Cross-Laminated Timber Design

Structural Properties, Standards, and Safety

Mustafa Mahamid

McGraw Hill

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Contents

Preface

Cross-laminated timber (CLT) is a relatively new system that started in Europe in the early 1990s. The wood design communities, the forest product industry, and researchers found in CLT an opportunity for increasing the use of wood in nonconventional and nontraditional applications. Following the European experience, forest product agencies in North America led by FPInnovations prepared peer-reviewed publications to provide immediate support for the design, construction, and manufacturing of CLT products, and provided technical information for implementing CLT systems in buildings codes and standards.

This book, in its first edition, provides the state of the art of recent developments in CLT design in its various disciplines. The book provides engineers practicing engineers and architects as well as students of these disciplines a comprehensive reference on the planning and design of CLT systems. It also gives the designer the information likely needed for all design phases. The book covers a general introduction to topics considered in design of CLT systems. These include codes and standards used in design of CLT systems; structural behavior, analysis, and design; structural design connections; hygrothermal performance of CLT assemblies; recommendations for design, construction, and maintenance; acoustics; fire safety for CLT projects; environmental aspects of wood as a construction material; and sustainability related to CLT.

The nine chapters of the book have been written by 11 contributors. They have presented their material in a ready-to-use form wherever possible. Therefore, derivations of formulas are omitted in all but a few instances, and many worked-out examples are given. Background information, descriptive matter, and explanatory material have been condensed or omitted. Because each chapter treats a subject that is broad enough to fill a book in itself, the contributors have had to select the material that, in their judgment, is likely to be most useful to the greatest number of users. References and sources of additional material are noted for most of the topics that could not be treated in sufficient detail. The editor is very grateful to the contributors for their tremendous efforts in writing, reviewing, and editing their work, and for their patience during the time it has taken to complete the first edition.

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CHAPTER 1

Introduction to Cross-Laminated Timber

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Cross-laminated timber (CLT) is an innovative wood product that was introduced in Austria and Germany in early 1990s and become a well-known engineered timber product of global interest.

CLT is usually composed of an uneven number of layers, usually three, five, or seven, as shown in Figs. 1.1 and 1.2, glued together on their wide face and sometimes on the narrow face as well. Nails or wooden dowels can be used as well to attach layers together, each layer is made of boards placed side by side, and the layers are arranged crosswise to each other at an angle of 90 degrees. Sometimes, and in special cases, two consecutive layers may be placed in the same direction to form a double layer that might be needed to increase the members' strength. CLT allows prefabricating full-size wall and floor elements as well as linear members that can support in- and out-of-plane loads. Among the various advantages of CLT include its lighter weight compared to other construction material, which results in smaller foundations, good thermal insulation, good sound insulation, and good performance when subjected to fire.

CLT applications are for residential and nonresidential structures; additional applications are mats that are used as temporary roads (see Fig. 1.3), temporary bridges, and crane supports during construction. CLT is a relatively new building system in North America and is a new class of timber products that is known as mass timber. CLT provides a competitive alternative to concrete, steel, and masonry in some building design applications. Masonry and concrete are heavy systems that have been used for single-family and multistory residential buildings around the world. Recent CLT projects in Europe and North America show that CLT can be competitive particularly in mid-rise and high-rise buildings.

This book covers structural, architectural, building science, environmental, and sustainability topics related to CLT; the book covers the following topics in detail:

- Codes and standards
- Structural design

FIGURE 1.1 Sample of CLT member—three-layer board arrangement.

FIGURE 1.2 Sample of CLT member—five-layer board arrangement. (*Courtesy of Sterling Lumber*.)

FIGURE 1.3 CLT mats used as temporary roads for construction purposes. (*Courtesy of Sterling Lumber*.)

- Connection design
- Hygrothermal performance of CLT assemblies: recommendations for design, construction, and maintenance
- Acoustics
- Fire
- Environmental aspects of wood as a construction material
- Sustainability

1.1 Codes and Standards

These CLT products can be used for structural and nonstructural applications. Although the production and design of CLT started in North America in 2008, these products have used in Europe for over 20 years. ANSI/APA PRG 320-2011 *Standard for Performance-Rated Cross Laminated Timber* [1] was the first North American CLT standard, and it was completed in December 2011. This standard, which was adopted by the 2015 *International Building Code* (IBC) [2], was subsequently revised and published as ANSI/APA PRG 320-2012 [3] in October 2012 and adopted by the 2015 *International Residential Code* (IRC) [4] in the United States and the 2014 CSA O86, *Engineering Design in Wood*, in Canada [5]. ANSI/APA PRG 320-2017 [6] was completed in October 2017 by the PRG 320 consensus-based canvas committee and approved by ANSI as the latest standard until early 2020. This version of the standard clarified and addressed issues that were emerging in CLT manufacturing in North America; ANSI/APA PRG 320-2017 [6] has been adopted by the 2018 IBC [7] and IRC [8]. The most recent ANSI/APA PRG 320 was published in January 2020 (ANSI/APA PRG 320 2019 [9]).

