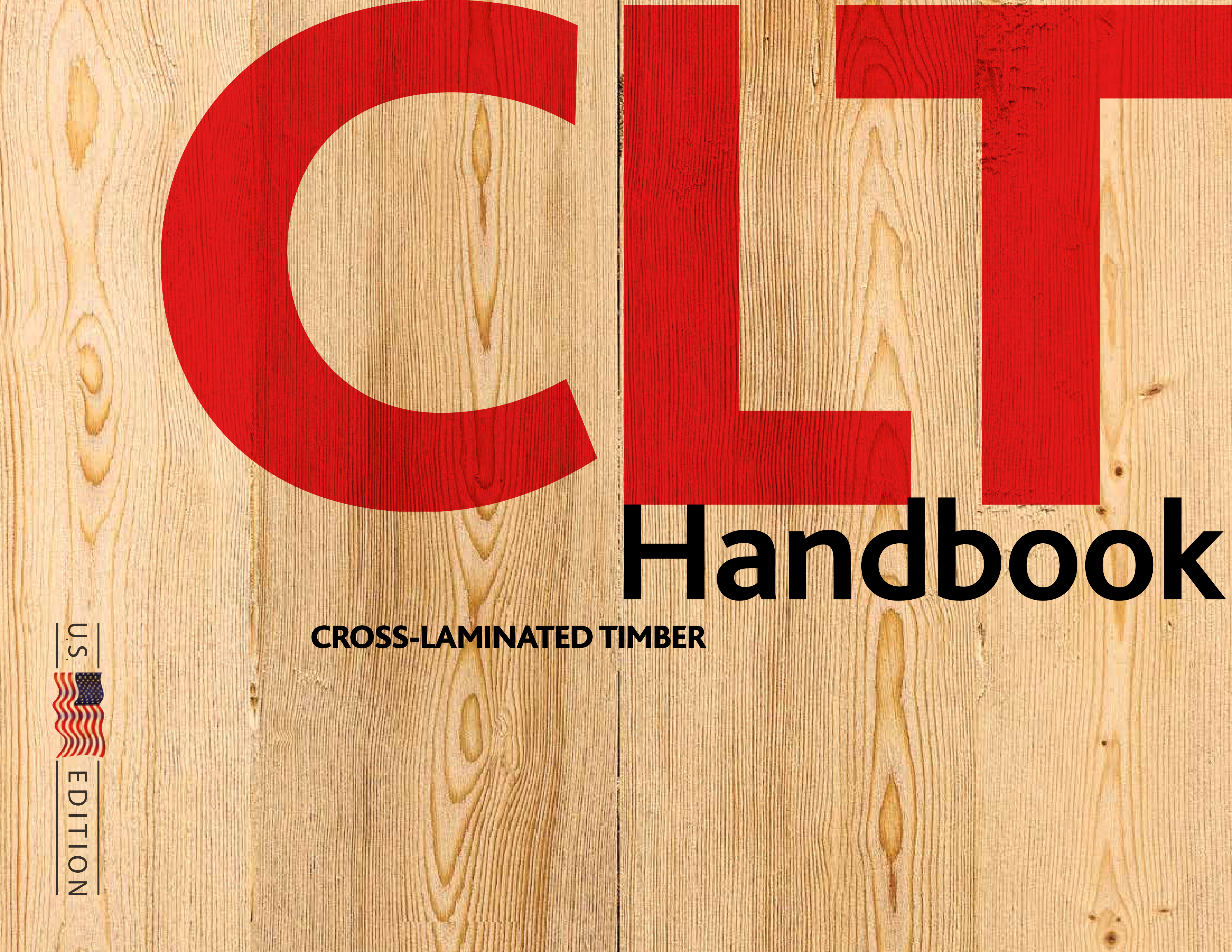


CLT Handbook

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).

The information contained in this Work represents current research results and technical information made available from many sources, including researchers, manufacturers, and design professionals. The information has been reviewed by professionals in wood design including professors, design engineers and architects, and wood product manufacturers. While every reasonable effort has been made to insure the accuracy of the information presented, and special effort has been made to assure that the information reflects the state-of-the-art, none of the above-mentioned parties make any warranty, expressed or implied, or assume any legal liability or responsibility for the use, application of, and/or reference to opinions, findings, conclusions, or recommendations included in this published work, nor assume any responsibility for the accuracy or completeness of the information or its fitness for any particular purpose.

This published Work is designed to provide accurate, authoritative information but is not intended to provide professional advice.
It is the responsibility of users to exercise professional knowledge and judgment in the use of the information.

CLT Handbook

CROSS-LAMINATED TIMBER

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

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

U.S. EDITION

2013

FPInnovations

Forest Products
Laboratory

AMERICAN
WOOD
COUNCIL

APA

WoodWorks
Wood
Products
Council

Funding for this publication
was provided by

BSLC
Binational Softwood Lumber Council

Forestry Innovation Investment

NORDIC
ENGINEERED WOOD

STRUCTURLAM
INNOVATIVE WOOD SPECIALISTS

CLT
CROSS LAMINATED TIMBER (C.L.T.) CANADA INC.

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.

