

CLT Handbook

CROSS-LAMINATED TIMBER

U.S.  EDITION

© 2013 FPInnovations and Binational Softwood Lumber Council. All rights reserved.

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).

No part of this published Work may be reproduced, published, or transmitted for commercial purposes, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, whether or not in translated form, without the prior written permission of FPInnovations and Binational Softwood Lumber Council.

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.

FC 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



Forest Products Laboratory



WoodWorks



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 Catocin 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)) ; 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, FPIInnovations, U.S. WoodWorks and their staff for providing the effort and expertise needed to prepare this work. We would also like to express our special thanks to all chapter authors, co-authors, and reviewers who shared their precious time and expertise in improving this manual.

Our very special thanks go to Loren Ross at AWC and Sylvain Gagnon at FPIInnovations 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

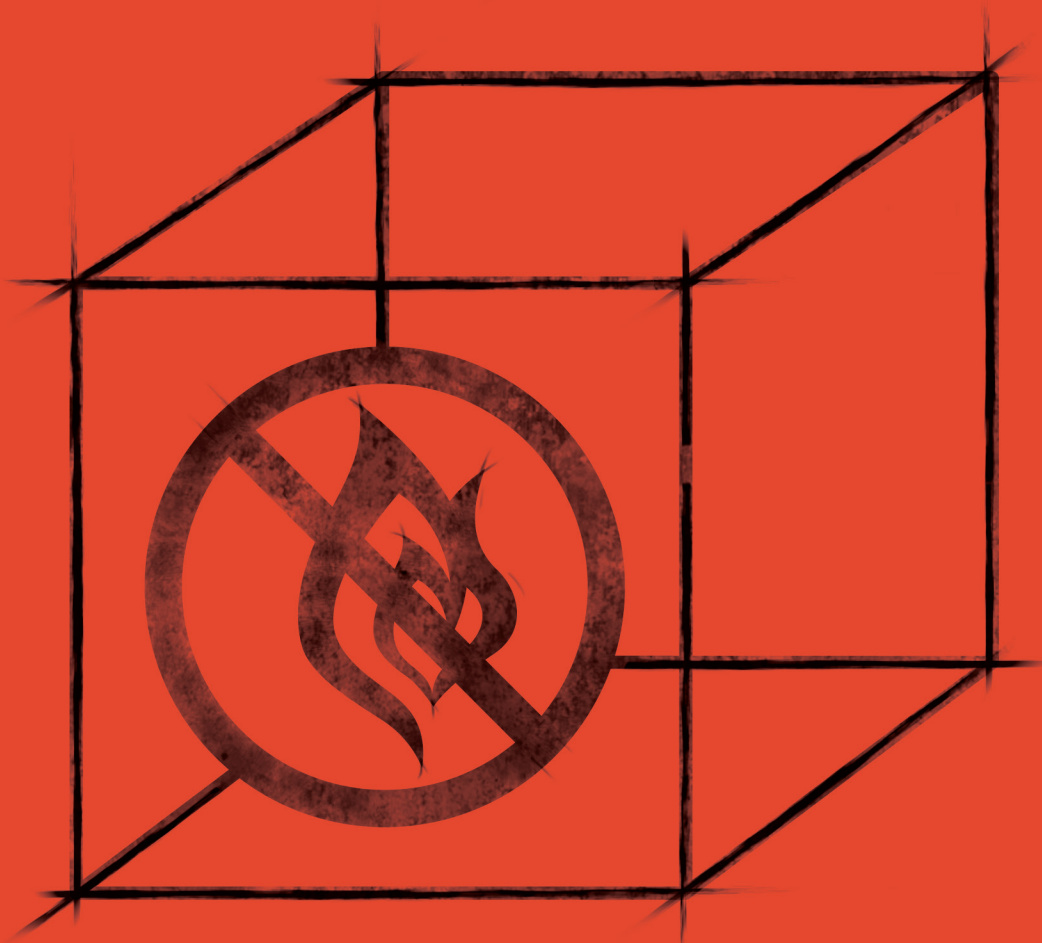
Building enclosure design for
cross-laminated timber construction

CHAPTER 11

Environmental performance
of cross-laminated timber

CHAPTER 12

Lifting and handling of
cross-laminated timber elements



Fire

Fire performance of
cross-laminated timber assemblies

CHAPTER 8

Authors

Christian Dagenais, Eng., M.Sc., FPInnovations
Robert H. White, Ph.D., USDA Forest Products Laboratory
Kuma Sumathipala, Ph.D., P.Eng., American Wood Council

Peer Reviewers

Sam Francis, M.En.Sc., American Wood Council
James Churchill, P.E., M.Sc. Civil Engineering, Umass Amherst
Joe McElvaney, City of Phoenix
Prof. Dr. Andrea Frangi, ETH Zurich, Institute of Structural Engineering, Switzerland

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.



© 2013 FPInnovations and Binational Softwood Lumber Council. All rights reserved.

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).

No part of this published Work may be reproduced, published, or transmitted for commercial purposes, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, whether or not in translated form, without the prior written permission of FPInnovations and Binational Softwood Lumber Council.

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

Cross-laminated timber (CLT) is a promising wood-based structural component and has potential to provide cost-effective building solutions for residential, commercial and institutional buildings as well as large industrial facilities. Market acceptance of CLT requires that it meets the applicable building code requirements.

CLT elements are used in building systems in a similar manner to concrete slabs and solid wall elements, as well as to those from heavy timber construction, by avoiding concealed spaces due to the use of massive timber elements, thus reducing the risk of fire spread beyond its point of origin. Moreover, CLT construction typically uses CLT panels for floor and loadbearing walls, which allow fire-rated compartmentalization, again reducing the risk of fire spread beyond its point of origin.

Structural fire performance of CLT assemblies can be assessed by conducting fire-resistance tests in accordance with ASTM E119 standard test methods. A fire-resistance rating is defined as the period of time a building element, component or assembly maintains the ability to perform its separating function (i.e., confining a fire by preventing or retarding the passage of excessive heat, hot gases or flames), continues to perform a given loadbearing function, or both. When designing CLT buildings, it is necessary to determine the fire-resistance rating provided by the assembly to ensure its performance satisfies the building code fire safety requirements.

The proposed design procedure for determining the fire resistance of CLT assemblies has been suitably adapted to the current design methodology found in Chapter 16 of the National Design Specification (NDS) for Wood Construction applicable to large timber elements. The proposed mechanics-based method which uses a standard nominal charring rate ($\beta_n = 1.5$ in./hr), a non-linear stepped charring rate adjustment, a zero-strength layer multiplier of 1.2, and a standard variability adjustment in the design to ultimate adjustment factor predicts average fire-resistance times for CLT wall and floor assemblies that closely track actual fire-resistance times for tested assemblies. While further refinements of this method are possible, these comparisons suggest that standardized adjustments to design stresses, a standardized stepped charring rate, and the use of the NDS behavioral equations adequately address fire-resistance design of CLT assemblies.

TABLE OF CONTENTS

Acknowledgements	ii			
Abstract	iii			
List of Figures	vi			
List of Tables	vi			
1	Introduction	1		
2	Fire Safety in Buildings	2		
	2.1	Objectives	2	
	2.2	Fire Performance Attributes of CLT	2	
	2.3	CLT and Fire Provisions of Building Codes	3	
3	Types of Construction and Occupancy Classification	4		
	3.1	Height and Area Limitations	4	
	3.2	Use of CLT in Type III Construction	5	
	3.3	Use of CLT in Type IV Construction	5	
	3.4	Use of CLT in Type V Construction	6	
	3.5	Types of CLT Fire-rated Walls	6	
4	Fire Resistance of CLT	7		
	4.1.1	Test Method – ASTM E119	9	
		4.1.1.1	Fire-resistance Requirements	11
	4.1.2	NDS Methodology for Wood Fire Design	11	
	4.1.3	Application of NDS Methodology to CLT	12	
		4.1.3.1	Charring Rate and Char Depth	12
		4.1.3.2	Effect of Adhesive Fire Performance on the Effective Char Depth	13
		4.1.3.3	Modified Effective Char Depth Calculation for CLT Assemblies	13
		4.1.3.4	Approximation of Member Strength and Capacity	15
		4.1.3.5	Structural Design of CLT Assemblies Exposed to Fire (Loadbearing Function)	15
	4.1.4	Fire Resistance of CLT Assemblies – Structural Requirement	16	
		4.1.4.1	Structural Fire Resistance	16
		4.1.4.2	Use of Protective Membranes to Increase Structural Fire Resistance	23

4.1.5	Fire Resistance of CLT Assemblies – Integrity Requirement	23
4.1.5.1	Effect of Joints on Integrity of CLT Walls and Floors	24
4.1.5.2	Use of Protective Membranes, Floor Coverings, and Interior Finish to Address Integrity	25
4.1.6	Fire Resistance of CLT Assemblies – Insulation Requirement	25
4.1.6.1	Theoretical Temperature Profiles for CLT Assemblies	25
4.1.6.2	Experimental Temperature Profile Data for CLT Assemblies	26
4.1.7	Comparison between Calculation Method and Experiments	28
4.1.8	Floor Design Example	31
4.1.8.1	Calculation of the Loadbearing Function after 90 Minutes of Standard Fire Exposure	31
4.1.8.2	Calculation of the Separating Function after 90 Minutes of Standard Fire Exposure	33
4.1.9	Wall Design Example	34
4.1.9.1	Calculation of the Loadbearing Function after 60 Minutes of Standard Fire Exposure	34
4.1.9.2	Calculation of the Separating Function after 60 Minutes of Standard Fire Exposure	37
5	Connections	38
6	Interior Finish	40
6.1	Flame Spread Index	40
6.1.1	Test Method – ASTM E84	40
6.1.2	Flame Spread Index (A, B and C Classes)	40
6.1.3	Areas of Likely Class A and Class B Requirements	41
6.1.4	Available Data for CLT and Other Wood Products	41
6.2	Fire-retardant Treatment and CLT	43
6.3	Use of Other Membrane Products to Address Interior Finish Requirements	44
6.4	Foam Plastic Insulation	44
6.5	Automatic Fire Sprinklers	44
7	Through Penetrations	45
7.1	Fire Stops through Fire Separations	45
7.2	Fire-resistant Joint Systems in CLT Construction	45
8	Nomenclature	48
9	Special Thanks	50
10	References	51
Appendix I – Additional Information		55
European Calculation Design Procedure		55
Canadian Calculation Design Procedure		56

List of Figures

- Figure 1** Fire resistance criteria per ASTM E119 8
- Figure 2** CLT fire-resistance wall tests conducted at NRCC in Ottawa (Canada) 9
- Figure 3** CLT fire-resistance floor tests conducted at NRCC in Ottawa (Canada) 10
- Figure 4** Standard time-temperature curve from ASTM E119 10
- Figure 5** Char depth adjusted for CLT assemblies with 1^{3/8} in. (35 mm) laminates (Test 4 from [24]) 14
- Figure 6** Char depth adjusted for CLT assemblies with 0.83" (21 mm) laminates (Test 8 from [24]) 15
- Figure 7** Nomenclature used in calculating fire resistance of a CLT exposed to fire from below 17
- Figure 8** CLT wall assembly subjected to combined bending and axial compression 22
- Figure 9** CLT panel-to-panel half-lapped joint detail 24
- Figure 10** Experimental temperature profiles from [24] and Equation 21 27
- Figure 11** Comparison between experiments and calculation methodology 30
- Figure 12** Examples of connections seen in CLT platform construction 39
- Figure 13** Examples of connections seen in CLT balloon construction 39
- Figure 14** Concealed metal plates 39
- Figure 15** Through and partial penetration in CLT assemblies 46-47

List of Tables

- Table 1** Example of basic height and area per floor limitations from Table 503 of the IBC 4
- Table 2** Example of height and total floor area limitations when sprinklered in accordance with NFPA 13 and open perimeter access from all sides, as per IBC 5
- Table 3** Effective charring rates and char layer thicknesses per the NDS methodology 12
- Table 4** Adjustment factors for fire design in accordance with [14] 16
- Table 5** Average maximum temperature rises at unexposed surface 28
- Table 6** CLT assemblies configuration details 29
- Table 7** Comparison between experiments and calculation methodology 30
- Table 8** Flame spread classes according with IBC 41
- Table 9** Flame spread indices for softwood lumber 42

1

INTRODUCTION

Cross-laminated timber (CLT) is a promising wood-based structural component and has great potential to provide cost-effective building solutions for residential, commercial, and institutional buildings as well as large industrial facilities. Code acceptance of CLT construction necessitates compliance with fire-related provisions of the building codes. This Chapter addresses some of the common code-mandated fire performance requirements.

In the United States, compliance with the building codes is generally accomplished by construction in accordance with the *International Building Code* (IBC) [1] or NFPA 5000 [2]. The intent of the IBC and NFPA 5000 is to establish minimum requirements to public safety through, among other things, structural strength, means of egress, stability, life safety, and property protection from fire as well as to provide safety for firefighters and first responders during emergency operations. As such, fire safety issues such as providing adequate structural integrity in fire conditions, limiting fire impact to people and property, as well as limiting fire spread through a building and to adjacent properties are critical attributes that need to be provided by every building design and structural systems. In this Chapter, the various aspects of the IBC fire-related provisions are addressed. In most cases, there are similar provisions in NFPA 5000.

Classification of a building as to its “type of construction” as defined in the IBC and NFPA 5000 is one of the key elements in identifying the limitations on the height and allowable floor areas of a building. As a relatively new type of construction in the United States, the inclusion of prescriptive language in the IBC and NFPA 5000 on CLT construction is only now being addressed. The 2015 edition of the IBC and NFPA 5000 would reference the ANSI/APA PRG 320 *Standard for Performance-Rated Cross-Laminated Timber* [3] as well as prescriptively allow CLT to be used in Type IV “Heavy Timber” construction.

2

FIRE SAFETY IN BUILDINGS

The building codes have historically been published as a prescriptive code and the requirements set forth within the building codes have traditionally been recognized as deemed-to-satisfy the Code objectives.

In the IBC, fire safety provisions are based on the NFPA Fire Concepts Tree [4] where fire impact management and fire ignition prevention are the two main cornerstones. Fire ignition may be addressed by following the International Fire Code and NFPA 1 [5, 6] while managing the impact of a fire is addressed by the many provisions given in the IBC.

2.1 Objectives

The fire safety provisions set forth in the IBC and NFPA 5000 interrelate to four fundamental objectives, which are as follow:

1. Provide life safety for the public, building occupants and emergency responders;
2. Protect property from fire as well as exposure to and from fire in adjacent buildings;
3. Provide limitation of financial loss (from the building and contents);
4. Limit the environmental impact of the fire.

These objectives can be met by different strategies taking into consideration the type of structure, the building occupancy, height and area as well as the active and passive fire protection systems. Another important fire safety measure is to subdivide the building into fire-rated compartments. Such compartmentalization concepts limit fire spread beyond its point of origin by using boundary elements (e.g., walls, ceilings, floors, partitions, etc.) having a fire-resistance rating not less than the minimum ratings prescribed in the IBC or NFPA 5000.

2.2 Fire Performance Attributes of CLT

CLT panels provide excellent fire resistance. This is due to the inherent nature of thick timber members to char slowly at a predictable rate, allowing massive wood systems to maintain significant structural capacity for extended durations when exposed to fire.

Being made from wood planks, CLT can contribute to the growth of a compartment fire. As such, a negatively perceived impact from using CLT is the potential increase of the fixed fuel load [7]. Limited research has been conducted to evaluate the impact of additional fixed fuel load from CLT panels to the fire growth. Frangi et al. [8] evaluated a 3-story CTL building built with 3 ⅜ in. (85 mm) thick wall panels and 5 ½ in. (142 mm) thick floor slabs exposed to a natural full-scale fire. In this particular experiment, walls were protected with a ½ in. (12.7 mm) fire-rated gypsum board (directly exposed to fire) as well as a ½ in. (12.7 mm) standard gypsum board while the ceilings were protected with 1 in. (25.4 mm) mineral wool insulation and a ½ in. (12.7 mm) fire-rated gypsum

board. In an attempt to replicate a similar fire severity, such as those encountered in typical residential dwellings, a design fire load of 69,600 Btu/ft.² (790 MJ/m²) was used and burned for a duration of slightly over 1 hour. It is reported that flashover occurred after about 40 minutes. The fire severity started to decline after 55 minutes and was extinguished, as planned, after an hour-long duration. Furthermore, the measured charred depth on the gypsum-protected CLT compartment elements were very low, ranging from approximately $\frac{3}{16}$ in. to $\frac{3}{8}$ in. (5 mm to 10 mm). No elevated temperatures were measured and no smoke was observed in the room above the fire room. From this full-scale design fire test, one can conclude that CLT buildings can be designed to limit fire spread beyond the point of origin, even when massive timber construction is used.

2.3 CLT and Fire Provisions of Building Codes

CLT elements are used in building systems in a similar manner to concrete slabs and solid wall elements as well as to those from heavy timber construction by limiting concealed spaces due to the use of massive timber elements, thus reducing the risk of concealed space fires.

Moreover, CLT construction typically uses CLT panels for floor and loadbearing walls, which allow fire-resistance-rated compartmentalization, thus again reducing the risk of fire spread beyond its point of origin (compartment of origin).

The various types of constructions defined within the IBC are discussed in detail in Section 3 of this Chapter, which will also highlight areas where CLT components may be used in compliance with the IBC.

3

TYPES OF CONSTRUCTION AND OCCUPANCY CLASSIFICATION

The five types of construction used to classify buildings in the codes, Types I to V, are described in Chapter 6 of the IBC. Use and Occupancy in buildings are classified into ten categories as described in Chapter 3 of the IBC. The “Type of Construction” and “Use and Occupancy Classification” together dictate the fire-resistance requirements of the building assemblies and the height and area limitations for code compliance. CLT construction can comply with provisions in Types of construction III, IV and V, as defined in Section 602 of the IBC. Type I and II construction require the major building elements to be built with noncombustible materials.

3.1 Height and Area Limitations

The provisions for height and areas limits are found in Chapter 5 of the IBC. The key elements in determining the limitations on height and area are the type of construction and the use and occupancy classification. These two elements are used with Table 503 of the IBC to determine basic limitations on height and area. A few examples from IBC Table 503 are reproduced in Table 1.

Table 1

Example of basic height and area per floor limitations from Table 503 of the IBC

Occupancy	Type of Construction				
	III-A	III-B	IV	V-A	V-B
Business	5 floors 28,500 ft. ²	3 floors 19,000 ft. ²	5 floors 36,000 ft. ²	3 floors 18,000 ft. ²	2 floors 9,000 ft. ²
Residential (R-1 and R-2) Hotel/Motel Apartment	4 floors 24,000 ft. ²	4 floors 16,000 ft. ²	4 floors 20,500 ft. ²	3 floors 12,000 ft. ²	2 floors 7,000 ft. ²

In addition to the number of stories limitation based on occupancy, each type of construction has a height limitation, in feet above grade plane, which is independent of the use and occupancy classification.

