an industry-academia joint research effort that resulted in the development of modern CLT. After several slow years, construction in CLT increased significantly in the early 2000s, partially driven by the green building movement but also due to better efficiencies, product approvals, and improved marketing and distribution channels. Another important factor has been the perception that CLT, like masonry and concrete, is a heavy construction system. Such systems are typical in single-family buildings and multi-story residential construction in many European countries.

The use of CLT panels in buildings has increased over the last few years in Europe. Hundreds of impressive buildings and other structures built around the world using CLT show the many advantages this product can offer to the construction sector. The European experience shows that CLT construction can be competitive, particularly in mid-rise and high-rise buildings. Easy handling during construction and a high level of prefabrication facilitate rapid project completion. This is a key advantage, especially in mid-rise construction (e.g., 5 to 10 stories). Lighter panels mean that foundations do not need to be as large. They also mean that smaller cranes can be used to lift panels higher. Good thermal insulation, good sound insulation and good performance under fire are added benefits that come as a result of a massive wood structure.

In this Chapter, we put forward an introduction to CLT as a product and CLT construction in general, along with different examples of buildings and other types of structures made with CLT panels. CLT is now available in North America and several projects already built in Canada and the United States, using CLT, are presented in this Chapter.

2

DEVELOPMENT OF CLT IN NORTH AMERICA

The driving force behind the development of CLT in North America is the need to provide alternative wood-based products and systems to architects, engineers and contractors. While this product is well established in Europe, work on the implementation of CLT products and systems has just begun in the United States and Canada. Interest in the use of CLT in North America and other industrialized countries outside of Europe is increasing.

Significant progress has been achieved in Canada with the publication of the Canadian edition of the CLT Handbook (FPInnovations, 2011) currently used for facilitating design and construction of CLT under the “Alternative Solutions” path in the Canadian building codes. This peer-reviewed Handbook was welcomed by the Canadian design and construction community, and it is being used in the design of early CLT projects. The technical information in the Handbook will also be instrumental in realizing CLT’s inclusion in the Canadian Standard for Engineering Design in Wood (CSA O86) and in the National Building Code of Canada.

This U.S. edition of the CLT Handbook is intended to assist the U.S. design and construction industry and provide a similar path to CLT’s code and standard inclusion as is being pursued in Canada. This comprehensive document provides key technical information related to the manufacturing, design and performance of CLT in construction in the following areas:

- Cross-laminated timber manufacturing
- Structural design of cross-laminated timber elements
- Lateral design (including wind and seismic performance) of cross-laminated timber buildings
- Connections in cross-laminated timber buildings
- Duration of load and creep factors for cross-laminated timber panels
- Vibration performance of cross-laminated timber floors
- Fire performance of cross-laminated timber assemblies
- Sound insulation of cross-laminated timber assemblies
- Building enclosure design of cross-laminated timber construction
- Environmental performance of cross-laminated timber
- Lifting and handling (including transportation) of cross-laminated timber elements

A harmonized North American CLT product standard, *Standard for Performance-Rated Cross-Laminated Timber* (ANSI/APA PRG 320), has been developed by the ANSI/APA CLT Standard Committee and published in December 2011 (ANSI, 2011). This standard was developed based on the consensus standard development process of APA–The Engineered Wood Association as a standards developer accredited by the American National Standards Institute (ANSI). The ANSI/APA PRG 320 standard has been approved by the Structural Committee of the International Code Council (ICC) for the 2015 International Building Code (IBC).

3

DEFINITION OF CROSS-LAMINATED TIMBER (CLT)

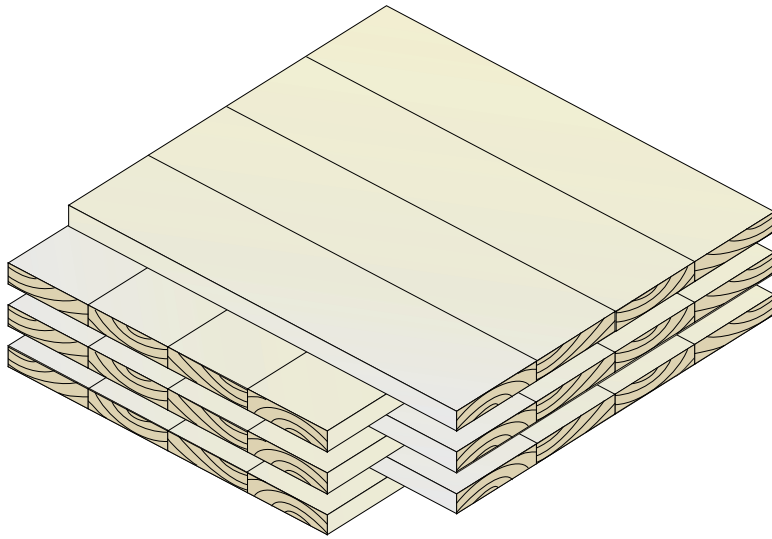
CLT panels consist of several layers of lumber boards stacked crosswise (typically at 90 degrees) and glued together on their wide faces and, sometimes, on the narrow faces as well. Besides gluing, nails or wooden dowels can be used to attach the layers. Innovative CLT products such as Interlocking Cross-laminated Timber (ICLT) are in the process of development in the United States as well. However, non-glued CLT products and systems are out of the scope of this Handbook.

A cross-section of a CLT element has at least three glued layers of boards placed in orthogonally alternating orientation to the neighboring layers. In special configurations, consecutive layers may be placed in the same direction, giving a double layer (e.g., double longitudinal layers at the outer faces and/or additional double layers at the core of the panel) to obtain specific structural capacities. CLT products are usually fabricated with an odd number of layers; three to seven layers is common and even more in some cases.

Thickness of individual lumber pieces may vary from 5/8 inch to 2.0 inches (16 mm to 51 mm) and the width may vary from about 2.4 inches to 9.5 inches (60 mm to 240 mm). Boards are finger jointed using structural adhesive. Lumber is visually graded or machine stress rated and is kiln dried. Panel sizes vary by manufacturer; typical widths are 2 ft. (0.6 m), 4 ft. (1.2 m), 8 ft. (2.4 m) and 10 ft. (3 m) while length can be up to 60 ft. (18 m) and the thickness can be up to 20 inches (508 mm). Transportation regulations may impose limitations to CLT panel size.

Lumber in the outer layers of CLT panels used as walls are normally oriented up and down, parallel to gravity loads, to maximize the wall's vertical load capacity. Likewise, for floor and roof systems, the outer layers run parallel to the major span direction.

Figure 1 illustrates a CLT panel configuration, while Figure 2 shows examples of possible CLT panel cross-sections. Figure 3 illustrates a 5-layer CLT panel with its two cross-sections.



