Texas Wood Design Symposium

Provider Number: G516

Structural Design of Mass Timber Framing Systems

February 25, 2020

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DCI Engineers

DCI ENGINEERS

Texas Wood Design Symposium
Houston, Texas
February 25, 2020

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Questions related to specific materials, methods, and services will be addressed at the conclusion of this presentation.

Course Description

Mass timber structural framing systems have high strength-to-weight ratios, are dimensionally stable, and are quickly becoming systems of choice for sustainably-minded designers. This presentation will provide a detailed look at the structural design processes associated with a variety of mass timber products, including glued-laminated timber (glulam), cross-laminated timber (CLT), and nail-laminated timber (NLT). Applications for the use of these products in gravity force-resisting systems under modern building codes will be discussed. Other technical topics will include design of mass timber for fire-resistance, connection options and design considerations, and detailing and construction best practices.

1 LU/HSW

Learning Objectives

At the end of the this course, participants will be able to:

1. Discuss mass timber products and building systems and their possibilities as structural framing.
2. Compare structural properties and performance characteristics of mass timber products and review their unique design considerations.
3. Review structural design steps for members and connections in common mass timber framing systems.
4. Highlight structural detailing best practices to address items such as shrinkage and expansion, load path continuity, and speed of construction.

Start with Why.

Photo: UBC

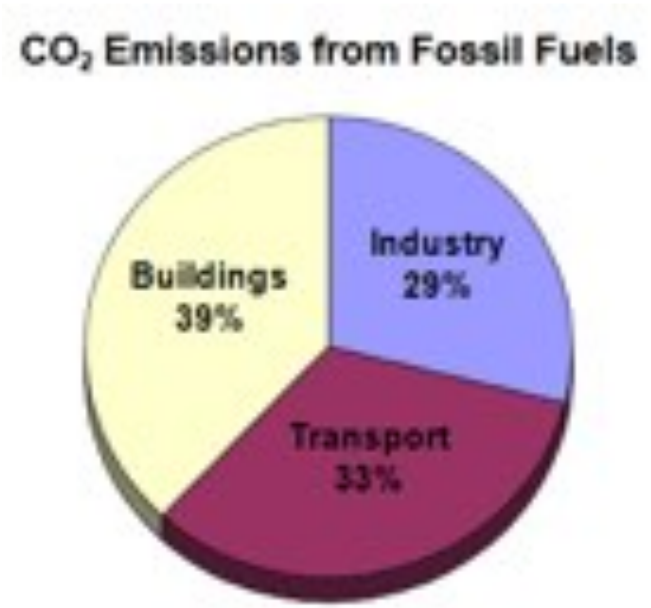
Why the Move to Mass Timber?

Why the Move to Mass Timber?

Photo: Jordan Benner

PUBLIC INTEREST SUSTAINABILITY AESTHETICS A BETTER WAY TO BUILD

Why the Move to Mass Timber?



Source: USGBC (2018)

PUBLIC INTEREST **SUSTAINABILITY** AESTHETICS A BETTER WAY TO BUILD

Why the Move to Mass Timber?

AUSTIN ENERGY
GREEN BUILDING

Declare.
RED LIST FREE

Photo: Oregon Forestry Resources Institute

U.S. GREEN BUILDING COUNCIL
LEED
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LIVING
BUILDING
CHALLENGE

GREEN
GLOBES

FSC

Why the Move to Mass Timber?

Photo: Mike Brewington

PUBLIC INTEREST SUSTAINABILITY **AESTHETICS** A BETTER WAY TO BUILD

Why the Move to Mass Timber?