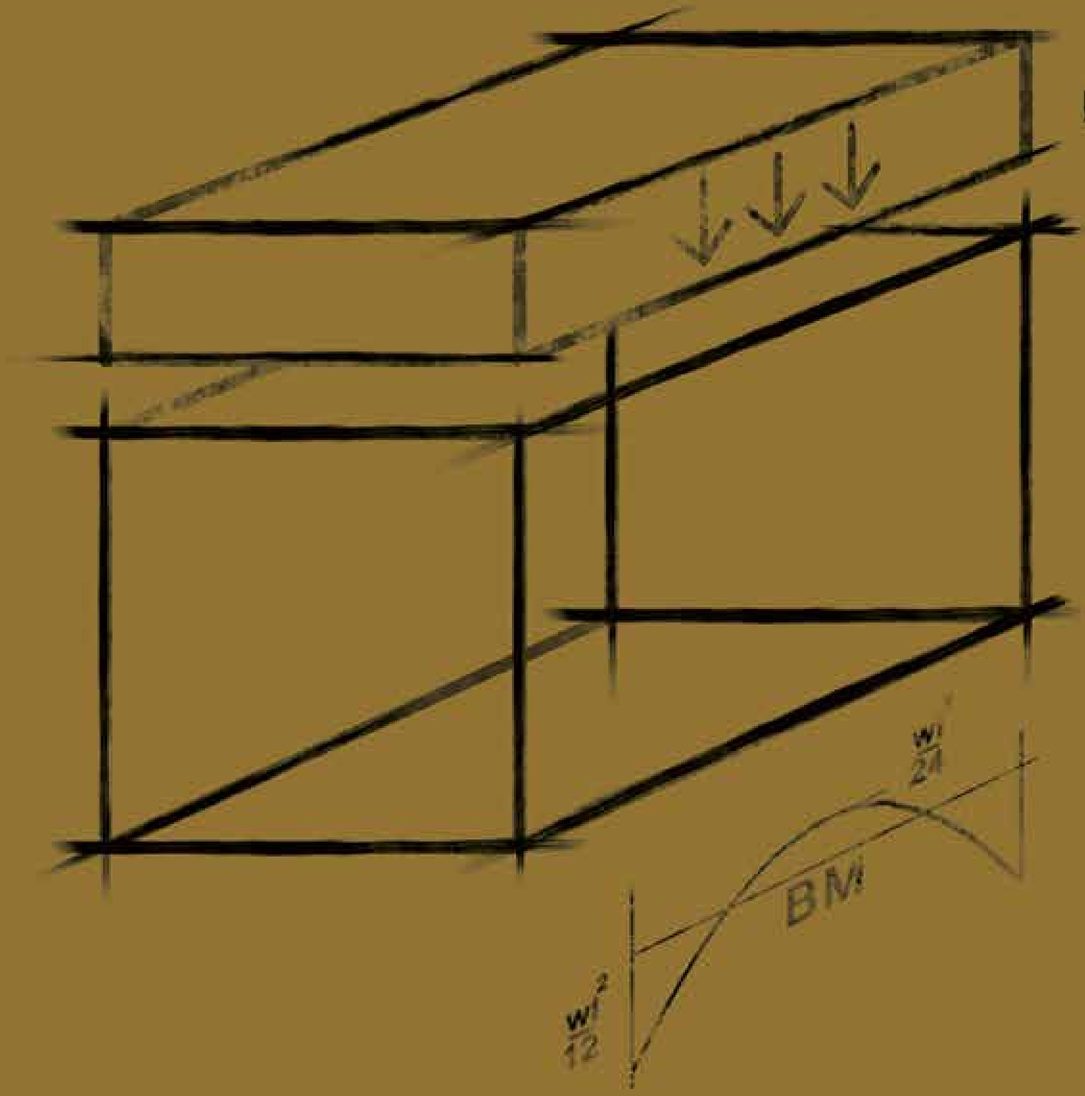
Such a piece of work would not be possible without the support from financing partners and, as such, we would like to express our special thanks to Binational Softwood Lumber Council, Forestry Innovation Investment (FII), Nordic Engineered Wood, Structurlam, and CLT Canada for their financial contribution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



Structural

Structural design of cross-laminated timber elements

CHAPTER 3

Authors

Loren A. Ross, M.Sc., EIT, American Wood Council
Sylvain Gagnon, Eng., FPInnovations
Edward Keith, M.S., P.E., APA

Peer Reviewers

D. Scott Nyseth, P.E., Stonewood Design
Tom Williamson, P.E., T. Williamson Timber Engineering LLC

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).

The information contained in this Work represents current research results and technical information made available from many sources, including researchers, manufacturers, and design professionals. The information has been reviewed by professionals in wood design including professors, design engineers and architects, and wood product manufacturers. While every reasonable effort has been made to insure the accuracy of the information presented, and special effort has been made to assure that the information reflects the state-of-the-art, none of the above-mentioned parties make any warranty, expressed or implied, or assume any legal liability or responsibility for the use, application of, and/or reference to opinions, findings, conclusions, or recommendations included in this published work, nor assume any responsibility for the accuracy or completeness of the information or its fitness for any particular purpose.

This published Work is designed to provide accurate, authoritative information but is not intended to provide professional advice. It is the responsibility of users to exercise professional knowledge and judgment in the use of the information.

ABSTRACT

Building using cross-laminated timber (CLT) began in Europe about two decades ago and has used a variety of methods for structural analysis. Experimental testing methods were the most accurate, yet they lacked versatility because changes in lay-up, material, or even manufacturing methods could cause a need for new testing. Consequently, three analytical approaches have been created and are commonly used in Europe as none have been universally accepted to date.

The mechanically jointed beams theory, or Gamma Method, appears in Annex B of Eurocode 5 (EN, 2004). According to this theory, the "Effective Stiffness" concept is introduced and a "Connection Efficiency Factor" (γ_i) is used to account for the shear deformation of the perpendicular layer(s), with $\gamma=1$ representing completely glued member, and $\gamma=0$ no connection at all. This approach provides a closed (exact) solution for the differential equation only for simply supported beams/panels with a sinusoidal load distribution. However, the differences between the exact solution and those for a uniformly distributed load or point loads are minimal and are acceptable for engineering practice (Ceccotti, 2003).

Blass and Fellmoser (2004) have applied the "Composite Theory" (also named K-method) to predict flexural properties of CLT. However, their work did not account for shear deformation in individual layers.

Recently, the "Shear Analogy" method (Kreuzinger, 1999) has been used in Europe and is more applicable for solid panels with cross layers. This methodology takes into account the shear deformation of the longitudinal and the cross layers and is not limited by the number of layers within a panel. This method more accurately predicts the stiffness properties of the CLT panels.

In the United States and Canada, the product standard (*Standard for Performance-Rated Cross-Laminated Timber* - ANSI/APA PRG 320) has adopted the Shear Analogy method to derive composite bending and shear stiffness properties.

The 2012 edition of the National Design Specification (NDS) for Wood Construction does not have specific provisions for CLT; however, the next edition is scheduled to include a chapter on CLT and many of the current provisions will apply. This Chapter of the CLT Handbook is based upon the current provisions of the NDS and the expectations of the future provisions of the NDS.

TABLE OF CONTENTS

List of Tables

List of Figures

1

TYPICAL ADJUSTMENT FACTORS

1.1 Introduction

Like other wood products, CLT reference design values are adjusted for specific conditions. Several factors used for different design values are listed below. Table 1 shows all the applicable adjustment factors for CLT.