Transverse Planks

Longitudinal Planks

Figure 1
CLT panel configuration

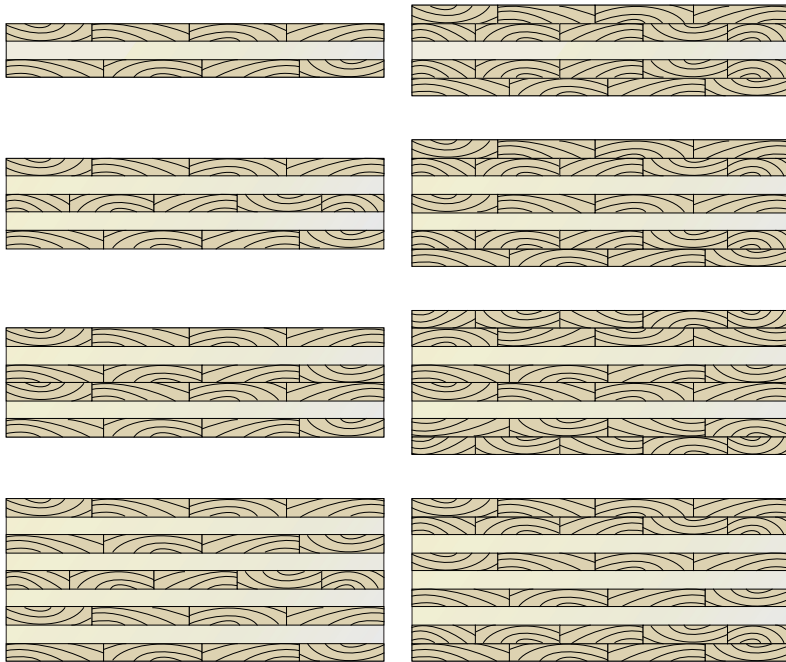


Figure 2
Examples of CLT panel cross-sections

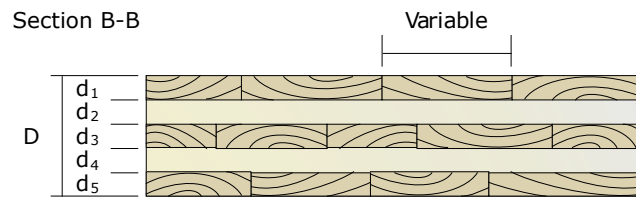
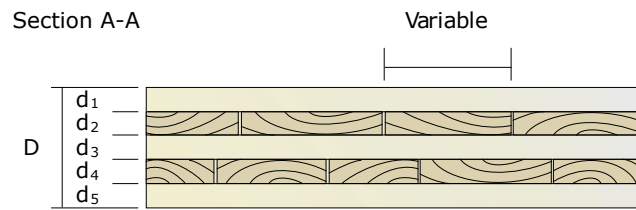
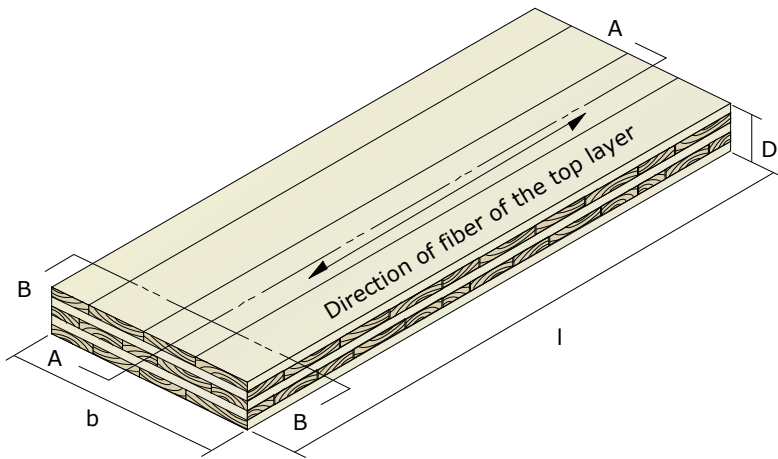


Figure 3
Example of CLT panel cross-sections and direction of fibers of the top layers

4

KEY ADVANTAGES OF CROSS-LAMINATING

Cross-laminated timber used for prefabricated wall and floor panels offers many advantages. The cross-laminating process provides improved dimensional stability to the product which allows for prefabrication of long, wide floor slabs, long single-story walls and tall plate heights conditions as in clerestory walls or multi-story balloon framed configurations. Additionally, cross-laminating provides relatively high in-plane and out-of-plane strength and stiffness properties, giving it two-way action capabilities similar to a reinforced concrete slab. The ‘reinforcement’ effect provided by the cross-lamination in CLT also considerably increases the splitting resistance of CLT for certain types of connection systems.

Figure 4 illustrates the primary difference between CLT and glulam products. Figure 5a shows a floor built with four individual CLT panels acting mostly in one direction, while Figure 5b illustrates the same floor, this time built with one CLT panel only, acting most likely in two directions (i.e., two-way action).

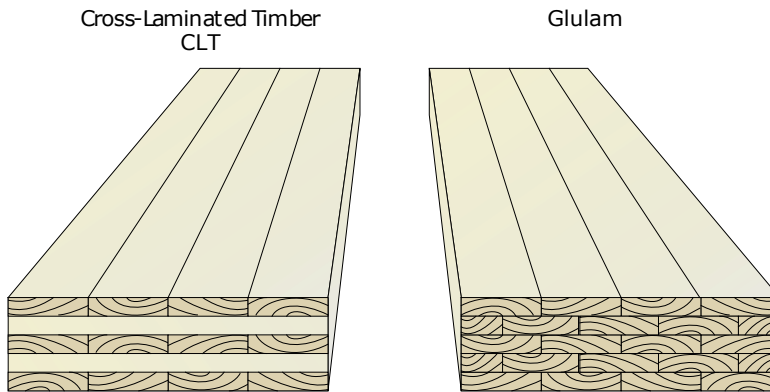
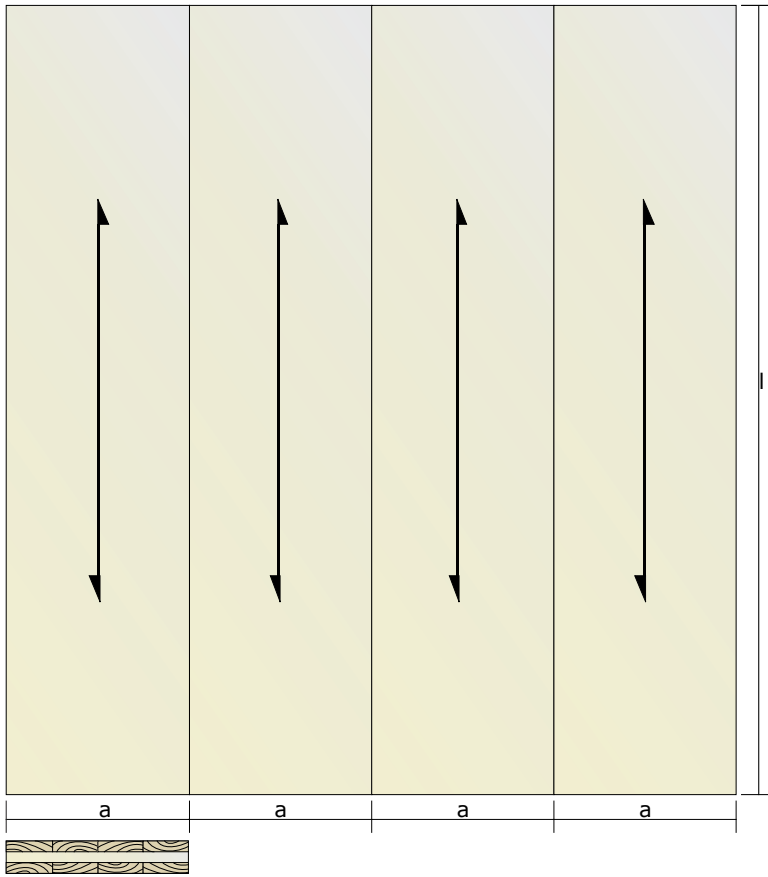
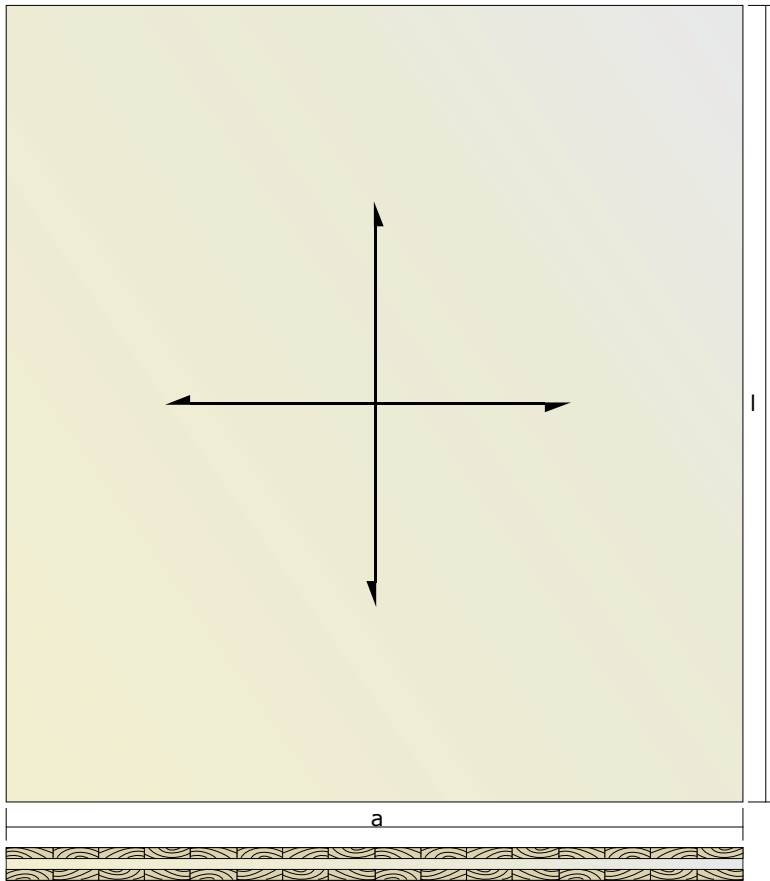