1.2 Structural Design

The structural design of CLT members represents a new generation of the design of wood structures. The structural use of large flat elements in wood construction was not known until few years ago with exception to thin panels. CLT is a new material for which code specification and regulations are still under development, and new provisions are being included in design codes slowly as research and knowledge evolve. CLT producers and suppliers as well as researchers in this field have done extensive research to come up with analysis and design methods and have laid out clear analysis and design methods to design such members. Despite the fact that CLT design is not fully regulated by design codes and jurisdictions, it has been used in structures through the process of certifying the products and through providing scientific evidence of the product to the local jurisdiction. The structural chapter introduces the available analysis and design methods of CLT members; the chapter is focused on the available methods that structural engineers can use and does not discuss how these methods were developed. For more details on modeling and derivation of these methods, the reader is referred to other publications.

1.3 Connection Design

Structural design consists of specifying the appropriate structural elements as well as joining them together to create structural systems. With the expansion of mass timber, there is a corresponding demand for long, high-strength fasteners that can be site installed with ease, speed, and precision. New lines of self-tapping structural screws have proven especially suitable for use with CLT for these reasons. Self-tapping screws will form the main focus of the connections chapter of this book. Connections must be strong enough to provide continuous load paths from applied gravity, wind, and seismic loads on the structure down to the foundation. The connection chapter provides extensive details on connections types, wood, connectors, and fastener limit states and details.

In addition to the required structural performance of CLT members in buildings, the book covers recommendations for design, construction and maintenance for hygrothermal, acoustics, fire, environmental aspects, and sustainability.

1.4 Hygrothermal Performance of CLT Assemblies: Recommendations for Design, Construction, and Maintenance

The hygrothermal performance of building assemblies is a result of their response to heat, air, and moisture transfer phenomena. The overall building service life, energy efficiency, and comfort and health of occupants require good control of the hygrothermal behavior of each assembly. In Chapter 5, the hygrothermal behavior of CLT assemblies is discussed with the aim of defining general design principles for durability. Practical recommendations for the design, construction, and maintenance of CLT structures are presented with the specific objective of maximizing service life and durability as related to hygrothermal performance. The heat, air, and moisture phenomena and relevant variables can be considered at different scales: at the material level, such as the hygrothermal parameters determined by the natural characteristics and composition of wood; at the product level, such as differences in the manufacturing process and product-specific characteristics of CLT panels; at the component/assembly level, such as the specific location of the assembly within the building and its performance requirements; and at the scale of the building and site, such as type of occupancy, climate zone, and construction type. In Chapter 5, these considerations are addressed in order of increasing scale, from the material and product level to the assembly level and to the scale of the whole building.

Building enclosures play an important role in the hygrothermal performance of a building and represent a buffer from the external environment. Principles and recommendations for the design of CLT enclosure assemblies regarding weather protection, moisture control, airtightness, and thermal control are presented in Chapter 5 with schematic examples. Design principles are presented that account for differential movement between parts of a mass-timber building. These details intend to prevent potential negative effects on structural integrity, enclosure performance, and serviceability.

Additionally, Chapter 5 presents an approach to durability, encompassing design, construction, and maintenance as well as techniques for the inspection and monitoring of CLT components over time.

1.5 Acoustics

The impact that acoustics may have on building occupants and on people in the environment surrounding the building should be considered in the design and construction of buildings. The study and practice of architectural acoustics is broadly intended to address these impacts. For the characterization of the various acoustical impacts, architectural acoustics can be subdivided into basic elements, including room acoustics, sound isolation, footfall/impact noise isolation, mechanical noise and vibration control, and environmental noise control.

Chapter 6 of the book provides an overview of the unique acoustic considerations to be made for the design of projects with CLT mass-timber structure. The chapter will begin with a broad overview of acoustics in buildings to frame the discussion of acoustic concepts. Then the chapter outlines the limited acoustic code requirements in the United States for relevant project types; the chapter also presents a comparison between CLT and other structural systems with regard to acoustic, CLT detailing and lab tests, and other analysis methods.

1.6 Fire

Chapter 7 of the book covers an extensive overview on fire as related to timber and CLT as well as building performance when exposed to fire. The chapter covers the basics of timber reaction to fire, wood structure and chemistry, wood pyrolysis and combustion, wood char, char rates, building stability during fire, expected building performance when exposed to fire, high-rise construction, and CLT fire resistance rating.

1.7 Environmental Aspects of Wood As a Construction Material

Chapter 8 covers the environmental aspects of wood as a construction material in comparison with other construction material, sustainability versus the increased use of wood, and durability of wood over time. These issues are addressed by examining the environmental implications of wood as a construction material with comparison to alternative materials based on a systematic assessment of a range of impact estimators. The assessments include single-family residential structure, multistory apartment building, and mid-rise office building.

The chapter also discusses the current state of North American forests and recent and historical trends in forest cover and growth-harvest relationships. Forest conditions and trends in other world regions are also examined.

1.8 Sustainability

Sustainability is covered in Chapter 9 since CLT is a wood product; it depends upon the availability of forest resources to be produced. All materials, including wood products, have environmental impacts and considerations of sustainability that are relevant when evaluating the use of CLT as well as other building materials. Chapter 9 discusses the concept of sustainability, what it means, and what is considered. The specifics of forest sustainability are also addressed, including historic factors, international conditions, and North American forest resources. The modern methods of forest protection, management, and restoration are described along with current concerns for forest health, carbon storage, sustainable livelihoods, and other benefits associated with sustainability. Finally, this chapter outlines the various ways that CLT and the use of CLT in construction can contribute to sustainability goals for forests, communities, and our built environment.