Table 1
Applicable adjustment factors

		ASD only	**ASD and LRFD**					**LRFD only**		
		Load Duration Factor	Wet Service Factor	Temperature Factor	Beam Stability Factor	Column Stability Factor	Format Conversion Factor	Resistance Factor	Time Effect Factor
							K_F	ϕ	
$F_b' S_{eff} = F_b S_{eff}$	x	C_D	C_M	C_t	C_L	-	2.54	0.85	λ
$F_t' A_{parallel} = F_t A_{parallel}$	x	C_D	C_M	C_t	-	-	2.70	0.80	λ
$F_v'(Ib/Q)_{eff} = F_v(Ib/Q)_{eff}$	x	C_D	C_M	C_t	-	-	2.88	0.75	λ
$F_c' A_{parallel} = F_c A_{parallel}$	x	C_D	C_M	C_t	-	C_P	2.40	0.90	λ
$F_{c\perp}' A = F_{c\perp} A$	x	-	C_M	C_t	-	-	1.67	0.90	-
$EI_{app}' = EI_{app}$	x	-	C_M	C_t	-	-	-	-	-
$EI_{app\text{-}min}' = EI_{app\text{-}min}$	x	-	C_M	C_t	-	-	1.76	0.85	-

1.2 Load Duration Factor, C_D

The load duration factor is applicable only for ASD design methodology. This factor accounts for wood's greater strength over short durations. The load durations are assumed to be the same for CLT products as they are for other wood products and can be found in Table 2.3.2 of the NDS.

1.3 Wet Service Factor, C_M

The wet service factor adjusts the strength properties of the wood in the absence of the assumed dry condition. Dry service conditions are defined for structural glued laminated timber as moisture content less than 16% in service, such as in most covered structures. At the time of manufacturing, PRG 320 requires that the moisture content of the laminations be no more than 15% and further states that the panels are only intended for use in dry service conditions. Contact the manufacturer if a wet service condition is expected.

1.4 Temperature Factor, C_t

The temperature factor adjusts the strength properties of the wood if it will see sustained elevated temperatures above 100°F. This adjustment should be considered for applications when frequent and sustained temperatures above 100°F will occur. Roof systems and other assemblies subject to diurnal temperature fluctuations from solar radiation are not applications that normally require adjustment for temperature (NDS Commentary). Section 2.3.3 of the NDS gives the adjustment factors, which depend on the material property being adjusted and whether it is a wet or dry service condition. It is assumed that these considerations are applicable to CLT as well.

2

DESIGN PROCEDURES FOR CLT ELEMENTS

2.1 Bending Members

The shear analogy method and the simplified method can be used for design of bending members resisting load perpendicular to the plane of the CLT. The shear analogy method has been adopted in the product standard PRG 320 for evaluating bending and shear stiffness. The simplified method for bending strength has also been adopted in the product standard PRG 320.

For members resisting loads in its plane, such as headers or lintels, a different model is needed. Currently, testing is being performed to develop a model to account for the composite action of the CLT.

2.1.1 Bending Members: Flexure (Out-of-plane)

For out-of-plane loads, the beam stability factor should be 1.0. The volume factor is not applicable to CLT.

The simplified method has been adopted in the product standard PRG 320 and calculates the capacity by using an extreme fiber capacity approach. The effective section modulus is found by dividing the effective bending stiffness, found with Equation [24] of this Chapter, by the modulus of elasticity of the outer layer and half the thickness of the panel. In equation form, it is as follows:

$$S_{eff} = \frac{2EI_{eff}}{E_1 h} \qquad [1]$$

where:

EI_{eff} = Effective bending stiffness
E_1 = Modulus of elasticity of outermost layer
h = Entire thickness of panel

The effective section modulus is then multiplied by allowable bending stress of the outermost layer and “the calculated moment capacities in the major strength direction are further multiplied by a factor of 0.85 for conservatism” (PRG 320-2011). Manufacturers will have already done this calculation to give the moment capacity of the member. For design, the induced bending moment must be less than the moment capacity. In equation form, it would appear as follows:

$$M_b \leq F_b' S_{eff} \qquad [2]$$

where:

M_b = Applied bending moment due to loads
$F_b{}'S_{eff}$ = Design bending strength of the panel provided by the manufacturer, calculated, or listed in the product standard PRG 320 and then multiplied by the applicable adjustment factors.

An example of the calculation of the bending moment capacity using the simplified method is given in Section 4.

2.1.2 Bending Members: Shear (Out-of-plane)

Similar to the flexural strength, a simplified method using the extreme fiber capacity is also available and has been proposed for the PRG 320 product standard. Using the simplified method, an effective $(Ib/Q)_{eff}$ can be calculated as follows:

$$\left(Ib/Q\right)_{eff} = \frac{EI_{eff}}{\sum_{i=1}^{n/2} E_i h_i z_i} \qquad [3]$$

where:

EI_{eff} = Effective bending stiffness
E_i = Modulus of elasticity of an individual layer
h_i = Thickness of an individual layer, except the middle layer, which is half its thickness
z_i = Distance from the centroid of the layer to the neutral axis, except for the middle layer, where it is to the centroid of the top half of that layer.

Manufacturers will likely have already done this calculation to give the shear capacity of the member. In equation form, design would appear as follows:

$$V_{planar} \leq F_v'(Ib/Q)_{eff} \qquad [4]$$

where:

V_{planar} = induced shear due to loads
$F_v{}'\ (Ib/Q)_{eff}$ = shear strength of the panel provided by the manufacture or calculated per the simplified method multiplied by the applicable adjustment factors.

2.1.3 Bending Members: Deflection (Out-of-plane)

One method to account for the shear deformation is to reduce the effective bending stiffness value, EI_{eff}, to an apparent EI. The derivation of this is done in the discussion of the shear analogy method presented in Section 3. Equation [5] is the final equation that explains how an apparent bending stiffness, EI_{app}, can be calculated by reducing the effective bending stiffness, EI_{eff}. In Equation [5], K_s is a constant based upon the influence of the shear deformation and is solved for various loading conditions in Table 2.

$$EI_{app} = \frac{EI_{eff}}{1 + \frac{K_s EI_{eff}}{GA_{eff} L^2}} \qquad [5]$$

Table 2

K_s values for various loading conditions

Loading	End Fixity	K_s
Uniformly distributed	Pinned	11.5
	Fixed	57.6
Concentrated at midspan	Pinned	14.4
	Fixed	57.6
Concentrated at quarter points	Pinned	10.5
Constant moment	Pinned	11.8
Uniformly distributed	Cantilevered	4.8
Concentrated at free-end	Cantilevered	3.6

2.2 Compression Members

2.2.1 Solid Columns and Walls

The column stability factor deserves additional discussion due to its complexity and reliance on other design values. For column and wall design, the load must be less than the adjusted compression strength multiplied by the area of the laminations where the grain is running parallel to the load, or in equation form as follows:

$$P_{parallel} \leq F'_c A_{parallel} \qquad [6]$$

where:

