CLT Handbook

CROSS-LAMINATED TIMBER

U.S. EDITION

The U.S. Edition of the CLT Handbook: cross-laminated timber can be electronically downloaded without charge from the website www.masstimber.com. Additional information can be obtained by visiting the websites of FPInnovations, USFPL, American Wood Council (AWC), APA and U.S. WoodWorks. Hard copies can be obtained through AWC (www.awc.org).

CLT Handbook

CROSS-LAMINATED TIMBER

U.S. EDITION

Edited by

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

FPInnovations
Pointe-Claire, QC
Special Publication SP-529E

2013

Funding for this publication was provided by

Publication

FPInnovations
570 boul. St. Jean
Pointe-Claire (QC)
H9R 3J9
www.fpinnovations.ca

Distribution of hard copies

AWC
222 Catoctin Circle SE
Suite 201
Leesburg, VA 20175
www.awc.org

Library and Archives Canada Cataloguing in Publication

CLT handbook : cross-laminated timber / edited by Erol Karacabeyli, Brad Douglas. -- U.S. ed.

(Special publication, ISSN 1925-0495 ; SP-529E)
Co-published by U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Binational Softwood Lumber Council (BSLC).
Includes bibliographical references.
Issued also in electronic format.
ISBN 978-0-86488-553-1

1. Laminated wood. 2. Laminated wood construction. 3. Engineered wood construction. 4. Laminated wood--Standards. 5. Laminated wood--Handbooks, manuals, etc. I. Karacabeyli, Erol, 1954- II. Douglas, Brad, 1960- III. Forest Products Laboratory (U.S.) IV. FPInnovations (Institute) V. Binational Softwood Lumber Council VI. Title: Cross-laminated timber. VII. Series: Special publication (FPInnovations (Institute)) ; SP-529E

TA666.C57 2013 624.1'84 C2012-908154-X

Library and Archives Canada Cataloguing in Publication

CLT handbook [electronic resource] : cross-laminated timber / edited by Erol Karacabeyli, Brad Douglas. -- U.S. ed.

(Special publication, ISSN 1925-0509 ; SP-529E)
Co-published by U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Binational Softwood Lumber Council (BSLC).
Includes bibliographical references.
Electronic monograph in PDF format.
Issued also in print format.
ISBN 978-0-86488-554-8

1. Laminated wood. 2. Laminated wood construction. 3. Engineered wood construction. 4. Laminated wood--Standards. 5. Laminated wood--Handbooks, manuals, etc. I. Karacabeyli, Erol, 1954- II. Douglas, Brad, 1960- III. Forest Products Laboratory (U.S.) IV. FPInnovations (Institute) V. Binational Softwood Lumber Council VI. Title: Cross-laminated timber. VII. Series: Special publication (FPInnovations (Institute) : Online) ; SP-529E

TA666.C57 2013 624.1'84 C2012-908155-8

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, FPInnovations, 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.

Our very special thanks go to Loren Ross at AWC and Sylvain Gagnon at FPInnovations for their work as project leaders and for their special efforts in gathering the expertise of everyone into a unique document. Special thanks also go to the Working Group, Dr. Borjen Yeh from APA, Dave Kretschmann from the U.S. Forest Products Laboratory, and Lisa Podesto from U.S. WoodWorks. Thanks also to Madeline Leroux for her work on the drawings, Odile Fleury for her help with bibliographic references, and Marie-Claude Thibault for her support in editing and coordination work.

Erol Karacabeyli, P.Eng. and **Brad Douglas**, P.E.
Co-editors
CLT Handbook, U.S. Edition

CONTENTS

CHAPTER 1 — Introduction to cross-laminated timber

CHAPTER 2 — Cross-laminated timber manufacturing

CHAPTER 3 — Structural design of cross-laminated timber elements

CHAPTER 4 — Lateral design of cross-laminated timber buildings

CHAPTER 5 — Connections in cross-laminated timber buildings

CHAPTER 6 — Duration of load and creep factors for cross-laminated timber panels

CHAPTER 7 — Vibration performance of cross-laminated timber floors

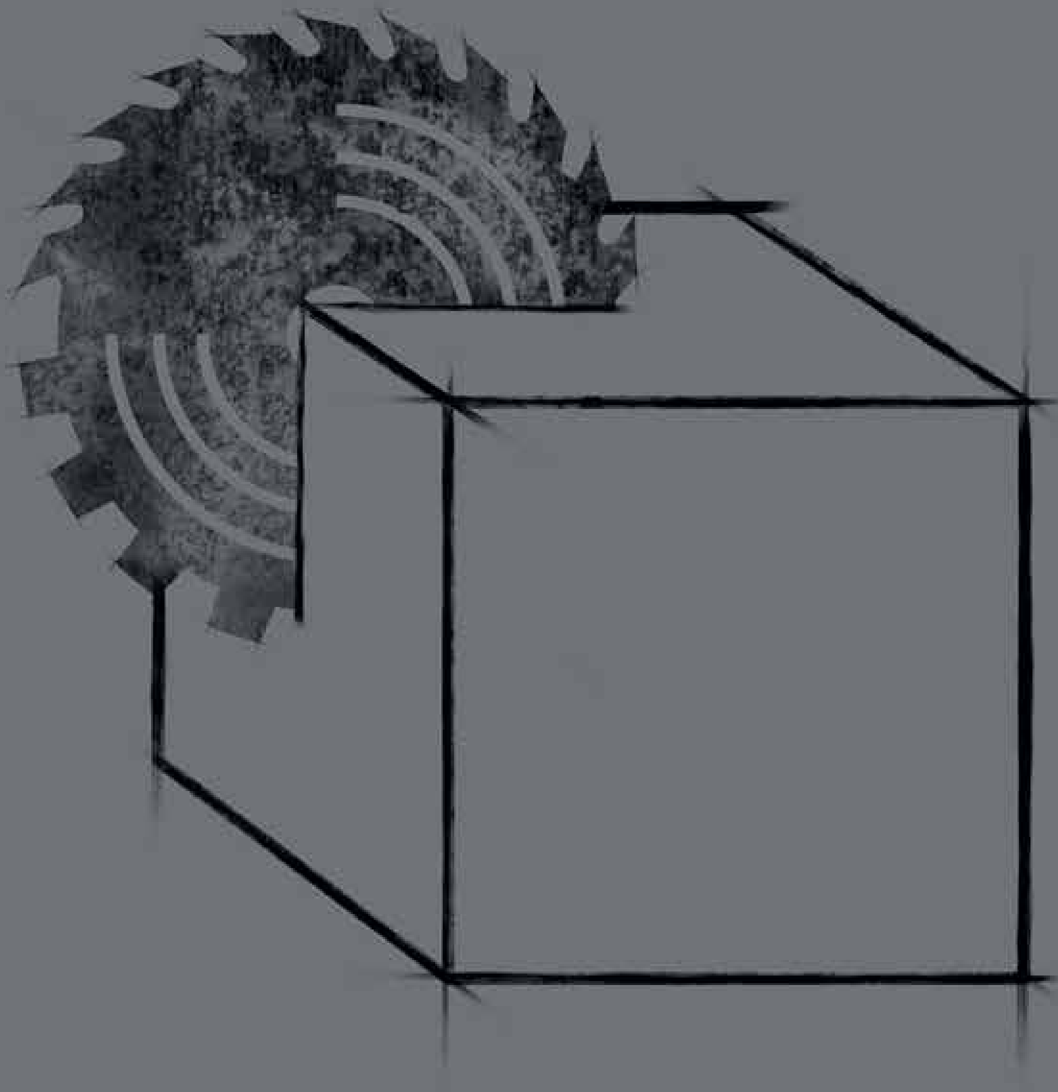
CHAPTER 8 — Fire performance of cross-laminated timber assemblies

CHAPTER 9 — Sound insulation of cross-laminated timber assemblies

CHAPTER 10 — Building enclosure design for cross-laminated timber construction

CHAPTER 11 — Environmental performance of cross-laminated timber

CHAPTER 12 — Lifting and handling of cross-laminated timber elements



Manufacturing

Cross-laminated timber manufacturing

CHAPTER 2

Authors

Borjen Yeh, Ph.D., P.E., APA
Dave Kretschmann, P.E., USDA Forest Products Laboratory
Brad (Jianhe) Wang, Ph.D., FPInnovations

Peer Reviewers

Conroy Lum, P.Eng., FPInnovations
Julie Frappier, Eng., Nordic Engineered Wood
Andre Morf, Structurlam

ACKNOWLEDGEMENTS

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:

The editing partners would also like to express their special thanks to Binational Softwood Lumber Council, Forestry Innovation Investment (FII), Nordic Engineered Wood, Structurlam, and CLT Canada for their financial contribution to studies in support of the introduction of cross-laminated timber products in the United States of America.