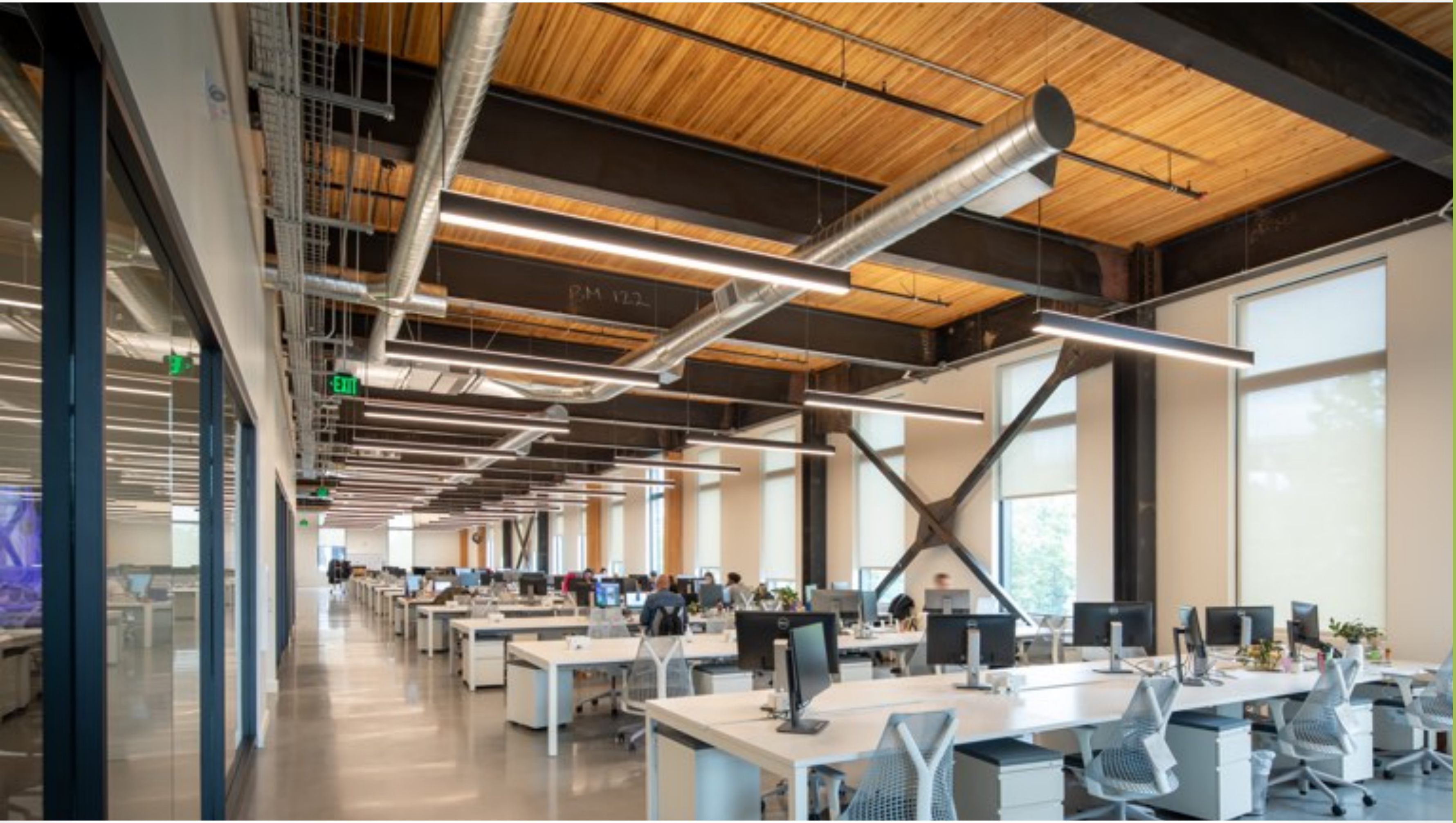

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Photo: Casey Braunger

PUBLIC INTEREST SUSTAINABILITY **AESTHETICS** A BETTER WAY TO BUILD

Why the Move to Mass Timber?

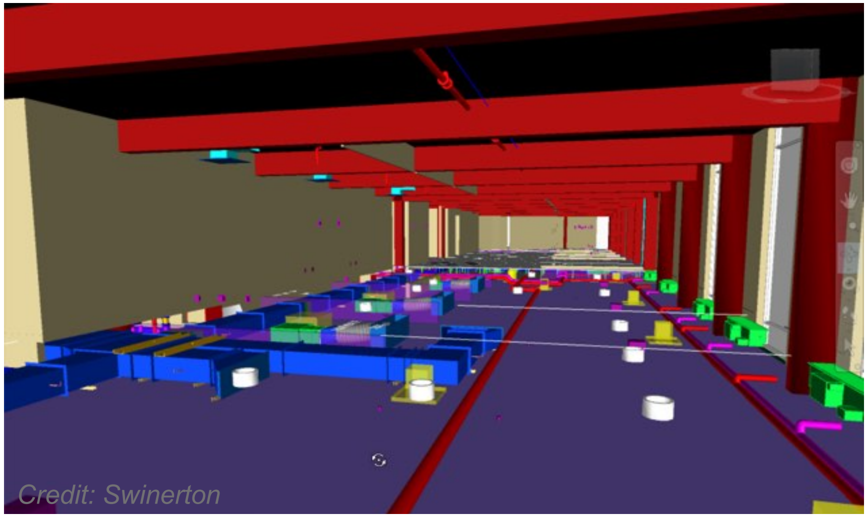
Photo: Justin Fenton

PUBLIC INTEREST SUSTAINABILITY **AESTHETICS** A BETTER WAY TO BUILD

Why the Move to Mass Timber?