The area limitations are for areas within the exterior walls. Interior walls built as “fire walls” (Section 706 of the IBC) can be used to subdivide a larger building into smaller areas, each of which may be considered a separate building that is within the limitations of Table 503. The tabular area, determined by finding the Type of Construction for a specific Use Group in Table 503 is then subject to increases for either Open Perimeter, or sprinkling, or both. Equation 5-1 in Section 506 of the IBC is used to calculate the maximum allowable building area per floor.

The allowable height and area of a building can also be increased when installing automatic fire sprinklers and providing perimeter access for emergency response vehicles. With the allowable increases, it is convenient to present allowable area as a total for the building rather than per floor. The following Table 2 presents this information for including automatic fire sprinklers in accordance with NFPA 13 [9] and perimeter access from all sides of the building.

Table 2

Example of height and total floor area limitations when sprinklered in accordance with NFPA 13 and open perimeter access from all sides, as per IBC

Occupancy	Type of Construction				
	III-A	III-B	IV	V-A	V-B
Business	6 floors 320,625 ft. ²	4 floors 213,750 ft. ²	6 floors 405,000 ft. ²	4 floors 202,000 ft. ²	3 floors 101,250 ft. ²
Residential (R-1 and R-2) Hotel/Motel Apartment	5 floors 270,000 ft. ²	5 floors 180,000 ft. ²	5 floors 230,625 ft. ²	4 floors 135,000 ft. ²	3 floors 78,750 ft. ²

3.2 Use of CLT in Type III Construction

In Type III construction, interior building elements can be combustible materials while the exterior walls are required to be of noncombustible materials. Thus, there is a potential to use CLT for the interior elements in Type III construction. Type III construction is further divided into subclassifications A and B based on the fire-resistance requirements.

3.3 Use of CLT in Type IV Construction

Type IV construction is also known as “Heavy Timber” (HT) construction. The 2015 IBC will prescriptively allow the use of CLT in Type IV construction, including exterior walls, interior walls, floors and roofs. CLT will be permitted within exterior wall assemblies not less than 6 inches (152 mm) in thickness and with a two-hour fire-resistance rating or less. CLT in exterior wall assemblies must be protected by fire retardant treated wood (FRTW) sheathing of not less than ¹⁵/₃₂ in. (12 mm) thick, gypsum board not less than ½ in. (13 mm) thick, or a noncombustible material on the exterior side of the exterior wall.

Loadbearing interior walls of CLT construction shall have a one-hour fire-resistance rating. Interior partitions shall be of solid wood construction formed by not less than two layers of 1 in. (25 mm) matched boards or 4 in. (102 mm) thick laminated construction, or of 1-hour fire-resistance-rated construction.

In Type IV construction, floors can be constructed with sawn or glued-laminated planks of a minimum thickness of 3 in. nominal (76 mm), splined or tongue-and-groove, that are covered with one of several prescribed floor coverings. CLT used as HT floors shall be not less than 4 in. (102 mm) in thickness. It shall be continuous from support to support and mechanically fastened to one another. Floors shall be constructed without concealed spaces.

Roofs shall also be without concealed spaces and can be constructed with sawn or glued-laminated planks of a minimum thickness of 2 in. nominal (50 mm), splined or tongue-and-groove. CLT used as timber roofs shall be not less than 3 in. nominal (76 mm) in thickness and shall be continuous from support to support and mechanically fastened to one another.

3.4 Use of CLT in Type V Construction

Type V construction is defined as that type of construction in which the structural elements, exterior walls, and interior walls can be of any materials permitted by the code. The 2015 editions of the IBC and NFPA 5000 would reference ANSI/APA PRG 320. As such, CLT complying with this standard would be permitted for use in Type V-A and Type V-B constructions. The subclassifications A and B are based on the fire-resistance requirements.

3.5 Types of CLT Fire-rated Walls

In the IBC, the terms used to describe various types of walls have very specific meanings in terms of the required fire performance. The following definitions are taken from the IBC:

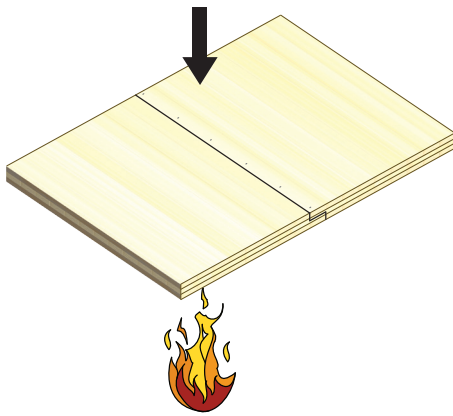
- Fire wall (Section 706) is “*a fire-resistance-rated wall having protected openings, which restricts the spread of fire and extends continuity from the foundation to or through the roof, with sufficient structural stability under fire conditions to allow collapse of construction on either side without collapse of the wall*”;
- Fire barrier (Section 707) is “*a fire resistance-rated wall assembly of materials designed to restrict the spread of fire in which continuity is maintained*”;
- Fire partition (Section 709 of IBC) is “*a vertical assembly of materials designed to restrict the spread of fire in which openings are protected*”; and
- Smoke barrier (Section 710) is “*a continuous membrane, either vertical or horizontal, such as a wall, floor or ceiling assembly that is designed and constructed to restrict the movement of smoke*”.

4

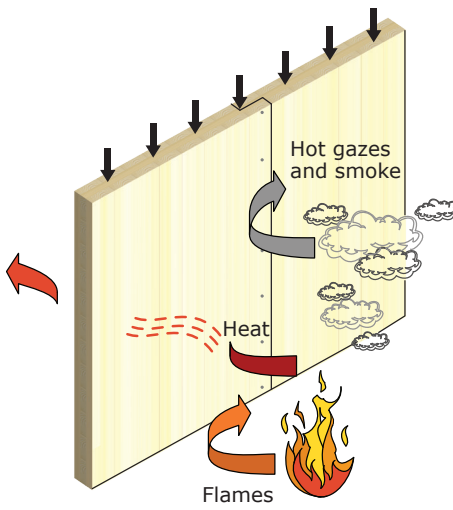
FIRE RESISTANCE OF CLT

Structural fire performance of building assemblies are assessed by conducting fire-resistance tests in accordance with ASTM E119 [10]. A fire-resistance rating is defined as the period of time a building element, component, or assembly maintains the ability to perform its separating function (i.e., confining a fire by preventing or retarding the passage of excessive heat, hot gases or flames), continues to perform a given loadbearing function, or both. More specifically, a standard fire-resistance test entails three failure/acceptance criteria (Figure 1):

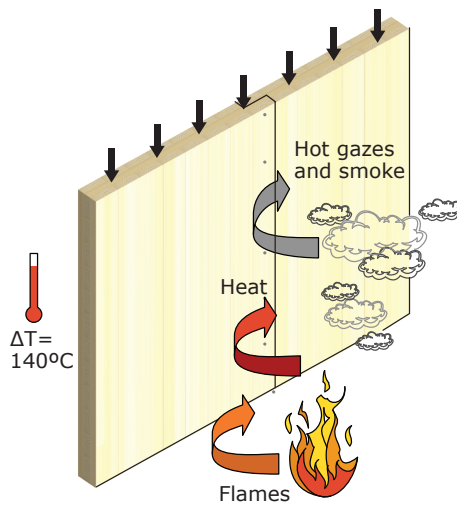
1. **Structural resistance:** the assembly must support the applied load for the duration of the test (relates to the loadbearing function);
2. **Integrity:** the assembly must prevent the passage of flame or gases hot enough to ignite a cotton pad (relates to the separating function);
3. **Insulation:**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



a) Structural resistance



b) Integrity



c) Insulation

Figure 1
Fire resistance criteria per ASTM E119

The time at which the assembly can no longer satisfy any one of these three criteria defines the assembly's fire resistance. Fire-resistance ratings are usually assigned in whole numbers of hours (e.g., 1 hour and 2 hours) or parts of hours (e.g., ½ hour or 30 min and ¾ hour or 45 min).

The requirements for the construction of fire-resistance-rated building elements are detailed in Chapter 7 of the IBC. These provisions include the details for addressing penetrations in rated building elements.

When designing CLT buildings, it is necessary to use products that comply with the required fire-resistance rating. In some instances, such as for some non-loadbearing partition wall assemblies, only the separating function is necessary in defining the fire resistance (e.g., the assembly must meet the insulation and integrity criteria only). In the case of loadbearing walls and all floor assemblies, the assembly must provide both the separating function as well as structural resistance not less than the duration of the fire-resistance rating required in the IBC. The determination of fire resistance of CLT assemblies has thereby been split into requirements for separating fire resistance and structural fire resistance in this Chapter.

The distinction of the portions of a CLT assembly needed for loadbearing and that needed for the separating fire protection function may provide opportunities for lower costs that have also been raised with respect to log structures. The full width of the CLT wall may not be needed to maintain the structural integrity of the wall during a fire. Thus, there is a potential to allow portions of the walls to be of different thicknesses. The entire wall would need to be thick enough to maintain the integrity and thermal criteria of the fire-resistance test, but only portions of the wall would need to be of the greater thickness for the structural criteria, if needed.

4.1.1 Test Method – ASTM E119

The fire-resistance rating of a building assembly is assessed by subjecting a specimen of the assembly to a standard fire-resistance test such as ASTM E119 or UL 263 [11] in the United States, as required by Section 703.2 of the IBC. Comparable standard tests such as ULC S101 [12] in Canada and ISO 834 [13] in some other countries are used in those countries. These three standards (ASTM E119, ULC S101 and ISO 834) have many similarities. They require a wall (Figure 2) or floor (Figure 3) assembly to be exposed to a post-flashover fire specified by a time-temperature curve (Figure 4).



a) Unprotected CLT before test b) Unexposed surface during test c) Protected CLT after test

Figure 2
CLT fire-resistance wall tests conducted at NRCC in Ottawa (Canada)



a) Unprotected CLT before test b) Unexposed surface during test c) Protected CLT after test

Figure 3

CLT fire-resistance floor tests conducted at NRCC in Ottawa (Canada)

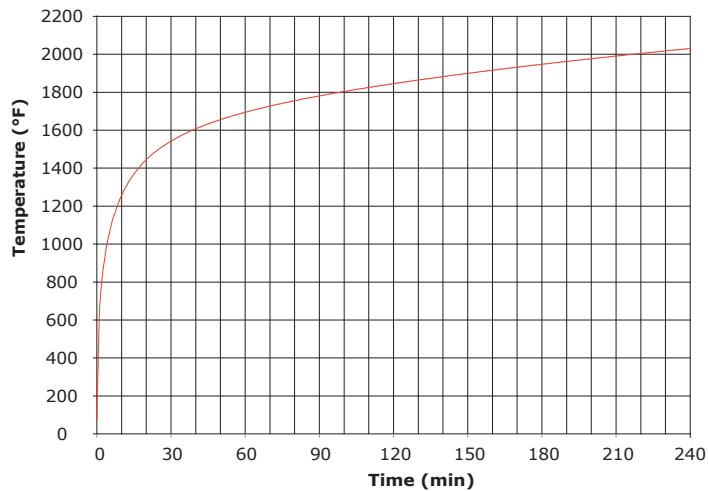


Figure 4

Standard time-temperature curve from ASTM E119

For loadbearing assemblies, the test standard requires the assembly to be loaded during fire exposure. It also requires the superimposed load to be the maximum load condition allowed under nationally recognized structural design criteria, such as those for allowable stress design in the *National Design Specification (NDS) for Wood Construction* [14], unless limited design criteria are specified and a corresponding reduced load is applied. A test conducted under the maximum load ensures that the fire-resistance rating obtained is appropriate for use in any equal or lesser loading conditions (assuming they satisfy the loadbearing requirements). Additional information regarding the loading conditions during a standard fire-resistance test of wood components can be found in ASTM D6513 and D7746 standards [15, 16].

However, it is rare that CLT structures will be structurally loaded anywhere near their ultimate capacity and quite often may be carrying loads below 20% of their design capacity due to serviceability limits (deflection or vibration). In addition, most test facilities do not have the capacity to load CLT assemblies to maximum loading conditions. As such, a rational fire-resistance calculation methodology, based on first principles such as charring rate, reduced effective cross-section, and load ratio, is more suitable to ensure an efficient and economical CLT building design.

4.1.1.1 Fire-resistance Requirements

The fire-resistance requirements stipulated in the IBC depend on the structural element, type of construction, use and occupancy classifications, distance from property line and other factors such as the special detailing requirements based on use and occupancy (Chapter 4 of IBC). The general requirements can be found in Table 601 of the IBC. For each type of building element, the table specifies the required fire-resistance rating depending on the type of construction. For example, exterior bearing walls must have a 1-hour rating in Type V-A construction and a 2-hour rating in Type IV construction. In Type V-B, the building elements are not required to have any fire resistance rating. As listed in Table 602 of the IBC, the fire-resistance ratings for the exterior walls are also a function of the fire separations distance from the adjacent property or building. For example, all buildings of occupancy group H (High-hazard) with a fire separation distance of less than 5 feet are required to have exterior walls with a 3-hour fire-resistance rating. There are also specific fire-resistance requirements for some specific circumstances, e.g., an exterior wall adjacent to exterior exit stairways (Section 1026.6) and exterior walls on each side of the intersection of fire wall (Section 706.5.1 of the IBC). In some limited situations, the installation of a NFPA 13 [9] automatic fire sprinkler system can be an alternative to a 1-hour fire-resistance requirement.

In addition, as stipulated in Section 705.5 of the IBC, when the fire separation distance is ten feet or less, the fire-resistance rating of an exterior wall must be determined from both sides, or symmetrically determined. When the fire separation distance is greater than ten feet, the fire resistance may be determined from the interior side only.

4.1.2 NDS Methodology for Wood Fire Design

The NDS methodology for determining the fire resistance of timber elements is a mechanics-based design method [17] based on ASD calculation procedures and is referenced in Section 721.1 of the IBC for exposed wood members and wood decking. It calculates the capacity of exposed wood members using basic wood engineering mechanics and has been incorporated in the 2001 and later editions of the NDS for fire-resistance calculations of up to 2 hours, limited by the test data available at the time.

The actual mechanical and physical properties of the wood are used and the capacity of the member is directly calculated for a given period of time. The section properties are computed assuming an effective charring rate (β_{eff}) at a given time (t) of fire exposure. Reductions of strength and stiffness of wood directly adjacent to the char layer are addressed by a zero-strength layer (d_0) that is 20% of the char depth. For a char depth of 1.5 in. (38 mm) at 60 minutes, the 20% corresponds to a zero-strength layer (d_0) of 0.3 in. (7.6 mm). The member strength properties are adjusted to the average strength value (i.e., mean or 50th percentile) based on existing accepted statistical procedures such as ASTM D2915 [18], used to evaluate allowable properties for structural lumber.

Finally, the wood members are designed using accepted engineering procedures found in the NDS and the failure occurs when the load applied on the member exceeds the member capacity which has been reduced due to fire exposure.

In order to estimate the reduced cross-sectional dimensions, the location of the char base must be determined as a function of time on the basis of empirical charring rate data. The char layer can be assumed to have zero strength and stiffness.

4.1.3 Application of NDS Methodology to CLT

4.1.3.1 Charring Rate and Char Depth

According to the NDS procedure, the effective charring rate and effective char depth can be estimated from published nominal 1-hour charring rate data using Equations 1 and 2.

$$\beta_{eff} = \frac{1.2\beta_n}{t^{0.187}} \quad [1]$$

$$a_{char} = \beta_{eff}t = 1.2\beta_n t^{0.813} \quad [2]$$

where β_{eff} is the effective charring rate (in./hr) adjusted for exposure time (t), β_n is the nominal linear charring rate (in./hr) based on a 1-hour exposure, t is the exposure time (hr) and a_{char} is the effective char depth (in.). According to Equation 1, the charring rate has a non-linear form [19] and therefore varies as a function of time. The 1.2 factor is the inclusion of the zero-strength layer within the effective charring rate β_{eff} . The charring rate that corresponds to visual observations of char depth is $\beta_n/t^{0.187}$. In addition to visual observation, the $\beta_n/t^{0.187}$ corresponds to char depths based on a 550°F (300°C) temperature criteria commonly used to measure the char depths over the duration of a fire test.

A nominal charring rate (β_n) of 1.5 in./hr (0.635 mm/min) is commonly assumed for solid-sawn and glue-laminated softwood members. For a nominal charring rate (β_n) of 1.5 in./hr, the effective charring rates (β_{eff}) and effective char layer thicknesses (a_{char}) for each exposed surface are shown in Table 3. Also shown in Table 3 are the corresponding visual char layer and zero-strength layer that make up the effective char layer thickness. The NDS limits the application of the methodology to ratings not exceeding 2 hours. Additional data is needed to validate the models for long periods. Deviations between the NDS model and a linear charring rate model used in other countries, which includes a fixed zero-strength layer, are more pronounced at durations exceeding 2 hours.

Table 3

Effective charring rates and char layer thicknesses per the NDS methodology

Required Fire Resistance	Effective Charring Rate, β_{eff} (in./hr)	Visual Char Layer Thickness (in.)	Zero-strength Layer (in.)	Effective Char Layer Thickness, a_{char} (in.)
45 min (¾-h)	1.90	1.19	0.24	1.42
60 min (1-h)	1.80	1.50	0.30	1.80
90 min (1½-h)	1.67	2.09	0.42	2.50
120 min (2-h)	1.58	2.64	0.53	3.16

4.1.3.2 Effect of Adhesive Fire Performance on the Effective Char Depth

ANSI/APA PRG 320 Standard for Performance-Rated Cross-Laminated Timber requires that, when for use in the United States, adhesive used in the manufacturing of CLT shall meet the requirements of AITC 405 [20] with the exception that Section 2.1.6 of AITC 405 (either ASTM D3434 [21] or CSA O112.9 [22]) is not required. Also, adhesives used shall be evaluated for heat performance in accordance with Section 6.1.3.4 of DOC PS1 [23]. Note 7 of ANSI/APA PRG 320 states “*The intent of the heat performance evaluation is to determine whether an adhesive has exhibited 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 recommended to consult with the adhesive manufacturer and the approved agency to develop an appropriate adjustment in product manufacturing and/or an end-use recommendation.*”

The CLT panels used for developing the fire-resistance calculation methodology were manufactured with a structural polyurethane (PUR) adhesive conforming to ANSI/APA PRG 320 standard for use in both United States and Canada. During the full-scale fire research on CLT [24], small pieces of the charred layers have been observed to fall off when the temperature at the CLT lamination interface (glue line) approached 550°F (300°C), indicating an adhesive failure. Analysis of the data indicated an acceleration of the charring rate subsequent to the failure of a laminate. Loss of the char layer when the char front reaches the glue line effectively resets the nonlinear charring rate used in the NDS methodology, resulting in an accelerated charring rate.