$P_{parallel}$ = Load applied parallel to the direction of the fibers

F_c' = Adjusted compression strength

$A_{parallel}$ = Area of layers with fibers running parallel to the direction of the load

2.2.2 Column Stability Factor, C_p

The column stability factor accounts for tendency of a column to buckle. Since CLT is a plate element, buckling only needs to be checked in the out-of-plane direction. Derived from the NDS, the formula for the column stability factor for CLT it is as follows:

$$C_p = \frac{1+\left(P_{cE}/P_c^*\right)}{2c} - \sqrt{\left[\frac{1+\left(P_{cE}/P_c^*\right)}{2c}\right]^2 - \frac{P_{cE}/P_c^*}{c}} \qquad [7]$$

where:

P^*_c = Composite compression design capacity (F_c*A) where F_c* is multiplied by all applicable adjustment factors except C_p

c = 0.9 for CLT

P_{cE} = $\dfrac{\pi^2 EI'_{app-min}}{l_e^2}$ (see Section 2.2.3).

2.2.3 Minimum Apparent Bending Stiffness, $EI_{app\text{-}min}$

The apparent bending stiffness, EI_{app}, should be determined using Equation [5]. The following equation can be used to adjust the average EI_{app} to a minimum value, $EI_{app\text{-}min}$, for use in column buckling design:

$$EI_{app-min} = 0.5184\,EI_{app} \qquad [8]$$

2.3 Tension Members

As wood should not be relied upon to resist tension perpendicular to the grain, only the grain parallel to the load should be included as the effective area. The total load has to be less than the adjusted tension strength multiplied by the area of the laminations where the grain is parallel to the load. In equation form,

$$T_{parallel} \le F_t' A_{parallel} \qquad [9]$$

where:

$T_{parallel}$ = Load applied parallel to the direction of the fibers

F_t' = Adjusted tensile strength

$A_{parallel}$ = Area of layers with fibers running parallel to the direction of the load.

2.4 Bending and Axially Loaded Members

For members undergoing both axial compression and flat-wise bending, an equation from chapter 15 of the NDS has been modified from stress inputs to loads for CLT.

$$\left(\frac{P}{F'_c A_{parallel}}\right)^2 + \frac{M + P\Delta\left(1 + 0.234\frac{P}{P_{cE}}\right)}{F'_b S_{eff}\left(1 - \frac{P}{P_{cE}}\right)} \leq 1.0 \qquad [10]$$

where:

P = Induced axial load

M = Induced bending moment

Δ = Eccentricity of axial load, measured perpendicular to the plane of the panel

P_{cE} = Critical buckling load (see Section 2.2.2).

2.5 Bearing of Members

2.5.1 Perpendicular to the Grain

The bearing area factor for CLT is 1.0, so is not included in Table 1. The design equation is as follows:

$$P \leq F'_{c\perp} A \qquad [11]$$

where:

P = Load applied

$F'_{c\perp}$ = Adjusted compression perpendicular to grain design value.

2.5.2 Parallel to the Grain

For bearing parallel to the grain or with a combination of parallel and perpendicular to grain, such as the bottom of a wall, parallel to the grain will dominate over perpendicular. The design equation is the following:

$$P_{parallel} \leq F_c^* A_{parallel} \qquad [12]$$

where:

$P_{parallel}$ = Load applied parallel to the direction of the fibers

F_c^* = Reference compression parallel to grain design value multiplied by all applicable adjustment factors except the column stability factor, Cp

$A_{parallel}$ = Area of layers with fibers running parallel to the direction of the load.

3

MODELING CLT ELEMENTS

3.1 Introduction on Modeling Used in CLT Floor, Roof and Wall Systems and Their Limitations

Different methods have been adopted for the determination of basic mechanical properties of CLT in Europe. Some of these methods are experimental in nature while others are analytical. For floor elements, experimental evaluation involves determination of flexural properties by testing full-size panels or sections of panels with a specific span-to-depth ratio. The problem with the experimental approach is that every time the lay-up, type of material, or any of the manufacturing parameters change, more testing is needed to evaluate the bending properties of such new products. Obviously, the analytical approach, once verified with the test data, offers a more general and less costly alternative. An analytical approach generally predicts strength and stiffness properties of CLT based on the material properties of the laminations that make up the CLT panel.

A common analytical approach that has been adopted for CLT in Europe is based on the "Mechanically Jointed Beams Theory" (also named Gamma Method) that is available in Annex B of Eurocode 5 (EN, 2004). According to this theory, the "Effective Stiffness" concept is introduced and a "Connection Efficiency Factor" (γ_i) is used to account for the shear deformation of the perpendicular layer, with $\gamma=1$ representing completely glued member, and $\gamma=0$ no connection at all. This approach provides a closed- (exact) solution for the differential equation only for simply supported beams/panels with a sinusoidal load distribution. However, the differences between the exact solution and those for uniformly distributed load or point loads are minimal and are acceptable for engineering practice (Ceccotti, 2003).

Blass and Fellmoser (2004) have applied the "Composite Theory" (also named K-method) to predict some design properties of CLT. However, this method does not account for shear deformation in individual layers but is reasonably accurate for high span-to-depth ratios.

Explanations and examples of both of the above methods can be found in the Canadian edition of the CLT Handbook.

Recently, the "Shear Analogy" method (Kreuzinger, 1999) has been developed and is applicable for solid panels with cross layers where the load is perpendicular to the panel. The methodology takes into account the shear deformation of the cross layer and is not limited to a restricted number of layers within a panel. This method seems to be the most accurate and adequate for CLT panels and has been adopted by the product standard (*Standard for Performance-Rated Cross-Laminated Timber* - ANSI/APA PRG 320). It is expected that future editions of the NDS will include CLT and be based upon this method.

Important Note: The proposed design procedures given in this Chapter only apply for cross-laminated timber products manufactured with a gluing process (i.e., face-glued). Therefore, nailed or doweled CLT products are out of the scope of this Chapter.

3.2 Mechanical Properties of CLT Elements Used in Floor and Wall Systems

3.2.1 Lamination Properties, Lumber Grade, and Moisture Content

Usually, thickness of the individual laminations currently produced varies from 5/8 in. (16 mm) to 2 in. (51 mm), with 1 1/2 in. (38 mm) being typical, and the width varies from 3 1/2 in. (89 mm) to 9 1/4 in. (235 mm). Laminations are finger jointed using structural adhesive to achieve long lengths. Laminations are visually or machine stress-rated and must be kiln dried to achieve average moisture content of 12 ± 3%. If structural composite lumber (SCL) is used, its moisture content will be 8 ± 3%.