Figure 4
CLT vs. glulam panel



(a)



(b)

Figure 5

- (a) Floor assembly made of four 3-ply CLT panels acting in one direction and
 - (b) Floor assembly made of one 3-ply CLT panel acting in both directions.
- Distance “a” may reach 10 ft. (3 m)

5

MANUFACTURING PROCESS

A typical manufacturing process of CLT includes the following steps: lumber selection, lumber grouping and planing, adhesive application, panel lay-up and pressing, product cutting, surface machining, marking and packaging. The key to a successful CLT manufacturing process is consistency in the lumber quality and control of the parameters that impact the quality of the adhesive bond. Stringent in-plant quality control tests are required to ensure that the final CLT products will fit for the intended applications.

Typically, lumber must be kiln dried to a moisture content of $12\% \pm 3\%$. Proper moisture content prevents dimensional variations and surface cracking. Lumber can be procured dried or further drying may be needed at the factory. Trimming and finger jointing are used to obtain the desired lengths and quality of lumber. Finger jointed CLT panels are also available in Europe, but are out of the scope of the North American ANSI APA/PRG 320 CLT product standard at this time.

Panel dimensions vary by manufacturer. The assembly process can take from 15 to 60 minutes depending on equipment and adhesive. Adhesive is the second material input in CLT. Types of adhesives used in North America must meet the same requirements as those used in glued laminated timber manufacturing and include qualified polyurethane, melamine and phenolic-based adhesives. Both face and edge gluing can be used. Once adhesive is applied, the assembly is pressed using hydraulic (more common) or vacuum presses and compressed air depending on panel thickness and adhesive used. The assembled panels are usually planed and/or sanded for a smooth surface at the end of the process. Panels are cut to size and openings are made for windows, doors and service channels, connections and ducts using CNC (Computer Numerical Controlled) routers which allow for high precision. For quality control purposes, compliance with product requirements prescribed in the product standard are typically checked at the factory (e.g., bending strength, shear strength, delamination).

Chapter 2, entitled *Cross-laminated timber manufacturing*, provides general information about CLT manufacturing targeted mainly to engineers, designers, and specifiers. The information contained in this Chapter may also be useful to potential U.S. CLT manufacturers.

Figures 6 and 7 illustrate a typical CLT wall and floor assembly, respectively.