The U.S. Edition of the CLT Handbook: cross-laminated timber can be electronically downloaded without charge from the website www.masstimber.com. Additional information can be obtained by visiting the websites of FPInnovations, USFPL, American Wood Council (AWC), APA and U.S. WoodWorks. Hard copies can be obtained through AWC (www.awc.org).

ABSTRACT

This Chapter provides general information about the manufacturing of CLT that may be of interest to the design community. The information contained in this Chapter may also provide guidance to CLT manufacturers in the development of their plant operating specification document.

Typical steps of the CLT manufacturing process are described, and key process variables affecting adhesive bond quality of CLT products are discussed. The manufacturing, qualification, and quality assurance requirements in accordance with the American National Standard for Performance-Rated Cross-Laminated Timber, ANSI/APA PRG 320, are discussed.

TABLE OF CONTENTS

Acknowledgements ii

Abstract iii

List of Tables vi

List of Figures vi

1 Introduction 1

2 Component Requirements 2

2.1 Laminations 2

2.2 Adhesives 3

2.3 Lamination Joints 4

3 CLT Requirements 5

3.1 Dimensions and Dimensional Tolerances 5

3.2 Stress Classes 5

3.3 Appearance Classification 8

4 CLT Manufacturing Process 9

4.1 Primary Lumber Selection 11

4.1.1 Lumber Moisture Content and Temperature 11

4.1.2 Lumber Characteristics Affecting Adhesive Bond Quality 12

4.2 Lumber Grouping 12

4.3 Lumber Planing 12

4.4 Lumber/Layers Cutting to Length 12

4.5 Adhesive Application 13

4.6 CLT Panel Lay-up 13

4.7 Assembly Pressing 13

4.8 CLT On-line Quality Control, Machining and Cutting 15

4.9 Product Marking, Packaging and Shipping 15

5 Qualification and Quality Assurance 16
5.1 Plant Pre-qualification 16
5.2 CLT Structural Performance Qualification 17
5.3 Process Change Qualification 18
5.4 Quality Assurance 18
5.5 Quality Assurance Tests 19
5.5.1 Delamination Tests 19
5.5.2 Visual Quality of CLT 19
6 Implementation of the Standard 20
7 Conclusions 21
8 References 22

List of Tables

Table 1 Required characteristic strengths and moduli of elasticity for PRG 320 CLT laminations 6

Table 2 Allowable design capacities for CLT (for use in the United States) 7

Table 3 Response to process changes according to ANSI/APA PRG 320 18

List of Figures

Figure 1 Cross-section of a 5-layer CLT panel 1

Figure 2 The manufacturing process of CLT products 10

Figure 3 Lumber shrinkage relief 14

Figure 4 Block shear ("B") and delamination ("D") specimen locations 17

1
INTRODUCTION

Cross-laminated timber (CLT) is defined as a prefabricated solid engineered wood product made of at least three orthogonally bonded layers of solid-sawn lumber or structural composite lumber (SCL) that are laminated by gluing of longitudinal and transverse layers with structural adhesives to form a solid rectangular-shaped, straight, and plane timber intended for roof, floor, or wall applications (see Figure 1). While this engineered wood product has been used in Europe for over 15 years, the production of CLT and design of CLT structural systems have just begun in North America with some manufacturers currently being in production or in the process of product qualification.

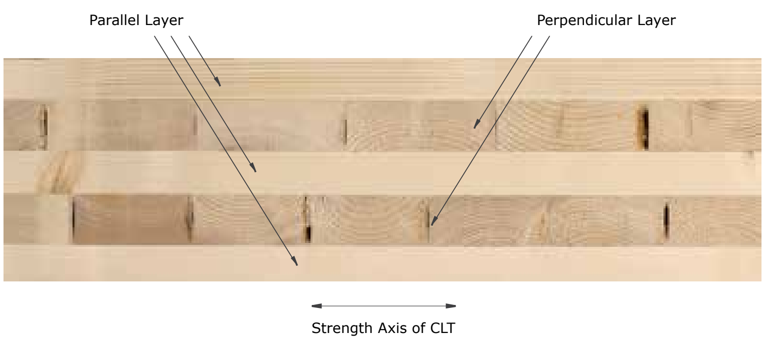


Figure 1
Cross-section of a 5-layer CLT panel

For the acceptance of new construction materials or systems such as CLT in North America, a consensus-based product standard is essential to the 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 bi-national CLT standard for North America using the consensus standard development process of APA as a standards developer accredited by the American National Standards Institute (ANSI). After 22 months of intensive committee meetings and balloting, the 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 Chapter describes and documents the background information and some key issues that were considered during the development of the ANSI/APA PRG 320 CLT standard.

2 COMPONENT REQUIREMENTS

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. Nail-laminated CLT or other CLT products manufactured without face bonds are outside the scope of the ANSI/APA PRG 320 standard.

Components (lumber/SCL laminations and adhesives) selected for CLT and the manufacturing processes (adhesive application, panel pressing, etc.) need to be carefully considered to ensure a reliable and consistent product. CLT products evaluated for code compliance by a recognized product certification agency or evaluation service as meeting ANSI/APA PRG 320 provide designers with an assurance for product quality and performance.

2.1 Laminations

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 [2] or the Canadian Lumber Standards Accreditation Board (CLSAB) under CSA O141 [3] with a minimum specific gravity (SG) of 0.35, as published in the National Design Specification for Wood Construction (NDS) [4] in the United States or the Engineering Design in Wood (CSA O86) [5] 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 phytosanitary requirements when the traceability (chain-of-custody) requirements of the lumber laminations can be properly demonstrated and certified.

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 the same lumber species or species combinations be used within the same layer of the CLT, while permitting adjacent layers of 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 [6]. In reality, however, it is 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 factor 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.

Lumber grades in the parallel layers of CLT are required to be at least 1200f-1.2E MSR or visually graded No. 2, and visually graded No. 3 for perpendicular layers. Remanufactured lumber is permitted as equivalent to solid-sawn lumber when qualified in accordance with ANSI/AITC A190.1 [7] in the United States or SPS 1, 2, 4, or 6 [8,9,10,11] 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 [12] or an independent testing agency accredited under ISO/IEC 17025 [13] in the United States, or a certification agency accredited under ISO Guide 65 [14] 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 inch (16 mm), but not thicker than 2 inches (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 inch (0.2 mm) or less, and the variation in thickness along the length of a lamination is limited to ±0.012 inch (0.3 mm). These maximum tolerances may need to be adjusted during qualification as so 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 2x lumber (1-3/8 inches 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 inches (61 mm), i.e., 2x3 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 2x lumber is used in the perpendicular layers, the net lamination width must be at least 4.8 inches (122 mm), i.e., 2x6 lumber.

This minimum lamination width in the perpendicular layers could become a problem for CLT manufacturers who prefer to use 2x3 (net 1-1/2 inches x 2-1/2 inches or 38 mm x 63 mm) or 2x4 (net 1-1/2 inches x 3-1/2 inches or 38 mm x 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 [15] 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 will be revisited as more information becomes available.

2.2 Adhesives

Another critical component for CLT is the adhesives. The standard requires that adhesives used for CLT manufacturing meet the requirements of AITC 405 [16] with the exception that the extreme gluebond durability tests in AITC 405 (either ASTM D3434 [17] or CSA O112.9 [18]), which are designed for adhesive qualification in exterior applications, are not required because CLT products manufactured according to ANSI/APA PRG 320 are 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% (i.e., 65% relative humidity and 68°F or 20°C). 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 must meet the requirements of CSA O112.10 [19] and ASTM D7247 heat durability [20], which is part of the requirements in AITC 405. In addition, in both Canada and the United States, CLT adhesives have to be evaluated for heat performance in accordance with PS1 [21]. 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 [22].