Such delamination effect was also observed in experiments carried by Frangi et al. [7] on one-component polyurethane structural adhesive, where it actually increased the charring rate of the CLT when exposed to fire. It should be noted however that, in Europe, structural adhesives must comply with performance requirements given in EN 301 [25] and EN 15425 [26]. The highest temperature in the tests according to these European standards is 158°F (70°C), being held over two weeks under constant loading of the bonded specimens. Therefore, the current European standards provide little or no information nor do they give a classification for adhesives at elevated temperature, appropriate for fire resistance design [7]. Such temperature exposure is also much lower than the temperature of the base charred layer, generally taken as 550°F (300°C) [27]. The question of the integrity of a laminate that has charred therefore involves performance at temperatures of 550°F (300°C) and higher.

Thus, the char depth model shown in Equation 2, used in the fire-resistance calculations, needs to be modified to address the potential delamination of CLT laminates. Extensive testing with a variety of products made with phenol-resorcinol-formaldehyde adhesive has shown that charring does not result in delamination when this adhesive is used. The delamination in the series of tests performed in Canada using an adhesive in compliance with ANSI/APA PRG 320 indicates that the ASTM D7247 [28] test may not be severe enough to address glue lines in the char layer (550°F or 300°C). Additional fire testing of CLT manufactured with PUR adhesive is warranted.

4.1.3.3 Modified Effective Char Depth Calculation for CLT Assemblies

The modified char depth model for CLT products made of adhesives that might delaminate when the char depth reaches the glue line is a simple step-wise approach that resets the time in the charring rate equation (Equation 1 without the 1.2 factor) to zero whenever the calculated char depth reaches the glue line of adjacent laminates. In the Canadian tests, this modification of the NDS charring rate model resulted in calculated char depths consistent with the char depths indicated by thermocouples recording temperatures of 300°C along the boards interface (i.e., glue lines), a widely used criterion for the base of the char layer (Figures 5 and 6 show the charring rates from tests conducted with 1.375 in. (35 mm) and 0.83 in. (21 mm) laminates). It can be seen from these two figures that the charring rate for CLT is influenced by the thickness of the layers whereas thinner layers heat up more rapidly than thicker layers, resulting in a faster time for a glue line to reach its critical failure temperature, which may lead to fall-off of the laminates. It can also be observed that the stepped model provides an average linear charring rate of 1.56 in./hr (0.66 mm/min) and 1.74 in./hr (0.74 mm/min) for laminates with thickness of 1.375 in. and 0.83 in., respectively.

Once the char depth is calculated using the step-wise approach, the 1.2 factor is applied for determining the effective char layer into the structural fire-resistance calculations. For example, assuming a CLT manufactured with 1 3/8 in. (35 mm) thick lumber boards required to have a 1-hour fire resistance, the lamination char fall-off would occur at 54 min (e.g., $[1\frac{3}{8} \text{ in.} \div (1\frac{1}{2} \text{ in./hr})]^{1.23} = 0.90 \text{ hr} = 54 \text{ min}$). The remaining 6 minutes provide a char depth of 0.23 in. (e.g., $[(1\frac{1}{2} \text{ in./hr}) \times (6/60 \text{ hr})^{0.813}] = 0.23 \text{ in.}$), for a total char depth of 1.61 in. The effective char depth for structural fire resistance is then 1.93 in., which is a 7% increase when compared to the 1.8 in. effective char depth obtained from the NDS nonlinear model shown in Equation 2, which does not consider potential delamination.

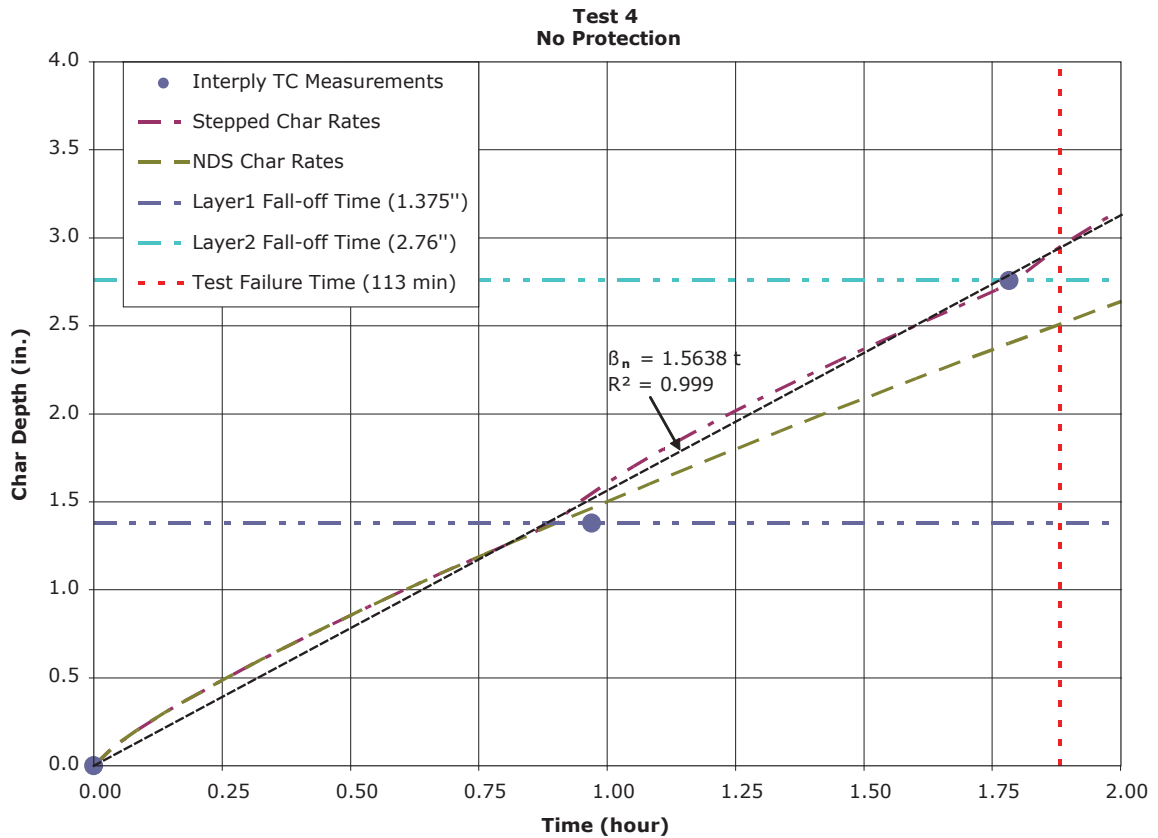


Figure 5
Char depth adjusted for CLT assemblies with 1 3/8 in. (35 mm) laminates (Test 4 from [24])

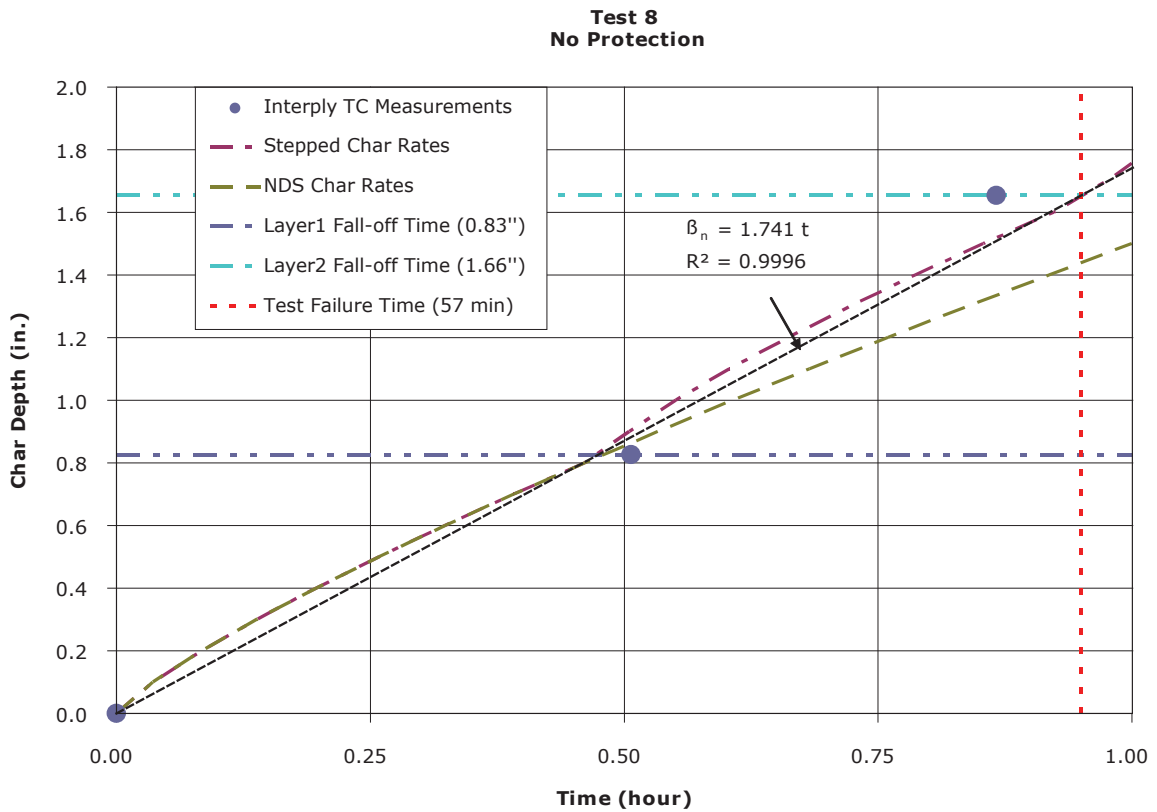


Figure 6
Char depth adjusted for CLT assemblies with 0.83" (21 mm) laminates (Test 8 from [24])

It is anticipated that CLT assemblies manufactured with adhesives that do not exhibit delamination at temperatures below the char front (i.e., that would char at a similar rate as a solid wood) may follow the standard NDS procedure for calculating the effective char depth, as per Equations 1 and 2, without the stepped charring rate adjustment.

4.1.3.4 Approximation of Member Strength and Capacity

As defined in ANSI/APA PRG 320, cross-laminated timber (CLT) is a prefabricated solid engineered wood product made from at least three (3) orthogonally bonded layers of finger jointed solid-sawn visually-graded or mechanically-graded lumber or structural composite lumber (SCL). As CLT is made of bonded layers similarly to glue-laminated timber, it is expected that the coefficient of variation for CLT is at least equal to or greater than clear wood; therefore, the strength adjustment factors (K) prescribed in [17] may be used. For CLT assemblies, the average strength can be approximated by multiplying design values (F_b , F_t , F_c , F_{bE} and F_{cE}) by the adjustment factors set forth in Table 16.2.2 of the NDS, which are summarized in Table 4.

Table 4

Adjustment factors for fire design in accordance with [14]

Strength	Strength Adjustment Factor (K)	Size Factor ⁽¹⁾	Volume Factor ⁽¹⁾	Flat Use Factor ⁽¹⁾	Beam Stability Factor ⁽²⁾	Column Stability Factor ⁽²⁾
Bending (F_b)	2.85	C_F	C_V	C_{fu}	C_L	-
Tensile (F_t)	2.85	C_F	-	-	-	-
Axial Compression (F_c)	2.58	C_F	-	-	-	C_p
Beam Buckling (F_{bE})	2.03	-	-	-	-	-
Column Buckling (F_{cE})	2.03	-	-	-	-	-

⁽¹⁾ Factor shall be determined using initial cross-section dimensions

⁽²⁾ Factor shall be determined using reduced cross-section dimensions

All member strength and cross-sectional properties should be adjusted prior to the interaction calculations. The interaction calculations should then be conducted in accordance with appropriate NDS provisions.

4.1.3.5 Structural Design of CLT Assemblies Exposed to Fire (Loadbearing Function)

Once the CLT assembly capacity has been determined using the effective section properties from Subsection 4.1.3.1 and the member strength approximations from Subsection 4.1.3.4 of this Chapter, the CLT assembly can be designed using accepted NDS design procedures for the loading condition shown in Equation 3.

$$L + D \leq KR_{ASD} \quad [3]$$

where $L+D$ are the load effect due to the sum of the live and dead loads and where KR_{ASD} is the nominal allowable design capacity adjusted to average ultimate capacity.

4.1.4 Fire Resistance of CLT Assemblies – Structural Requirement

The procedure set forth in ASTM E119 is applicable to floor and roof assemblies with or without attached, furred, or suspended ceilings and requires application of fire exposure to the underside of the specimen under test. When evaluating wall assemblies, the specimen is exposed to fire from one side only. This structural requirement is essential in limiting the risk of structural failure or collapse of physical elements due to the effects of a fire.

4.1.4.1 Structural Fire Resistance

This calculation procedure applies only to CLT panel assemblies exposed to the ASTM E119 standard fire-resistance test exposure.

Calculation of the structural fire-resistance failure time of CLT floor or wall assemblies is outlined in the five steps described hereafter. The time at which the CLT assembly can no longer support the applied load defines its structural fire resistance (t_{struc}).

Figure 7 shows a CLT panel exposed to fire and some of the nomenclature used in calculating its fire resistance. Note that the classical laminates wood composite theory, as described by Bödig & Jayne [29], is the most suitable method for fire design as the cross-section reduces as function of time and then becomes asymmetrical (e.g., unbalanced lay-up). Cross plies are not taken into account in the calculation of the design resistive moment for floors nor the resisting wall compression capacity (i.e., $E_{90} = G_0 = G_{90} = 0$). Also, calculations are typically made for a unit width of CLT panel, typically 1 foot.

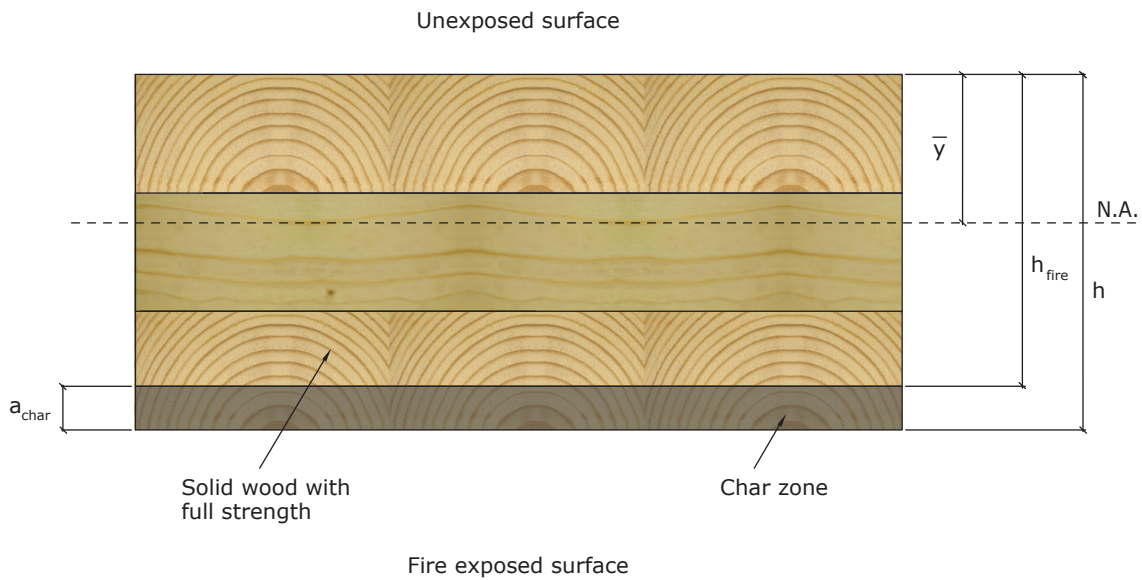


Figure 7

Nomenclature used in calculating fire resistance of a CLT exposed to fire from below

Step 1: Calculation of lamination fall-off time

Calculate the time required to reach every glued interface (i.e., glue lines) as per Equation 4. This time step will determine the number of charred layers considering potential delamination due to the adhesive performance at elevated temperature.

$$t_{fo} = \left(\frac{h_{lam}}{\beta_n} \right)^{1.23} \quad [4]$$

where:

- t_{fo} = time to reach a glued interface (hr)
- h_{lam} = lamella thickness (in.)
- β_n = nominal charring rate = 1.5 in./hour

The number of layers of laminations that may fall-off is then rounded to the lowest integer as follows:

$$n_{lam} = INT \left(\frac{t}{t_{fo}} \right) \quad [5]$$

where:

n_{lam} = number of laminations that may fall-off (rounded to lowest integer)
 t = required fire resistance (hours).

Step 2: Calculation of the effective char depth

Calculate the effective depth of char based on the number of laminations that may delaminate by using the stepped charring rate model described in Subsection 4.1.3.3 of this Chapter. The effective depth of char can be calculated as follows:

$$a_{char} = 1.2 \left[n_{lam} \cdot h_{lam} + \beta_n \left(t - (n_{lam} \cdot t_{fo}) \right)^{0.813} \right] \quad [6]$$

where:

a_{char} = effective depth of char (in.).

Step 3: Determination of effective residual cross-section

The effective cross-section depth remaining for design under fire conditions (h_{fire}) can be calculated as:

$$h_{fire} = h - a_{char} \quad [7]$$

where:

h_{fire} = effective cross-section depth (in.)
 h = initial cross-section depth of the CLT panel (in.)

Since the stiffness of the crossing plies is ignored (i.e., $E_{90} = 0$), should h_{fire} fall within a cross ply (i.e., between plies that are parallel to the applied stress), h_{fire} is reduced to the distance from the unexposed face to the edge of the nearest inner ply of the major strength direction.

Step 4: Find location of neutral axis and section properties of the effective residual cross-section

Equation 8 shall be used to calculate the location of the neutral axis (\bar{y}) when the plies parallel to the direction of the applied stress do not all have the same modulus of elasticity.

$$\bar{y} = \frac{\sum_i \tilde{y}_i h_i E_i}{\sum_i h_i E_i} \quad [8]$$

where:

\bar{y} = distance from the unexposed surface of the panel to the neutral axis (in.)
 \tilde{y}_i = distance from the unexposed surface of the panel to the centroid of ply i (in.)
 h_i = remaining depth of ply i (in.)
 E_i = modulus of elasticity of the ply i in the major strength axis (psi).

It should be reminded that the modulus of elasticity for plies perpendicular to the applied stress (i.e., E_{90}) can typically be approximated as $E/30$. However, in fire design, this value can conservatively be assumed to equal zero when calculating the neutral axis and section properties of asymmetrical cross-sections by the classical laminates wood composite theory.

If the plies in the direction of the applied stress all consist of the same grade and species group and therefore have the same modulus of elasticity, Equation 5 can be reduced to the following equation:

$$\bar{y} = \frac{\sum_i \tilde{y}_i h_i}{\sum_i h_i} \quad [9]$$

The effective bending stiffness of the effective residual cross-section can be determined using Equation 10 as follow:

$$EI_{eff} = \sum_i \frac{b_i h_i^3}{12} E_i + \sum_i b_i h_i d_i^2 E_i \quad [10]$$

where:

- EI_{eff} = effective bending stiffness (lb·in.²)
- d_i = distance from the neutral axis to the centroid of ply i (in.)
- b_i = unit width of the CLT panel (typically 1 foot)
- h_i = distance from the neutral axis to the centroid of ply i (in.).