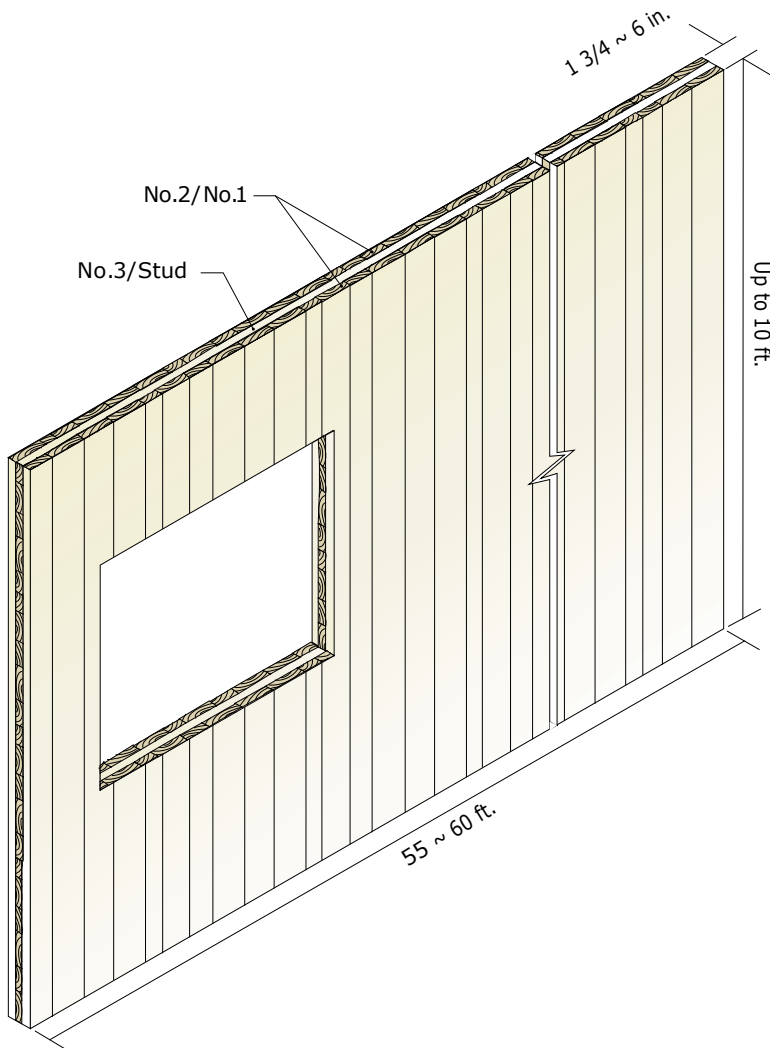


Figure 6
CLT wall

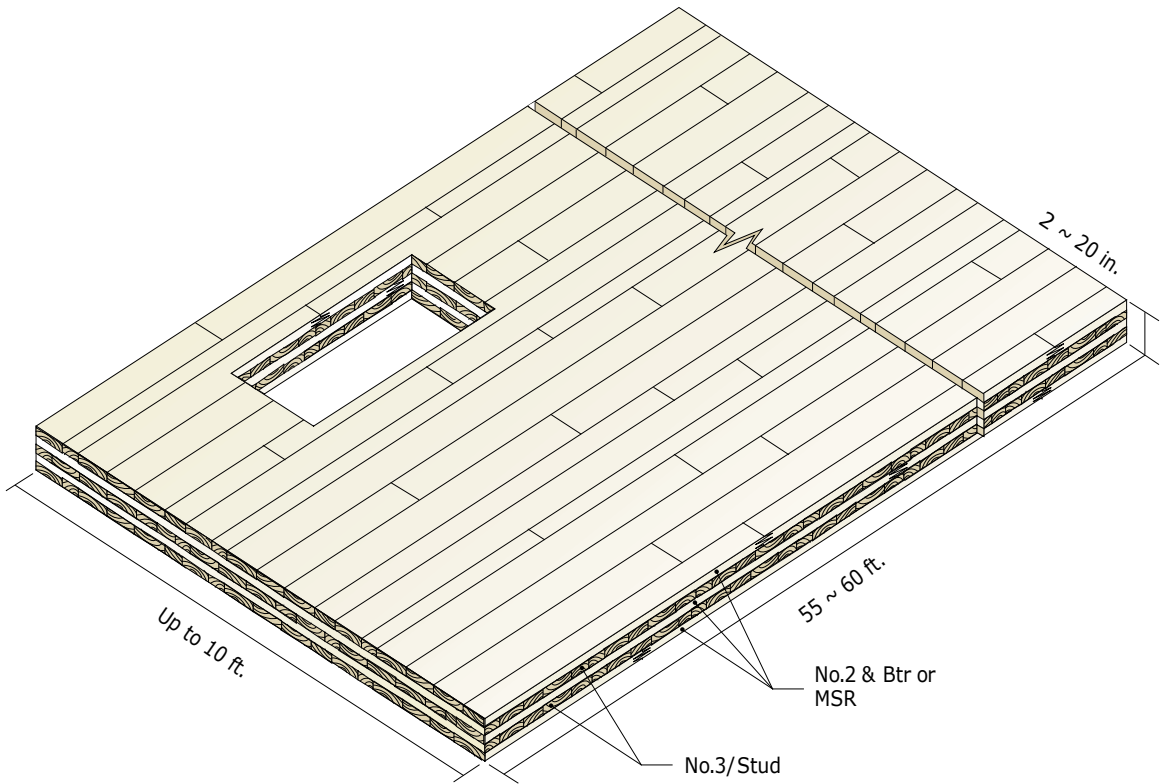


Figure 7
CLT floor or roof

6

STRUCTURAL DESIGN AND SERVICEABILITY CONSIDERATIONS OF CLT

CLT panels are typically used as load-carrying plate elements in structural systems such as walls, floors and roofs. For floor and roof CLT elements, key critical characteristics that must be taken into account are the following:

- In-plane and out-of-plane bending strength, shear strength, and stiffness
- Short-term and long-term behavior:
 - instantaneous deflection
 - long-term deflection (creep deformation)
 - long-term strength for permanent loading
- Vibration performance of floors
- Compression perpendicular to grain issues (bearing)
- Fire performance
- Sound insulation
- Durability.

For wall elements, the followings are key characteristics that must be taken into account at the design stage:

- Load-bearing capacity (critical criterion)
- In-plane and out-of-plane shear and bending strength
- Fire performance
- Sound insulation
- Durability.

The following sections provide a brief summary of the key design and performance attributes of CLT panels and assemblies.

6.1 Proposed Analytical Design Methods

Various different design methods have been adopted in Europe for the determination of basic mechanical properties of CLT. Some of these methods are based on testing while others are more analytical. For floor elements, a testing method of evaluation involves determination of flexural properties by testing full-size panels or sections of panels with a specific span-to-depth ratio. The problem with the testing based approach is that every time the lay-up, type of material, or any other manufacturing parameters change, more testing is needed to evaluate the bending and shear properties of such new product configurations.

Analytical approach, once verified with the test data, offers a more general and less costly alternative. An analytical approach generally predicts strength and stiffness properties of CLT panels based on the input material properties of the laminate boards that make up the CLT panel. Some of the proposed European methods are described in detail in the Canadian edition of the CLT Handbook (FPInnovations, 2011). One of them, the shear analogy method, is the method used by ANSI APA/PRG 320 for determining the bending and shear stiffness of various lay-ups (ANSI, 2012).

The proposed analytical procedures for determining basic mechanical properties of CLT panels for designers are given in Chapter 3 entitled *Structural design of cross-laminated timber elements*.

6.2 Lateral Design of CLT Buildings

Based on both a literature review of research work conducted around the world and the results of a series of quasi-static tests conducted at FPInnovations on regular and tall walls, CLT wall panels can be used as an effective lateral load resisting system (Ceccotti, 2008). Results from small- and large-scale shake table seismic tests on two CLT buildings in Japan by the Trees and Timber Research Institute of Italy (CNR-IVALSA) in 2009 demonstrated that CLT structures perform quite well when subjected to seismic force (Figure 8).

FPInnovations' shearwall and assembly tests to date have also shown that the CLT wall panels demonstrated adequate seismic performance when nails or slender screws are used with steel L-brackets to connect the walls to the floors below (this ensures a ductile failure in the connection instead of a brittle failure in the panel). The use of hold-downs installed with nails on each end of the walls tends to further improve their seismic performance. Use of diagonally placed long screws to connect CLT walls to the floor below is not recommended in high seismic zones due to lower ductility and brittle failure mechanisms. Use of half-lapped joints in longer walls can be an effective solution not only to reduce the wall stiffness and thus reduce the seismic input load, but also to improve wall ductility. Timber rivets in smaller groups with custom made brackets were found to be effective connectors for CLT wall panels due to their potentially high ductility. Further research in this field is needed to clarify the use of timber rivets in CLT and to verify performance of CLT walls under seismic loading with alternative types of connection systems (e.g., bearing types). A 2-story CLT assembly has also been tested at FPInnovations and the results confirmed the shake table tests conducted by CNR-IVALSA (Figure 9).

While most CLT buildings are platform framed, they are far less susceptible to develop soft story failure mechanisms than other platform framed structural systems. Since the nonlinear behavior (and the potential damage) is localized in the hold-down and L-bracket connection areas, the panels—that are also the vertical load carrying elements—are virtually left intact in place and uncompromised, even after failure of the connections. In addition, all CLT walls on a single level contribute to the lateral and gravity resistance, providing a degree of redundancy and a system sharing effect. Vertical and lateral load sharing can also take place between levels, creating a honeycomb effect.

Chapter 4 entitled *Lateral design of cross-laminated timber buildings* provides general information about lateral design of CLT structures. Recommendations related to seismic modification factors are also made.



Figure 8
Seven-story CLT building tested at E-Defense Laboratory in Miki as a part of the SOFIE Project and CLT test assembly at FPInnovations



Figure 9
CLT test assembly at FPInnovations

6.3 **Connections and Construction of CLT Structures**

Connections in timber construction, including those built with CLT, play an important role in maintaining the integrity of the timber structure and in providing strength, stiffness, stability and ductility. Consequently, they require thorough attention of the designers.

Traditional and innovative connection systems have been used in CLT assemblies in Europe and North America. Common types of connections in CLT assemblies include: panel-to-panel (floors, walls and roofs), wall-to-foundation, wall-to-wall intersections and wall-to-floor/roof assemblies. Basic panel-to-panel connection can be established through single or double exterior splines made with engineered wood products, single or double interior splines, or half-lapped joints. Metal brackets, hold-downs and plates are used to transfer forces at the wall to floor/roof interfaces and in wall-to-wall intersections. Innovative types of connection systems can also be used which lead to enhanced performance or quicker assembly.