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

- Phenolic types such as phenol-resorcinol formaldehyde (PRF);
- Emulsion polymer isocyanate (EPI); and
- One-component polyurethane (PUR).

PRF is a well-known adhesive for structural use which is 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 there may be considerable variations 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 discussed with the adhesive supplier.

In addition to cost and working properties, each adhesive type possesses other attributes that may be important. For example, among the three adhesives indicated above, PRF is dark brown whereas EPI and PUR are light-coloured. 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.

2.3 Lamination Joints

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, unless the interlaminar shear strength and creep of CLT are evaluated by testing. 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/AITC A190.1 in the United States and CSA O177 [23] 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.

3
CLT REQUIREMENTS

3.1 Dimensions and Dimensional Tolerances

The CLT thickness is limited to 20 inches (508 mm) or less in ANSI/APA PRG 320. This is considered an upper limit that the CLT may be handled in production and transportation. In addition, dimension tolerances permitted at the time of manufacturing are as follows:

- Thickness: ± 1/16 inch (1.6 mm) or 2% of the CLT thickness, whichever is greater;
- Width: ± 1/8 inch (3.2 mm) of the CLT width; and
- Length: ± 1/4 inch (6.4 mm) of the CLT length.

Textured or other face or edge finishes are permitted to alter the tolerances. However, the designers need to compensate for any loss in cross-section and/or the specified strength due to such alterations.

The standard also specifies the CLT panel squareness, defined as the length of the two panel face diagonals measured between panel corners, to be within 1/8 inch (3.2 mm) or less. In addition, the CLT panel straightness, defined as the deviation of edges from a straight line between adjacent panel corners, is required to not exceed 1/16 inch (1.6 mm).

3.2 Stress Classes

As part of the standardization effort, seven CLT stress classes are stipulated in ANSI/APA PRG 320, while custom CLT products are also recognized, provided that the products are qualified by an approved agency in accordance with the qualification and mechanical test requirements specified in the standard. The stress classes are presented in the form of structural capacities, such as bending strength (F_bS), bending stiffness (EI), and shear rigidity (GA). This allows for the needed flexibility to CLT manufacturers in conformance with the product standard based on the available material resources and required design capacities.

The stress classes were developed based on the following prescriptive lumber species and grades available in North America:

- E1: 1950f-1.7E Spruce-Pine-Fir MSR lumber in all parallel layers and No. 3 Spruce-Pine-Fir lumber in all perpendicular layers
- E2: 1650f-1.5E Douglas fir-Larch MSR lumber in all parallel layers and No. 3 Douglas fir-Larch lumber in all perpendicular layers
- E3: 1200f-1.2E Eastern Softwoods, Northern Species, or Western Woods MSR lumber in all parallel layers and No. 3 Eastern Softwoods, Northern Species, or Western Woods lumber in all perpendicular layers

- E4: 1950f-1.7E Southern Pine MSR lumber in all parallel layers and No. 3 Southern Pine lumber in all perpendicular layers
- V1: No. 2 Douglas fir-Larch lumber in all parallel layers and No. 3 Douglas fir-Larch lumber in all perpendicular layers
- V2: No. 1/No. 2 Spruce-Pine-Fir lumber in all parallel layers and No. 3 Spruce-Pine-Fir lumber in all perpendicular layers
- V3: No. 2 Southern Pine lumber in all parallel layers and No. 3 Southern Pine lumber in all perpendicular layers

The required characteristic strengths and moduli of elasticity for CLT laminations are listed in Table 1. As seen from the list above, both mechanically graded lumber (for "E" classes) and visually graded lumber (for "V" classes) are included in this standard. Also included are three major species groups in North America, i.e. Douglas fir-Larch, Spruce-Pine-Fir, and Southern Pine. With the published lumber properties in the lay-up, the design capacities of the CLT were derived based on the "shear analogy" method developed in Europe [24] and the following assumptions:

- The modulus of elasticity of lumber in the perpendicular to grain direction, E_{90}, is 1/30 of the modulus of elasticity of lumber in the parallel to grain direction, E_0;
- The modulus of shear rigidity of lumber in the parallel to grain direction, G_0, is 1/16 of the modulus of elasticity of lumber in the parallel to grain direction, E_0; and
- The modulus of shear rigidity of lumber in the perpendicular to grain direction, G_{90}, is 1/10 of the modulus of shear rigidity of lumber in the parallel to grain direction, G_0.

Table 1
Required characteristic strengths and moduli of elasticity[(a)] for PRG 320 CLT laminations

CLT Grade	Laminations in the Major Strength Direction of the CLT						Laminations in the Minor Strength Direction of the CLT					
	$f_{b,0}$ (psi)	E_0 (10^6psi)	$f_{t,0}$ (psi)	$f_{c,0}$ (psi)	$f_{v,0}$ (psi)	$f_{s,0}$ (psi)	$f_{b,90}$ (psi)	E_{90} (10^6psi)	$f_{t,90}$ (psi)	$f_{c,90}$ (psi)	$f_{v,90}$ (psi)	$f_{s,90}$ (psi)
E1	4,095	1.7	2,885	3,420	425	140	1,050	1.2	525	1,235	425	140
E2	3,465	1.5	2,140	3,230	565	190	1,100	1.4	680	1,470	565	190
E3	2,520	1.2	1,260	2,660	345	115	735	0.9	315	900	345	115
E4	4,095	1.7	2,885	3,420	550	180	1,205	1.4	680	1,565	550	180
V1	1,890	1.6	1,205	2,565	565	190	1,100	1.4	680	1,470	565	190
V2	1,835	1.4	945	2,185	425	140	1,050	1.2	525	1,235	425	140
V3	2,045	1.6	1,155	2,755	550	180	1,205	1.4	680	1,565	550	180

For SI: 1 psi = 6.895 kPa

[(a)] The characteristic values may be obtained from the published allowable design values for lumber in the United States as follows:

$f_{b,0}$ = 2.1 x published allowable bending stress (F_b), $f_{t,0}$ = 2.1 x published allowable tensile stress (F_t),
$f_{c,0}$ = 1.9 x published allowable compressive stress parallel to grain (F_c), $f_{v,0}$ = 3.15 x published allowable shear stress (F_v), and $f_{s,0}$ = 1/3 x calculated $f_{v,0}$.

The design capacities are provided in the format of Allowable Stress Design for the United States, as shown in Table 2. The allowable bending strengths can be readily converted to the characteristic bending strengths (fifth percentile with 75% confidence) by multiplying by an adjustment factor of 2.1. The allowable bending stiffness and shear rigidity are based on the mean values and no adjustments are required.

Table 2
Allowable design capacities [a, b, c] for CLT (for use in the United States)

CLT Grade	CLT Thickness (in.)	Lamination Thickness in CLT Lay-up (in.)							Major Strength Direction			Minor Strength Direction		
		=	⊥	=	⊥	=	⊥	=	$F_bS_{eff,0}$ (lb.-ft./ft.)	$EI_{eff,0}$ (10^6 lb.-in.^{2}/ft.)	$GA_{eff,0}$ (10^6 lb./ft.)	$F_bS_{eff,90}$ (lb.-ft./ft.)	$EI_{eff,90}$ 10^6 lb.-in.^{2}/ft.)	$GA_{eff,90}$ (10^6 lb./ft.)
E1	4 1/8	1 3/8	1 3/8	1 3/8					4,525	115	0.46	160	3.1	0.61
	6 7/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8			10,400	440	0.92	1,370	81	1.2
	9 5/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	18,375	1,089	1.4	3,125	309	1.8
E2	4 1/8	1 3/8	1 3/8	1 3/8					3,825	102	0.53	165	3.6	0.56
	6 7/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8			8,825	389	1.1	1,430	95	1.1
	9 5/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	15,600	963	1.6	3,275	360	1.7
E3	4 1/8	1 3/8	1 3/8	1 3/8					2,800	81	0.35	110	2.3	0.44
	6 7/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8			6,400	311	0.69	955	61	0.87
	9 5/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	11,325	769	1.0	2,180	232	1.3
E4	4 1/8	1 3/8	1 3/8	1 3/8					4,525	115	0.53	180	3.6	0.63
	6 7/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8			10,425	441	1.1	1,570	95	1.3
	9 5/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	18,400	1,090	1.6	3,575	360	1.9
V1	4 1/8	1 3/8	1 3/8	1 3/8					2,090	108	0.53	165	3.6	0.59
	6 7/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8			4,800	415	1.1	1,430	95	1.2
	9 5/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	8,500	1,027	1.6	3,275	360	1.8
V2	4 1/8	1 3/8	1 3/8	1 3/8					2,030	95	0.46	160	3.1	0.52
	6 7/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8			4,675	363	0.91	1,370	81	1.0
	9 5/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	8,275	898	1.4	3,125	309	1.6
V3	4 1/8	1 3/8	1 3/8	1 3/8					2,270	108	0.53	180	3.6	0.59
	6 7/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8			5,200	415	1.1	1,570	95	1.2
	9 5/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	9,200	1,027	1.6	3,575	360	1.8