Similarly, if the plies in the direction of the applied stress all consist of the same grade and species group and therefore have the same modulus of elasticity, Equation 10 can be reduced to the following equation for determining the moment of inertia of the effective residual cross-section:

$$I_{eff} = \sum_i \frac{b_i h_i^3}{12} + \sum_i b_i h_i d_i^2 \quad [11]$$

where:

- I_{eff} = moment of inertia of the effective residual cross-section (in.⁴).

Step 5: Calculation of structural resistance

Using the effective reduced cross-section determined in Step 3 and ignoring any contribution to the strength provided by the plies perpendicular to the applied stress, calculate the member capacity by multiplying the adjusted stress design values by using accepted NDS design procedures related to fire design of wood members.

The calculation of the design resisting moment and the resisting axial compression capacity has been split into Steps 5a and 5b respectively due to the different interactions used.

Step 5a: Calculation of the design resisting moment

The design resisting moment of a CLT assembly can be calculated using the procedure of Section 3.3 of NDS. The effective section modulus of the residual cross-section (S_{eff}) is calculated based on the moment of inertia of the plies running in the direction of the applied stress (I_{eff}) and the location of the neutral axis (\bar{y}) as shown in Equation 12.

$$S_{eff} = \frac{EI_{eff}}{E(h_{fire} - \bar{y})} \quad [12]$$

where:

S_{eff} = effective section modulus (in.³)

E = modulus of elasticity of the ply that sustains the greatest tensile stress, typically E_i (psi).

If the plies in the direction of the applied stress all consist of the same grade and species group and therefore have the same modulus of elasticity, Equation 12 can be reduced to the following equation:

$$S_{eff} = \frac{I_{eff}}{h_{fire} - \bar{y}} \quad [13]$$

The size factor (C_p), volume factor (C_v), and lateral stability factor (C_l) for CLT panels should all be set to unity. The design resisting moment of a CLT assembly is thereby calculated based on the adjusted allowable bending stress value of the wood and the effective section modulus of the residual cross-section as shown in Equation 14.

$$M' = KF_b S_{eff} = 2.85F_b S_{eff} \geq M \quad [14]$$

where:

M' = design resisting moment in fire design (lb·in.)

K = adjustment factor in bending as per Table 4 and NDS = 2.85

F_b = bending stress design value of the wood (Tables 4A, 4B, 4C or 4F of NDS)

S_{eff} = effective section modulus (in.³)

M = maximum induced moment (lb·in.).

Note that the residual cross-section, neutral axis, moment of inertia and section modulus are continually changing during fire exposure as the cross-section is being reduced. Therefore, in cases where fire resistance may be the controlling design factor, it is recommended that these calculations be completed in a spreadsheet so the bending moment resistance can be calculated as a function of time.

An example showing the calculation of the bending moment resistance of a CLT floor assembly is shown in Subsection 4.1.8 of this Chapter.

Step 5b: Calculation of resisting axial compression capacity

The resisting axial compression capacity of a CLT assembly can be calculated using the procedures of Sections 3.6 and 3.7 of NDS. The effective area of the residual cross-section (A_{eff}) is calculated based on the area of the plies running in the direction of the applied axial stress.

In order to calculate the CLT wall stability factor (C_p), the slenderness ratio must be calculated using Equation 15.

$$\text{Slenderness ratio} = \frac{l_e}{\sqrt{\frac{12I_{eff}}{A_{eff}}}} \quad [15]$$

where:

l_e = effective length, typically equal to the unbraced height of the wall assembly (in.)

I_{eff} = moment of inertia of the effective residual cross-section (in.⁴)

A_{eff} = area of the effective residual cross-section (in.²).

The CLT wall stability factor shall be calculated as follows:

$$C_P = \frac{1 + (P_{cE}/P_c^*)}{2c} - \sqrt{\left[\frac{1 + (P_{cE}/P_c^*)}{2c} \right]^2 - \frac{P_{cE}/P_c^*}{c}} \quad [16]$$

where:

C_P = CLT wall stability factor

$P_{cE} = \frac{\pi^2 EI'_{min}}{l_e^2}$ = resisting critical buckling capacity in fire design (lb.)

$P_c^* = KF_c^* A_{eff} = 2.58F_c^* A_{eff}$ (as per Table 4 and NDS) (lb.)

$EI'_{min} = E'_{min} I_{eff}$ (psi)

$E'_{min} = KE_{min} = 2.03 E_{min}$ (as per Table 4 and NDS) (psi)

$E_{min} = E[1 - 1.645 COV_E] \cdot 1.03/1.66 = 0.518 E$ (as per Table 4 and NDS) (psi)

$COV_E = 0.10$ (as per NDS)

$c = 0.9$ (applicable to glue-laminated timber, as per NDS)

The size factor (C_P) for CLT panels should be set to unity. The resisting axial compression capacity of a CLT assembly is thereby calculated based on the adjusted allowable axial compression stress value of the wood and the effective area of the residual cross-section as shown in Equation 17.

$$P' = KF_C A_{eff} C_P = 2.58F_C A_{eff} C_P \geq P_{load} \quad [17]$$

where:

P' = resisting axial compression capacity in fire design (lb.)

K = adjustment factor in compression as per Table 4 and NDS = 2.58

F_C = axial compression stress design value of the wood (Tables 4A, 4B, 4C or 4F of NDS)

A_{eff} = effective area (in.²)

P_{load} = axial compression load (lb.)

When exposed to fire, a CLT wall assembly is subjected to second-order effects (i.e., P-Δ effects) due to the charring of the fire exposed surface. The cross-section reduces as a function of time which causes the neutral axis to shift towards the unexposed surface, thus creating an increasing eccentricity as a function of time (Figure 8). It is strongly recommended to calculate the fire resistance of a CLT wall assembly by using the procedures of

Section 15.4 of NDS for combined bending and axial loading. The time at which the CLT wall assembly can no longer support the applied axial load defines its structural fire resistance (t_{Struct}). Equation 18 provides an alternate form of NDS Equation 15.4-2 for use with CLT assemblies.

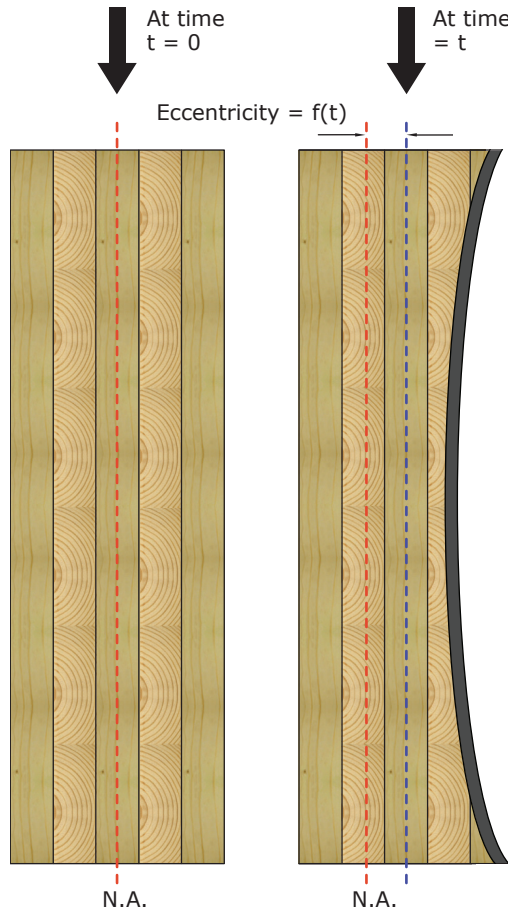


Figure 8
CLT wall assembly subjected to combined bending and axial compression

$$\left(\frac{P}{P'}\right)^2 + \frac{M + P\Delta\left(1 + 0.234\frac{P}{P_{cE}}\right)}{F'_b S_{eff}\left(1 - \frac{P}{P_{cE}}\right)} \leq 1.0 \quad [18]$$

where:

- P = axial compression load (lb.)
- P' = resisting axial compression capacity in fire design (lb.)
- M = maximum induced moment (lb.-in.)
- $P_{cE} = \frac{\pi^2 E'_{min}}{l_e^2}$ = resisting critical buckling capacity in fire design (lb.)
- $P_c^* = KF_c^* A_{eff} = 2.58F_c^* A_{eff}$ (as per Table 4 and NDS) (lb.)
- $E'_{min} = E'_{min} I_{eff}$ (psi)
- $E'_{min} = KE_{min} = 2.03 E_{min}$ (as per Table 4 and NDS) (psi)

- $E_{\min} = E[1-1.645 \text{ COV}_E] \cdot 1.03/1.66 = 0.518 E$ (as per Table 4 and NDS) (psi)
 $\text{COV}_E = 0.10$ (as per NDS)
 Δ = deflection due to out-of-plane loading (bending), including the distance from the neutral axis to the centroid of load point (typically at mid-depth) (in.)
 F'_b = adjusted bending design value for fire design (Tables 4A, 4B, 4C or 4F of NDS)
 S_{eff} = effective section modulus (in.³).

Note that the residual cross-section, neutral axis, moment of inertia and slenderness ratio are continually changing during fire exposure as the cross-section is being reduced. Therefore, in cases where fire resistance may be the controlling design factor, it is recommended that these calculations be completed in a spreadsheet so the axial capacity can be calculated as a function of time.

An example showing the calculation of a CLT wall assembly subjected to combined bending and axial load is shown in Subsection 4.1.9 of this Chapter.

4.1.4.2 Use of Protective Membranes to Increase Structural Fire Resistance

The mechanics-based design procedure in NDS Chapter 16, as discussed in Subsections 4.1.2 to 4.1.4, is approved for fire-resistance calculations of exposed wood members up to 2 hours. Full-scale fire-resistance wall and floor tests have been conducted on CLT alone and with gypsum board protection and demonstrate that the NDS design procedure can also be used with CLT with a few slight modifications. While the NDS design procedure is currently limited to 2-hr resistance calculations of the wood members acting alone, fire-resistance tests exceeding 2 hours have been conducted and have shown that the fire resistance of CLT assemblies can be increased above the calculated fire resistance of the CLT alone when protective membranes are used.

The above calculations are based on an unprotected CLT panel fully exposed to standard fire exposure. If gypsum board is applied on the fire exposed sides, experiments completed on tension members by the U.S. Forest Products Laboratory (FPL) [30] and on CLT assemblies protected by Type X gypsum boards by FPInnovations [24, 31] indicate that the following times can be added to the structural failure time of unprotected assemblies calculated in accordance with Subsection 4.1.4.1 of this Chapter:

- a) 30 minutes when one (1) layer of $\frac{5}{8}$ in. (15.9 mm) Type X gypsum board is applied;
- b) 60 minutes when two (2) layers of $\frac{5}{8}$ in. (15.9 mm) Type X gypsum board are applied.

The gypsum board protective membranes shall be attached directly to the CLT panels using $2\frac{1}{4}$ in. (57 mm) Type S drywall screws spaced at 12 in. (305 mm) on center along the perimeter and throughout. Screws shall be kept at least $1\frac{1}{2}$ in. (38 mm) from the sides of each board edge. When using a single thermal protective membrane, the gypsum board joints shall be covered with tape and coated with joint compound. When using two layers of thermal protective membranes, the face layer joints shall be covered with tape and coated with joint compound. In all cases, the screw heads of the exposed layer shall also be covered with joint compound.

4.1.5 Fire Resistance of CLT Assemblies – Integrity Requirement

As mentioned in Subsection 4.1.1, integrity is one of the two requirements of the separating function of building assemblies. The time at which the CLT panel-to-panel joint detailing can no longer prevent the passage of flame or gases hot enough to ignite a cotton pad defines the integrity fire resistance (t_{int}). This requirement is essential in limiting the risk of fire spread to compartments beyond the compartment of fire origin.

Such panel-to-panel joint performance depends on its configuration and connection details (refer to Chapter 5 of this Handbook) whereas the integrity failure may occur when the connection detail can no longer withstand the applied load in either shear or withdrawal. For instance, when using wood screws to connect CLT panels together, a minimum of penetration not less than six times the wood screw diameter is required for single shear connections.

As the exposed face chars over a period of time, the allowable thickness for providing an adequate lateral or withdrawal capacity reduces. Further to the full-scale fire-resistance tests and inspired by the European methodology for timber assemblies, a simple calculation model has been developed for half-lapped CLT panel-to-panel joints (Figure 9) and is represented in Equation 19.

$$t_{Int} = K_j \frac{h}{\beta_n} = 0.35 \frac{h}{\beta_n} \quad [19]$$

where:

t_{Int} = integrity fire resistance time (hours)

K_j = CLT panel-to-panel joint coefficient = 0.35 (for half-lapped joint)

h = CLT panel thickness (in.)

β_n = nominal charring rate based on a 1-hour exposure (one-dimensional) = 1.5 in./hr.

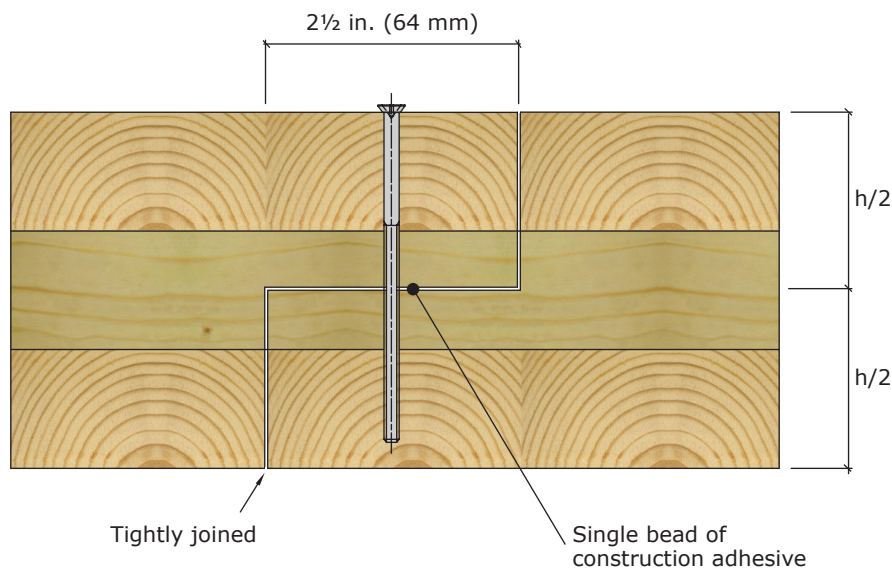


Figure 9
CLT panel-to-panel half-lapped joint detail

4.1.5.1 Effect of Joints on Integrity of CLT Walls and Floors

The panel-to-panel joint configuration can affect the integrity performance of CLT assemblies. The sides of individual CLT panels are shielded from full fire exposure by adjacent panels collectively acting as a joint. Partial exposure may occur as panels shrink and joints between panel open.

So far, only half-lapped joints have been evaluated (Figure 9) where the joint was located at mid-depth of the CLT panels and overlapping for at least 2 1/2 in. (64 mm). The joints were also fastened using self-tapping wood screws of 3 1/2 in. (90 mm), 6 1/4 in. (160 mm) and 8 3/4 in. (220 mm) for CLT assemblies made of 3-, 5- and 7-ply respectively. A bead of construction adhesive was also used to ensure that the joint was sealed.

However, connection details of CLT assemblies may also consist of single or double surface splines or internal spline(s). These tightly fitted joint profiles should provide sufficient fire resistance, but have yet to be properly evaluated for fire resistance in CLT assemblies.

The integrity of building assemblies is also regulated in the IBC by the requirements that through-penetrations (i.e., service penetrations) in assemblies be fire-resistance rated (refer to Section 7 for more details).

4.1.5.2 Use of Protective Membranes, Floor Coverings, and Interior Finish to Address Integrity

The calculation shown in Subsection 4.1.5 is based on an unprotected CLT panel-to-panel half-lapped joint fully exposed to standard fire exposure. When the integrity requirement cannot be fulfilled by the CLT panels alone, additional floor coverings or wall sheathings can be used to increase the integrity failure time. For example, the thickness of the floor coverings may be added to the CLT assembly thickness (b) when using Equation 19. If gypsum board is applied on the fire exposed side, the assigned time listed in Subsection 4.1.4.2 can be added to the unprotected CLT assembly integrity failure time.

Moreover, when adding a concrete topping, the integrity criteria may be assumed to be respected as the concrete topping will prevent the flame penetration through the assembly and the joint coefficient (k_j) may then be set to unity.

4.1.6 Fire Resistance of CLT Assemblies – Insulation Requirement

As mentioned in Subsection 4.1.1, insulation is one of the requirements of the separating function of building assemblies. The time at which the CLT assembly can no longer prevent the temperature on the unexposed surface from rising above 325°F (180°C) at any location, or an average of 250°F (140°C) measured at a number of locations, above the initial temperature, defines the insulative fire resistance (t_{ins}). This requirement is essential in limiting the risk of fire spread to compartments beyond the compartment of fire origin as well as allowing safe egress on the unexposed side of the assembly.

4.1.6.1 Theoretical Temperature Profiles for CLT Assemblies

Heat transfer occurs from regions of high temperature to regions of cooler temperature within solids (e.g., from the fire room of origin to adjacent compartments through a wall or floor assembly). Such heat transfer mode in solid materials is called conduction and is a well-known mechanism that satisfies Fourier's law of conduction. Conduction is also related to the material thermal conductivity (k) represented by the three dimensional (3-D) differential equation shown in Equation 20.

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left[k \frac{\partial T}{\partial x} \right] + \frac{\partial}{\partial y} \left[k \frac{\partial T}{\partial y} \right] + \frac{\partial}{\partial z} \left[k \frac{\partial T}{\partial z} \right] + \dot{Q} \quad [20]$$

where:

- ρ = density of material (kg / m³)
- c = specific heat of material (J / kg·K)
- k = thermal conductivity of material (W / m·K)
- $\partial T / \partial t$ = temperature as a function of time t (K / s)
- $\partial T / \partial x$ = temperature in the x-direction (K / m)
- $\partial T / \partial y$ = temperature in the y-direction (K / m)
- $\partial T / \partial z$ = temperature in the z-direction (K / m)
- \dot{Q} = rate of heat consumption per unit volume due to chemical reaction (W / m³).

The rate of heat absorption per unit volume due to chemical reaction consists of two parts: 1) the pyrolysis of the wood (Q''_{pw}) expressed by an Arrhenius function; and 2) the heat of evaporation of water per unit volume (Q''_w). More information in regards to the rate of heat, pyrolysis of the wood and heat of evaporation of water can be found in [32, 33].