Basic mechanical properties of the laminations used in CLT elements may vary from one producer to another. However, the ANSI/APA product standard, PRG 320-2011, uses a system where the letter and number designation of the non-custom CLT grade indicates the lamination grading system and minimum properties. An "E" signifies that the parallel laminations are MSR lumber while a "V" signifies visually graded laminations. The number indicates the species and grade. See Chapter 2 entitled *Cross-laminated timber manufacturing* and PRG 320 for more information.

3.2.2 Rolling Shear Modulus and Shear Deformation

3.2.2.1 Rolling Shear Modulus

Rolling shear strength and stiffness in CLT has been identified as a key issue that can control the design and performance of CLT floor and wall systems. Similar to plywood, the laminations oriented crosswise affect the load bearing behavior because of the material's and product's anisotropy (Mestek et al., 2008). Work performed at the University of British Columbia (Bejtka and Lam, 2008) on CLT panels built with Canadian lodgepole pine laminations has confirmed this finding. The magnitude of the effective bending stiffness of the panel and consequently the stress distribution in the layers depend largely on the rolling shear modulus of the cross-wise layers (Fellmoser and Blass, 2004).

The rolling shear modulus will depend on many factors such as species, cross-layer density, lamination thickness, moisture content, sawing pattern configurations (annual rings orientation), size and geometry of the lamination's cross-section, etc. Dynamic and numerical methods have been developed recently in Europe to measure the rolling shear modulus (Steiger et al., 2008).

Likewise, the rolling shear strength will depend on many factors, including lamination size within the CLT layers. Manufacturers select lamination widths for the cross-layers so that the rolling shear should not control the design. The product standard, PRG 320, requires that the laminations of the cross-layer, if not edge bonded, have a net width of 3.5 times the lamination thickness unless testing is done to evaluate the rolling shear strength.

In the product standard, the rolling shear modulus G_R is assumed to be 1/10 of the shear modulus parallel to the grain of the laminations, G_0 (i.e., $G_R \approx G_0/10$). Based on experience and a review of literature, the shear modulus G of wood products is generally assumed to be established between 1/12 and 1/20 of the true modulus of elasticity, i.e., $E_{true}/G_0 \approx 12$ to 20. For example, for softwood lumber, this ratio may be assumed to be 16, as done in PRG 320. Using this ratio for laminations made of visually graded No. 1/No. 2 SPF sawn lumber with an MOE of 1,400 ksi results in G_0 being about 87.5 ksi and a rolling shear modulus of 8.8 ksi. In this case, the given magnitude of the rolling shear modulus in the literature seems to be on the conservative side. Thus, assuming a rolling shear modulus of 7.5 ksi in all cases, for example SPF, D Fir-L, SP and Hem-Fir lumber, and machine stress-rated (MSR) and visually graded laminations, is conservative. Figure 1 illustrates the rolling shear deformation behavior of a 5-layer CLT cross-section.

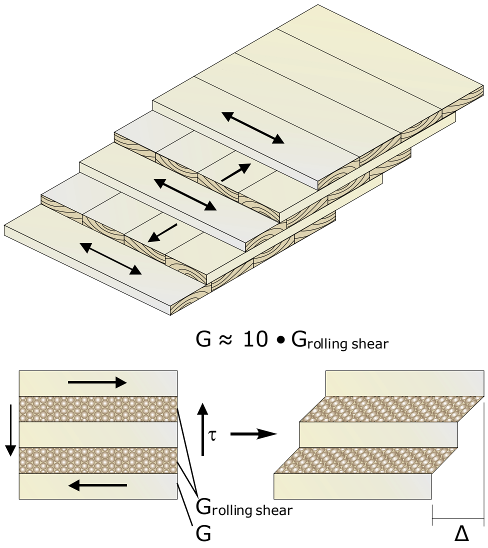


Figure 1
Rolling shear deformation of a 5-layer CLT panel

3.2.2.2 Shear Deformation

Shear deformation for CLT can be larger than for other wood products because of the reduced rolling shear modulus G_R of the cross-lamination layers. The amount of deformation will depend upon the loading, span-to-depth ratio, and end fixity of the panels. For a uniformly-loaded, simply-supported slab with a span-to-depth ratio of 30, the contribution of shear deformation to the total deformation of the panel was about 11% while it was 22% for a slab with a span-to-depth ratio of 20.

3.3 Shear Analogy Method for CLT Elements

During the last decade, various types of analytical models for the evaluation of basic mechanical properties of CLT slab elements have been developed and proposed. This section provides more detailed information about the method adopted by the PRG 320 product standard and the future NDS.

It is important to note that, since CLT panels are a relatively flexible and light building material for slabs resisting out-of-plane loading, the design (e.g., minimum thickness and maximum span) is often more driven by serviceability criteria (e.g., vibration, deflection and creep) than by strength criteria (e.g., bending and shear strength).

3.3.1 General Assumptions and Procedure

The shear analogy method is, according to the literature (Blass and Fellmoser, 2004), the most precise design method for CLT. Tests performed at FPInnovations have confirmed this finding. It is used, with the help of a plane frame analysis program, to consider the different moduli of elasticity and shear moduli of single layers for nearly any system configuration (e.g., number of layers, span-to-depth ratio). The effect of shear deformations is not neglected. In the shear analogy method, the characteristics of a multi-layer cross-section or surface (such as multi-layer CLT panels) are separated into two virtual beams A and B. Beam A is given the sum of the inherent flexural and shear stiffnesses of the individual plies along their own centers, while beam B is given the "Steiner" points, or increased moment of inertia because of the distance from the neutral axis, of the flexural and shear stiffness of the panel. These two beams are coupled with infinitely rigid web members, so that an equal deflection between beams A and B is obtained. By overlaying the bending and shear stiffness (stresses) of both beams, the end result for the entire cross-section can be obtained (Figure 2).