References

[1] APA—The Engineered Wood Association. Standard for Performance-Rated Cross Laminated Timber, ANSI/APA PRG 320. Tacoma, Washington, U.S.A. 2011.
[2] International Code Council. International Building Code. Country Club Hills, Illinois, U.S.A. 2015.

[3] APA—The Engineered Wood Association. Standard for Performance-Rated Cross Laminated Timber, ANSI/APA PRG 320. Tacoma, Washington, U.S.A. 2012.
[4] International Code Council. International Residential Code. Country Club Hills, Illinois, U.S.A. 2015.
[5] Engineering Design in Wood CSA O86, Canadian Standards Association, 2014.
[6] APA—The Engineered Wood Association. Standard for Performance-Rated Cross Laminated Timber, ANSI/APA PRG 320. Tacoma, Washington, U.S.A. 2017.
[7] International Code Council. International Building Code. Country Club Hills, Illinois, U.S.A. 2018.
[8] International Code Council. International Residential Code. Country Club Hills, Illinois, U.S.A. 2018.
[9] APA—The Engineered Wood Association. Standard for Performance-Rated Cross Laminated Timber, ANSI/APA PRG 320. Tacoma, Washington, U.S.A. 2020.

CHAPTER 2

Product Standard for Cross-Laminated Timber

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APA—The Engineered Wood Association

Introduction

Cross-laminated timber (CLT), as shown in Figs. 2.1 and 2.2, is a prefabricated engineered wood product made of at least three orthogonal layers of graded sawn lumber or structural composite lumber (SCL) that are laminated by gluing with structural adhesives to form a solid rectangular-shaped, straight, and plane timber intended for structural (roof, floor, or wall) applications. These CLT products can be used for structural and nonstructural applications. For the purpose of this chapter, these CLT products are intended for structural applications, such as those used in building construction, and are different from those used in nonstructural applications, such as the truck mats used in oil fields.

While these engineered wood products have been used in Europe for over 20 years, the production of structural CLT and design of CLT structural systems started in North America around 2008. Today, there are four major manufacturers of structural CLT in North America. They are DR Johnson Wood Innovations in Riddle, Oregon; Nordic Structures in Chibougamau, Quebec; Smartlam in Columbia Fall, Montana; and Structurlam Products in Penticton, British Columbia, as shown in Fig. 2.3. There are at least three additional CLT manufacturers that are expected to join the production in North America in 2018. Check with www.apawood.org/manufacturer-directory for the latest directory for CLT manufacturers certified by APA.

For the acceptance of new construction materials or systems in North America, such as CLT, a consensus-based product standard is essential to the manufacturers, designers, and regulatory bodies. In recognition of this need, APA—The Engineered Wood Association in the United States and FPInnovations in Canada initiated a joint standard development process in 2010. The intent was to develop a binational CLT standard for North America using the consensus standard development process of APA as a standards developer accredited by the ANSI. After months of intensive committee meetings and balloting, the

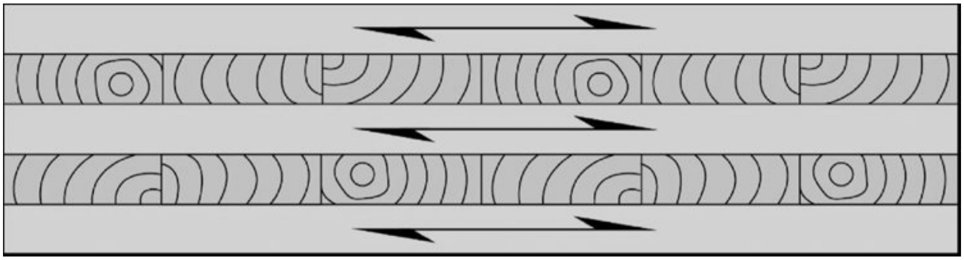

FIGURE 2.1 Cross section of a five-layer CLT Panel (arrows indicate the strength direction).

first North American CLT standard was completed as the ANSI/APA PRG 320-2011 *Standard for Performance-Rated Cross Laminated Timber* [1] in December 2011. This standard, which was adopted by the 2015 *International Building Code* (IBC) was subsequently revised and published as ANSI/APA PRG 320-2012 [2] in October 2012 and