For SI: 1 in. = 25.4 mm; 1 ft. = 304.8 mm; 1 lb. = 4.448 N

(a) This table represents one of many possibilities that CLT could be manufactured by varying lamination grades, thicknesses, orientations, and layer arrangements in the lay-up.
(b) Custom CLT grades that are not listed in this table are permitted in accordance with ANSI/APA PRG 320.
(c) The allowable properties can be converted to the characteristic properties by multiplying the tabulated F_bS by 2.1, and EI and GA by 1.0.

It should be noted that, based on the recent full-scale CLT tests for thicker CLT (depths of 7 layers or more), the standard includes a tentative strength reduction factor of 0.85 for the calculated bending strengths in the major strength direction. It remains unclear at this point if such a factor can be attributed to the volume effect. In general, a shorter span-to-depth ratio is often associated with interlaminar shear failure during flexure. Research is underway to investigate this phenomenon and it will be addressed in the future version of the standard.

Custom CLT classes are permitted in ANSI/APA PRG 320 when accepted by an approved agency in accordance with the qualification and mechanical test requirements specified in the standard. This may include double outer layers or unbalanced lay-ups when clearly identified for installation, as required by the manufacturer and the approved agency. However, the standard requires a unique CLT grade designation be assigned by the approved agency if the custom product represents a significant product volume of the manufacturer to avoid duplication with an existing CLT grade designation that has been assigned to other manufacturers.

3.3 Appearance Classification

There are no mandatory appearance classifications for CLT in ANSI/APA PRG 320. The Committee elected to leave the CLT appearance classifications to be agreed upon between the buyer and seller. However, non-mandatory classifications based largely on selected glulam appearance classifications in ANSI/AITC A190.1 are included in the appendix, which covers the Architectural and Industrial Appearance Classifications. A series of guidelines for the development of a protocol for classifying CLT panels into different appearance classifications based on gaps and checks have been drafted by FPInnovations from research findings [25]. Depending on the market demand, the appearance classifications may be standardized in the future as more CLT products are used in North America.

4 CLT MANUFACTURING PROCESS

CLT panels are manufactured in three or more layers of the same or different thicknesses of dimension lumber or boards in a 90° crisscross pattern. The orthogonal arrangement of layers in CLT adds dimensional stability and two-way action capability to the product. In certain cases, two adjacent layers can be aligned in the same direction to meet certain specifications. Fundamentally, it is possible to produce any CLT thickness by combining thicknesses up to maximum 2 inches (50 mm). As previously mentioned, the final CLT thickness is limited to 20 inches (508 mm) or less in ANSI/APA PRG 320 for practical reasons.

Figure 2 shows schematically the typical CLT manufacturing process, which involves the following nine basic steps:

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

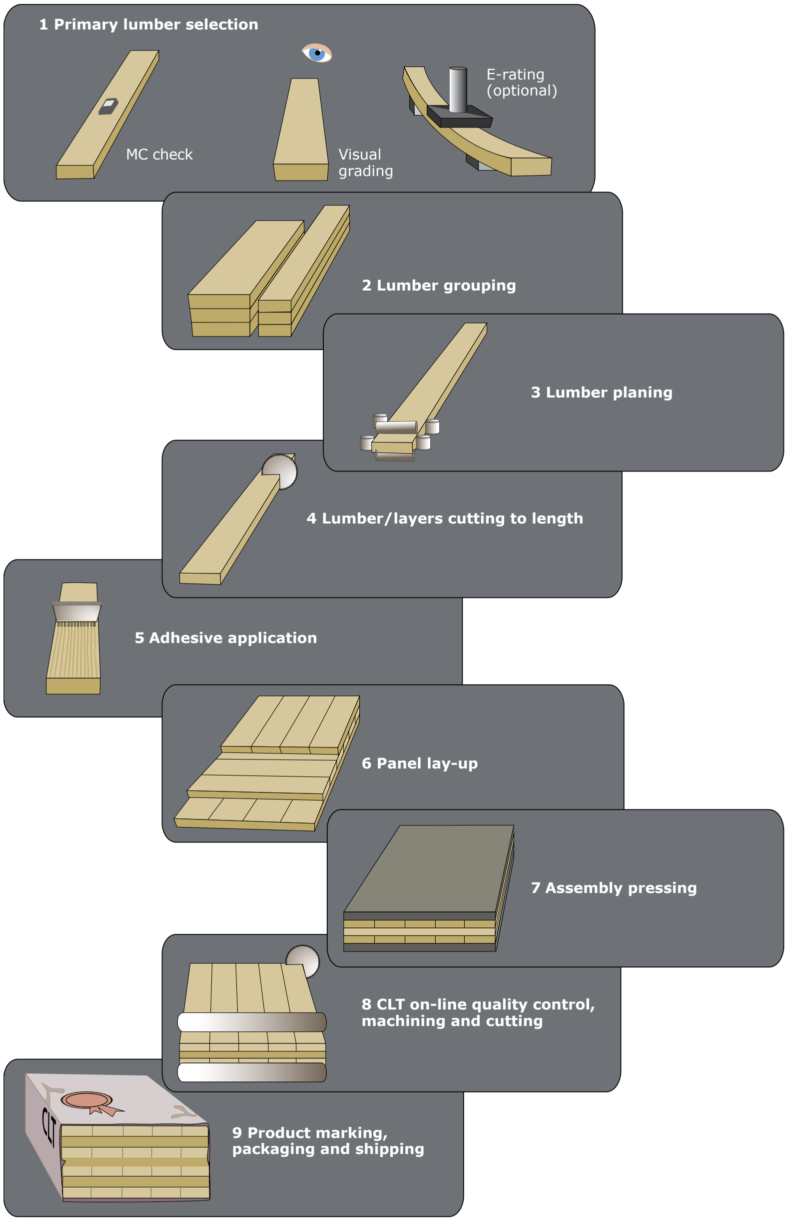


Figure 2
The manufacturing process of CLT products

Each step may include several sub-steps. Step 1 includes lumber moisture content (MC) check and quality control (QC) inspection. Lumber will normally arrive graded to the grades listed in Section 3.2 so the QC step generally involves further visual inspection with or without E-rating. For a CLT plant with an annual capacity below 1 million ft^3 (30,000 m^3), Step 3 is to plane (or surface) lumber on all four sides before cutting up to length for face-gluing. For a CLT plant with an annual capacity of 1 million ft^3 (30,000 m^3) or above, Step 3 could involve secondary lumber preparation [26], which has the following three options: lumber end-jointing only, lumber edge-gluing only, and both lumber end-jointing and edge-gluing.

The key to a successful CLT manufacturing process is consistency in the lumber quality and control of the parameters that affect the quality of the adhesive bond. Much of what is described in this section appears in the in-plant manufacturing standard approved by the inspection or certification agency.

4.1 Primary Lumber Selection

In Europe, some manufacturers produce two grades of CLT panels: construction grade and appearance grade. Lumber stock may be selected in accordance to the grade of the CLT panel; for appearance grade CLT, the outermost layer(s) may have specific visual characteristics for aesthetic purposes. Some European manufacturers produce a so-called composite CLT by surface bonding wood composites or engineered wood products, such as oriented strand board (OSB), plywood and LVL, to CLT. This composite CLT is outside the scope of this Chapter.