Researchers in Europe have developed design procedures for traditional connections in CLT. These include dowels, wood screws, and nails, which are commonly used in Europe for designing CLT assemblies. Empirically based equations were developed for the calculation of characteristic embedment properties of each type of fastener (i.e., dowels, screws, nails), depending on the location with respect to the plane of the panel (perpendicular to or on edge). Those equations were verified with testing and results seem to correspond well with calculated predictions (Uibel and Blass, 2006 and 2007). Yield mode equations were adopted for the design using CLT fastener embedment strength equations. Empirical equations have also been developed for the calculation of the withdrawal resistance of the various types of fasteners in CLT based on hundreds of tests. Based on limited exploratory validation tests conducted at FPInnovations using self-tapping screws on European CLT, the proposed embedment equations seem to provide reasonable predictions of both the lateral and withdrawal capacity based on the Canadian timber design provisions (Muñoz et al., 2010). More work is needed, however, to validate the proposed equations using North American made CLT and different types of fasteners.

Due to the reinforcing effect of cross-lamination in CLT, it is speculated that current minimum geometric requirements given in the *National design specification (NDS) for wood Construction* for dowels, screws and nails in solid timber or glulam could be applicable to CLT. However, designers need to be cautious about this as further

verification is needed, considering the specific features of individual panel types. Brittle failure modes, which have not yet been investigated, also need to be taken into account.

Chapter 5, entitled *Connections in cross-laminated timber assemblies*, is mainly focused on CLT assemblies. However, since all buildings are considered to be mixed construction to a certain extent, the scope covers hybrid construction, where traditional wood-based systems (e.g., light frame, glulam, etc.) or materials such as concrete or steel are mixed with CLT to resist vertical and lateral loads.

6.4 Duration of Load and Creep Behavior

Cross-laminated timber products are used as load-carrying slabs and wall elements in structural systems, thus load duration and creep behavior are critical characteristics that must be addressed in structural design. Given its lay-up configuration with orthogonal arrangement of layers bonded with structural adhesive, CLT is more prone to time-dependent deformations under load (creep) than other engineered wood products such as glued-laminated timber.

Time dependent behavior of structural wood products is addressed in design standards by load duration factors that adjust design properties. Since CLT has been recently introduced into the North American market, the current design standards and building codes do not specify load duration and creep adjustment factors for CLT. Until this can be rectified, options are proposed for those specifying CLT systems in Chapter 6, entitled *Duration of load and creep factors for cross-laminated timber panels*. These include not only load duration and service factors, but also an approach for accounting for creep in CLT structural elements.

Since cross-laminated timber is not yet covered by the NDS, the intent is to recommend a suitable approach that accounts for the duration of load and creep factors in the design of CLT.

6.5 Vibration Performance of Floors

Studies at FPInnovations found that bare CLT floor systems differ from traditional lightweight wood joisted floors with typical mass around 4 lb./ft.² (20 kg/m²) and fundamental natural frequency above 15 Hz, and heavy concrete slab floors with a mass above 40 lb./ft.² (200 kg/m²) and fundamental natural frequency below 9 Hz. Based on FPInnovations' test results, bare CLT floors were found to have mass varying from approximately 6 lb./ft.² (30 kg/m²) to 30 lb./ft.² (150 kg/m²), and a fundamental natural frequency above 9 Hz. Due to these special properties, the standard vibration controlled design methods for lightweight and heavy floors may not be applicable for CLT floors.

Some CLT manufacturers have recommended that deflection under a uniformly distribution load (UDL) be used to control floor vibration problems. Using this approach, the success in avoiding excessive vibrations in CLT floors relies mostly on the designer's judgment. Besides, static deflection criteria can only be used as an indirect control method because they ignore the influence of mass characteristics of the floors. Therefore, a new design methodology is needed to determine the vibration controlled spans for CLT floors.

A proposed design methodology for controlling vibrations of CLT floors under normal walking is given in Chapter 7 entitled *Vibration performance of cross-laminated timber floors*.

6.6 Fire Performance of Cross-laminated Timber Assemblies

Cross-laminated timber panels have great potential for providing cost-effective building solutions for residential, commercial and institutional buildings as well as large industrial facilities in accordance with the International Building Code (IBC).

The intent of the IBC is to establish the minimum requirements for public safety. The code is addressing such things as structural strength and stability, means of egress, life safety and protection of property from fire as well as providing safety for firefighters and emergency responders during emergency operations. As such, fire safety issues such as providing adequate structural integrity, limiting impact to people and property as well as limiting fire spread through a building and/or to adjacent properties during a fire are critical for every building design and structural system.

Structural integrity and fire spread capability of building assemblies can be assessed by conducting full-scale fire-resistance tests in accordance with ASTM E119 standard test methods. Fire resistance is defined as the ability of a material or their assemblies to prevent or retard the passage of excessive heat, hot gases or flames under conditions of fire. A fire-resistance rating is defined as the period of time a building element, component or assembly maintains the ability to confine a fire (separating function), and/or continues to perform a given structural function. More specifically, a standard fire-resistance test entails three failure/acceptance criteria:

1. Mechanical resistance: the assembly must support the applied load for the duration of the test;
2. Integrity: the assembly must prevent the passage of flame or gases hot enough to ignite a cotton pad;
3. Insulation: the assembly must prevent the temperature rise on the unexposed surface from being greater than 325°F (180°C) at any location, or an average of 250°F (140°C) measured at a number of locations, above the initial temperature.

The time at which the assembly can no longer satisfy any one of these three criteria defines its fire-resistance rating.

In order to facilitate future Code acceptance for the design of CLT panels for fire resistance, a research project has recently been completed at FPInnovations. The main objective of the project was to develop and validate a generic calculation procedure to calculate the fire-resistance ratings of CLT wall and floor assemblies. A series of full-scale fire-resistance experiments in accordance with ASTM E119 standard time-temperature curve were conducted to allow a comparison between the fire resistance measured during a standard fire-resistance test and that calculated using the proposed procedure.

Results of the full-scale fire tests show that CLT panels have the potential to provide excellent fire resistance often comparable to typical heavy construction assemblies of non-combustible construction. Due to the inherent nature of thick timber members to slowly char at a predictable rate, CLT panels can maintain significant structural capacity for an extended duration of time when exposed to fire.

In addition to the fire-resistance calculation method of CLT assemblies, Chapter 8, entitled *Fire performance of cross-laminated timber assemblies*, provides requirements related to fire safety in buildings, namely in regards to the types of construction prescribed in the IBC, fire-resistance requirements, connection detailing, interior finishes, through-penetrations and exterior walls.

6.7 Sound Insulation of Cross-laminated Timber Buildings

Adequate levels of noise/sound control in multi-family buildings are mandatory requirements of most building codes in the world. In many jurisdictions, these requirements are as strictly enforced as those for structural sufficiency and fire safety.

Chapter 9, entitled *Sound insulation of cross-laminated timber buildings*, first attempts to answer simple questions related to the definition of sound, its sources, quantification and methods of measurement, acceptable levels of sound, differences between sound and noise, etc. Of course, when verbalizing such questions, some obvious answers naturally emerge in the reader's mind.

This Chapter also introduces the International Building Code's (IBC) requirements for sound insulation. State of the art construction details for CLT walls and floor/ceiling assemblies generally meeting IBC requirements are provided based on the results of tests performed in various laboratories and fields. A step by step guide finally leads the reader to assemblies that will meet the occupants' satisfaction.