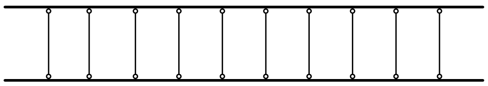


Figure 2
Beam modeling using the shear analogy method

Beam A is assigned a bending stiffness equal to the sum of the inherent bending stiffness of all the individual layers or individual cross-sections as shown in Equation [13].

$$B_A = \sum_{i=1}^{n} E_i \cdot I_i = \sum_{i=1}^{n} E_i \cdot b_i \cdot \frac{h_i^3}{12} \qquad [13]$$

where:

$B_A = (EI)_A$
b_i = Width of each individual layer, usually taken as 1 ft. for CLT panels
h_i = Thickness of each individual layer

The bending stiffness of beam B is calculated using the parallel axis theorem (given as the sum of the Steiner points of all individual layers):

$$B_B = \sum_{i=1}^{n} E_i \cdot A_i \cdot z_i^2 \qquad [14]$$

where B_B is $(EI)_B$ and z_i is the distance between the center point of each layer and the neutral axis.

Additionally, beam B contains the shear stiffness. The shear stiffness of beam B, S_B, is $(GA)_B$ and can be calculated as:

$$\frac{1}{S_B} = \frac{1}{a^2} \cdot \left[\frac{h_1}{2 \cdot G_1 \cdot b_1} + \sum_{i=2}^{n-1} \frac{h_i}{G_i \cdot b_i} + \frac{h_n}{2 \cdot G_n \cdot b_n} \right] \qquad [15]$$

In the above equations, the values for E_0 (E parallel to the grain) shall be used for the longitudinal laminations while E_{90} (E perpendicular to the grain) = $E_0/30$ is used for cross laminations. Also, in the same equations, the shear modulus for the longitudinal laminations should be assumed to be G, while that for the cross laminations shall be, for the rolling shear, G_R ($G_R \approx G/10$).

The continuity of deflections between beams A and B ($\Delta_A = \Delta_B$) must be valid at every point. Using a spreadsheet, the virtual section sizes of beams A and B and the values for M_A, M_B, V_A and V_B are produced. Bending moments $M_{A,i}$ and shear forces $V_{A,i}$ of each individual layer of beam A can be obtained using the Equations [16] and [17], respectively.

$$M_{A,i} = \frac{E_i \cdot I_i}{B_A} \cdot M_A \qquad [16]$$

$$V_{A,i} = \frac{E_i \cdot I_i}{B_A} \cdot V_A \qquad [17]$$

where M_A and V_A are the bending and shear forces on beam A, and B_A is derived from Equation [13].

Bending stresses $\sigma_{A,i}$ and shear stresses $\tau_{A,i}$ of each individual layer of beam A can be obtained using the Equations [18] and [19], respectively.

$$\sigma_{A,i} = \pm \frac{M_{A,i}}{I_i} \cdot \frac{h_i}{2} \qquad [18]$$

$$\tau_{A,i} = \frac{E_i \cdot I_i}{B_A} \cdot 1.5 \cdot \frac{V_A}{b \cdot h_i} \qquad [19]$$

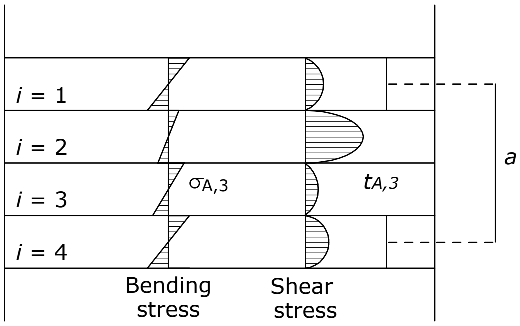


Figure 3
Bending and shear stresses in beam A using the shear analogy method (source: Kreuzinger)

Axial forces $N_{B,i}$, normal stresses $\sigma_{B,i}$ of each individual layer of beam B, and shear stresses at the interface of the two layers of beam B, $\tau_{B,i,i+1}$, can be obtained using the Equations [20], [21] and [22], respectively.

$$N_{B,i} = \frac{E_i \cdot A_i \cdot z_i}{B_B} \cdot M_B \qquad [20]$$

$$\sigma_{B,i} = \frac{N_{B,i}}{b_i \cdot h_i} = \frac{E_i \cdot z_i}{B_B} \cdot M_B \qquad [21]$$

$$t_{Bi,i+1} = \frac{V_B}{B_B} \cdot \sum_{j=i+1}^{n} E_j \cdot A_j \cdot z_j \qquad [22]$$

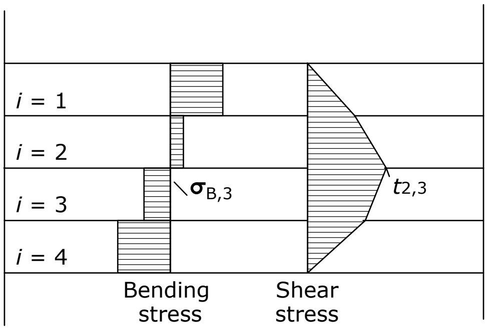


Figure 4
Normal and shear stresses in beam B using the shear analogy method (source: Kreuzinger)

The final stress distribution obtained from the superposition of the results from beams A and B is shown in Figure 5. It should be noted that the shear distribution in Figure 5 includes the influence of the connector devices that will not be existent for a CLT panel.

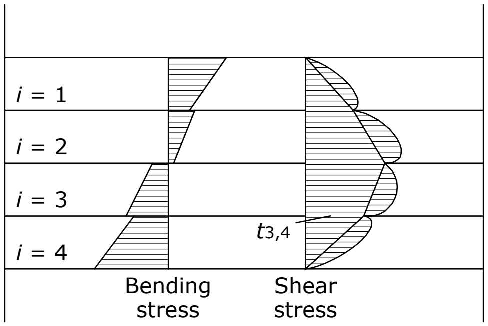


Figure 5
Final stress distribution obtained from the superposition of the results from beams A and B (source: Kreuzinger)

Using the shear analogy method, the maximum deflection $\Delta_{\max}$ in the middle of the CLT slab under a uniformly distributed load w can be calculated as a sum of the contribution due to bending and shear:

$$\Delta_{\max} = \frac{5}{384}\cdot\frac{wL^4}{EI_{eff}} + \frac{1}{8}\cdot\frac{wL^2k}{GA_{eff}} \qquad [23]$$

where:

EI_{eff} = Effective bending stiffness of composite section
GA_{eff} = Effective shear stiffness of composite section

The effective bending stiffness can be obtained using Equation [24]:

$$EI_{eff} = \sum_{i=1}^{n} E_i \cdot b_i \cdot \frac{h_i^3}{12} + \sum_{i=1}^{n} E_i \cdot A_i \cdot z_i^2 \qquad [24]$$

The effective shear stiffness can be obtained using Equation [25]:

$$GA_{eff} = \frac{a^2}{\left[\left(\frac{h_1}{2 \cdot G_1 \cdot b}\right) + \left(\sum_{i=2}^{n-1} \frac{h_i}{G_i \cdot b_i}\right) + \left(\frac{h_n}{2 \cdot G_n \cdot b}\right)\right]} \qquad [25]$$

An example of the calculation of the effective true bending stiffness EI_{eff} and effective shear stiffness GA_{eff} using the shear analogy method is given in Section 4.