- Prefabrication opportunities
- Integrated project delivery
- Leveraging BIM
- Faster project delivery
- Safer/quieter site
- Reduced construction traffic
- Fewer on site personnel

Why the Move to Mass Timber?


Credit: Swinerton


Credit: Swinerton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PUBLIC INTEREST SUSTAINABILITY AESTHETICS **A BETTER WAY TO BUILD**

Overview

- Mass Timber Materials Overview
- Mass Timber Design
  - Codes
  - Resources
  - Structural Design
  - Special Considerations
  - Tips for Success
- Fire Design
- Connections
- Additional Resources

Mass Timber Materials

Overview

Mass Timber Materials

Horizontal Elements (Floors/Roofs)

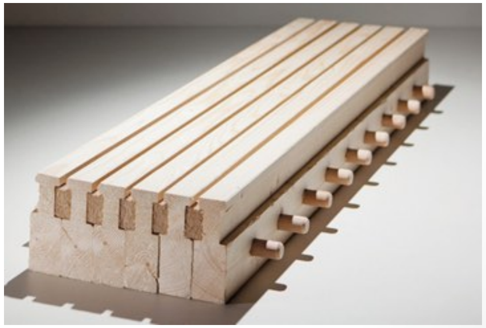
GLULAM
GLT

Nail Laminated Timber (NLT)

Cross Laminated Timber (CLT)

T&G Decking

Mass Plywood Panel (MPP)



Dowel Laminated Timber (DLT)

Mass Timber Materials

Horizontal Elements (Floors/Roofs)

GLULAM

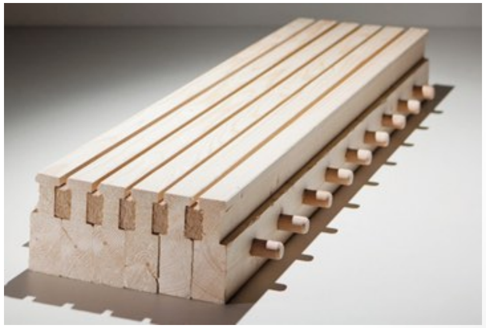
GLT

Nail Laminated Timber (NLT)

Cross Laminated Timber (CLT)

T&G Decking

Mass Plywood Panel (MPP)

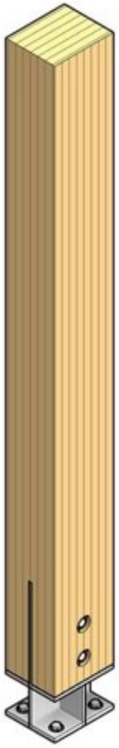


Dowel Laminated Timber (DLT)

Mass Timber Materials

Vertical Elements (Walls/Columns)

Cross Laminated
Timber (CLT)



Glulam

GLULAM

Photo: Brad Kahn

GLULAM

- Glue-laminated from nominal 2x material
  - Glued, pressed & planed
- Beams and columns
- One-way spanning
- Various stress grades
- Various species

- Doug-Fir
- Southern Pine
- Spruce-Pine-Fir
  - “Canadian” Spruce
  - “Black” Spruce
- European Spruce

The Workhorse!