6.8 Building Enclosure Design of Cross-laminated Timber Construction

Building envelope design has important implications for the energy performance and durability of the structure as well as indoor air quality. The key performance requirements of the envelope, discussed in Chapter 10 entitled *Building enclosure design of cross-laminated timber construction*, are prevention of water intrusion and control of heat, air, and moisture flow.

The use of prefabricated CLT panels does not modify the basic heat, air, and moisture control design principles for an exterior wall or roof assembly. However, the design of CLT assemblies requires attention due to the unique characteristics of this product. CLT panels are made from massive, solid wood elements and therefore provide some level of thermal insulation and thermal mass. Although CLT panels may have an inherent level of air tightness as a panel product produced with high precision, an additional air barrier is recommended, and it is critical that panel joints and interfaces as well as penetrations such as windows and doors be properly air sealed. CLT panels have a relatively high capacity to store moisture, but relatively low vapor permeability. If exposed to excessive wetting during construction, the panels may absorb a large amount of moisture, which may result in slow drying.

This Chapter provides guidance on heat, air, and moisture control in wall and roof assemblies that utilize CLT panels in various North American climate zones. The overarching strategies are to place insulation in such a way that the panels are kept warm and dry, to prevent moisture from being trapped or accumulating within the panels, and to control airflow through the panels and at the joints and interfaces between them. In certain climates, preservative treatment of CLT is recommended to provide additional protection against potential hazards such as termites.

It is intended that these guidelines should assist practitioners in adapting CLT construction to North American conditions and ensuring a long life for their buildings. However, these guidelines are not intended to substitute for the input of a professional building scientist.

7

ENVIRONMENTAL PERFORMANCE OF CLT

The environmental footprint of CLT is frequently discussed as potentially beneficial when compared to functionally equivalent non-wood alternatives, particularly concrete systems.

In Chapter 11, entitled *Environmental performance of cross-laminated timber*, the role of CLT in sustainable design is addressed. The embodied environmental impacts of CLT in a mid-rise building are discussed, with preliminary results from a comprehensive life cycle assessment (LCA) study.

Chapter 11 discusses other aspects of CLT's environmental profile, including impact on the forest resource and impact on indoor air quality from CLT emissions. The ability of the North American forest to sustainably support a CLT industry is an important consideration and is assessed from several angles, including a companion discussion regarding efficient use of material. Market projections and forest growth-removal ratios are applied to reach a clear conclusion that CLT will not create a challenge to the sustainable forest practices currently in place in North America and safeguarded through legislation and/or third party certification programs.

Finally, to assess potential impact on indoor air quality, CLT products with different thicknesses and glue lines were tested for their volatile organic compounds (VOCs) including formaldehyde and acetaldehyde emissions. CLT was found to be in compliance with European labeling programs as well as the most stringent CARB limits for formaldehyde emissions. Testing was done on Canadian species, as there was no U.S. supplier of CLT at the time of this writing; because VOC emissions are affected by species, this work should be repeated for products made from different species.

8

CLT IN CONSTRUCTION

The prefabricated nature of CLT permits high precision and a construction process characterized by faster completion, increased safety, less demand for skilled workers on site, less disruption to the surrounding community and less waste. Openings for windows, doors, staircases and utilities are pre-cut using CNC (Computer Numerical Controlled) machines at the factory. Buildings are generally assembled on site but panels are prefabricated and transported to the site, where they are connected by means of mechanical fastening systems such as bolts, lag bolts, self-tapping screws, ringed annual shank nails, and so on.

CLT as a building system is quite adaptable, performing well in long spans in floors, walls and roofs, with the potential for a high degree of exterior and interior finishes preinstalled off-site. Its ability to be used as either a panelized or a modular system makes it ideally suited for additions to existing buildings. It can be used jointly with any other building material, such as light wood frame, heavy timber, steel or concrete, and accepts a range of finishes. CLT panels can also be built compositely with reinforced concrete to enable longer spans (i.e., longer than 30 feet or 10 m). Good thermal insulation, good sound insulation and an impressive performance under fire conditions are added benefits which result from the massiveness of the wood structure.

8.1 Considerations for Transportation and Construction Site Limitations

Before undertaking the design of a CLT building, a plan should be drawn up for transporting the prefabricated CLT elements and storing them on site. Transporting CLT panels can be costly and, depending on the size of the element, may require specialized transportation services. The construction site itself may have restrictions due to size or to local regulations. It is best to start by making sure that the route from the plant to the construction site will allow movement of the truck, including its load, without any obstacles. This is especially critical for oversize loads. Considerations for transportation of CLT elements are presented in Chapter 12 entitled *Lifting and handling of cross-laminated timber elements*.

8.2 Materials on the Construction Site

Wood-based building materials must be stored properly on the site if not used immediately. Good planning is essential to ensure that CLT assemblies have the necessary handling space and proper material flow during construction. Stacking of the panels on the construction site must match the planned installation sequence to avoid additional costs and to reduce the risk of accidents or breaking.

When CLT panels are stored on site, great care must be taken to protect them against the elements and vandalism. If panels must be placed temporarily on the ground prior to installation, they should be put down on skids of sufficient number to protect the panels from standing water. The panels must also be completely protected from the weather by appropriate wrapping or by other measures.

Figure 10 shows CLT panel packs in the process of being unloaded from a truck for storage on site. In this example, the packs are completely wrapped (six faces) and are placed on wood skids to protect them from standing water. Although this packaging practice may be adequate, it is crucial to also use high-quality tarpaulin and to ensure that the packs remain sealed. If there are openings, water could infiltrate and remain trapped.



Figure 10

Storage on construction site – individually wrapped bundles stacked on lumber skids

Figure 11 shows truck platforms left on construction site. They will be recovered on the next trip. This can reduce costs by allowing independent scheduling of transportation and unloading.



Figure 11

Truck platforms left on construction site – will be recovered on the next trip

8.3 Lifting and Handling of CLT Elements

The emerging CLT construction industry has developed a range of techniques for lifting and handling CLT panels. The complexity of the structure or its location often dictates the techniques and systems to be used. Naturally, erecting an 8-story building in a downtown area typically requires more preparation and skill than a single-family residence built in the country. But if that country house is to be perched high in the mountains, more efforts may be required (Figures 12).



Figure 12
Lifting and handling of CLT elements by cableway (courtesy of KLH)

There are several types of lifting equipment that can be used on construction sites. Each has its own characteristics for lifting and handling heavy loads such as CLT panels. Therefore, it is essential to choose the right lifting and handling system for each type of component. Several lifting and handling systems and techniques are presented in Chapter 12.

8.4 Construction Accessories and Materials

Numerous construction accessories and materials are required on a construction site. In addition to the items and tools normally required in conventional wood construction, suggestions are made in Chapter 12 for products, tools, and accessories that may be useful or essential on a construction project using CLT panels.

9

ASSESSMENT OF MARKET OPPORTUNITY

This assessment of market opportunity relies on the latest construction statistics for the United States only. These statistics (floor area by building type) were multiplied by use factors and hence volumes for CLT were estimated.

9.1 Methodology

A 3-tier approach was followed:

1. Estimation of manufacturing costs;
2. Assessment of cost competitiveness of the building shell; and
3. Use of different market penetration scenarios to estimate the market opportunity.

These points are explained below. All costs are presented in U.S. dollars.