Materials with a high thermal conductivity (such as steel) are usually considered to be good thermal conductors, while those having a low thermal conductivity (such as wood) are considered to be good thermal insulators. As such, the transient or steady-state heat transfer by conduction is low when compared with other materials having higher thermal conductivity.

Solving transient heat conduction through a solid material that exhibits charring can be challenging without the use of advanced computer models such as finite element software. Such temperature predictions may be useful for determining the time of charring of the wood when conducting a performance-based design.

4.1.6.2 Experimental Temperature Profile Data for CLT Assemblies

As the use of finite element analysis may not be available to most building designers, there are experimental temperature profile data for solid wood slabs. In one such generic profile [34], the temperature at a distance from the char front is given for when the member behaves as a semi-infinite solid, as shown in Equation 21:

$$T = T_i + (T_p - T_i) \left(1 - \frac{x}{a}\right)^2 \quad [21]$$

where:

- T = temperature (°C)
- T_i = initial temperature (°C)
- T_p = char front temperature (°C)
- x = distance from the char front (mm)
- a = thermal penetration depth (mm).

Based on data for eight species [19], the best fit values for the thermal penetration depth (a) were 1.34 in. (34 mm) for spruce, 1.30 in. (33 mm) for western red cedar and southern pine, and 1.38 in. (35 mm) for the redwood specimens [34]. In the 1993 Eurocode 5, “a” was assigned a value of 40 [34]. Thus, no temperature rise on the back surface is calculated to occur until the residual CLT thickness is less than 1.4 in. (35 mm) or 1.6 in. (40 mm). The thickness from the base of the char layer required to keep the temperature below the 250°F (140°C) average temperature rise criteria (or temperature of about 320°F (160°C)) indicated by Equation 21 is 0.5 in. (12 mm) but the slab (the backside being no longer at the ambient temperature) will no longer be behaving as a semi-infinite solid. Thus, the required thickness for the back surface is greater than this 0.5 inch value. The Wood Handbook [27] notes the temperature at ¼ in. (6 mm) inward from the base of the char layer in a semi-infinite slab subjected to ASTM E119 exposure is about 350°F (180°C).

In order to facilitate future Code acceptance for the design of CLT panels for fire resistance, a research project has recently been completed at FPInnovations. The main objective of the project aimed at developing and validating a generic calculation procedure to compute the fire-resistance ratings of CLT wall and floor assemblies. A series of full-scale wall and floor fire-resistance experiments in accordance with ASTM E119 standard time-temperature curve has been conducted to allow a comparison between the fire resistance measured during a standard fire-resistance test and that calculated using the proposed alternative method. Figure 10 shows the experimental temperature profile data obtained from this series of full-scale fire-resistances tests in accordance with ASTM E119 and ULC S101 standards compared to the profile obtained by using Equation 21.

It can be seen from the results in Table 5 that the insulation requirement is easily met, even for a temperature difference of 1836°F (1000°C) through an effective residual CLT thickness as thin as 1.92 in. (49 mm).

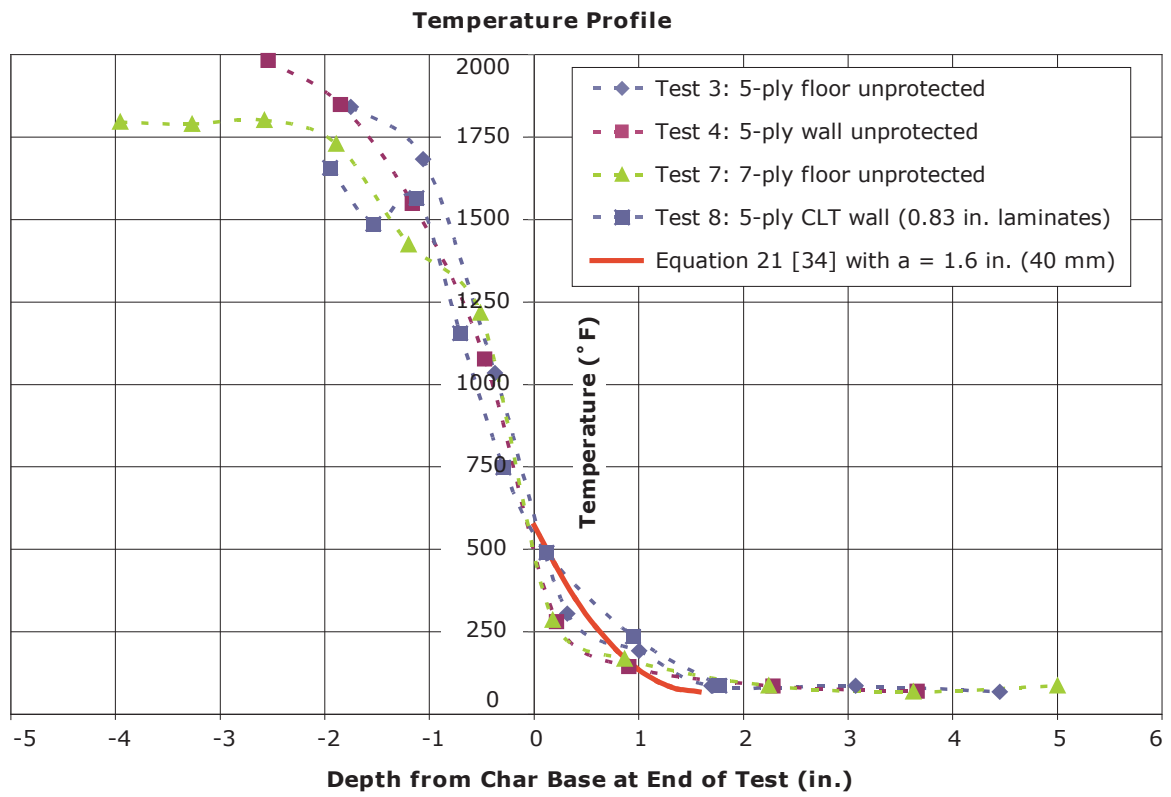


Figure 10
Experimental temperature profiles from [24] and Equation 21

Table 5

Average maximum temperature rises at unexposed surface

Assembly	Failure Time (min)	Effective Residual Thickness (in.)	Temperature			Temperature Rise on Unexposed Surface (°F)
			Furnace (°F)	Unexposed Surface (°F)	Initial Condition (°F)	
Wall 1	106	3.82	1817	75	73	2
Wall 2	113	3.62	1859	70	70	0
Wall 3	57	1.93	1922	86	70	16
Floor 1	77 *	4.13	1780	72	73	1
Floor 2	96	4.13	1800	68	68	0
Floor 3	86	2.20	1783	140	72	68
Floor 4	124	3.50	1843	81	73	8
Floor 5	178	4.13	1920	86	68	18

* Test was stopped due to equipment safety concerns. Failure was not reached.

4.1.7 Comparison between Calculation Method and Experiments

FPInnovations, in close collaboration with the National Research Council of Canada (NRCC), conducted eight fire-resistance tests to develop and validate a generic fire-resistance calculation procedure of CLT assemblies for code compliance (as described in Subsections 4.1.4 to 4.1.6 of this Chapter).

Different load ratios were applied depending on the number of plies and the assembly type (wall or floor). The assemblies were outfitted with thermocouples, embedded throughout the assemblies at five locations and in the panel-to-panel joints, and deflection gauges at nine locations.

Assemblies consisted of CLT panels, which were constructed either of SPF No.1, No.2, No.3 or MSR lumber boards and came from different manufacturers across Canada. The dimensions of the floor assemblies were 142 in. x 190 in. (3.61 m x 4.85 m) and the wall assemblies were 144 in. x 120 in. (3.66 m x 3.05 m) high. All assemblies used a half-lapped panel-to-panel joint which was fastened with self-tapping screws. The joints were also sealed during assembly using a ¼ in. (6 mm) bead of construction adhesive.

The panels were manufactured with a structural polyurethane adhesive conforming to ANSI/APA PRG 320 standard. Some of the CLT panels were fully exposed to fire (unprotected) while others were protected with Type X gypsum boards. Table 6 summarizes the configuration details of each tested CLT assemblies.

Table 6

CLT assemblies configuration details

	# of Plies	Lumber Grade in Major Strength Direction	Thickness in. (mm)	Gypsum Board Protection in. (mm)	Superimposed Load	Load Ratio (ASD) %
Wall	3	MSR 1650 f_b -1.5E	4.49 (114)	2 x ½ (12.7)	22818 lb./ft. (333 kN/m)	58
	5	MSR 1950 f_b -1.7E	6.89 (175)	Unprotected	22818 lb./ft. (333 kN/m)	29
	5	No.1/No.2	4.13 (105)	Unprotected	4934 lb./ft. (72 kN/m)	23
Floor	3	MSR 1650 f_b -1.5E	4.49 (114)	2 x ½ (12.7)	56 psf (2.7 kPa)	46
	5	MSR 1950 f_b -1.7E	6.89 (175)	Unprotected	246 psf (11.8 kPa)	75
	3	No.1/No.2	4.13 (105)	1 x ⅝ (15.9)	50 psf (2.4 kPa)	90
	5	No.1/No.2	6.89 (175)	1 x ⅝ (15.9)	169 psf (8.1 kPa)	120
	7	No.1/No.2	9.65 (245)	Unprotected	305 psf (14.6 kPa)	119

Note: Load ratios are based on $F_c' A_{eff}$ for walls and $F_b' S_{eff}$ for floors, under normal design conditions.

It should be noted that some specimens were loaded beyond their allowable strength capacities because the load ratios were derived based on ULC S101 requirement, which follows the limit states design philosophy (similar to LRFD), as opposed to the provisions given in ASTM D6513 and D7746, which follow the ASD philosophy.

The measured times to fire-resistance failure are compared to calculated fire resistance of CLT assemblies in Table 7 and Figure 11. The insulation requirement is not listed as this requirement was met in all cases, as shown in Table 5; therefore, only the structural (loadbearing) and integrity failure times are given, calculated as per Subsections 4.1.4 and 4.1.5 of this Chapter.

Table 7

Comparison between experiments and calculation methodology

	# of Plies	Experiments	Calculation Methodology		
		Failure Time (min)	Structural (min)	Integrity (min)	Assigned Fire Resistance (min)
Wall	3	106 (R)	63	102	63
	5	113 (R)	103	96	96
	5	57 (R)	53	57	53
Floor	3	77 (*)	81	102	81
	5	96 (E)	109	96	96
	3	86 (E)	59	87	59
	5	124 (E)	120	126	120
	7	178 (R)	107	135	107

* Test was stopped due to equipment safety concerns. Failure was not reached.
R = Structural Failure, E = Integrity Failure

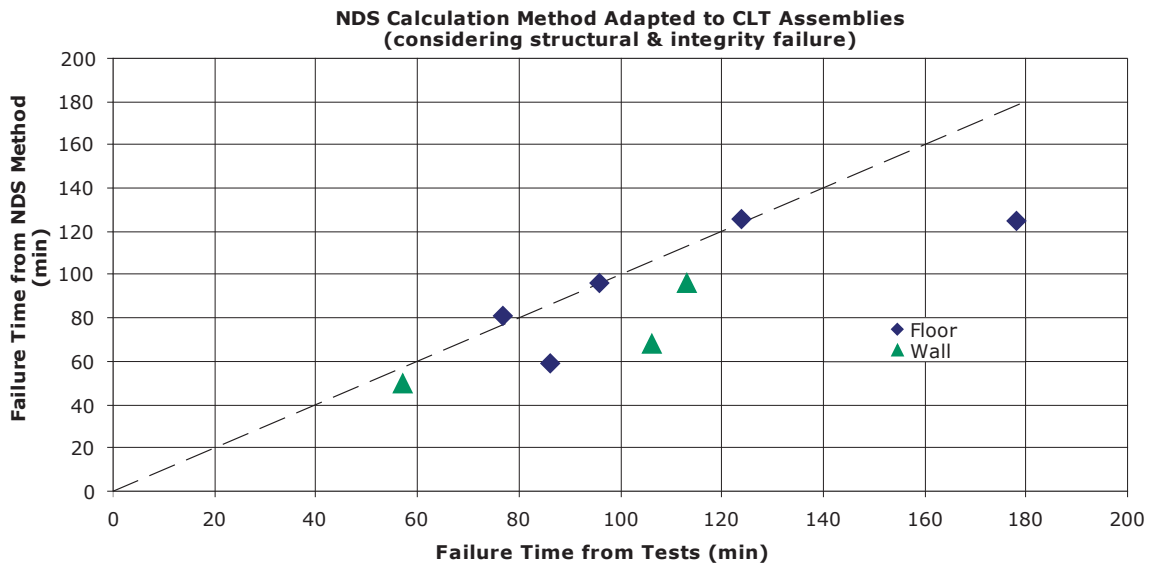


Figure 11

Comparison between experiments and calculation methodology

As can be seen in Figure 11, the mechanics-based method which uses a standard nominal charring rate ($\beta_n = 1.5$ in./hr), a non-linear stepped charring rate adjustment, a zero-strength layer multiplier of 1.2, and a standard variability adjustment in the design to ultimate adjustment factor predicts average fire-resistance times for CLT wall and floor assemblies that closely track actual fire-resistance times for tested assemblies. The experimental results that deviate the most from the predicted results were of a conservative nature since they exceeded the predicted results. While further refinements of this method are possible, these comparisons suggest that standardized adjustments

to design stresses, a standardized stepped charring rate, and the use of the NDS behavioral equations adequately address fire-resistance design of CLT assemblies.

4.1.8 Floor Design Example

The following floor design example follows the steps listed above for determining whether the fire resistance of an exposed 5-ply CLT floor assembly meets the hypothetically required fire-resistance rating of 90 minutes. The floor assembly has the following specifications:

- 5-ply CLT floor panel made from 1 3/8 in. x 3 1/2 in. lumber boards (CLT thickness of 6 7/8 in.)
- V2 CLT grade as per ANSI/PRG 320
 - $F_b S_{eff,0} = 4,675 \text{ lb.}\cdot\text{ft.}/\text{ft.}$
- Floor span = 18 feet (216 in.)
- Major strength direction plies
 - $F_{b,0} = 875 \text{ psi}$
 - $E_0 = 1.4 \times 10^6 \text{ psi}$
 - Specific gravity = 0.42 (26.1 lb./ft.³)
- Minor strength direction plies
 - $F_{b,90} = 500 \text{ psi}$
 - $E_{90} = 1.2 \times 10^6 \text{ psi}$
 - Specific gravity = 0.42 (26.1 lb./ft.³)
- Adhesive in accordance with ANSI/PRG 320 requirements (with potential delamination)
- Panels connected using a half-lapped joint as per Figure 9
- Applied load of 50 psf (live)
- Induced bending moment representing a load ratio of 56%.

4.1.8.1 Calculation of the Loadbearing Function after 90 Minutes of Standard Fire Exposure

Step 1: Calculation of lamination fall-off time

The time to reach a glue line is calculated from Equation 4 as follows:

$$t_{fo} = \left(\frac{h_{lam}}{\beta_n} \right)^{1.23} = \left(\frac{1\frac{3}{8}''}{1\frac{1}{2}''/hr} \right)^{1.23} = 0.90 \text{ h} = 54 \text{ min}$$

The number of layers of laminations that may fall-off is rounded to the lowest integer as follows:

$$n_{lam} = INT \left(\frac{90}{54} \right) = 1 \text{ laminate}$$

Step 2: Calculation of the effective char depth

The effective depth of char based on the number of laminations that may delaminate can be calculated as follows:

$$a_{char} = 1.2 \left[n_{lam} \cdot h_{lam} + \beta_n \left(t - (n_{lam} \cdot t_{fo}) \right)^{0.813} \right]$$
$$a_{char} = 1.2 \left[1 \cdot 1\frac{3}{8}'' + 1.5 \frac{in.}{hr} \left(\frac{90}{60} - \left(1 \cdot \frac{54}{60} \right) \right)^{0.813} \right] = 2.84 in.$$

Step 3: Determination of effective residual cross-section

The remaining cross-section is then calculated using Equation 4:

$$h_{fire} = h - a_{char} = 6\frac{7}{8} - 2.84 = 4.035 in.$$

In this example, the third ply has started to char and its residual thickness is 1.285 in. Its centroid is located at 3.393 in. from the unexposed side.

Step 4: Determination of location of neutral axis and section properties of the effective residual cross-section

Since the V2 CLT grade is of a symmetrical lay-up in accordance with ANSI/PRG 320, the simplified Equations 9 and 11 can be used to determine the neutral axis and the moment of inertia of the reduced cross-section:

$$\bar{y} = \frac{\sum_i \tilde{y}_i h_i}{\sum_i h_i} = \frac{\left(\frac{1.375}{2} \times 1.375 \right) + (3.393 \times 1.285)}{1.375 + 1.285} = 1.994 in.$$

$$I_{eff} = \sum_i \frac{b_i h_i^3}{12} + \sum_i b_i h_i d_i^2$$
$$= \left(\frac{12 \cdot (1.375)^3}{12} \right) + \left(\frac{12 \cdot (1.285)^3}{12} \right)$$
$$+ \left(12 \cdot 1.375 \cdot \left(1.994 - \frac{1.375}{2} \right)^2 \right)$$
$$+ (12 \cdot 1.375 \cdot (3.393 - 1.994)^2) = 63.1 \frac{in.^4}{ft.}$$

Step 5a: Calculation of design resisting moment

Using the effective reduced cross-section determined in Step 3 and ignoring any contribution to the strength provided by the cross-ply (i.e., minor strength direction), the design resisting moment of the CLT floor assembly capacity can be determined by using accepted NDS design procedures as described with Equations 13 and 14:

$$S_{eff} = \frac{I_{eff}}{h_{fire} - \bar{y}} = \frac{63.1 \frac{in.^4}{ft.}}{4.035 in. - 1.994 in.} = 30.9 \frac{in.^3}{ft.}$$

$$\begin{aligned} M' &= KF_b S_{eff} = 2.85 \cdot (0.85 \cdot 875 \text{ psi}) \cdot 30.9 \frac{in.^3}{ft.} = 65,498 \frac{lb. \cdot in.}{ft.} \\ &= 5,458 \frac{lb. \cdot ft.}{ft.} \end{aligned}$$

After 90 minutes of standard fire exposure, a thickness of 2.84 in. from the CLT panel has been volatilized into char ($h_{fire} = 4.035$ in.), which reduced the dead load portion of the applied load as follows:

$$w_{Total} = Live + Dead = 50 + \left(26.1 \cdot \frac{4.035}{12} \right) = 58.8 \text{ psf}$$

The induced bending moment in fire-resistance design is then equal to:

$$M_{max} = \frac{w_{Total} \cdot Span^2}{8} = \frac{58.8 \text{ psf} \cdot (18 \text{ ft.})^2}{8} = 2,381 \frac{lb. \cdot ft.}{ft.} \quad (\leq M')$$

The induced bending moment represents a load ratio of 44%, thus the CLT floor assembly meets the required 90 minutes fire resistance under these loads, span, and CLT grade and configurations.