GLULAM

Photo: Duncan Rawlinson

Photo: Thos L. Bryant

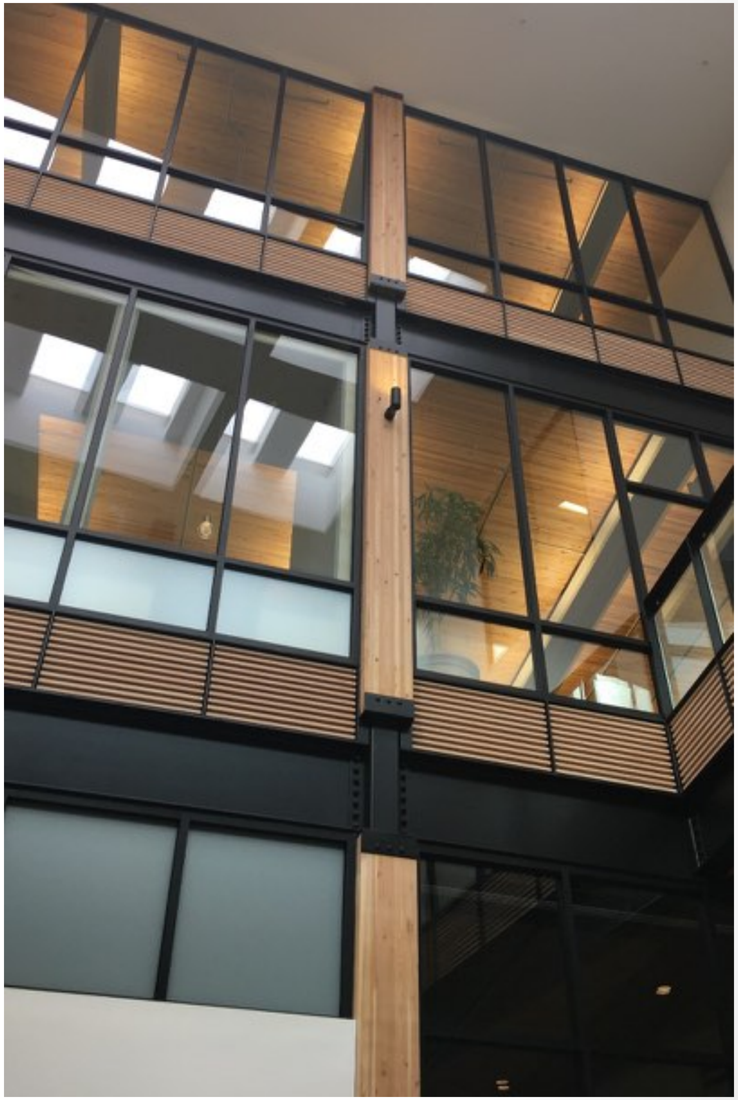
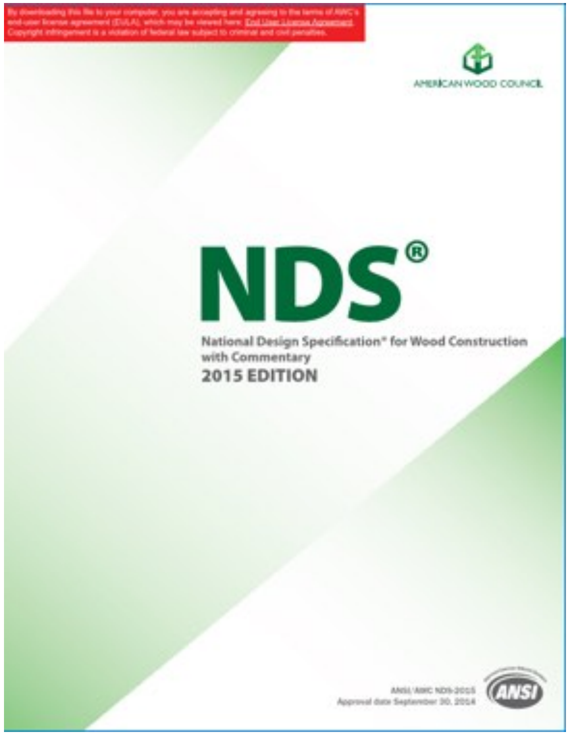


Photo: Michael Dupras

Design Codes



AMERICAN WOOD COUNCIL

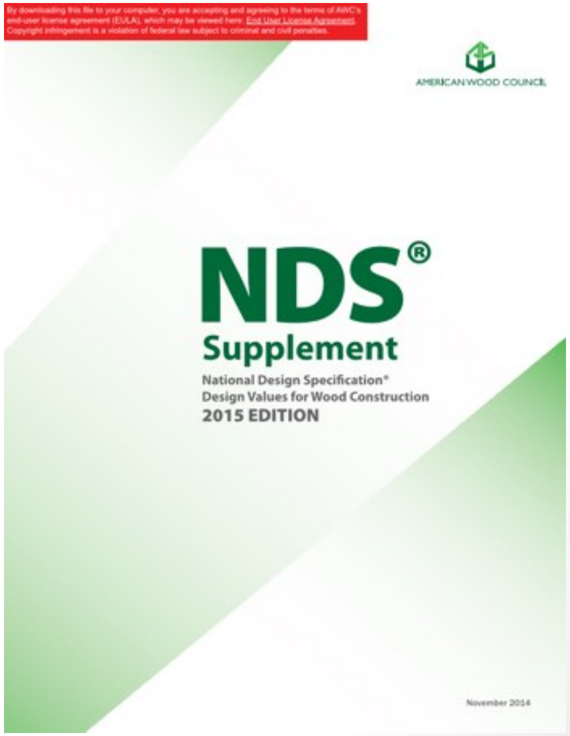
NDS®

National Design Specification® for Wood Construction
with Commentary
2015 EDITION