9.1.1 CLT Assembly Costs

In-house simulation work established the average production cost of CLT at \$19.20 per cubic foot¹. Two panel thicknesses were used: 3-ply 4 ¼ in. (108 mm) for walls and 5-ply 7 in. (178 mm) for floors. The cost of the assembly per square foot was calculated as a function of thickness plus a 25% profit markup. Connectors and erection costs were also included (\$0.70 and \$1.24 per sq. ft., respectively). Similarly, the cost of engineering and CAD work by the manufacturer was added at \$1.00/sq. ft. This resulted in assembly costs of approximately \$12 and \$19 per square foot for walls and floors, respectively. These prices may increase if visual grade is desired or if lumber prices go up with respect to the baseline of this study

9.1.2 Construction Statistics

Market size was calculated using the McGraw-Hill 2011, with 1 to 10 stories as base. The year 2011 was selected as a proxy for mid-term demand (2015) based on available forecasts from the same source². The 10+ story segment was not included though it is feasible to expect some future penetration in this height class (currently 10+ story apartments represent 10% of the 1 to 10 stories apartment floor area).

9.1.3 Sample Selection

Fourteen common building types were selected for this study. The selection was based on their current share of the non-residential market. Altogether, 86 combinations of building type, story class, and frame material were analyzed to calculate their shell unit costs and compare them against the CLT solution. Shell costs include the structural components of a building; namely walls, floors, shafts, and roof.

¹ Delivered within a 300-mile radius. Total lumber costs, including remanufacturing and post dry, amount to \$400/MBF.

² 2011 values were multiplied by 1.79 to reflect expected demand levels for 2015.

9.1.4 Shell Unit Costs and Competitiveness

Shell unit costs (\$/sq. ft. of floor area) were obtained from simulations on conceptual buildings (average) performed using the square cost estimator feature of Costworks™, an appraisal tool from RSMeans. Normally, each situation included costing 4-6 material choices, sometimes including light wood frame. A side-by-side comparison of shell unit costs for CLT vs. the incumbent materials allowed the estimation of cost competitiveness (see Section 9.2.1 for more details).

9.1.5 CLT Assembly Costs

The square footage of each assembly (e.g., total sq. ft. of exterior walls) was calculated from Costworks™ using average parameters and dimensions by building type. These square footages were multiplied by CLT's unit assembly costs (e.g., \$/sq. ft. of wall area) to calculate the total cost by assembly and shell. The CLT assembly configuration varied according to building type. The default exterior wall assembly consisted of:

- 3-ply CLT
- Vinyl siding
- Furring (2"x4")
- Fire-rated (FR) gypsum
- 3 in. expanded polystyrene (EPS)
- Vapor retarder.

Industrial buildings considered metal siding (corrugated steel) and interior fire-rated (or Type X) gypsum. Floors consisted of 5-ply CLT plus plywood underlayment. It is acknowledged that some situations may call for thicker panels, for instance a 7-ply CTL panel.

Roof consisted of a gang-nailed wood truss assembly for all buildings except industrial. Industrial buildings considered metal deck with open web steel joists, beams, and hollow steel columns. All roof assemblies considered roof coverings (built-up) and insulation (2 in. EPS + 1 in. perlite).

Partitions considered 3-ply CLT plus 5/8 in. Type X gypsum board on both sides. Twenty percent of partitions were considered to be load-bearing and using CLT, the balance assuming metal studs. Non-CLT buildings considered drywall on metal studs.

Shafts assumed a 5-ply panel.

Parking garages considered 5-ply CLT for all assemblies. They also included glulam beams and columns (22 in. x 22 in.), including connectors and installation costs. Epoxy coating was included too.

Not included:

- Land
- Foundations (savings are expected due to lighter foundations)
- Time savings (time savings estimated at 20% vs. concrete).

9.2 Results

9.2.1 Shell Cost Competitiveness

Light wood frame is the most economical system in low-rise projects, with CLT becoming normally more competitive only at higher building heights or sizes (Figure 13). Most industrial buildings and—to some extent—parking garages showed similar or slightly higher shell costs for CLT and therefore may represent an attractive choice for CLT given their relatively regular footprint and repetitive layout. Besides mid-rise and industrial, retail (1-2 stories) and educational (2-3 stories) buildings are also good bets for CLT. It must be noted that shell costs normally account for about 20-30% of the total cost of a finished concrete/steel building and, therefore, is expected that some of these differences in shell costs will be less noticeable when considering total unit costs.

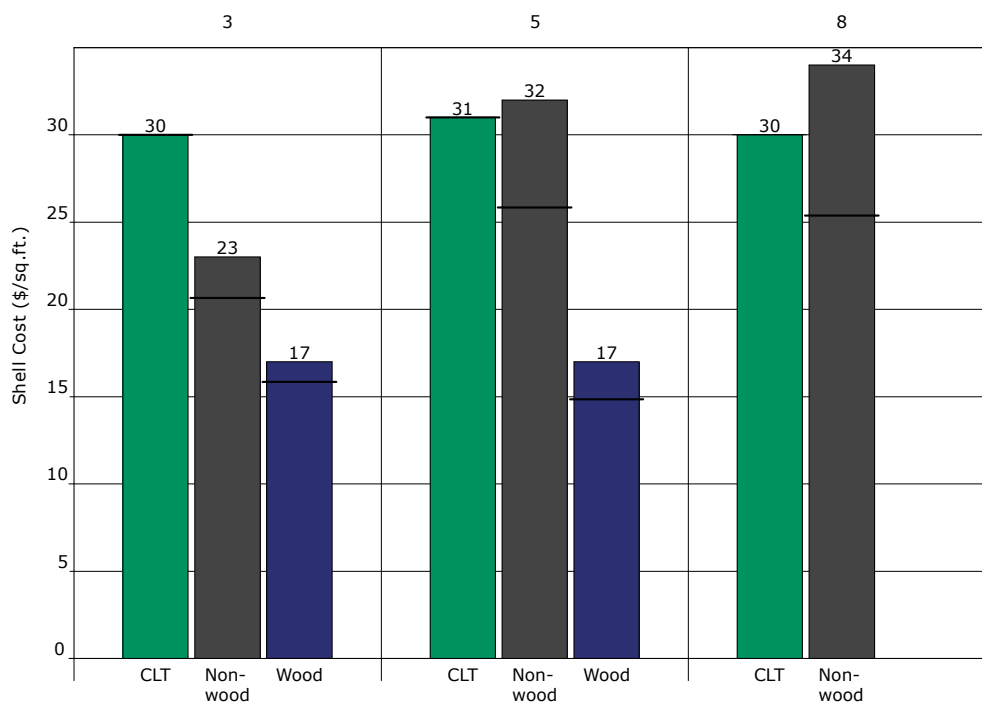


Figure 13
Unit shell cost by story class and frame material apartments

9.2.2 Assessment of Demand

Two market penetration scenarios were considered: 5% and 15%. Based on shell costs, a competitiveness factor was assigned to each situation. This 'c-factor' acted as a multiplier on the floor area per situation. Building code limitations were considered too. For instance, only low-rise health buildings are included in the assessment. For other building types, it is assumed that code will allow CLT in the future. For a more conservative demand estimate, the reader may choose considering only the 1-4 story segment (94%).

In summary, the U.S. market opportunity for CLT is estimated at 0.9 to 2.7 BBF (Table 1) approximately³. To provide a framework for these numbers, total consumption of softwood lumber in the United States in 2011 was estimated at 85.4 million m³. No reliable forecast for 2015 is available in order to estimate the equivalency or share of those 1.5-4.5 million m³ of potential opportunity. To put these numbers in perspective, the assessment

³ CLT buildings consume 0.1 to 1+ ft³ of CLT per sq. ft. of floor area, with an average around 0.6 ft³/sq. ft.

represents a potential increase of 2 to 7 percent in total U.S. softwood lumber demand over 2011 consumption. This demand is equivalent to somewhere between two and six billion dollars of CLT shell value⁴. Demand is concentrated on the East Coast, the Great Lakes States, Texas, and California (Figure 14).