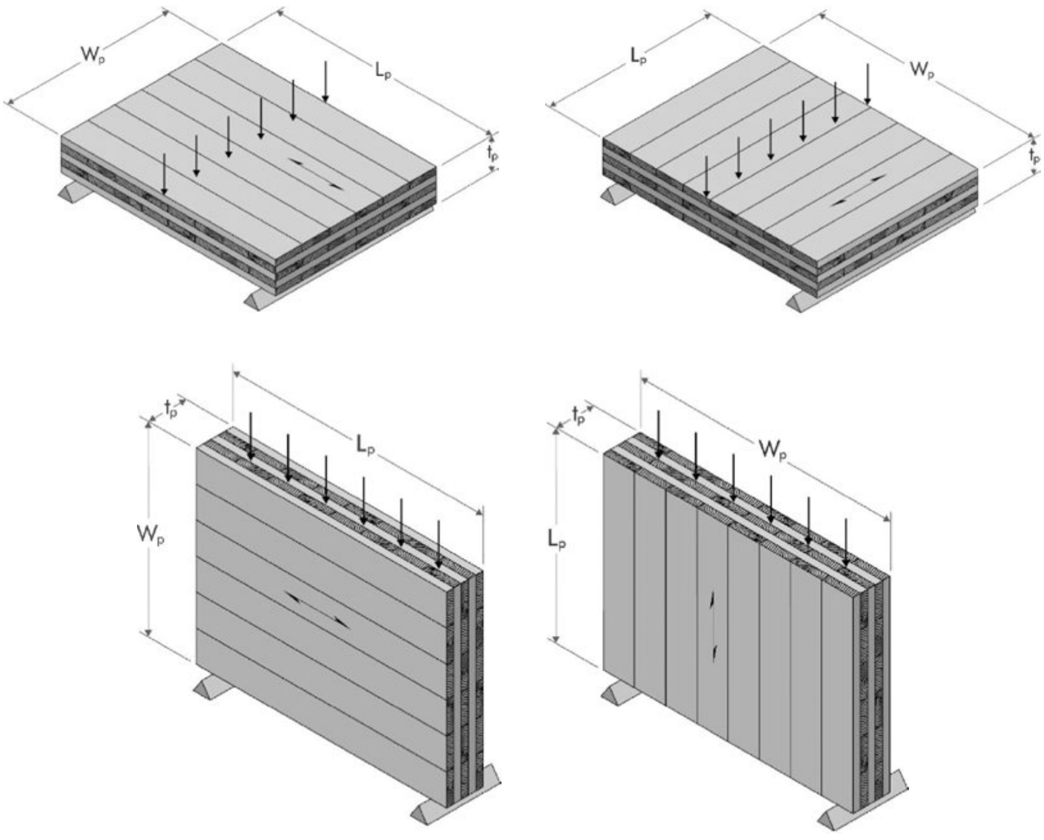

FIGURE 2.2 CLT orientations (top left: flatwise bending in the major strength direction; top right: flatwise bending in the minor strength direction; bottom left: edgewise bending in the major strength direction; bottom right: edgewise bending in the minor strength direction).

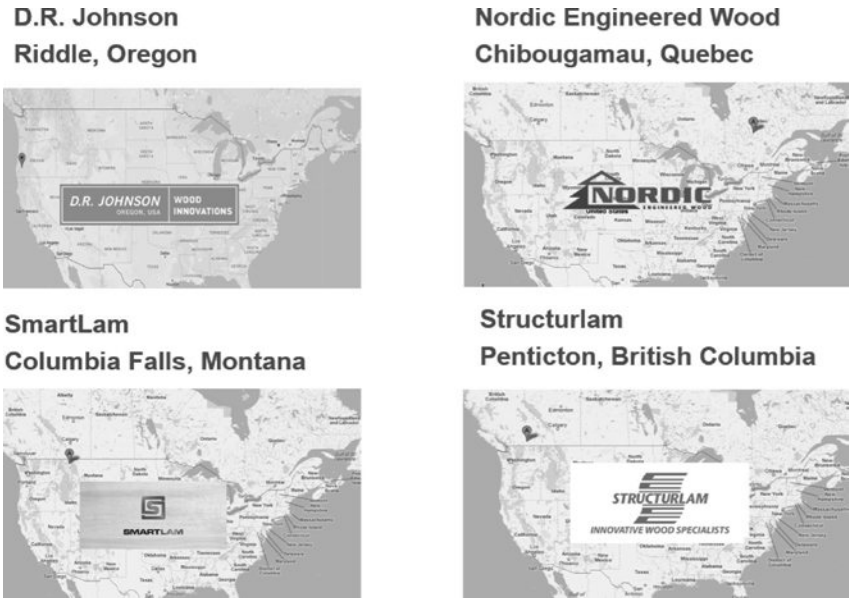

FIGURE 2.3 Current major structural CLT manufacturers in North America.

adopted by the 2015 *International Residential Code* (IRC) in the United States and the 2014 CSA O86, *Engineering Design in Wood*, in Canada.

In October 2017, a new ANSI/APA PRG 320-2017 was completed by the PRG 320 consensus-based canvas committee and approved by ANSI as the latest standard. ANSI/APA PRG 320-2017 [3], which have been adopted by the 2018 IBC and IRC, clarified and addressed issues that were emerging in CLT manufacturing in North America. This chapter provides detailed information for the background and key considerations based on ANSI/APA PRG 320-2017. The provisions directed quoted from ANSI/APA PRG 320-2017 are shown in *Italic* in the text below. Note that the referenced sections in the directed quoted provisions are those from ANSI/APA PRG 320-2017.

2.1 Scope of ANSI/APA PRG 320

The scope of ANSI/APA PRG 320, as stated in ANSI/APA PRG 320-2017, is as follows:

1. SCOPE

Cross-laminated timber (CLT) panels referenced in this standard are defined in 3.2 and shall be qualified and trademarked in accordance with this standard. This standard provides dimensions and tolerances, performance requirements, test methods, quality assurance, and trademarking for CLT panels.