Most adhesives require that surfaces be planed prior to adhesive application and pressing to ensure a strong and durable bondline. This means that graded lumber, which is usually supplied surfaced on four sides (S4S), will need to be re-planed just prior to bonding. Depending on the amount of wood removed, this may alter the grade of the lumber so a grade verification step may need to be added. While there may be savings in using rough sawn lumber (only planed once, thus resulting in higher fiber recovery), the manufacturing process will more likely have to include a lumber grading step (visual grading with or without E-rating) after planing as the amount of wood removed will be more than when using S4S lumber.

4.1.1 Lumber Moisture Content and Temperature

Packages of kiln dried lumber are usually solid-stacked and dried to a MC of 19% or less at the time of surfacing. The standard MC specification for lumber may not be suitable for all CLT manufacturing processes. Some adhesives are more sensitive to MC than others. It is best to conduct trials with production runs on lumber with representative levels of MC, remembering that MC levels may vary from season to season. Lacking information on the interaction between the manufacturing process and lumber MC, it is recommended that lumber having a MC of 12 ± 3% be targeted 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. Another reason for limiting the MC variation is to minimize the development of internal stresses between pieces due to differential shrinkage, which is dependent on differential MC, growth ring orientation and species. It is recommended that the maximum difference in MC between adjacent pieces that are to be joined not exceed 5 percentage points.

The lumber packages should be wrapped and stored in a warehouse to prevent wetting. Storage facilities of sufficient capacity should be available to maintain the required MC and temperature of the lumber. To achieve the target MC, the package must be unpacked, stickered by row to allow air circulation and re-stacked for drying. A hand-held radio-frequency MC meter (capacitance type) or an electrical resistance moisture meter can be used to check the lumber MC. Capacitance-based MC meters with sets of metallic plates placed above and below the lumber to measure the electric capacitance as the lumber passes transversally at line speed can be used in production. Other on-line MC meters using emerging technologies, such as bench-type Near-Infrared (NIR) moisture spectroscopy or a microwave MC sensor may be installed to continuously monitor the MC of lumber pieces as they pass by. Note that the former can only measure the MC on the surface, while the latter allows a deeper penetration of microwave field into the product, leading to a more accurate MC measurement. More research and development is needed to adapt the latter to emerging technologies for on-line measurement of lumber.

Wood temperature will affect the bondline 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 be at least 60°F (15°C). The wood temperature and MC, as well as the ambient temperature in the manufacturing facility, may change throughout the year, which points to the need for a QC program that includes monitoring these parameters. As the effect of temperature and MC on the bondline and panel quality is better understood, revisions can be made to the in-plant manufacturing standard to better allocate monitoring resources.

4.1.2 Lumber Characteristics Affecting Adhesive Bond Quality

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 bondline 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 bondline.

It is important that the impact of these characteristics, if permitted, be taken into account in the product manufacturing and expected bondline performance. In ANSI/APA PRG 320, for example, this is addressed by grading to achieve an "effective bondline area" of a minimum of 80%. Consider wane, for example. Wane is the presence of bark or a lack of wood at the corner of a square-edged lumber piece. It 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.

4.2 Lumber Grouping

In production, preparation of lumber for the major and minor strength directions of the CLT may follow different steps. In grouping lumber for these two directions, the MC level and visual characteristics of lumber are primary considerations. For E-class CLT products, lumber E-rating is performed for all parallel layers whereas visual grading is performed for all perpendicular layers. For V-class CLT, lumber visual grading is performed for all parallel and perpendicular layers. In general, for the purpose of establishing panel capacities, all lumber in the major strength direction will be required to have the same engineering properties. Similarly, the lumber for the minor strength direction (cross plies) will have a single set of engineering properties. To ensure aesthetic quality, the exposed surfaces of the outermost layers may be of a better visual appearance. In some cases, it may be desirable to place higher quality lumber in designated areas in a panel where fasteners will be installed to maximize the effectiveness of fastening.

4.3 Lumber Planing

Lumber planing (or surfacing) helps activate or "refresh" the wood surface to reduce oxidation for improved gluing effectiveness. Removal of a very thin surface layer ensures better bonding [26]. Lumber planing must achieve the required precision to ensure optimal gluing. In most cases, planing on all four sides is required to ensure dimensional uniformity. However, in some cases, only face and back planing may suffice if the width tolerance is acceptable and lumber edges are not glued. In general, removing 0.1 inch (2.5 mm) from the thickness and 0.15 inch (3.8 mm) from the width is recommended [26]. Due to the inevitable variations in drying efficiency and wood characteristics, it is possible for recently kiln-dried lumber pieces to exhibit higher-than-average MC after planing. If this problem is encountered, steps should be taken to remove and recondition those pieces. The suitability of those pieces for bonding after reconditioning may need to be assessed.

4.4 Lumber/Layers Cutting to Length

A cutting station rips the lumber (or layers if edge-gluing is used) lengthwise for stacking. Transverse layers may be generated from the longitudinal layers by breaking cross-cutting into shorter sections based on the dimensions of the press, if the same grade and size of wood is used for both parallel and perpendicular layers.

4.5 Adhesive Application

In a typical glue application system used in a through-feed process, which is generally seen for PUR and PRF adhesives, the extruder heads move and apply parallel lines/threads of the adhesive in an air tight system with direct supply from an adhesive container. The layers may be lightly wetted with water mist to help the curing reaction when PUR adhesives are used. The production feed speed is generally around 60 – 200 feet/min (18 - 60 m/min).

If the CLT layers are formed in advance, the glue applicator will consist of a series of side-by-side nozzles installed on a beam, and will travel longitudinally over the layers. The typical speed takes about 12 seconds for 50 feet (15 m) long layers [26]. Adhesive application should occur shortly after planing to overcome such issues as surface oxidation, ageing and dimensional instability of the wood, and improve wettability and bonding effectiveness.

The actual adhesive spread rate (or glue spread level) should be checked against that specified by the adhesive manufacturers. The desired rate is affected by the quality of the wood and the application system. The amount of adhesive applied must ensure uniform wetting of the wood surface. Proper spread rate is evidenced by very slight but even squeeze-out along the entire bondline. The adhesive applicator and spread rate are generally adhesive dependent.

The bonding surfaces of surfaced lumber must be clean and free from adhesive-repellent substances such as oils, greases or release agents, which would have a detrimental effect on bond quality. Disruptions in the manufacturing process may be caused by issues related to adhesive application, such as exceeding the maximum allowed assembly time, which may result in adhesive pre-cure. Procedures should be in place to promptly resolve the cause of such disruptions. Such procedures should be included in the in-plant manufacturing standard.

Edge gluing of wood pieces that make up the CLT layers is not a common practice among manufacturers due to the added manufacturing cost. In order for edge-gluing to be effective, edge planing must be done in advance. As a trade-off between cost and improved product performance, edge-gluing of selected layers as needed could be adopted.

4.6 CLT Panel Lay-up

In general, CLT panel lay-up is similar to plywood with adjacent layers aligned perpendicular to each other, the only difference being that each layer of the CLT panel consists of multiple lumber pieces. A minimum "effective bonding area" of 80% is specified in ANSI/AP PRG 320. While there are a number of wood characteristics that may affect the available bond area, the producer is ultimately responsible to find the most effective way of meeting the requirements. In the case of wane, this may be accomplished by orienting wood pieces such that the bark and pith faces of adjacent pieces face up. Doing this also has the advantage of reducing the tendency for the panel to warp.

The assembly time is defined as the time interval between the spreading of the adhesive on the layers and the application of target pressure to the assembly. The manufacturing process and any restart after a temporary disruption should be designed to ensure that the assembly time does not exceed the maximum target set out in the adhesive specification. In some cases, these may need to be more restrictive than the adhesive manufacturer specifications if ambient conditions are not ideal.

4.7 Assembly Pressing

Pressing is a critical step of the CLT manufacture accounting for proper bond development and CLT quality. Two main types of press are used for CLT manufacturing: vacuum press (flexible membrane) and hydraulic press (rigid platen). A vacuum press generates a theoretical maximum clamping pressure of 14.5 psi (0.1 MPa). Such a low pressure may not be sufficient to suppress the potential warping of layers and overcome their surface irregularities in order to create intimate contact for bonding. To address this deficiency, lumber shrinkage reliefs can be introduced by longitudinally sawing through partial thickness of the lumber to release the stress and in turn reduce the chances of developing cracks when CLT panels lose moisture, as shown in Figure 3. However, the relief kerfs cannot be too wide or too deep because they may reduce the bonding area and affect the panel capacity. It should be noted that the use of lumber shrinkage relief may affect the CLT performance and should be tested as part of the product qualification.