Since shear deflection can be significant in CLT, its contribution needs to be included. One such method would be to adjust the effective bending stiffness to an apparent bending stiffness. From the 2010 Wood Handbook, the general deflection of a beam, including shear deflection, is the following:

$$\Delta = \frac{k_b w l^3}{EI_{eff}} + \frac{k_s w l}{GA'} \qquad [26]$$

where k_b and k_s are constants that depend upon the loading and fixity of the beam and A′ is a modified beam area that is (5/6)bh for rectangular cross sections. An EI_{app} can be found if a generic bending deflection equation, $(K_s wl^3)/EI_{app}$, is equated to Equation [26] as shown in the following equation:

$$\frac{k_b w l^3}{EI_{eff}} + \frac{6 k_s w l}{5 GA_{eff}} = \frac{K_s w l^3}{EI_{app}} \qquad [27]$$

The apparent bending stiffness can be found from reducing the effective bending stiffness per the following:

$$EI_{app} = \frac{EI_{eff}}{1 + \frac{K_s EI_{eff}}{GA_{eff} L^2}} \qquad [28]$$

where $K_s = (6/5)(k_s/k_b)$ and is solved for several cases in Table 1 of Section 2.1.3.

4

DESIGN EXAMPLES

The main purpose of the following examples is to illustrate the proposed design methods for calculating the basic design properties of cross-laminated timber panels used in North American buildings. Engineers shall be informed that not all the necessary checks are included in each example as some steps may already be calculated by the manufacture or product standard. All examples are based upon the following E1, 5-layer CLT panel (see PRG 320):

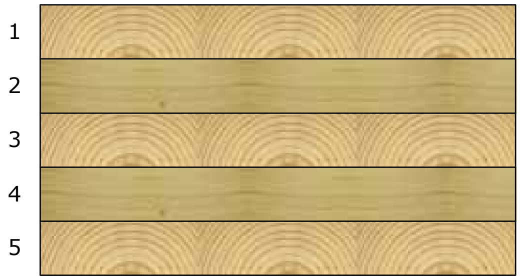


Figure 6
Cross-section of a 5-layer CLT panel

For a 5-layer, E1 panel:

h_i = Thickness of an individual layer = 1 3/8 in.
b = Design width = 12 in.

Major strength axis (parallel to grain)

$F_{b,0}$ = Bending strength = 1950 psi
E_0 = Modulus of elasticity = $1.7x10^6$ psi
$F_{t,0}$ = Tensile strength = 1375 psi
$F_{c,0}$ = Compression strength = 1800 psi
$F_{v,0}$ = Shear strength = 135 psi
$F_{s,0}$ = Rolling shear strength = 45 psi

Minor strength axis (perpendicular to grain)

$F_{b,90}$ = Bending strength = 500 psi
E_0 = Modulus of elasticity = $1.2x10^6$ psi
$F_{v,0}$ = Shear strength = 135 psi
$F_{s,0}$ = Rolling shear strength = 45 psi

4.1 Bending Members

4.1.1 Finding EI_{eff}

Based on Equation [24], a table is used to help in calculating the effective stiffness, EI_{eff}. The width of each layer, b, is assumed to be 12 inches and every layer thickness, h, is assumed to be 1.375 inches for this panel. For layers 2 and 4, which are oriented in the minor strength axis, the E is divided by 30 per PRG 320 to adjust for bending perpendicular to the strong axis.

$$EI_{eff} = \sum_{i=1}^{n} E_i \cdot b_i \cdot \frac{h_i^3}{12} + \sum_{i=1}^{n} E_i \cdot A_i \cdot z_i^2 \qquad [24]$$

Table 3

Parallel axis theorem calculations for EI_{eff}

Layer	E (x 10^6 psi)	z (in.)	$Ebh^3/12$ (lb.-in.^{2})	EAz^2 (lb.-in.^{2})	Sum of Layer
1	1.7	2.75	4.4	212.1	216.5
2	1.2/30=0.04	1.375	0.1	1.2	1.4
3	1.7	0.0	4.4	0.0	4.4
4	0.04	1.375	0.1	1.2	1.4
5	1.7	2.75	4.4	212.1	216.5
				Total	**440**

4.1.2 Finding GA_{eff}

Equation [25] is used to solve for GA_{eff}. For the shear modulus, PRG 320 assumes that G = E/16 and that for the minor strength axis, G should be divided by 10 for rolling shear. A table is used for ease of calculations.

Table 4

Intermediate calculations for GA_{eff}

Layer	G (x 10^6 psi)	h/G/b (x 10^6 psi)
1	1.7/16= 0.10625	1.078
2	1.2/(16 x 10)=0.0075	15.278
3	0.01625	1.078
4	0.0075	15.278
5	0.01625	1.078

$$GA_{eff} = \frac{a^2}{\left[\left(\frac{h_1}{2 \cdot G_1 \cdot b}\right) + \left(\sum_{i=2}^{n-1} \frac{h_i}{G_i \cdot b_i}\right) + \left(\frac{h_n}{2 \cdot G_n \cdot b}\right)\right]} \qquad [25]$$

$$GA_{eff} = \frac{5.5^2}{\left[\left(\frac{1.078}{2}\right) + (15.278 + 1.078 + 15.278) + \left(\frac{1.078}{2}\right)\right.} \quad [29]$$

$$GA_{eff} = 0.92 \quad [30]$$

4.1.3 Finding $F_bS_{eff,0}$ Using the Simplified Method

Equation [1] is used to calculate $F_bS_{eff,0}$. The product standard, PRG 320, uses a further reduction "for conservatism" by multiplying by 0.85.

$$S_{eff} = \frac{2EI_{eff}}{E_1 h} = \frac{2 \times 440}{1.7 \times 6.875} = 75.29\ in.^3 \quad [31]$$

$$F_b S_{eff} = \frac{0.85 \times 1950 \times 75.29}{12} = 10{,}400\ lb. - ft. \quad [32]$$

4.1.4 Finding $F_s(Ib/Q)_{eff}$ Using the Simplified Method

Equation [3] is used to calculate $F_s(Ib/Q)_{eff}$. A table is used to help in making the calculation.