CLT panels shall be used in dry service conditions, such as in most covered structures, where the average equilibrium moisture content of solid wood is less than 16 percent in the U.S., and is 15 percent or less over a year and does not exceed 19 percent in Canada. CLT panels qualified in accordance with the provisions of this standard are intended to resist the effects of moisture on structural performance as may occur due to construction delays or other conditions of similar severity. Products carrying a trademark of this standard shall be *used in accordance with the installation requirements prescribed in the recommendations provided by the CLT manufacturer, an approved agency, and/or its trade association. Finger joining, edge gluing, and face gluing between CLT panels, and camber of CLT panels are beyond the scope of this standard.*

Based on the stated scope, CLT products qualified and trademarked to ANSI/APA PRG 320 is limited to dry service conditions, such as in most covered structures where the mean equilibrium moisture content (EMC) of solid-sawn lumber is less than 16 percent (i.e., 65 percent relative humidity and 68°F or 20°C) in the United States and is 15 percent or less over a year and does not exceed 19 percent in Canada. Therefore, the CLT products manufactured to ANSI/APA PRG 320 may not be suitable for exterior applications where the products are exposed to the elements. Also, it should be noted that nail-laminated timber (NLT), dowel-laminated timber (DLT), finger-jointed or scarf-jointed CLT (in the billet form), or other CLT products manufactured without structural adhesive bonds are outside the scope of ANSI/APA PRG 320.

It is important to note that CLT products evaluated by a recognized inspection or product certification agency as meeting ANSI/APA PRG 320 is required by the U.S. and Canadian building codes to provide the designers with an assurance for product quality and performance. For example, the following are the requirements in the 2018 International Building Code (IBC) [4], the 2018 International Residential Code (IRC) [5], and the 2014 CSA O86, Engineering Design in Wood [6], which is referenced by the 2015 National Building Code (NBC) of Canada [7]. Therefore, CLT products that are not certified as in conformance to ANSI/APA PRG 320 are not in compliance with the IBC, IRC, and NBC, unless specifically approved by the engineer of record and the authority having jurisdiction (building regulators).

(2018 IBC) 2303.1.4 Structural glued cross-laminated timber.
Cross-laminated timbers shall be manufactured and identified in accordance with ANSI/APA PRG 320.

(2018 IRC) R502.1.6 Cross-laminated timber.
Cross-laminated timber shall be manufactured and identified as required by ANSI/APA PRG 320.

(2014 CSA O86) 8.1 Scope
The design values and methods given in Clause 8 apply only to panels of primary and custom CLT stress grades manufactured and certified in accordance with ANSI/APA PRG 320 and layups as defined in Clause 8.2. Panels with alternative CLT layups shall be designed in accordance with Clause 4.3.2.

It is very important for the designer to understand that the acceptance of CLT products that have not demonstrated conformance to ANSI/APA PRG 320 is not as simple as a conversion of design properties published by the CLT suppliers, especially for those products imported from outside of North America. The CLT design standards in North America were developed based on an array of performance expectations stipulated in ANSI/APA PRG 320, such as heat durability, moisture durability, and fire performance, in addition to the compatibility of the design value derivation in North America. Accepting CLT products without demonstrated conformance to ANSI/APA PRG 320, as required by the U.S. and Canadian building codes, carries the responsibility of structural engineering and fire safety design, as well as the acceptance of product quality and durability in structural and fire performance.

2.2 Components for CLT

The major components for CLT include laminations, adhesives, and lamination joints (end joints, face joints, and edge joints if used). To manufacture a structural CLT, the quality of these components must be qualified and then quality controlled on an ongoing basis under an in-plant quality management system, which should cover the manufacturing processes and under a third-party independent product certification program.

2.2.1 Laminations

CLT is manufactured with laminations of dimension lumber or SCL, such as laminated veneer lumber (LVL), laminated strand lumber (LSL), or oriented strand lumber (OSL), which are bonded with structural adhesives through face joints, end joints, and/or edge joints. The requirements for lumber laminations in ANSI/APA PRG 320 are as follows:

6.1 Laminations—Lumber

6.1.1 Lumber species
Any softwood lumber species or species combinations recognized by American Lumber Standards Committee (ALSC) under PS 20 or Canadian Lumber Standards Accreditation Board (CLSAB) under CSA O141 with a minimum published specific gravity of 0.35, as published in the National Design Specification for Wood Construction (NDS) in the U.S. and CSA O86 in Canada, shall be permitted for use in CLT manufacturing provided that other requirements specified in this section are satisfied. The same lumber species or species combination shall be used within a single layer of CLT. Adjacent layers of CLT shall be permitted to be made of different species or species combinations.

6.1.2 Lumber grades
The minimum grade of lumber in the parallel layers of CLT shall be 1200f-1.2E MSR or visual grade No. 2. The minimum grade of lumber in the perpendicular layers of CLT shall be visual grade No. 3. Remanufactured lumber shall be considered as equivalent to solid-sawn lumber when qualified in accordance with Section 4.3.4 of ANSI A190.1 in the U.S. or SPS 1, 2, 4, or 6 in Canada. Proprietary lumber grades meeting or exceeding the mechanical properties of the lumber grades specified above shall be permitted for use provided that they are qualified in accordance with the requirements of an approved agency.

6.1.3 Lamination sizes

a. *Major Strength Direction—The net width of a lamination shall not be less than 1.75 times the lamination thickness for the parallel layers.*
b. *Minor Strength Direction—If the laminations in the perpendicular (cross) layers are not edge bonded, the net width of a lamination shall not be less than 3.5 times the lamination thickness for the perpendicular (cross) layers unless the interlaminar shear strength and creep are evaluated by testing in accordance with Section 8.5.5 and the principles of ASTM D6815, respectively.*
c. *Both Directions—The net thickness of a lamination for all layers at the time of gluing shall not be less than 5/8 inch (16 mm) or more than 2 inches (51 mm). In addition, the lamination thickness shall not vary within the same CLT layer.*

6.1.4 Moisture content
The moisture content of the lumber at the time of CLT manufacturing shall be 12 ± 3%. The moisture content of the SCL at the time of CLT manufacturing shall be 8 ± 3%.