Figure 3
Lumber shrinkage relief

A rigid hydraulic press can generate much higher vertical clamping pressure and side clamping pressure than a vacuum press. To minimize the potential gaps between the lumber pieces in the main layers, application of side clamping pressure in the range of 40 to 80 psi (276 to 550 kPa) is recommended concomitantly with vertical pressing.

A side clamping pressure is sometimes needed to ensure that gaps between laminations in the major strength direction are not too wide. CLT product specifications may have a maximum permitted gap between adjacent laminations in the outer and inner layers. To effectively apply side clamping pressure to the assembly, the length of the cross plies must be less than the total width of the main laminations.

If the CLT layers are formed via edge-gluing in advance, a vertical press without side clamping pressure would suffice. Some vertical presses allow for multiple panels to be pressed simultaneously at high clamping pressures up to 870 psi (6 MPa) [26]. A lateral unloading device is generally used to un-stack multiple CLT panels loaded in a single opening press. The assembly should be pressed within the specified assembly time. Both assembly time (time between when the adhesive is applied and when the target pressure is applied) and pressing time (time under the target pressure) are dependent on the ambient temperature and air humidity. If the assembly time is shorter than the minimum recommended by the adhesive manufacturer, the pressing time may need to be increased to compensate. During pressing, it is recommended that the ambient temperature be higher than 60°F (15°C) because some adhesives may take longer to cure at low temperatures.

Structural cold-set adhesives such as PRF, EPI, and PUR are commonly adopted to avoid having to heat the panels during pressing, or the laminations prior to lay-up. The pressing time required is generally from 10 minutes to several hours depending on the type of adhesive. In general, commercial PRF takes the longest pressing time, followed by PUR and EPI. To shorten the pressing time, radio frequency (RF) technologies could be applied for CLT manufacturing. It was preliminarily tested that with RF pressing of an EPI bonded 3-ply CLT assembly, the pressing time can be shortened to only about 15 minutes without sacrificing panel bond strength. Also, the adhesive spread rate may be cut by more than 30% off target specification amount. During RF pressing, arcing and burning, as generally seen when pressing with high-alkaline phenol formaldehyde (PF) adhesives, can be avoided. Meanwhile, the moisture in the lumber could redistribute to help partially release internal stress for achieving high panel dimensional stability. However, there is a cost issue associated with an investment and installation of an RF press.

4.8 CLT On-line Quality Control, Machining and Cutting

An industrial sanding machine designed for wood composite products such as plywood may be used to sand one CLT panel at a time to the target thickness with a tolerance of +0.004 inch (0.1 mm). Tighter tolerances may be specified by building project. After sanding, CLT panels are then conveyed to a machining station where a multi-axis numerically-controlled machine cuts out openings for windows and doors, splices and other required parts, as well as proceeds the required machining for connections. Cutting is performed under strictly controlled conditions for maximum accuracy. Minor repairs are carried out manually at this stage of the manufacturing process.

4.9 Product Marking, Packaging and Shipping

Product marking ensures that the correct product is specified, delivered and installed. It is also an important part of product conformity assessment by providing the information to allow designers, contractors and the authority having jurisdiction to check the authenticity of the product. CLT products represented as conforming to the ANSI/APA PRG 320 standard are required to bear the stamp of an approved agency which either inspects the manufacturer or has tested a random sampling of the finished products in the shipment being certified for conformance with the standard.

CLT products represented as conforming to ANSI/APA PRG 320 standard are required to be identified with marks containing the following information:

(a) CLT grade qualified in accordance with this standard;
(b) CLT thickness or identification;
(c) Mill name or identification number;
(d) Approved agency name or logo;
(e) Symbol of "*ANSI/APA PRG 320*" signifying conformance to this standard;
(f) Any manufacturer's designations which shall be separated from the grade-marks or trademarks of the approved agency by not less than 6 inches (152 mm); and
(g) "Top" stamp on the top face of custom CLT panels used for roof or floor if manufactured with an unbalanced lay-up.

Non-custom and other required marks must be placed on standard products at intervals of 8 feet (2.4 m) or less in order that each piece cut from a longer piece will have at least one of each of the required marks. For products manufactured to meet specific job specifications (custom products), the marking may contain information less than that specified for standard CLT products. However, custom products must bear at least one mark containing a required identification. When long CLT products shipped to a job site are to be cut later into several members for use in the structure, the frequency of marking must be applied at intervals of 8 feet (2.4 m) or less.

Additional markings on the panels may show the main direction loading of the panels in the structure and, possibly, the zones designed to receive connectors. Because CLT panels are intended for use under dry service conditions, the panels should be protected from weather during transportation, storage and construction on the job site.

5 QUALIFICATION AND QUALITY ASSURANCE

The ANSI/APA PRG 320 standard also stipulates the requirements for plant pre-qualification, structural performance qualification, and quality assurance.

5.1 Plant Pre-qualification

The plant pre-qualification is intended to ensure the CLT plant is qualified for the manufacturing factors, such as the assembly time, lumber MC, adhesive spread rate, clamping pressure, pressing time and wood surface temperature, prior to the normal production. The plant pre-qualification can be conducted with full-thickness CLT panels of 24 inches (610 mm) or more in the major strength direction and 18 inches (457 mm) or more in the minor strength direction. Two replicated CLT panels are required to be manufactured for pre-qualification for each combination of factors considered. The two replicated CLT panels must not be extracted from a single full-size CLT panel.

The plant pre-qualification includes the evaluation of gluebond (block shear) and durability. Figure 4 shows the locations where the block shear and delamination specimens should be taken for the pre-qualification to ensure the dispersion of the specimens within a sampled CLT qualification panel. Results obtained from the pre-qualification are required to be documented and serve as the basis for manufacturing factors specified in the in-plant manufacturing standard.

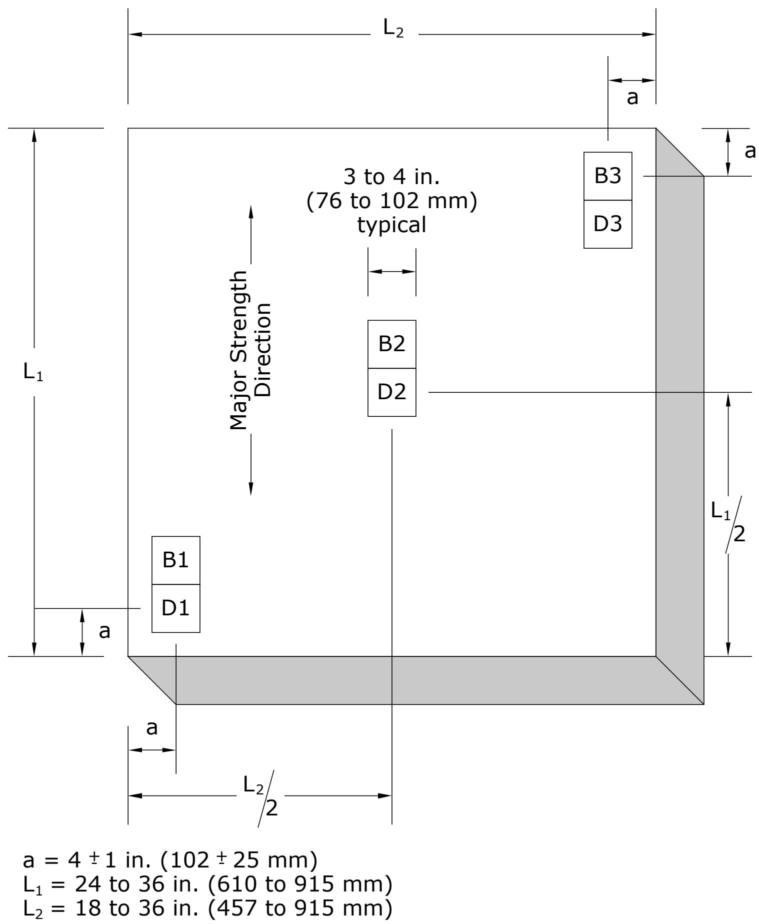


Figure 4
Block shear ("B") and delamination ("D") specimen locations

5.2 CLT Structural Performance Qualification

To confirm the major CLT design properties, structural performance tests are required in accordance with ANSI/APA PRG 320. These tests include bending strength, bending stiffness, and interlaminar shear in both major and minor strength directions. The sample size for bending stiffness must be sufficient for estimating the population mean within 5% precision with 75% confidence, or 10 specimens, whichever is greater. The sample size for bending strength and interlaminar shear must be sufficient for estimating the characteristic value with 75% confidence in accordance with ASTM D2915 [27].