Table 5

Intermediate calculations for $(Ib/Q)_{eff}$

Layer	E (x 10^6 psi)	z (in.)	Ehz
1	1.7	2.750	6.428
2	1.2/30=0.04	1.375	0.076
3	1.7	0.688	1.607
		Sum	**8.111**

$$(Ib/Q)_{eff} = \frac{EI_{eff}}{\sum_{i=1}^{n/2} E_i h_i z_i} = \frac{440}{8.111} = 54.25\ in.^2 \quad [33]$$

$$F_s (Ib/Q)_{eff} = 54.25 \times 45 = 2{,}441\ lb. \quad [34]$$

4.1.5 Finding EI_{app} for a Uniform Load for a Length of 20 ft., Supported by Pinned Ends

The effective bending stiffness, EI_{eff}, is adjusted to an apparent stiffness, EI_{app}, to account for shear deflection. From Table 2, K_s = 11.5 in the case of a uniform load with pinned ends is used in Equation [5].

$$EI_{app} = \frac{EI_{eff}}{1 + \frac{K_s EI_{eff}}{GA_{eff} L^2}} = \frac{440}{1 + \frac{11.5 \times 440}{0.92 \times (20 \times 12)^2}} = 402\ lb. - in.^2 \quad [35]$$

4.2 Compression Members

For a 10 ft. tall wall resisting 75 kips per ft. of floor live load in the major strength direction, determine if the CLT above is adequate using ASD. Wet service and temperature factors are 1.0.

4.2.1 Finding $EI_{app\text{-}min}$

EI_{app} for a constant moment, pinned end condition is determined. From Table 2, K_s= 11.8 for this condition.

$$EI_{app} = \frac{EI_{eff}}{1+\dfrac{K_s EI_{eff}}{GA_{eff} L^2}} = \frac{440}{1+\dfrac{11.8\times 440}{0.92\times(20\times 12)^2}} = 400\ lb.-in.^2 \qquad [36]$$

This value is then adjusted from an average value to a minimum design value with Equation [8].

$$EI_{app-\min} = 0.5184 EI_{app} = 0.5184\times 400 = 207\ lb.-in.^2 \qquad [37]$$

4.2.2 Finding C_p

P_{cE} is calculated as:

$$P_{cE} = \frac{\pi^2 EI'_{app-\min}}{l_e^2} = \frac{\pi^2\times 207\times 10^6}{(10\times 12)^2} = 142{,}000\ lb. \qquad [38]$$

P^*_c is then calculated using the sum of all cross-sectional areas for layers running parallel to the load, or $F_c A_{parallel}$.

$$F_c A_{parallel} = (1800)(1.375)(12)(3) = 89{,}100\ lb. \qquad [39]$$

Since the wet service, temperature, and load duration factors are 1.0, $P^*_c = F_c A_{parallel}$. Finally, Equation [7] is used to find C_p. Remember that c=0.9 for CLT.

$$C_p = \frac{1+\left(P_{cE}/P_c^*\right)}{2c} - \sqrt{\left[\frac{1+\left(P_{cE}/P_c^*\right)}{2c}\right]^2 - \frac{P_{cE}/P_c^*}{c}} \qquad [40]$$

$$C_p = \frac{1+(142{,}000/89{,}100)}{2(0.9)} - \sqrt{\left[\frac{1+(142{,}000/89{,}100)}{2(0.9)}\right]^2 - \frac{(142{,}000/89{,}100)}{0.9}} = 0.89 \qquad [41]$$

4.2.3 Checking Column Capacity

Finally, the compression capacity, $F_c'A_{parallel}$, is calculated using Equation [6]. Since the wet service, temperature, and load duration factors are 1.0, the only adjustment factor that has an effect is C_p, which is 0.89.

$$F_c'A_{parallel} = F_c^* A_{parallel} = F_c C_p A_{parallel} = (1800)(1.375)(12)(3)(0.89) = 79{,}300\ lb. \geq 75{,}000\ lb. \qquad \text{Okay}$$

5

REFERENCES

American Wood Council (AWC). 2012. *National design specification (NDS) for wood construction*. ANSI/AWC NDS-2012. Leesburg, VA: AWC.

APA – The Engineered Wood Association. 2011. *Standard for performance-rated cross-laminated timber*. ANSI/APA PRG 320. Tacoma, WA: APA.

Bejtka, I., and F. Lam. 2008. Cross laminated timber as innovative building material. In *Proceedings of the CSCE Annual Conference, Québec, QC*. Montréal, QC: Canadian Society for Civil Engineering (CSCE). CD-ROM.

Blass H.J., and P. Fellmoser. 2004. Design of solid wood panels with cross layers. In *Proceedings of the 8th World Conference on Timber Engineering, June 14-17, 2004, Lahti, Finland*, 2:543-548.

Ceccotti A. 2003. Composite structures. In *Timber Engineering*, ed. S. Thelandersson and H.J. Larsen, chapter 21. West Sussex, England: John Wiley and Sons.

European Committee for Standardization (CEN). 2004. *Eurocode 5: Design of timber structures. Part 1-1: General – Common rules and rules for buildings*. EN 1995-1-1. Brussels: CEN. 124 p.

Fellmoser, P., and H.J. Blass. 2004. Influence of rolling shear modulus on strength and stiffness of structural bonded timber elements. In *Proceedings of CIB-W18 Meeting, Edinburgh, United Kingdom*, paper 37-6-5.

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

Kreuzinger H. 1995. Mechanically jointed beams and columns. In *Timber Engineering – STEP 1*, ed. H.J. Blass et al., B11/1-8. Almere, The Netherlands: Centrum Hout.

______. 1999. Platten, Scheiben und Schalen – ein Berechnungsmodell für gängige Statikprogramme. *Bauen mit Holz* 1:34-39.

Mestek, P., H. Kreuzinger, and S. Winter. 2008. Design of cross laminated timber (CLT). Paper presented at the *10th World Conference on Timber Engineering, June 2-5, 2008, Miyazaki, Japan*.

Steiger, R., A. Gülzow, and D. Gsell. 2008. Non-destructive evaluation of elastic material properties of cross laminated timber (CLT). In *Proceedings of the COST E53 Conference, October 29-30, 2008, Delft, The Netherlands*, p. 171-182.

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
Binational Softwood Lumber Council

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
Binational Softwood Lumber Council

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