6.2 Laminations—Structural Composite Lumber
SCL products meeting the requirements of ASTM D5456 and the equivalent specific gravity specified in 6.1.1 shall be permitted for use. SCL laminations must also meet the requirements of 6.1.3 through 6.1.6.

ANSI/APA PRG 320 utilizes the European experience in engineering theories and manufacturing processes of CLT and takes into consideration the characteristics of the North American lumber resource, manufacturing preference, and end-use expectations. For example, the standard permits the use of any softwood lumber species or species combinations recognized by the American Lumber Standards Committee (ALSC) under PS 20 [8] or the Canadian Lumber Standards Accreditation Board (CLSAB) under CSA O141 [9] with a minimum specific gravity (SG) of 0.35, as published in the National Design Specification for Wood Construction (NDS) [10] in the United States or the Engineering Design in Wood (CSA O86) [6] in Canada. One advantage of using standard-grade lumber is that such lumber will typically be marked as "HT" (heat treated), meaning that the resulting CLT product will also meet national and international phyto-sanitary requirements when the traceability (chain-of-custody) requirements of the lumber laminations can be properly demonstrated and certified. Note that CLT products made of hardwood lumber species are not part of ANSI/APA PRG 320 due to the lack of manufacturing experience and insignificance in commercial production volume for structural applications in North America today.

The minimum SG of 0.35 is intended as the lower bound for the CLT connection design since it is the near minimum value of commercially available wood species in North America, western woods in the United States, and northern species in Canada. To avoid differential mechanical and physical properties of lumber, the standard requires that the same lumber species or species combination be used within the same layer of the CLT while permitting adjacent layers of the CLT to be made of different species or species combinations. The standard also permits the use of SCL when qualified in accordance with ASTM D5456 [11]. In reality, however, it may be still years away before SCL would be used in CLT production because of apparent challenges in the face bonding of SCL to SCL or SCL to lumber. Due to the thickness variation and surface oxidation or inactivation of SCL, surface planing or sanding may be required for SCL before gluing. Another consideration is its cost competitiveness with lumber. Nonetheless, the advantage of SCL that can be produced in a long and wide billet form is one important reason that the ANSI/APA PRG 320 Committee elected to include SCL in the standard. Other attractive factors also include free of natural defects, such as wane, shake, and knots; more uniform stiffness and strength; and greater dimensional stability. The ANSI/APA PRG 320 Committee is working on more provisions that will be added to a future version of ANSI/APA PRG 320 to guide the use of SCL in CLT production.

Lumber grades in the parallel and perpendicular layers of CLT are required to be at least 1200f-1.2E MSR or visually graded No. 2 and visually graded No. 3, respectively. Remanufactured lumber is permitted as equivalent to solid-sawn lumber when qualified in accordance with ANSI A190.1 [12] in the United States or SPS 1, 2, 4, or 6 [13–16] in Canada. Proprietary lumber grades meeting or exceeding the mechanical properties of the lumber grades specified above are permitted provided that they are qualified in accordance with the requirements of an approved agency, which is defined in the standard as an independent inspection agency accredited under ISO/IEC 17020 [17] or an independent testing agency accredited under ISO/IEC 17025 [18] in the United States or a certification agency accredited under ISO/IEC 17065 [19] in Canada. This allows for a great flexibility in the utilization of forest resources in North America.

The net lamination thickness for all CLT layers at the time of gluing is required to be at least 5/8 in. (16 mm) but not thicker than 2 in. (51 mm) to facilitate face bonding. In addition, the lamination thickness is not permitted to vary within the same CLT layer except when it is within the lamination thickness tolerances—at the time of face bonding, variations in thickness across the width of a lamination is limited to ±0.008 in. (0.2 mm) or less, and the variation in thickness along the length of a lamination is limited to ±0.012 in. (0.3 mm). These maximum tolerances may need to be adjusted during qualification so as to produce acceptable face bond performance.

The net lamination width is required to be at least 1.75 times the lamination thickness for the parallel layers in the major strength direction of the CLT. This means that if 2× lumber (1-3/8 in. or 35 mm in net thickness after surfacing prior to gluing) is used in the parallel layers, the minimum net lamination width must be at least 2.4 in. (61 mm), i.e., 2 × 3 lumber. On the other hand, the net lamination width is required to be at least 3.5 times the lamination thickness for the perpendicular layers if the laminations in the perpendicular (cross) layers are not edge-bonded, unless the interlaminar shear strength and creep of the CLT are evaluated by testing. This means that if 2× lumber is used in the perpendicular layers, the net lamination width must be at least 4.8 in. (122 mm), i.e., 2 × 6 lumber.