It should be noted that, according to Subsection 4.1.4.2, a directly applied $\frac{5}{8}$ in. Type X gypsum board provides an extra 30 minutes to the fire resistance by delaying the time of ignition of the CLT panels. Therefore, the use of such protective membrane would provide a CLT assembly with 2 hours of fire resistance (90 min + 30 min = 120 min).

4.1.8.2 Calculation of the Separating Function after 90 Minutes of Standard Fire Exposure

The separating function of the CLT floor assembly is determined by using Equation 19 as follows:

$$t_{Int} = K_j \frac{h}{\beta_n} = 0.35 \times \frac{6\frac{7}{8} \text{ in.}}{1.5 \frac{in.}{hr}} = 1.6 \text{ hr} = 96 \text{ min}$$

As with the loadbearing function, a directly applied $\frac{5}{8}$ in. Type X gypsum board provides an extra 30 minutes to the fire resistance by delaying the time of ignition of the CLT panels underneath. Therefore, the use of such protective membrane would provide a CLT assembly with 2 hours of fire resistance (96 min + 30 min = 126 min).

4.1.9 Wall Design Example

The following wall design example follows the steps listed above for determining whether the fire resistance of a 3-ply CLT wall assembly meets the hypothetically required fire-resistance rating of 1 hour. The wall assembly has the following specifications:

- 3-ply CLT wall panel made from 1 3/8 in. x 3 1/2 in. lumber boards (CLT thickness of 4 1/8 in.)
- E1 CLT grade as per ANSI/PRG 320
 - $F_b S_{eff,0} = 4,525 \text{ lb.}\cdot\text{ft.}/\text{ft.}$
 - $EI_{eff,0} = 115 \times 10^6 \text{ lb.}\cdot\text{in.}^2/\text{ft.}$
 - $GA_{eff,0} = 0.46 \times 10^6 \text{ lb.}/\text{ft.}$
- Wall height = 12 feet (144 in.)
- Major strength direction plies
 - $F_{b,0} = 1,950 \text{ psi}$
 - $F_{c,0} = 1,800 \text{ psi}$
 - $E_0 = 1.7 \times 10^6 \text{ psi}$
 - Specific gravity = 0.50 (31.1 lb./ft.³)
- Minor strength direction plies
 - $F_{b,90} = 500 \text{ psi}$
 - $E_{90} = 1.2 \times 10^6 \text{ psi}$
 - Specific gravity = 0.42 (26.1 lb./ft.³)
- Adhesive in accordance with ANSI/PRG 320 requirements (with potential delamination)
- Panels connected using a half-lapped joint as per Figure 9
- Panels protected by a one layer of 5/8 in. Type X gypsum board
- Applied load of 8,425 plf (live)
- Induced load representing a load ratio of 41% of the resisting axial compression capacity and 40% of the bearing capacity.

4.1.9.1 Calculation of the Loadbearing Function after 60 Minutes of Standard Fire Exposure

Since the protective membrane provides a 30 min onset of charring to the CLT panels in accordance with Subsection 4.1.4.2, the structural fire-resistance calculation is conducted for a fire exposure of 30 minutes only.

Step 1: Calculation of lamination fall-off time

The time to reach a glue line is calculated from Equation 4 as follows:

$$t_{fo} = \left(\frac{h_{lam}}{\beta_n} \right)^{1.23} = \left(\frac{1\frac{3}{8}''}{1\frac{1}{2}''/hr} \right)^{1.23} = 0.90 \text{ h} = 54 \text{ min}$$

Since the fire exposure of 30 minutes is lower than the estimated time of potential lamination fall-off, Equation 2 can be used to calculate the effective char depth.

Step 2: Calculation of the effective char depth

The effective charring rate can then be calculated using Equation 2 for a fire exposure of 30 minutes as follows:

$$a_{char} = \beta_{eff} t = 1.2 \beta_n t^{0.813} = 1.2 \cdot 1.5 \frac{in.}{hr} \cdot \left(\frac{30}{60}\right)^{0.813} = 1.02 \text{ in.}$$

Step 3: Determination of effective residual cross-section

The remaining cross-section is then calculated using Equation 4:

$$h_{fire} = h - a_{char} = 4.125 - 1.02 = 3.105 \text{ in.}$$

In this wall design example, since h_{fire} falls within a ply of the major strength direction (i.e., within the third ply), only a portion of the exposed ply ($1.375 - 1.02 = 0.35$ in.) and the complete first unexposed ply can still be considered for this fire resistance design example. The third ply centroid is located at 2.925 in. from the unexposed side.

Step 4: Determination of location of neutral axis and section properties of the effective residual cross-section

Since the E1 CLT grade is of a symmetrical lay-up (along the major strength direction) in accordance with ANSI/PRG 320, the simplified Equations 6 and 8 can be used to determine the neutral axis and the moment of inertia of the reduced cross-section:

$$\bar{y} = \frac{\sum_i \tilde{y}_i h_i}{\sum_i h_i} = \frac{\left(\frac{1.375}{2} \times 1.375\right) + (2.925 \times 0.35)}{1.375 + 0.35} = 1.14 \text{ in.}$$

$$I_{eff} = \sum_i \frac{b_i h_i^3}{12} + \sum_i b_i h_i d_i^2 = \left(\frac{12 \cdot (1.375)^3}{12}\right) + \left(\frac{12 \cdot (0.35)^3}{12}\right) + \left(12 \cdot 1.375 \cdot \left(1.14 - \frac{1.375}{2}\right)^2\right) + \left(12 \cdot 0.35 \cdot (2.925 - 1.14)^2\right) = 19.4 \frac{in.^4}{ft.}$$

$$A_{eff} = \sum_i b_i h_i = (12 \cdot 1.375) + (12 \cdot 0.35) = 20.7 \frac{in.^2}{ft.}$$

Step 5b: Calculation of resisting axial compression capacity

Using the effective reduced cross-section determined in Step 3 and ignoring any strength and stiffness contribution from the cross-ply (i.e., minor strength direction), the resisting axial capacity of the CLT wall assembly can be determined by using accepted NDS design procedures as described with Equations 15 to 17.

$$\text{Slenderness ratio} = \frac{l_e}{\sqrt{\frac{12 I_{eff}}{A_{eff}}}} = \frac{144}{\sqrt{\frac{12 \times 19.4}{20.7}}} = 42.9 \quad (\leq 50)$$

$$\begin{aligned} E'_{min} &= 2.03 E [1 - 1.645 COV_E] \cdot \frac{1.03}{1.66} \\ &= 2.03 \cdot 1.7 \times 10^6 \text{ psi} \cdot (1 - 1.645 \cdot 0.10) \cdot \frac{1.03}{1.66} \\ &= 1.79 \times 10^6 \text{ psi} \end{aligned}$$

$$P_{cE} = \frac{\pi^2 E I'_{eff}}{l_e^2} = \frac{\pi^2 \cdot (1.79 \times 10^6 \cdot 19.4)}{(144)^2} = 16,528 \text{ plf}$$

$$\begin{aligned} P_c^* &= 2.58 \cdot F_c (C_D C_M C_t) \cdot A_{eff} = 2.58 \cdot 1,800 \cdot (1 \cdot 1 \cdot 1) \cdot 20.7 \\ &= 96,131 \text{ plf} \end{aligned}$$

$$\frac{P_{cE}}{P_c^*} = \frac{16,528}{96,131} = 0.17$$

$$\begin{aligned} C_P &= \frac{1 + (P_{cE}/P_c^*)}{2c} - \sqrt{\left[\frac{1 + (P_{cE}/P_c^*)}{2c} \right]^2 - \frac{P_{cE}/P_c^*}{c}} \\ &= \frac{1 + 0.17}{2 \cdot 0.9} - \sqrt{\left[\frac{1 + 0.17}{2 \cdot 0.9} \right]^2 - \frac{0.17}{0.9}} = 0.17 \end{aligned}$$

$$P' = K F_c A_{eff} C_P = 2.58 \cdot 1800 \text{ psi} \cdot 20.7 \frac{\text{in.}^2}{\text{ft.}} \cdot 0.17 = 16,342 \text{ plf or } \frac{\text{lb.}}{\text{ft.}}$$

After 30 minutes of standard fire exposure, a thickness of 1.02 in. from the CLT panel has been volatilized into char ($h_{\text{fire}} = 3.1$ in.) and the gypsum board has probably started to fall-off, which reduced the dead load portion of the induced axial load as follows:

$$\begin{aligned} P &= \text{Live} + \text{Dead} \\ &= 8,425 + \left(31.1 \cdot \frac{0.35 + 1.375}{12} \cdot 12 \right) \\ &\quad + \left(26.1 \cdot \frac{1.375}{12} \cdot 12 \right) = 8,515 \text{ plf} \end{aligned} \quad (\leq P')$$

Such induced axial load represents a load ratio of 52%, thus the CLT floor assembly meets the required 1 hour fire resistance under these loads, wall height, CLT grade and configurations as well as with a $\frac{5}{8}$ in. Type X gypsum board protective membrane on the fire exposed side.

As mentioned in Subsection 4.1.4.1, a CLT wall assembly is subjected to second-order effects (i.e., P- Δ effects) due to the charring of the fire exposed surface (Figure 8). It is strongly recommended to calculate the fire resistance of a CLT wall assembly by using the procedures of Section 15.4 of NDS for combined bending and axial loading, as shown in Equation 18.

$$S_{eff} = \frac{I_{eff}}{h_{fire} - \bar{y}} = \frac{19.4 \frac{in.^4}{ft.}}{3.1 in. - 1.14 in.} = 9.9 \frac{in.^3}{ft.}$$

$$\begin{aligned} M' &= KF_b S_{eff} = 2.85 \cdot (0.85 \cdot 1950 \text{ psi}) \cdot 9.9 \frac{in.^3}{ft.} = 46,766 \frac{lb \cdot in.}{ft.} \\ &= 3,897 \frac{lb \cdot ft.}{ft.} \end{aligned}$$

$$e = \frac{h}{2} - \bar{y} = \frac{4\frac{1}{8}}{2} - 1.14 = 0.92 \text{ in.}$$

$$\Delta_f = \frac{(P e) l_e^2}{16 E I_{eff}} = \frac{8,515 \cdot \left(\frac{4\frac{1}{8}}{2} - 1.14\right) \cdot 144^2}{16 \cdot 1.7 \times 10^6 \cdot 19.4} = 0.31 \text{ in.}$$

$$\Delta = e + \Delta_f = 0.92 + 0.31 = 1.23 \text{ in.} = 0.10 \text{ ft.}$$

$$\left(\frac{P}{P'}\right)^2 + \frac{M + P\Delta \left(1 + 0.234 \frac{P}{P_{cE}}\right)}{F'_b S_{eff} \left(1 - \frac{P}{P_{cE}}\right)} \leq 1.0$$

$$\left(\frac{8,515}{16,342}\right)^2 + \frac{0 + \left[8,515 \cdot 0.10 \cdot \left(1 + 0.234 \times \frac{8,515}{16,528}\right)\right]}{3,897 \cdot \left(1 - \frac{8,515}{16,528}\right)} = 0.78 \quad (\leq 1.0)$$

4.1.9.2 Calculation of the Separating Function after 60 Minutes of Standard Fire Exposure

The separating function of the CLT wall assembly is determined by using Equation 19 as follows:

$$t_{Int} = K_j \frac{D}{\beta_n} = 0.35 \cdot \frac{4\frac{1}{8} \text{ in.}}{1.5 \frac{\text{in.}}{\text{hr}}} = 0.96 \text{ hr} = 57 \text{ min}$$

According to Subsection 4.1.4.2, a directly applied $\frac{5}{8}$ in. Type X gypsum board provides an extra 30 minutes to the fire resistance by delaying the time of ignition of the CLT panels. Therefore, the use of such protective membrane would provide a CLT assembly with 1 hour of fire resistance (57 min + 30 min = 87 min).

5

CONNECTIONS

As described in Chapter 5 of this Handbook, entitled *Connections in cross-laminated timber buildings*, there is a wide variety of fasteners and many different types of joint details that can be used to establish wall-to-wall, wall-to-floor, and inter-story connections in CLT assemblies or to connect CLT panels to other wood-based elements, or to concrete or steel in hybrid construction. While long self-tapping screws are typically recommended by CLT manufacturers and are commonly used for panel-to-panel connections in floor (as per Figure 9) and floor-to-wall assemblies, traditional dowel-type fasteners such as wood screws, nails, lag screws, rivets, bolts and dowels can also be effectively used in connecting panel elements.

Connections in heavy timber construction, including those built with CLT, play an essential role in providing strength, stiffness, stability, ductility and structural fire resistance. Moreover, connections using metallic fasteners such as bolts, dowels and steel plates or brackets are widely used to assemble heavy timber components or CLT panels and to provide an adequate load path for gravity and/or lateral loads. Consequently, these connections require designers' attention to ensure that connections are not the weak link in heavy timber buildings exposed to fire.

Performance of timber connections exposed to fire can be quite complex due to the influence of numerous parameters such as the type of fasteners, the geometry of the connection, different failure modes as well as different thermal conductivity properties of steel, wood and char layer components. As such, most building codes, including the IBC, do not provide specific fire design methodology for determining the fire performance of timber connections.

Due to the high thermal conductivity of steel, metallic fasteners and plates directly exposed to fire may heat up and conduct heat into the wood members. The wood components may then experience charring on the exposed surface and around the fastener. As a result, the capacity of a metallic connection is reduced to the strength reduction of the steel fasteners at elevated temperatures and the charring of the wood members [35-43]. Therefore, where a fire resistance rating is required by the IBC, connections and fasteners are required to be protected from fire exposure by wood, gypsum board or other protection approved for the required rating.

However, some connections are not vulnerable to the damaging impact of fire. For example, a CLT wall-to-floor connection used to resist wind or seismic load, as shown in Figure 12, will not be significantly impacted by fire. However, connections used to resist gravity loads, as shown in Figure 13, may require some special considerations for increasing their resistance to fire exposure from underneath.

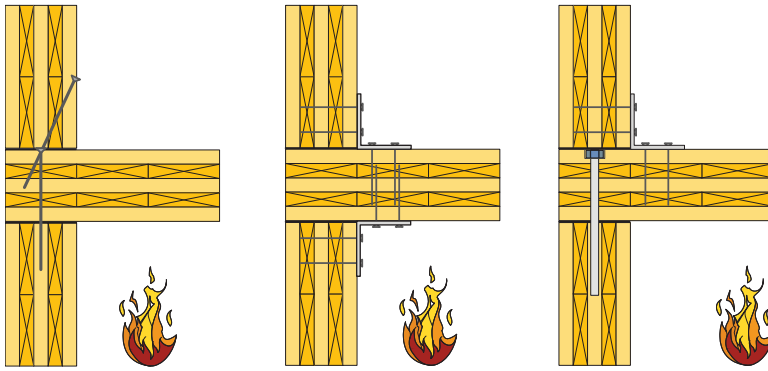


Figure 12
Examples of connections seen in CLT platform construction

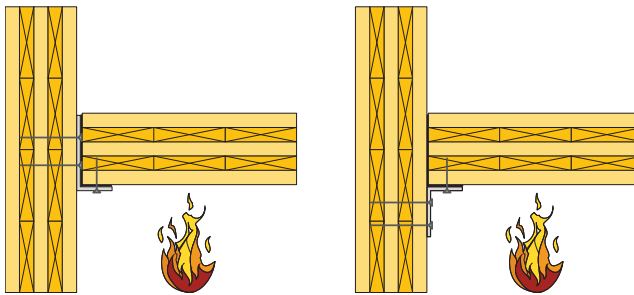


Figure 13
Examples of connections seen in CLT balloon construction

To improve aesthetics, designers often prefer to conceal connection systems. Hidden metal plates similar to those shown in Figure 14 can be used, but they require machining to produce the grooves in the CLT panel to conceal the metal plates.

When the connections are used in fire-retardant or preservative treated wood, recommendations with regard to the types of metal fasteners need to be obtained from the chemical manufacturer since some treatments cause corrosion of certain metals.

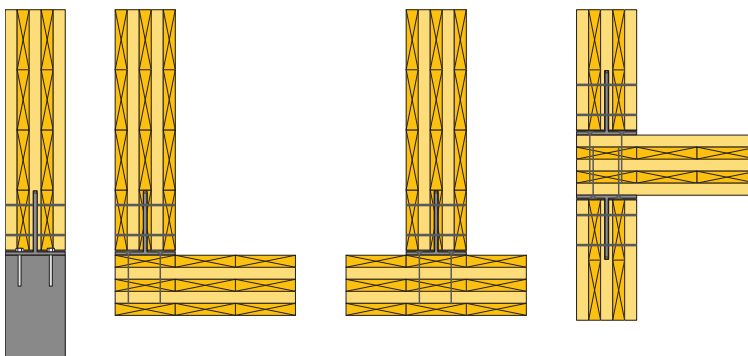


Figure 14
Concealed metal plates

It is advisable to review the recommendations provided in Chapter 5 of this Handbook with respect to proper detailing of connections in CLT assemblies.

6

INTERIOR FINISH

The spread of flames over solid materials is a fundamental behavior influencing the fire dynamics and growth within a compartment. Therefore, many provisions of the IBC and NFPA 5000 limit the use of combustible interior finishes such as the interior wall and ceiling finish as well as interior floor finish. The IBC and NFPA 5000 limit the allowable flame spread and smoke development of interior finishes based on the location, building occupancy and availability of an automatic fire suppression system. These provisions are set forth in Chapter 8 of the IBC and are intended to limit the spread of fire and products of combustion through a building in a manner that allows safe egress of the occupants and limits the damage to the building in which the fire originated.

6.1 **Flame Spread Index**

Interior finishes are traditionally classified with respect to their flame spread index and smoke development evaluated in accordance with ASTM E84 [44] standard for interior walls and ceiling finish. Interior floor finish and floor coverings may be regulated by the critical radiant flux test (ASTM E648 [45] or its NFPA 253 equivalent [46]).

The ASTM E84 standard is the most commonly used test method for determining the surface burning characteristics of building materials. A flame spread index (FSI), expressed as a dimensionless number, is defined as a comparative measure of surface flame spread. The smoke development index (SDI) is also expressed as a dimensionless number and is defined as a comparative measure of smoke density measurements.

6.1.1 **Test Method – ASTM E84**

The ASTM E84 standard test method, also called the “Steiner Tunnel”, exposes a nominal 24 ft. long x 20 in. wide (7.32 m x 508 mm) specimen to a controlled air flow and flaming fire exposure calibrated in a way to spread the flame through the entire length of the tunnel when testing red oak specimen for 5.5 min. This test method is also the UL 723 [47] standard.

6.1.2 **Flame Spread Index (A, B and C Classes)**

Interior finish materials are grouped in three classes in accordance with Section 803.1 of the IBC. Each class is assigned a range of FSI, as shown in Table 8. As noted in the Table, the SDI limit is 450 for all three classes.