The bending tests are required to be conducted flatwise (loads are applied perpendicular to the face layer of CLT) in accordance with the third-point load method of ASTM D198 [28] or ASTM D4761 [29] using the specimen width of not less than 12 inches (305 mm) and the on-center span of approximately 30 times the specimen depth. The Committee considered that a minimum specimen width of 12 inches (305 mm) is necessary to distinguish CLT from typical beam elements. However, it has been reported that, for some CLT lay-ups, the use of the span-to-depth ratio of 30 for bending tests in the minor strength direction may result in excessive deflection before the specimen reaches the peak load. Therefore, it is expected that this provision will be revisited in the near future. The weight of the CLT panel is permitted to be included in the determination of the CLT bending strength.

The interlaminar shear tests are required to be conducted flatwise in accordance with the center-point load method of ASTM D198 or ASTM D4761 using the specimen width of not less than 12 inches (305 mm) and the on-center span of 5 to 6 times the specimen depth. The bearing length must be sufficient to avoid bearing failure, but not greater than the specimen depth. All specimens must be cut to length without overhangs, which are known to increase the interlaminar shear strength in shear tests.

5.3 Process Change Qualification

When process changes occur in production, qualification tests are required, depending on the extent of the changes and their impacts to the CLT performance. ANSI/APA PRG 320 lists some key changes and the required responses, as summarized in Table 3 below:

Table 3
Response to process changes according to ANSI/APA PRG 320

Process Change	Response
Press equipment Adhesive formulation class Addition or substitution of species from a different species group Changes to the visual grading rules that reduce the effective bond area or the effectiveness of the applied pressure (e.g., warp permitted)	Plant pre-qualification and structural re-evaluation
Other changes to the manufacturing process or component quality not listed above Adhesive composition (e.g., fillers and extenders)	Plant pre-qualification
Increase in panel width or length of more than 20%	Structural re-evaluation

5.4 Quality Assurance

Quality assurance is required by ANSI/APA PRG 320 to ensure the CLT product quality through detecting changes in properties that may adversely affect the CLT performance. In this regard, an on-going evaluation of the manufacturing process, including end, face, and edge (if used) joints in laminations, effective bonding area, lamination grade limitations, and the finished production inspection, is required to be conducted by the CLT manufacturer to confirm that the product quality remains in satisfactory compliance to the product specification requirements. The production must be held pending results of the quality assurance testing on representative samples. In addition, the product quality assurance must be audited by an independent inspection or certification agency on a regular basis in accordance with the building code requirements.

As there are a number of process-related issues that would affect the integrity of the bond line, there should be a process in place to qualify a plant to ensure that it has the means to assess and control the quality of the input components and the final product. Industrial mass production of CLT panels requires an in-plant quality control (QC) program.

5.5 Quality Assurance Tests

5.5.1 Delamination Tests

The ANSI/APA PRG 320 standard uses delamination testing as a means to assess quality and moisture durability of the bond line. In the delamination test, a square (or core) specimen obtained from a pre-qualification or production panel is saturated with water and then dried to evaluate the adhesive bond line's ability to resist the wood shrinkage and swelling stresses. The delamination test also assesses somewhat the ability of the adhesive to withstand moisture degradation. In the delamination test, separation in the wood adjacent to the bond line, as opposed to separation in the adhesive, is not considered delamination. The limits on the amount of delamination are based on the glulam standards. However, this provision will be reviewed when more plant data are gathered and analyzed in the immediate future. When all these requirements are met, the manufacturing process is deemed to be producing CLT with bond lines of acceptable quality.

Preliminary tests carried out at FPInnovations suggest that wood failure results from block shear specimens tested under vacuum-pressure-dry conditions could be used to assess the bond quality. For additional information on this topic, refer to the report on block shear testing of CLT [30].

5.5.2 Visual Quality of CLT

Wood shrinkage is not equal in all directions due to the anisotropic nature of wood. As a result, drying checks may develop in CLT panels during storage and use if the MC of the wood at the time of manufacture is significantly different from the equilibrium MC at the ambient conditions. The shrinkage can develop tensile stresses which could exceed the local wood strength perpendicular to the grain causing checks or cracks. Although the checks may partially or fully close if exposed to higher humidity environment, they will reappear when the panel is re-dried.

Checks affect the aesthetic value of the surface, and could thus lower the product's market acceptance. In addition to limiting the MC of the lumber at the time of manufacturing, surface checking can potentially be minimized by using quarter-sawn lumber and by laying up the outer layers in such a way that their growth rings are concave from the bond line. A disadvantage of this arrangement is that it will not help minimize panel warping. As for gaps forming between lumber pieces, this can be minimized or prevented by edge-gluing, but this will likely increase the development of checks.

An exploratory study has been carried out to develop a procedure for quantifying the severity of or potential for checking [25]. The intention is for such tests to provide an indication of the appearance of these CLT products after long-term exposure in service to dry conditions, or the effectiveness of steps taken to minimize checking.

Gaps at the unglued edges of adjacent laminations and checks normally will not have a significant impact on strength properties. However, some of the panel's physical properties, such as thermal conductivity, moisture diffusion and fire performance may be affected. These properties may have an impact on energy performance and durability of the building assembly.

6 IMPLEMENTATION OF THE STANDARD

In North America, a limited number of CLT production lines have been recently commercialized. Several structures have also been constructed using CLT panels manufactured in North America. However, due to the lack of CLT standards in North America, these structures were generally designed and constructed under an engineer seal, and approved by the regulatory body on a case-by-case basis. With the publication of the ANSI/APA PRG 320 standard, it is expected that the acceptance of CLT products will be accelerated, especially as the standard has been approved by the Structural Committee of the International Code Council (ICC) for the 2015 International Building Code (IBC) in the United States to recognize CLT products, when manufactured in accordance with ANSI/APA PRG 320, as an acceptable construction material in compliance with the code. The CSA O86 Committee in Canada is also evaluating the adoption of CLT into the Canadian code.

It should be noted that ANSI/APA PRG 320 is not a CLT design standard and does not address design-specific issues, such as creep, duration of load, volume effect, moisture effect, lateral load resistance, connections, fire, energy, sound, and floor vibration. Design guides for many of those topics are provided in other chapters of this CLT Handbook. In the end, however, the general agreement from the engineered wood products industry is to codify those provisions in a new chapter of the NDS in the United States and CSA O86 in Canada. However, this step is likely to take several years to accomplish due to the need for a significant amount of supporting data in North America.

Fortunately, several research projects have been underway through collaborative efforts by the wood industry, government, and construction, engineering, and research communities under the multi-disciplinary NSERC Strategic Research **N**etwork for **E**ngineered **W**ood-based **Build**ing **S**ystems (NEWBuildS) in Canada (more information about the activities of NEWBuildS can be found at http://www.newbuildscanada.ca/). Built on the knowledge and experience from Europe, it is anticipated that the research results from North America would expedite the completion of the design standards in both the NDS and CSA O86.

In the meantime, ISO Technical Committee (TC) 165 on Timber Structures has also initiated a project to develop an ISO standard for CLT under the leadership of Mr. Kretschmann, of the Forest Products Laboratory of the U.S. Department of Agriculture. This ISO standard is intended to harmonize the CLT standards from North America and Europe as an international standard, which will encourage the use of CLT in building construction globally.

From a product certification perspective, APA as well as other accredited certification agencies in North America can trademark CLT products in accordance with ANSI/APA PRG 320 to provide the designers with construction materials that are consistent in quality and recognized by the building codes. As a result, the designers can focus on the architectural and structural designs without the concern of material supplies and quality. This is a very significant step toward the wide acceptance of the relatively new construction products, such as CLT, in North America.