This minimum lamination width in the perpendicular layers could become a problem for CLT manufacturers who may prefer to use 2 × 3 (net 1½ in. × 2½ in. or 38 mm × 63 mm) or 2 × 4 (net 1½ in. × 3½ in. or 38 mm × 89 mm) lumber. However, the Committee was concerned about the unbonded edge joints, which could leave gaps as potential stress risers. These, in turn, may reduce the effective interlaminar shear strength and stiffness and may result in excessive creep. Therefore, in this case, the manufacturers will have to either edge-glue the laminations or demonstrate the conformance to the standard by conducting interlaminar shear tests and ASTM D6815 [20] creep tests. It should be noted that this is an interim measure due to the lack of data at this point in time to address the concerns. As a result, it is expected that this provision may be revisited as more information becomes available.

The selection of lumber laminations represent a key step in CLT manufacturing, and the lumber grade should be selected in accordance to the CLT layup of the CLT panel. In addition, for a CLT appearance classification (discussed below), the outermost layer(s) may have specific visual characteristics for aesthetic purposes.

Most adhesives require that surfaces be planed prior to adhesive application and pressing to ensure a strong and durable gluebond. ANSI/APA PRG 320 recommends the following:

Note 5. It may be necessary to plane the lamination surface within 48 hours of face bonding for some wood species.

When the graded lumber is replaned just prior to bonding, depending on the amount of wood removed, this may alter the grade of the lumber, so a grade verification may be necessary. The use of rough-sawn lumber may seem to result in some saving because the lumber is required to be only planed once, and a lumber grading for visual or E-rating after planing may increase the net cost.

It should be noted that the packages of kiln-dried lumber are usually solid-stacked and dried to a moisture content (MC) of 19 percent or less at the time of surfacing, which may not be suitable for all CLT manufacturing processes. For example, some adhesives are sensitive to MC variations. ANSI/APA PRG 320 recommends that lumber having a MC of 12% ± 3% for CLT manufacturing to ensure proper bond quality of the product. If SCL is used, the target MC should be 8% ± 3% at the time of CLT manufacturing. It is recommended that the maximum difference in MC between adjacent pieces that are to be joined in CLT not exceed 5 percentage points. A handheld or online MC meter can be used to check the lumber MC.

ANSI/APA PRG 320 does not specifically address the wood temperature for CLT manufacturing with the expectation that this will be self-regulated by the adhesive manufacturer's specification. In general, wood temperature will affect the gluebond quality, and the adhesive manufacturer's recommendations should be followed. The ambient temperature in the manufacturing facility may also have an effect on some process parameters, such as the open assembly time and adhesive curing time. Therefore, it is recommended that the ambient temperature for the CLT manufacturing be at least 60°F (15°C).

In addition to the lumber MC and temperature, there are other lumber characteristics that may affect the quality of the adhesive bond. These either impact on the pressure that is effectively applied to the gluebond or simply reduce the available bonding surface. Lumber warp in the form of bow, crook, cup, and twist are examples of the former. Wane is a common example of the latter. Standard grades of framing lumber permit these characteristics to varying degrees. While these limits are acceptable for wood frame construction, some of these characteristics need to be restricted when manufacturing CLT in order to ensure formation of a good gluebond.

It is important that the impact of these characteristics, if permitted, be taken into account in the product manufacturing and expected gluebond performance. In ANSI/APA PRG 320, for example, this is addressed by grading to achieve an effective bond area of a minimum of 80 percent, as shown below:

8.3 Qualification of Effective Bond Area

8.3.1 General

The manufacturer shall establish visual grading rules for the bonded faces and limit the average glue skip to maintain an average effective bond area of 80% or more.

The manufacturer's visual grading rules established to achieve the effective bond area shall include major visual characteristics based on characteristic measurements consistent with standard lumber grading rules.

For example, wane will reduce the bonding area and concentrate the stresses in a CLT panel. However, wane cannot be ignored because it is a permitted characteristic in all lumber visual grades. The effect of wane can be accommodated by removing pieces with excessive amounts of wane and/or rearranging or reorienting pieces with wane.

2.2.2 Adhesives

Another critical component for CLT is the adhesives. The requirements for CLT adhesives in ANSI/APA PRG 320 are as follows:

6.3 Adhesives

a. *In the U.S., adhesives used for CLT manufacturing shall meet the requirements of ANSI 405 with the exception that Section 2.1.6 of ANSI 405 (either ASTM D3434 or CSA O112.9) is not required. In addition, adhesives shall be evaluated for heat performance in accordance with Section 6.1.3.4 of DOC PS1.*
b. *In Canada, adhesives shall meet the requirements of CSA O112.10, and Sections 2.1.3 and 3.3 (ASTM D7247 heat durability) of ANSI 405. In addition, adhesives shall be evaluated for heat performance in accordance with Section 6.1.3.4 of DOC PS1.*
c. *For use in both the U.S. and Canada, adhesives shall meet both a and b in this section.*

The standard requires that the adhesives used for CLT manufacturing meet the requirements of ANSI 405 [21] with the exception that the extreme gluebond durability tests in ANSI 405 (either ASTM D3434 [22] or CSA O112.9 [23]), which are designed for adhesive qualification in exterior applications, is not required because CLT products manufactured to ANSI/APA PRG 320 are limited to dry service conditions, such as in most covered structures where the mean EMC of solid-sawn lumber is less than 16 percent (i.e., 65 percent relative humidity and 68°F or 20°C) in the United States and is 15 percent or less over a year and does not exceed 19 percent in Canada. Note that ANSI 405 includes ASTM D7247 heat durability tests [24]. CLT products qualified in accordance with the standard are intended to resist the effects of moisture on structural performance, as it may occur due to construction delays or other conditions of similar severity.