Table 1
Market opportunity (2015)

Volumes BF ¹ (000s)										
		Total Volume			5% scenario			15% scenario		
		2015 (e)			2015 (e)			2015 (e)		
Project Header	Project Use	1-4	5-10	Total	1-4	5-10	Total	1-4	5-10	Total
Non-residential	Commercial	7,130,609	235,318	7,365,926	356,530	11,766	368,296	1,069,591	35,298	1,104,889
	Industrial	1,205,566	987	1,206,553	60,278	49	60,328	180,835	148	180,983
	Institutional	5,762,991	126,732	5,889,723	288,150	6,337	294,486	864,449	19,010	883,458
	Miscellaneous	821,803	248	822,051	41,090	12	41,103	123,270	37	123,308
	Total	14,920,968	363,285	15,284,253	746,048	18,164	764,213	2,238,145	54,493	2,292,638
Residential	Apartments	2,075,353	807,351	2,882,704	103,768	40,368	144,135	311,303	121,103	432,406
	Total	2,075,353	807,351	2,882,704	103,768	40,368	144,135	311,303	121,103	432,406
Grand total		16,996,321	1,170,636	18,166,957	849,816	58,532	908,348	2,549,448	175,595	2,725,044

¹BF=Board feet

Clearly, the 1-4 story segment represents the largest market opportunity given its share of the market. This is especially true for the non-residential market, notably commercial and institutional buildings making up 87% of the non-residential opportunity. Conversely, in the case of apartments, nearly 40% of the opportunity comes from the 5 to 10-story height class. However, recent trends towards cheaper for rent wood-framed apartment buildings might hinder the inroad of CLT into this segment.

This estimate does not include possible inroads into the high-end single-family market.

⁴ 25% GC overhead and profit included.

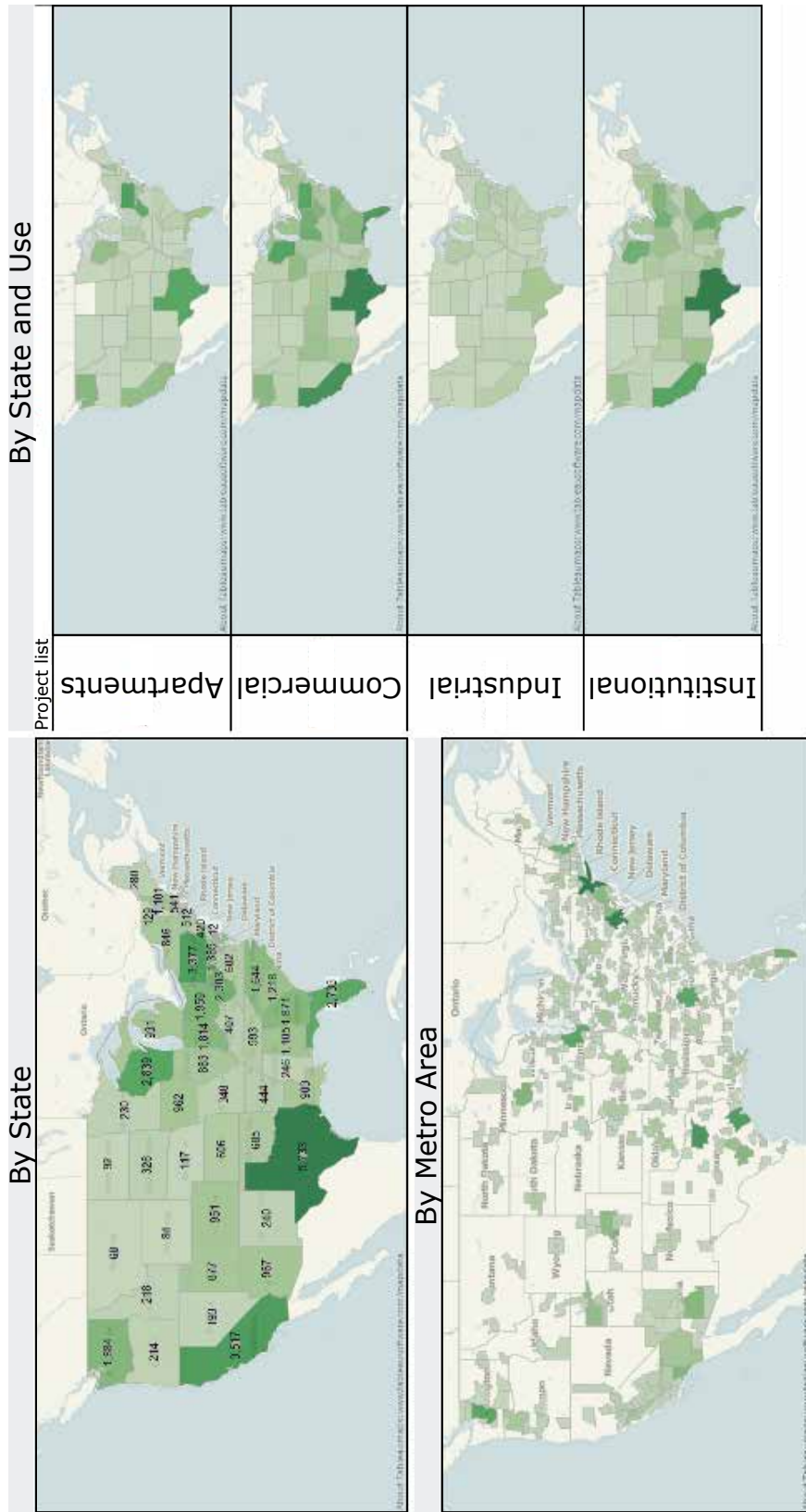


Figure 14
Estimated demand 2015 (5% scenario, 000 ft.³)

10

BUILDING EXAMPLES

The purpose of this section is to introduce interesting examples of buildings built around the world using CLT elements.

10.1 Residential Buildings



Figure 15
Single-family house in Rykkinn, Norway



Figure 16
Single-family house in Klagenfurt, Austria (courtesy of KLH)



Figure 17
Country house in Québec, Canada



Figure 18
Garlick Residence, Oroville, WA, United States (courtesy of Structurlam Products Ltd.)



Figure 19
Multi-family building in Judenburg, Austria (courtesy of KLH)



Figure 20
Multi-family building in Chibougamau, Québec, Canada (courtesy of Nordic Engineered Wood)



Figure 21
Multi-family building in Berlin, Germany



Figure 22
Multi-family building in Växjö, Sweden





Figure 23
10-story apartment building in Australia
(courtesy of Lend Lease, www.forteliving.com.au)

10.2 Office and Commercial Buildings



Figure 24
Impulsezentrum, Graz, Austria (courtesy of KLH)



Figure 25
Montana Long Hall (photo courtesy of Darryl Byle in connection with ITS Smartwoods)



Figure 26
Viken Skog BA, Hønefoss, Norway (courtesy of Moelven)



Figure 27
Juwi head office, Wörrstadt, Germany (courtesy of Binderholz)



Figure 28
Werkstatt, Fügen, Austria (courtesy of Binderholz)



Figure 29
Kommissionshalle, Katsch, Austria (courtesy of KLH)

10.3 Hybrid Structures



Figure 30
Parking garage in Innsbruck, Austria (courtesy of KLH)



Figure 31
Residential building in South Carolina, United States (courtesy of Binderholz)



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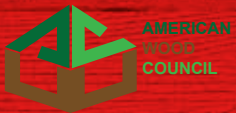
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