7 CONCLUSIONS

With the publication of the consensus-based CLT standard, ANSI/APA PRG 320, in North America, the engineered wood products industry has taken a very significant step toward the commercialization of the CLT products and systems. A continuing improvement of the standard can be expected for the next few years as more experience is gathered through the production and commercialization processes. This standard, when adopted into national building codes, will recognize the CLT products as construction materials in compliance with the codes and gain wide acceptance by the design and construction industries.

While, in the short-term, CLT products are expected to be designed by engineers or architects experienced in timber engineering, efforts are underway to develop CLT design handbooks and ultimately design standards that will standardize the design requirements, just like other existing engineered wood products in North America. It is believed that the truly collaborative efforts that have been demonstrated by the wood industry, government, and construction, engineering, and research communities throughout the development of ANSI/APA PRG 320 in the last two years will make this a reality at the shortest time possible.

8 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] National Institute of Standards and Technology. *American Softwood Lumber Standard.* Voluntary Product Standard PS 20. Washington D.C., U.S.A. 2010.

[3] Canadian Standards Association. *Softwood Lumber.* CSA O141. Toronto, Ontario, Canada. 2005.

[4] American Wood Council. *National Design Specification for Wood Construction.* ANSI/AWC NDS. Leesburg, Virginia, U.S.A. 2012.

[5] Canadian Standards Association. *Engineering Design in Wood.* CSA O86. Toronto, Ontario, Canada. 2009.

[6] ASTM International. *Standard Specification for Evaluation of Structural Composite Lumber Products.* ASTM D5456. West Conshohocken, Pennsylvania, U.S.A. 2011.

[7] American Institute of Timber Construction. *Structural Glued Laminated Timber.* ANSI/AITC A190.1. Centennial, Colorado, U.S.A. 2007.

[8] National Lumber Grades Authority. *Special Products Standard for Fingerjoined Structural Lumber.* SPS 1. New Westminster, British Columbia, Canada. 2011.

[9] National Lumber Grades Authority. *Special Products Standard for Machine Graded Lumber.* SPS 2. New Westminster, British Columbia, Canada. 2010.

[10] National Lumber Grades Authority. *Special Products Standard for Fingerjoined Machine Graded Lumber.* SPS 4. New Westminster, British Columbia, Canada. 2011.

[11] National Lumber Grades Authority. *Special Products Standard for Structural Face-Glued Lumber.* SPS 6. New Westminster, British Columbia, Canada. 2010.

[12] ISO. *General Criteria for the Operation of Various Types of Bodies Performing Inspection.* ISO/IEC 17020. Geneva, Switzerland. 1998.

[13] ISO. *General Requirements for the Competence of Testing and Calibration Laboratories.* ISO/IEC 17025. Geneva, Switzerland. 2005.

[14] ISO. *General Requirements for Bodies Operating Product Certification Systems.* ISO Guide 65. Geneva, Switzerland. 1996.

[15] ASTM International. *Standard Specification for Evaluation of Duration of Load and Creep Effects of Wood and Wood-Based Products.* ASTM D6815. West Conshohocken, Pennsylvania, U.S.A. 2009.

[16] American Institute of Timber Construction. *Standard for Adhesives for Use in Structural Glued Laminated Timber.* AITC 405. Centennial, Colorado, U.S.A. 2008.

[17] ASTM International. *Standard Test Method for Multiple-Cycle Accelerated Aging Test (Automatic Boil Test) for Exterior Wet Use Wood Adhesives.* ASTM D3434. West Conshohocken, Pennsylvania, U.S.A. 2006.

[18] Canadian Standards Association. *Evaluation of Adhesives for Structural Wood Products (Exterior Exposure).* CSA O112.9. Toronto, Ontario, Canada. 2010.

[19] Canadian Standards Association. *Evaluation of Adhesives for Structural Wood Products (Limited Moisture Exposure).* CSA O112.10. Toronto, Ontario, Canada. 2008.

[20] ASTM International. *Standard Test Method for Evaluating the Shear Strength of Adhesive Bonds in Laminated Wood Products at Elevated Temperatures.* ASTM D7247. West Conshohocken, Pennsylvania, U.S.A. 2007.

[21] National Institute of Standards and Technology. *Structural Plywood.* Voluntary Product Standard PS 1. Washington D.C., U.S.A. 2009.

[22] Frangi, A., M. Fontana, E. Hugi, and R. Jobstl. *Experimental Analysis of Cross-Laminated Timber Panels in Fire.* Fire Safety Journal 44: 1078–108. 2009.

[23] Canadian Standards Association. *Qualification Code for the Manufacturers of Structural Glued-Laminated Timber.* CSA O177. Toronto, Ontario, Canada. 2006.

[24] Gagnon, S. and M. Popovski. *Structural Design of Cross-Laminated Timber Elements.* In: Chapter 3, CLT Handbook. FPInnovations. Québec, Quebec, Canada. 2011.

[25] Casilla, R.C., C. Lum, C. Pirvu, and B.J. Wang. *Checking in CLT Panels: An Exploratory Study.* Publication W-2877. FPInnovations. Vancouver, B.C., Canada. 2011.

[26] Julien, F. *Manufacturing Cross-Laminated Timber (CLT): Technological and Economic Analysis.* Report to Quebec Wood Export Bureau. 201001259-3257AAM. FPInnovations. Québec, Quebec, Canada. 2010.

[27] ASTM International. *Standard Practice for Sampling and Data-Analysis for Structural Wood and Wood-Based Products.* ASTM D2915. West Conshohocken, Pennsylvania, U.S.A. 2010.

[28] ASTM International. *Test Methods of Static Tests of Lumber in Structural Sizes.* ASTM D198. West Conshohocken, Pennsylvania, U.S.A. 2009.

[29] ASTM International. *Standard Test Methods for Mechanical Properties of Lumber and Wood-Based Structural Material.* ASTM D4761. West Conshohocken, Pennsylvania, U.S.A. 2005.

[30] Casilla, R., C. Pirvu, B. J. Wang, and C. Lum. *Block Shear Testing of CLT Panels - An Exploratory Study.* FPInnovations. Vancouver, B.C., Canada. 2011.

[31] Gagnon, S. and C. Pirvu, eds. 2011. *CLT Handbook : Cross-laminated timber*. Canadian ed. Special Publication SP-528E. Québec, QC: FPInnovations. 1 v.

FPInnovations

570, boul. St-Jean
Pointe-Claire, QC
Canada H9R 3J9
514 630-4100

www.fpinnovations.ca

Forest Products Laboratory

1 Gifford Pinchot Drive
Madison, WI
USA 53726
608 231-9200

www.fpl.fs.fed.us

BSLC

P.O. Box 45029
Ocean Park RPO
Surrey, BC
Canada V4A 9L1
604 536-7730

www.softwoodlumber.org

American Wood Council

222 Catoctin Circle SE
Suite 201
Leesburg, VA
USA 20175
202 463-2766

www.awc.org

APA

7011 S 19th Street
Tacoma, WA
USA 98466-5333
253 565-6600

www.apawood.org

WoodWorks Wood Products Council

1111 19th Street NW
Suite 800
Washington, DC
USA 20036
866 966-3448

www.woodworks.org

Forestry Innovation Investment

1130 West Pender Street
Suite 1200
Vancouver, BC
Canada V6E 4A4
604 685-7507

www.bcfii.ca

www.fpinnovations.ca

Special Publication SP-529E

FPInnovations

570, boul. St-Jean
Pointe-Claire, QC
Canada H9R 3J9
514 630-4100

www.fpinnovations.ca

Forest Products Laboratory

1 Gifford Pinchot Drive
Madison, WI
USA 53726
608 231-9200

www.fpl.fs.fed.us

BSLC

P.O. Box 45029
Ocean Park RPO
Surrey, BC
Canada V4A 9L1
604 536-7730

www.softwoodlumber.org

American Wood Council

222 Catoctin Circle SE
Suite 201
Leesburg, VA
USA 20175
202 463-2766

www.awc.org

APA

7011 S 19th Street
Tacoma, WA
USA 98466-5333
253 565-6600

www.apawood.org

WoodWorks

1111 19th Street NW
Suite 800
Washington, DC
USA 20036
866 966-3448

www.woodworks.org

Forestry Innovation Investment

1130 West Pender Street
Suite 1200
Vancouver, BC
Canada V6E 4A4
604 685-7507

www.bcfii.ca