Table 8

Flame spread classes according with IBC

Class	Flame Spread Index	Smoke Development Index
A	0-25	0-450
B	26-75	0-450
C	76-200	0-450

6.1.3 Areas of Likely Class A and Class B Requirements

FSI requirements are set forth in Table 803.9 of the IBC and are based on the building occupancy, location within the building, and whether the building is protected by automatic fire sprinklers. Exit enclosures, exit passageways, and corridors providing access to exits usually require materials having a more restrictive class (Class A and B), while other areas such as rooms and enclosed spaces may allow materials assigned as Class C.

Interior finish materials applied on walls, ceilings or structural elements required to provide a fire-resistance rating shall comply with Section 803.11 of the IBC with respect to interior finish directly attached to the structural elements or attached to furring strips not exceeding 1 3/4 in. (44 mm) in thickness directly applied to the structural elements.

6.1.4 Available Data for CLT and Other Wood Products

ASTM E84 is used only to provide dimensionless measures and description of the response of materials, products, or assemblies to heat and flame under controlled conditions. It does not by itself incorporate all factors required for fire-hazard or fire-risk assessment of materials, products, or assemblies under actual fire conditions. It also does not necessarily provide a good understanding of how fire would spread in real-scale scenarios.

A listing of flame spread data for generic wood products can be found in *Design for Code Acceptance (DCA) 1* published by the American Wood Council [48]. Per ANSI/APA PRG 320, the CLT can be constructed of any softwood lumber species or species combination recognized by the American Lumber Standards Committee (ALSC) under PS 20 [49] or by the Canadian Lumber Standards Accreditation Board (CLSAB) under CSA O141 [50] with a minimum published specific gravity of 0.35, as published in the NDS in the United States and CSA O86 [51] in Canada. Reported flame spread indices for softwood lumber of 1 in. thickness as reported in DCA No. 1 are listed in Table 9. As noted in the AWC DCA 1 publication, the ASTM E84 test method has been revised a number of times over the years referenced by the source reports. Slightly different flame spread indices, usually lower, result from more recent ASTM E84 flame spread tests when compared to older tests but the changes have not been deemed sufficient to change the classifications. As noted in the AWC DCA 1 publication, the available data for the smoke development index have all been less than the code prescribed limit of 450 for all three classes.

Table 9

Flame spread indices for softwood lumber

Species	Flame Spread Index
Cedar, Alaska yellow	50
Cedar, Pacific Coast yellow	78
Cedar, Port Orford	60
Cedar, Western Red	70-73
Cypress	145-150
Douglas-fir	70-100
Douglas-fir flooring, ¾ in.	83-98
Fir, Amabilis (Pacific Silver)	69
Fir, White	65
Hem-fir species group	60
Larch, Western	45
Pine, Eastern White	85
Pine, Idaho White	72
Pine, Lodgepole	98
Pine, Northern White	120-215
Pine, Ponderosa	105-230 ^a
Pine, Red	142
Pine, Southern Yellow	130-195
Pine, Sugar	95
Redwood	70
Spruce, Engelmann	55
Spruce, Northern	65
Spruce, Sitka	74

^a In 18 tests of ponderosa pine, three had values over 200 and the average of all tests is 154.

6.2 Fire-retardant Treatment and CLT

Wood products can be treated with fire retardants to increase their fire performance such as delaying time to ignition, reducing heat release rate, and lowering flame spread ratings. Such fire-retardant treatments (FRT) may also reduce the smoke development of FRT wood and wood-based products. While FRT enhances the flame spread performance of wood and wood-based products, such treatments do not make them noncombustible materials.

There are two types of FRT: coatings and pressure-impregnated chemicals. There are also two objectives for treating wood products with fire-retardant chemicals. One objective is to take advantage of provisions in the codes in with fire-retardant treated wood (FRTW) as a prescribed alternative. The other objective is to meet requirements in the codes for a specified flame spread index.

Only FRT by means of pressure-impregnated chemicals are an option for addressing code provisions that prescribe or allow for the use of FRTW including the FRTW specified as an option for protection of a CLT exterior wall in Type IV construction. The term “fire-retardant treated wood” is limited to wood pressure treated with fire retardant chemicals that comply with the requirements in the code for FRTW (Section 2303.2 of IBC). These requirements are more stringent than the Class A flame spread index requirement for interior finish applications. These requirements include the “30-min E84 test”, which is described in a new ASTM E2768 standard [52].

CLT components conforming to FRTW specifications are not expected to be available in the near future. The wood industry currently does not recommend the use of fire-retardant treatments of glulam. This is likely due to the potential effects of proprietary treatments on the mechanical properties and the performance of the adhesives.

If CLT components are subjected to pressure-impregnated fire-retardant treatments, it needs to be noted that the tabulated design values and capacities published in the NDS are for untreated members. The effect of FRT on mechanical properties will need to be addressed in the design. Reference design values, including connection design values, for lumber and CLT pressure-treated with fire retardant chemicals should be obtained from the manufacturer providing the treatment.

In addition to pressure treatments, fire-retardant surface treatments may also be used to address interior finish requirements that are more restrictive than the flame ratings for untreated wood. Surface treatments including clear intumescent coatings allow the designers to use CLT unprotected (e.g., without gypsum board or other cladding) while achieving the more restrictive finish rating requirements. While the code permits the use of coatings to address the finish rating requirements, field application of these coatings and questions of durability in certain applications may create difficulties in its acceptance in new construction by the authorities having jurisdiction. Structural wood panel products with a fire-rated factory-applied coating are available.

In an attempt to evaluate such effect on CLT assemblies, three treated CLT panels of 4 1/8 in. (105 mm) in thickness have been evaluated for flame spread in accordance with ULC S102 [53]. The tested specimens provided an average flame spread index of 25 [54]. It is expected that, when tested in accordance with ASTM E84, such fire-retardant coated CLT would exhibit a similar Class A rating.

Some components used in CLT construction may need to be treated with preservatives to improve resistance to decay and insects. Some commercial interior FR treatments do provide some resistance to decay and insects. This is likely due to boron chemicals in the formulations. Currently, there is no commercial treatment that is a combined treatment for preservation and fire in exterior applications. One option to address such situations is to use a FR coating on preservative-treated wood.

Pressure impregnated FR treatments are marketed to reduce the flame spread index and provide lower flammability performance. Such FR treatments do not have an appreciable effect on the charring rate which is the important parameter in the fire-resistance rating. Thus, they are not used to improve fire resistance ratings.

Past research by FPInnovations and FPL examined the potential for some coatings to improve the fire-resistance ratings of wood building elements. On this manner, Richardson & Cornelissen [55] conducted studies to identify coatings which could improve fire resistance of wood decking by delaying the onset of charring. Thirty coating systems were identified by manufacturers claiming intumescent properties on Douglas-fir tongue-and-groove planks coated on one side as per the manufacturers recommendations (e.g., exposed to an ASTM E119 standard fire for 30 minutes). Results showed that the char formation was reduced by as much as 70% and, therefore, applying such intumescent or fire-retardant coatings to purlins and undersides of heavy timber decking components will substantially improve the fire performance of such timber systems. FPL examined the effect of various coatings on the charring rate of wood [56] and developed equations that could be incorporated with current fire-resistance calculations for wood members [57]. However, at the present time, coatings do not have general code acceptance as a method to improve the fire resistance of wood products and are not marketed for such purpose.

6.3 Use of Other Membrane Products to Address Interior Finish Requirements

The most common method to address FSI and SDI interior finish requirements will likely be the installation of gypsum board. Gypsum board and gypsum sheathing have a Class A flame spread index. For situations where there is no fire-resistance rating requirement, regular gypsum board or non-fire-rated gypsum board can be used. When used to address fire-resistance requirements, the gypsum board will need to be fire-rated as either Type X or Type C. Likewise the interior finish requirements for low FSI can also be address by decorative hardwood plywood panels, particleboard, or medium density fiberboard panel products that have been treated with fire-retardant chemicals to achieve a Class A FSI. Such wood panel products are typically not treated to achieve the more stringent performance requirement for FRTW in the codes. Lumber and construction grade plywood panels are FR treated and marketed as products that satisfy the FRTW requirements in addition to the Class A flame spread index.

6.4 Foam Plastic Insulation

If foam plastic insulation is incorporated in CLT construction, the code provisions pertaining to foam plastic insulation will need to be addressed (Section 2603 of IBC). These provisions require foam plastic insulation to be protected from the interior by a 15 minute thermal barrier unless the application is one of those excluded. This requirement is normally satisfied with a ½ in. thick non-fire-rated gypsum board. Current acceptance requirements specified in the NFPA standard for thermal barriers cannot be met with untreated wood regardless of thickness. In addition to the thermal barrier requirement, Section 2603 of the IBC includes other provisions pertaining to the use of foam plastics in exterior walls of buildings of Types I, II, III, and IV construction.

6.5 Automatic Fire Sprinklers

Automatic fire sprinklers are an important fire safety feature in any building. They are addressed in Section 903 of the IBC. For certain buildings and occupancies, the codes will require the installation of an approved automatic fire sprinkler system. As discussed previously, the inclusion of such a system in a building may provide benefits in terms of allowable heights and areas and in terms of lower fire-resistance requirements for building elements. The applicable standards for automatic fire sprinkler systems are NFPA 13, 13R and 13D [9, 58, 59].

7

THROUGH PENETRATIONS

Penetrations in fire rated assemblies are required to be sealed to maintain the assembly's rating. Section 712 of the IBC requires penetrations of an assembly to have a fire-resistance rating and to be sealed by a fire stop system tested in accordance with ASTM E814 standard [60]. A fire stop system can be defined as a material, component, or system and its means of support, used to fill gaps between fire separations, fire separations and other construction assemblies, or used around items which wholly or partially penetrate fire separations, to restrict the spread of fire and often smoke thus maintaining the integrity of a fire separation [61]. It is thereby an essential fire protection measure for achieving a proper integrity performance of fire-rated assemblies.

7.1 Fire Stops through Fire Separations

As stipulated in section 712.3.1.1 of the IBC, penetrations in fire-rated assemblies such as fire separations shall be installed as tested in an approved fire-resistance rated assembly. Through penetrations, meaning an opening that passes through an entire assembly, shall be protected by an approved fire stop system, installed as tested per ASTM E814, with a minimum F-rating and T-rating not less than 1 hour. An F-rating can be defined as the time period where the through penetration fire stop system limits the spread of fire through the penetration while a T-rating is the time period where the fire stop system, including the penetrating element, limits the maximum temperature rise to 325°F (163°C) above its initial temperature through the penetration on the unexposed side.

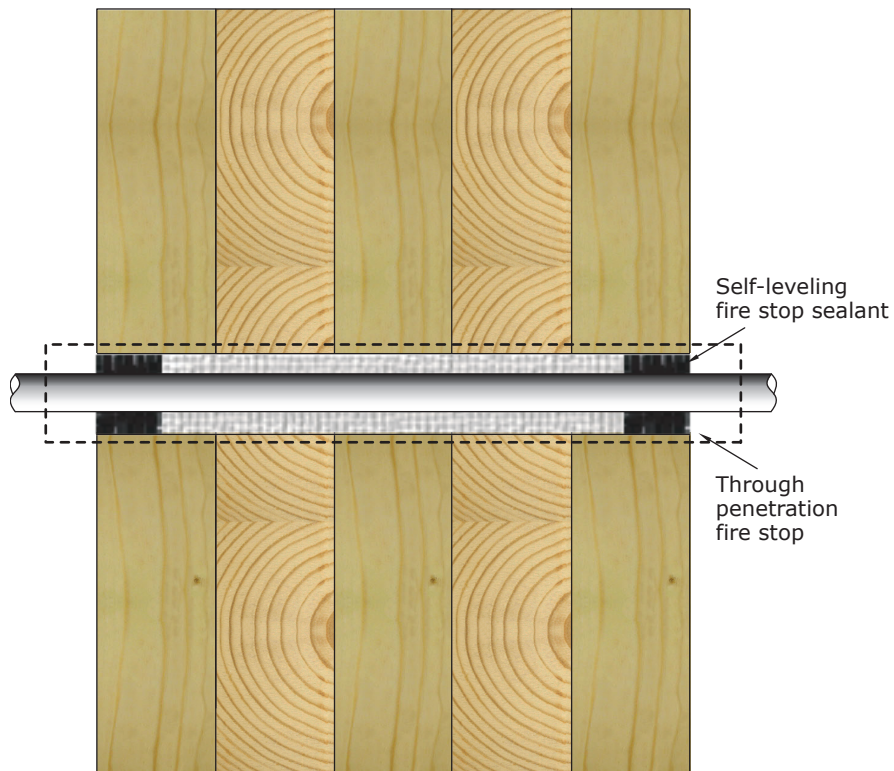
7.2 Fire-resistant Joint Systems in CLT Construction

Very little information is available on the fire performance of fire stops used in CLT assemblies with partial and full penetrations. Further research needs to be carried out in a near future in order to adequately investigate the fire performance of fire stop systems in CLT construction.

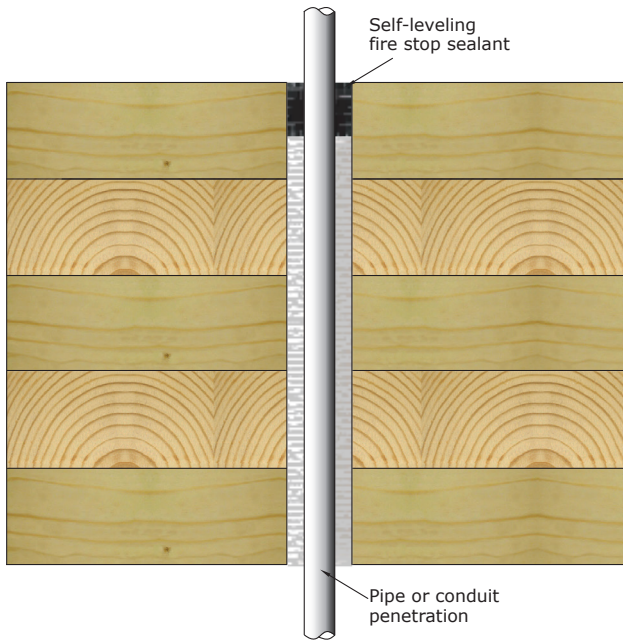
However, there are numerous fire stop systems that are already approved for use with concrete and/or light-frame construction. Both of these types of constructions have similarities to CLT, where concrete is massive and typically does not have void cavities, and light-frame contains wood elements. Commonly-used fire stop systems can be classified under nine main categories, as follows:

1. Through-penetration fire stops;
2. Membrane-penetration fire stops;
3. Construction joint fire stops;
4. Building perimeter fire stops;
5. Caulks and sealants;
6. Mortar and grouts;
7. Foams;
8. Coatings, sprays and wraps;
9. Blocks, pillows and bags.

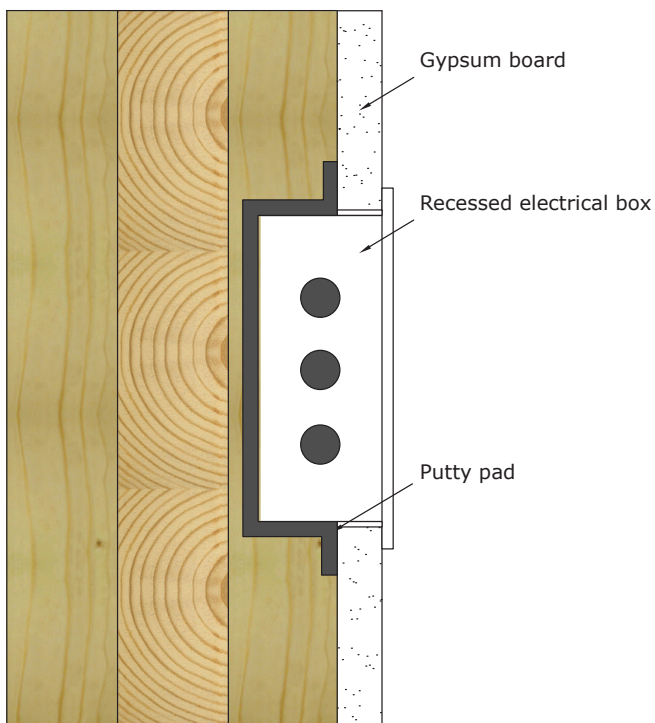
It is anticipated that fire stop systems, listed for use with wood-frame construction, may be acceptable for use with CLT construction (Figure 15). However, due to the proprietary nature of most fire stop systems, it is recommended that a qualified fire protection engineer undertakes or oversees the design and use of fire stop systems in CLT construction.



a) Fire stop sealant in a through penetration



b) Fire stop sealant in a through penetration



c) Membrane protection in a partial penetration

Figure 15
Through and partial penetration in CLT assemblies

8

NOMENCLATURE

β_{eff}	= effective charring rate (inches/hour)
β_n	= nominal charring rate = 1.5 inches/hour
Δ_f	= deflection due to out-of-plane loading (bending) (in.)
ρ	= density of material (kg / m^3)
a	= thermal penetration depth (mm)
a_{char}	= effective depth of char (in.)
b_i	= unit width of the CLT panel (typically 1 foot)
c	= 0.9 (applicable to glue-laminated timber, as per NDS)
c	= specific heat of material used for heat transfer calculations ($\text{J} / \text{kg}\cdot\text{K}$)
d_i	= distance from the neutral axis to the centroid of ply i (in.)
d_0	= zero-strength layer thickness (in.)
e	= distance from the neutral axis to the centroid of load point (typically at mid-depth) (in.)
h	= initial cross-section depth of the CLT panel (in.)
h_{fire}	= effective cross-section depth (in.)
h_i	= remaining depth of ply i (in.)
h_{lam}	= thickness of a laminate (in.)
k	= thermal conductivity of material ($\text{W} / \text{m}\cdot\text{K}$)
l_c	= effective length, typically equal to the unbraced height of a wall assembly (in.)
n_{lam}	= number of laminations that may fall-off (rounded to lowest integer)
t	= fire exposure time (hours)
t_{fo}	= time to reach a glued interface (hours)
t_{ins}	= fire resistance, insulation requirement (hours)
t_{int}	= fire resistance, integrity requirement (hours)
t_{struc}	= fire resistance, structural requirement (hours)
x	= distance from the char front (mm)
\bar{y}	= distance from the unexposed surface of the panel to the neutral axis (in.)
\bar{y}_i	= distance from the unexposed surface of the panel to the centroid of ply i (in.)