In Canada, CLT adhesives have to meet the requirements of CSA O112.10 [25] and ASTM D7247 heat durability, which are part of the requirements in ANSI 405. In addition, in both countries, CLT adhesives have to be evaluated for heat performance in accordance with PS1 [26]. The intent of the heat performance evaluation is to determine if an adhesive will exhibit heat delamination characteristics, which may increase the char rate of the CLT when exposed to fire in certain applications. If heat delamination occurs, the CLT manufacturer is expected to consult with the adhesive manufacturer and the approved agency to develop appropriate strategies in product manufacturing and/or end-use recommendations for the CLT fire design [27].

It is important to note that ANSI/APA PRG 320 does not currently have pass/fail criteria on adhesive heat delamination. This is because the standard CLT char rate, as stipulated in Chapter 16 of the NDS, has assumed the occurrence of adhesive heat delamination under fire exposure. However, in recent full-scale compartment fire tests, it was discovered that a certain type of CLT adhesive that causes adhesive heat delamination can result in a fire regrowth and second flashover, which is a concern by the fire service for mid- to high-rise tall wood buildings that may have a delayed firefighting if the automatic sprinklers are also malfunctioning or manually deactivated for some reason. Therefore, the ANSI/APA PRG 320 Committee is actively working with the International Code Council (ICC) Ad Hoc Committee on Tall Wood Buildings to revise the adhesive qualification requirements in ANSI/APA PRG 320 to prohibit adhesives that exhibit the heat delamination and fire regrowth behavior. In the meantime, the ANSI 405 Committee has also just approved the addition of CSA O177 [28] small-scale flame test to ANSI 405-2018 glulam adhesive standard. Since ANSI 405 is directly referenced in ANSI/APA PRG 320, the CSA O177 small-scale flame test will become a new requirement for all CLT adhesives when ANSI/APA PRG 320 adopts ANSI 405-2018.

Several types of structural adhesives have been successfully used in CLT production, as listed below:

- Phenolic types, such as phenol-resorcinol formaldehyde (PRF)
- Melamine types, such as melamine formaldehyde (MEL)
- Emulsion polymer isocyanate (EPI)
- One-component polyurethane (PUR)

PRF and MEL are well-known adhesives for structural use and commonly used for glulam manufacturing in North America. EPI adhesive is used for wood I-joist and lamination. PUR adhesive has been commonly used in Europe to produce CLT. It should be noted that not all formulations within an adhesive type will meet the requirements of the structural adhesive standard and that there may be considerable variation in working properties within each adhesive type. Documentation showing that the adhesive has met the appropriate standards is required for CLT product certification. In addition, the working properties of the adhesive needed by the manufacturing process should be considered and discussed with the adhesive supplier.

In addition to cost and working properties, each adhesive type may possess other attributes that may be important. For example, among the four adhesive types indicated above, PRF is dark brown, whereas MEL, EPI, and PUR are light colored. PUR is manufactured without the addition of solvents or formaldehyde and is moisture reactive. EPI is also free from formaldehyde. Due to the chemical reaction, PUR normally produces slight foaming during hardening.

2.2.3 Lamination Joints

Lamination joints include end joints, face joints, and edge joints. The requirements for lamination joints in ANSI/APA PRG 320 are as follows:

> ***6.4 Lamination Joints***
>
> ***6.4.1 General***
> *The lamination joints of CLT shall meet the requirements specified in this section.*
>
> ***6.4.2 End joints in laminations***
> *The strength, wood failure, and durability of lamination end joints shall be qualified in accordance with Section 12.1.3 of ANSI A190.1 and meet the requirements specified therein in the U.S., or shall be qualified in accordance with Section 9.5 of CSA O177 and meet the requirements specified therein in Canada.*
>
> ***6.4.3 Edge and face joints in laminations***
> *The wood failure and durability of the face and edge (when required for structural performance) joints shall be qualified in accordance with Section 12.1.2 of ANSI A190.1 and meet all requirements, except for the shear strength, specified in Sections 12.1.2(b) of that standard in the U.S., or shall be qualified in accordance with Sections 9.2 and 9.3 of CSA O177 and meet all requirements, except for the shear strength, specified therein in Canada.*

Adhesive-bonded edge joints between laminations in the same layer of CLT are not required in accordance with ANSI/APA PRG 320 unless CLT's structural and/or fire performance is qualified based on the use of adhesive-bonded edge joints. As previously mentioned, laminations with unbonded edge joints in the perpendicular layers are subject to the minimum width limitation of 3.5 times the lamination thickness. On the other hand, the end joints within the same lamination, as applicable (e.g., SCL layers may be provided in full width and full length), and the face joints between adjacent laminations must be qualified in accordance with the glulam standard, ANSI A190.1 in the United States and CSA O177 in Canada, with the exception that the interlaminar shear strength criteria do not apply due to the lower interlaminar shear strength when adjacent laminations are perpendicular. However, these provisions will be reviewed when more plant data are gathered and analyzed in the immediate future.

It should be also noted that the gap in the unbonded edge joint of the CLT is not specified in the current ANSI/APA PRG 320 even though the intent is to have the edge joint as tight as possible. In practicality, however, it is very difficult to have a completely tight unbonded edge joints. Therefore, the ANSI/APA PRG 320 Committee is currently