A_{eff}	= area of the effective residual cross-section (in. ²)
C_F	= size factor = 1.0 for CLT components
C_p	= CLT wall stability factor
COV_E	= modulus of elasticity coefficient of variation (as per NDS)
D	= applied permanent (dead) load (lb./ft. ² or lb./ft.)
E	= modulus of elasticity of the ply that sustains the greatest tensile stress, typically E_i (psi)
E_i	= modulus of elasticity of the ply i in the major strength axis (psi)
E_{90i}	= modulus of elasticity of the ply i in the minor strength axis (psi)
E_{min}	= modulus of elasticity for column stability design (as per NDS) (psi)
E'_{min}	= adjusted modulus of elasticity of the ply i in the major strength axis (psi)
EI_{eff}	= effective bending stiffness (lb.-in. ²)
EI'_{min}	= $E'_{\text{min}} I_{\text{eff}}$
F_b	= bending stress design value of the wood (Tables 4A, 4B, 4C or 4F of NDS)
F_{bE}	= beam buckling stress design value of the wood (Tables 4A, 4B, 4C or 4F of NDS)
F_c	= axial compression stress design value of the wood (Tables 4A, 4B, 4C or 4F of NDS)
F_t	= tensile stress design value of the wood (Tables 4A, 4B, 4C or 4F of NDS)
G_0	= shear modulus of the ply in the major strength axis (psi)
G_{90}	= shear modulus of the ply in the minor strength axis (psi)
I_{eff}	= moment of inertia of the effective residual cross-section (in. ⁴)
K	= adjustment factor as per Table 4 and NDS
K_j	= CLT panel-to-panel joint coefficient = 0.35 for half-lapped joints
L	= applied live load (lb./ft. ² or lb./ft.)
M	= maximum induced moment (lb.-in.)
M'	= design resisting moment in fire design (lb.-in.)
P	= axial compression load (lb.)
P_{cE}	= $\frac{\pi^2 EI'_{\text{min}}}{L_e^2}$ = resisting critical buckling capacity in fire design (lb.)
P^*_c	= $KF_c * A_{\text{eff}} = 2.58F_c * A_{\text{eff}}$ (as per Table 4 and NDS) (lb.)
P'	= resisting axial compression capacity in fire design (lb.)
Q	= rate of heat consumption per unit volume due to chemical reaction (W / m ³)
R_{ASD}	= allowable design capacity as per NDS
S_{eff}	= effective section modulus (in. ³)
T	= temperature (°C)
T_i	= initial temperature (°C)
T_p	= char front temperature (°C)
$\partial T / \partial t$	= temperature as a function of time t (K / s)
$\partial T / \partial x$	= temperature in the x-direction (K / m)
$\partial T / \partial y$	= temperature in the y-direction (K / m)
$\partial T / \partial z$	= temperature in the z-direction (K / m)

9

SPECIAL THANKS

The authors wish to express their thanks to FPInnovations' industry members Julie Frappier, Eng. from Nordic Engineered Wood and Andre Morf from Structurlam, and to Dr. Nourredine Bénichou of the National Research Council of Canada.

Special thanks to those who reviewed the Chapter and provided valuable comments. Specifically, the authors would like to thank Sam Francis of the American Wood Council, James Churchill, P.E. of Churchill Engineering Inc., Joe McElvaney from the City of Phoenix and Prof. Dr. Andrea Frangi from the Institute of Structural Engineering of ETH Zurich. The authors are also grateful for the extensive review and valuable comments made by Bradford Douglas from the American Wood Council.

10

REFERENCES

- [1] ICC. 2009. *International building code*. Washington, DC: International Code Council.
- [2] NFPA. 2012. *Building construction and safety code*. NFPA 5000. Quincy, MA: National Fire Protection Association.
- [3] ANSI. 2011. *Standard for performance-rated cross-laminated timber*. ANSI/APA PRG 320-2011. New York, NY: American National Standards Institute.
- [4] NFPA. 2012. *Guide to the Fire Safety Concepts Tree*. NFPA 550. Quincy, MA: National Fire Protection Association.
- [5] ICC. 2009. *International fire code*. Washington, DC: International Code Council.
- [6] NFPA. 2012. *Fire code*. NFPA 1. Quincy, MA: National Fire Protection Association.
- [7] A. Frangi, M. Fontana, E. Hugi and R. Jöbstl. 2009. Experimental analysis of cross-laminated timber panels in fire. *Fire Safety J.* 44 (8):1078-1087.
- [8] A. Frangi, G. Bochicchio, A. Ceccotti and M.P. Lauriola. 2008. Natural full-scale fire test on a 3-storey XLam timber building. Paper presented at the *World Conference on Timber Engineering*, 2008, Miyazaki, Japan.
- [9] NFPA. 2013. *Standard for the installation of sprinkler systems*. NFPA 13. Quincy, MA: National Fire Protection Association.
- [10] ASTM. 2012. *Standard test methods for fire tests of building construction and materials*. ASTM E119-12. West Conshohocken, PA: ASTM International.
- [11] UL. 2011. *Fire tests of building construction and materials*. UL 263. Canmas, WA: Underwriters Laboratories Inc.
- [12] ULC. 2007. *Standard method of fire endurance tests of building construction materials*. ULC S101-07. Toronto, ON: Underwriters Laboratories of Canada.
- [13] ISO. 1999. *Fire-resistance test - Elements of building construction - Part 1 : General requirements*. ISO 834-1. Geneva, Switzerland: International Standard Organization.
- [14] AF&PA. 2005. *National design specification (NDS) for wood construction*. Washington, DC: American Forest & Paper Association.
- [15] ASTM. 2008. *Standard practice for calculating the superimposed load on wood-frame walls for standard fire-resistance tests*. ASTM D6513-08. West Conshohocken, PA: ASTM International.
- [16] ASTM. 2011. *Standard practice for calculating the superimposed load on wood-frame floor-ceiling assemblies for standard fire-resistance tests*. ASTM D7746-11. West Conshohocken, PA: ASTM International.
- [17] AF&PA. 2003. *Calculating the fire resistance of exposed wood members*. Technical Report 10. Washington, DC: American Forest & Paper Association.

- [18] ASTM. 2003. *Standard practice for evaluating allowable properties for grades of structural lumber*. ASTM D2915-03. West Conshohocken, PA: ASTM International.
- [19] R.H. White. 1992. Charring rate of wood for ASTM E119 exposure. *Fire Technology* 28 (1):5-30.
- [20] AITC. 2008. *Standard for adhesives for use in structural glued laminated timber*. AITC 405. Centennial, CO: American Institute of Timber Construction.
- [21] ASTM. 2006. *Standard test method for multiple-cycle accelerated aging test (automatic boil)*. ASTM D3434-00(2006). West Conshohocken, PA: ASTM International.
- [22] CSA. 2010. *Evaluation of adhesives for structural wood products (exterior exposure)*. CSA O112.9-10. Mississauga, ON: Canadian Standards Association.
- [23] NIST. 2009. *Structural plywood*. Voluntary Product Standard PS 1. Gaithersburg, MA: National Institute of Standards and Technology.
- [24] L. Osborne, C. Dagenais and N. Bénichou. 2012. Preliminary CLT fire resistance testing report. Project No. 301006155. Ottawa, ON: FPInnovations.
- [25] CEN. 1997. *Adhesives, phenolic and aminoplastic for load-bearing timber structures*. EN 301. Brussels, Belgium: European Committee for Standardization.
- [26] CEN. 2008. *Adhesives - One component polyurethane for load bearing timber structures - Classification and performance requirements*. EN 15425. Brussels, Belgium: European Committee for Standardization.
- [27] R.H. White and M.A. Dietenberger. 2010. Fire safety of wood construction. Chapter 18 in *Wood handbook: Wood as an engineering material*, 18-1 - 18-22. Madison, WI: Forest Products Laboratory.
- [28] ASTM. 2007. *Standard test method for evaluating the shear strength of adhesive bonds in laminated wood products at elevated temperatures*. ASTM D7247-07a. West Conshohocken, PA: ASTM International.
- [29] J. Bodig and B.A. Jayne. 1993. *Mechanics of wood and wood Composites*. New York, NY: Van Nostrand Reinhold Company Inc.
- [30] R.H. White. 2009. Fire resistance of wood members with directly applied protection. Paper presented at the *Eleventh Fire and Materials Conference*, January 26-28, 2009, San Francisco, CA.
- [31] S.T. Craft, R. Desjardins and J.R. Mehaffey. 2011. Investigation of the behaviour of CLT panels exposed to fire. Paper presented at the *Twelfth International Fire and Materials Conference*, San Francisco, CA.
- [32] SFPE. 2008. *The SFPE handbook of fire protection engineering*. 4th ed. Quincy, MA: Society of Fire Protection Engineers.
- [33] L. Lu. 2012. Fire modelling heat transfer computer model of a 3-ply cross-laminated timber board under standard fire exposure using ANSYS. CFS Final Report 3.22. Ottawa, ON: FPInnovations.
- [34] M.L. Janssens and R.H. White. 1994. Short communication: Temperature profiles in wood members exposed to fire. *Fire & Materials* 18:263-265.
- [35] L. Peng, G. Hadjisophocleous, J. Mehaffey and M. Mohammad. 2010. On the fire performance of wood-wood-wood and wood-steel-wood connections using bolts and dowels as fasteners. Paper presented at *Interflam: 12th International Conference on Fire Science and Engineering*, 2010, Nottingham, UK.
- [36] SP Trätekt. 2010. *Fire safety in timber buildings - Technical guideline for Europe*. SP Report 2010:19. Stockholm, Sweden: SP Trätekt (Swedish Institute for Wood Technology Research).
- [37] A. Frangi, C. Erchinger and M. Fontana. 2010. Experimental fire analysis of steel-to-timber connections using dowels and nails. *Fire and Materials* 34:1-19.
- [38] M. Audebert. 2010. Approche expérimentale et modélisation du comportement au feu d'assemblages bois sous différents types de sollicitations. PhD diss., Université Blaise-Pascal - Clermont II, Clermont-Ferrand.
- [39] J. Norén. 1996. Load-bearing of nailed joints exposed to fire. *Fire and Materials* 20:133-143.
- [40] P. Lau. 2006. Fire resistance of connections in laminated veneer lumber (LVL). M.Sc. thesis, University of Canterbury, New-Zealand.

- [41] P. Moss, A.H. Buchanan, M. Fragiaco, P. Lau and T. Chuo. 2009. Fire performance of bolted connections in laminated veneer lumber. *Fire and Materials* 33:223-243.
- [42] P. Moss, A.H. Buchanan, T. Nilsen and M. Fragiaco. 2011. Fire resistance of connections using steel plates and mechanical fasteners in timber structures. *Journal of Structural Fire Engineering* 2:243-258.
- [43] P. Racher, K. Laplanche and D. Dhima. 2006. Thermo-mechanical modelling of the timber connection behaviour under fire. Paper presented at the *Fourth International Workshop Structures in Fire (SiF' 2006)*, Aveiro, Portugal.
- [44] ASTM. 2012. *Standard test method for surface burning characteristics of building materials*. ASTM E84-12. West Conshohocken, PA: ASTM International.
- [45] ASTM. 2012. *Standard test method for critical radiant flux of floor-covering systems using a radiant heat energy source*. ASTM E648-10e1. West Conshohocken, PA: ASTM International.
- [46] NFPA. 2011. *Standard method of test for critical radiant flux of floor covering systems using a radiant heat energy source*. NFPA 253. Quincy, MA: National Fire Protection Association.
- [47] UL. 2008. *Tests for surface burning characteristics of building materials*. UL 723. Canmas, WA: Underwriters Laboratories Inc.
- [48] AWC. 2010. *Design for code acceptance 1: Flame spread performance of wood products*. Washington, DC: American Wood Council.
- [49] NIST. 2010. *American softwood lumber*. Voluntary Product Standard PS 20. Gaithersburg, MD: National Institute of Standards & Technology.
- [50] CSA. 2010. *Softwood lumber*. CSA O141-05. Mississauga, ON: Canadian Standards Association.
- [51] CSA. 2009. *Engineering design in wood*. CSA O86-09. Mississauga, ON: CSA Standards.
- [52] ASTM. 2011. *Standard test method for extended duration surface burning characteristics of building materials (30 min tunnel test)*. ASTM E2768-11. West Conshohocken, PA: ASTM International.
- [53] ULC. 2010. *Standard method of test for surface burning characteristics of building materials and assemblies*. ULC S102-10. Toronto, ON: Underwriters Laboratories of Canada.
- [54] ITS. 2012. Surface burning characteristics of treated cross-laminated timber. Report No. 100712618OQ-001b. Coquitlam, BC: Intertek Testing Services NA Ltd.
- [55] L.R. Richardson and A.A. Cornelissen. 1987. Fire-resistant coatings for roof/ceiling deck timbers. *Fire and Materials* 11:191-194.
- [56] R.H. White. 1984. Use of coatings to improve fire resistance of wood. In *Fire resistive coatings: The need for standards*, 24-39. West Conshohocken, PA: ASTM International.
- [57] R.H. White. 1986. An empirical model for predicting performance of fire-resistive coatings in wood construction. *Journal of Testing and Evaluation* 14 (2):97-108.
- [58] NFPA. 2013. *Standard for the installation of sprinkler systems in residential occupancies up to and including four stories in height*. NFPA 13R. Quincy, MA: National Fire Protection Association.
- [59] NFPA. 2013. *Standard for the installation of sprinkler systems in one- and two-family dwellings and manufactured homes*. NFPA 13D. Quincy, MA: National Fire Protection Association.
- [60] ASTM. 2011. *Standard test method for fire tests of penetration firestop systems*. ASTM E814-11a. West Conshohocken, PA: ASTM International.
- [61] J.K. Richardson, J.D. Quirt and R. Hlady. 2007. Best practice guide on fire stops and fire blocks and their impact on sound transmission. NRCC-49677. Ottawa, ON: National Research Council Canada.
- [62] J. Schmid, J. König and J. Kohler. 2010. Design model for fire exposed cross-laminated timber. Paper presented at the *Sixth International Conference on Structures in Fire*, June 24, 2010, Michigan State University, East Lansing, MI.

- [63] CEN. 2004. *Eurocode 5 : Design of timber structures - Part 1-2 : General - Structural fire design*. Brussels, Belgium: European Committee for Standardization.
- [64] CEN. 2003. *Eurocode 0 : Basis*. Brussels, Belgium: European Committee for Standardization.
- [65] S. Craft. 2011. Fire performance of cross-laminated timber. Chapter 8 in *CLT handbook*. Québec, QC: FPInnovations.
- [66] AF&PA. 2006. Fire design. Chapter M16 in *ASD/LRFD manual for engineered wood construction*. 2005 ed. Washington, DC: American Forest & Paper Association.
- [67] S. Gagnon, and C. Pirvu, eds. 2011. *CLT handbook: Cross-laminated timber*. Canadian ed. Special Publication SP-528E. Quebec, QC: FPInnovations.

APPENDIX I

ADDITIONAL INFORMATION

European Calculation Design Procedure

There is a very limited quantity of full-scale fire resistance tests performed with CLT constructions. An adapted methodology for CLT assemblies has thereby been developed in Europe and is currently being used on proprietary basis by European CLT manufacturers [7, 62]. The European model follows the same principles as those prescribed in Eurocode 5: part 1-2 [63] applicable to timber components. However, it evaluates only the loadbearing function of CLT assemblies based on a one-dimensional charring rate. As of 2012, this new method has yet to be implemented into the European regulatory environment.

The design procedure prescribed in Eurocode 5: part 1-2 allows calculating the structural and the integrity requirements of timber components. The structural requirement can be determined using the reduced cross-section method using a constant charring rate as a function of time. The constant charring rate is however only valid for elements unprotected throughout the time of fire exposure. An advanced procedure for predicting the char rate of timber initially protected can also be found in Eurocode 5: part 1-2.

The European fire-resistance calculation method uses a strength adjustment factor (k_f), a modification factor for fire design ($k_{mod,fi}$) and a partial safety factor for fire design ($\gamma_{M,fi}$) as well as a zero-strength layer (d_o) of 7 mm ($^{9}/_{32}$ in.) to account for the wood heated zone (assumed to provide no strength, nor rigidity). According to Schmid et al. [62], the zero-strength layer for CLT assemblies should however be taken as 10 mm ($^{25}/_{64}$ in.) for floors and 16 mm ($^{5}/_{8}$ in.) for walls, and is a function of the number of plies, residual thickness, whether the assembly is protected or unprotected, and the stress distribution (exposed side in tension or compression). The strength adjustment factor allows converting the 5th percentile strength property to the 20th percentile in normal conditions and is based on products' coefficient of variation. For example, a solid timber beam would have a strength adjustment of 1.25 while a glued-laminated timber (who typically exhibits a lower COV than timber) would have a 1.15 strength adjustment factor. The modification and partial safety factors are both set to unity in fire design. Furthermore, a combination factor for quasi-permanent action ($\psi_{2,1}$) ranging from 0.3 to 0.8 depending on the building occupancy group in accordance with Eurocode 0 [64] is also recommended, thus providing a reduced load combination for fire design.

Furthermore, Eurocode 5: part 1-2 also prescribes a joint coefficient (k_j) for determining the integrity fire resistance of timber cladding and gypsum boards having gaps not more than roughly 2 mm ($^{1}/_{12}$ in.), similarly to Equation 19 of this Chapter. Profiles such as half-lapped joints greater than 30 mm ($1\ ^{3}/_{16}$ in.), single tongue-and-groove greater than 15 mm ($^{5}/_{8}$ in.), internal spline greater than 30 mm ($1\ ^{3}/_{16}$ in.) and double tongue-and-grooves have assigned joint coefficient (k_j) of 0.3, 0.4 and 0.6, respectively. The joint coefficient may also be set to unity when additional floor covering or wall sheathing is used over the joint.

The European method also stipulates that the requirements with respect to integrity are assumed to be satisfied where the requirements with respect to insulation have been satisfied and panels remain fixed to the timber frame on the unexposed side.

Canadian Calculation Design Procedure

More recently, a Canadian fire-resistance design method has been published in 2011 and is largely based on the European model [65]. The Canadian model, as of 2011, evaluates only the loadbearing function of CLT assemblies. Further investigations have been carried out by FPInnovations and the National Research Council of Canada in an attempt to better understand fire behavior of CLT assemblies in fire conditions. It has been found that integrity (i.e., panel-to-panel connection) is one of the predominant failure modes of CLT floor assemblies under load [24]. Such failure mode was not observed in CLT wall assemblies under load. The latter usually exhibits buckling due to second-order effects (i.e., $P-\Delta$ effects). The future edition of the Canadian CLT Handbook will address the fire integrity performance of CLT assemblies in a similar manner as it will be addressed in Subsection 4.1.5 of this Chapter.

It should be noted that both European and Canadian methods follow the limit states design philosophy, which is similar, to a certain degree, to the Load & Resistance Factor Design (LRFD) prescribed in [66]. Therefore, such methods should not be used in the United States when using the Allowable Stress Design (ASD) philosophy.



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

Bilateral 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



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



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

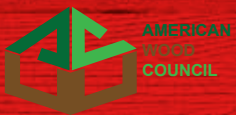
www.fpl.fs.fed.us

BSLC

Woodland Softwood Lumber Council

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

www.softwoodlumber.org



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

www.awc.org



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