ANSI/AWC NDS-2015
Approval date September 30, 2014

<u>Specification</u>

Chapter 5



AMERICAN WOOD COUNCIL

NDS®
Supplement

National Design Specification®
Design Values for Wood Construction
2015 EDITION

November 2014

<u>Supplement</u>

Table 5A – Beams

Table 5B –
Columns/Braces

Design Resources

APA

Glulam

PRODUCT GUIDE

APA Glulam Product Guide

Glulam

STRUCTURAL GLUED LAMINATED TIMBER

Chapter 5 – Structural Glued Laminated Timber

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Glulam

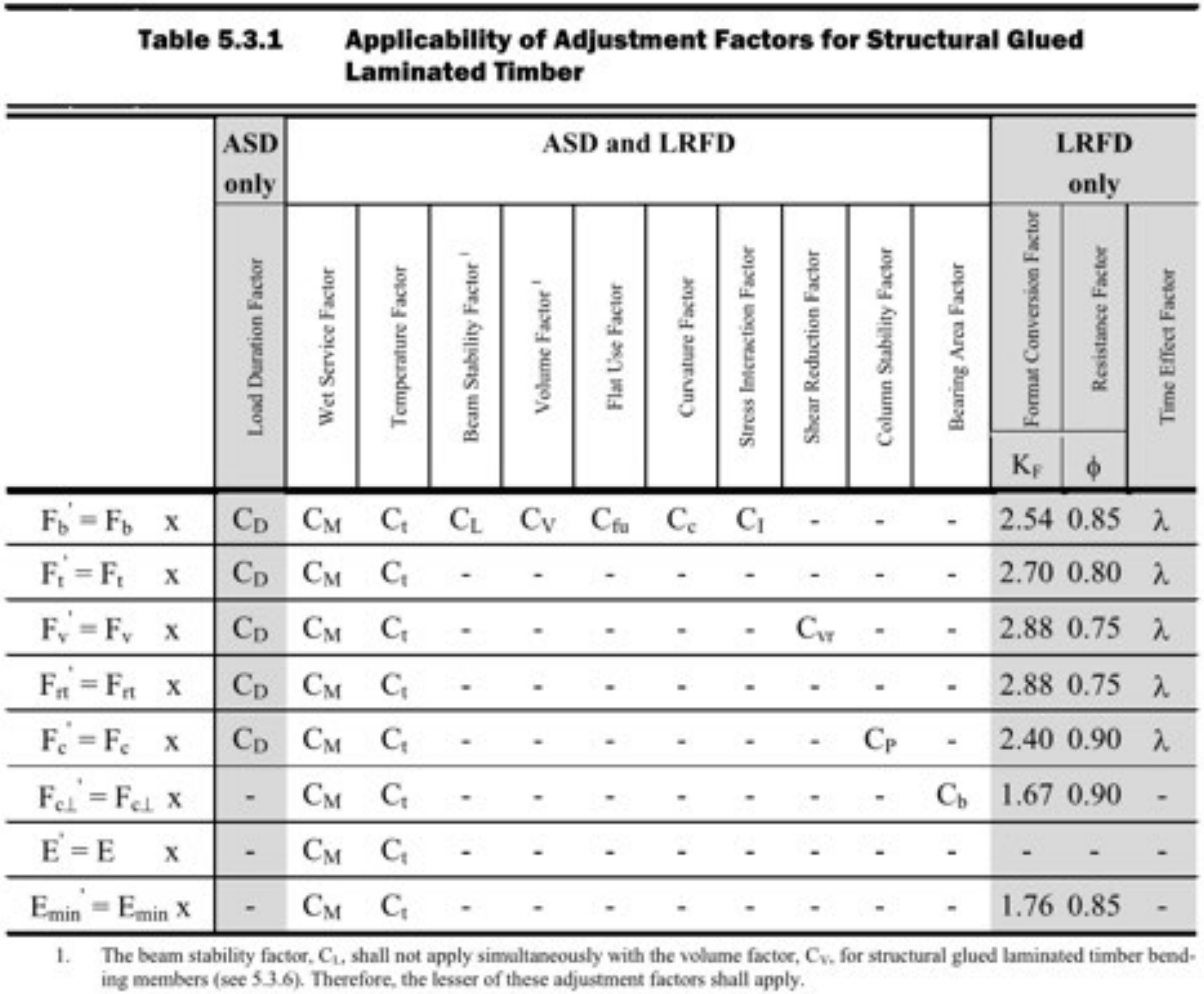


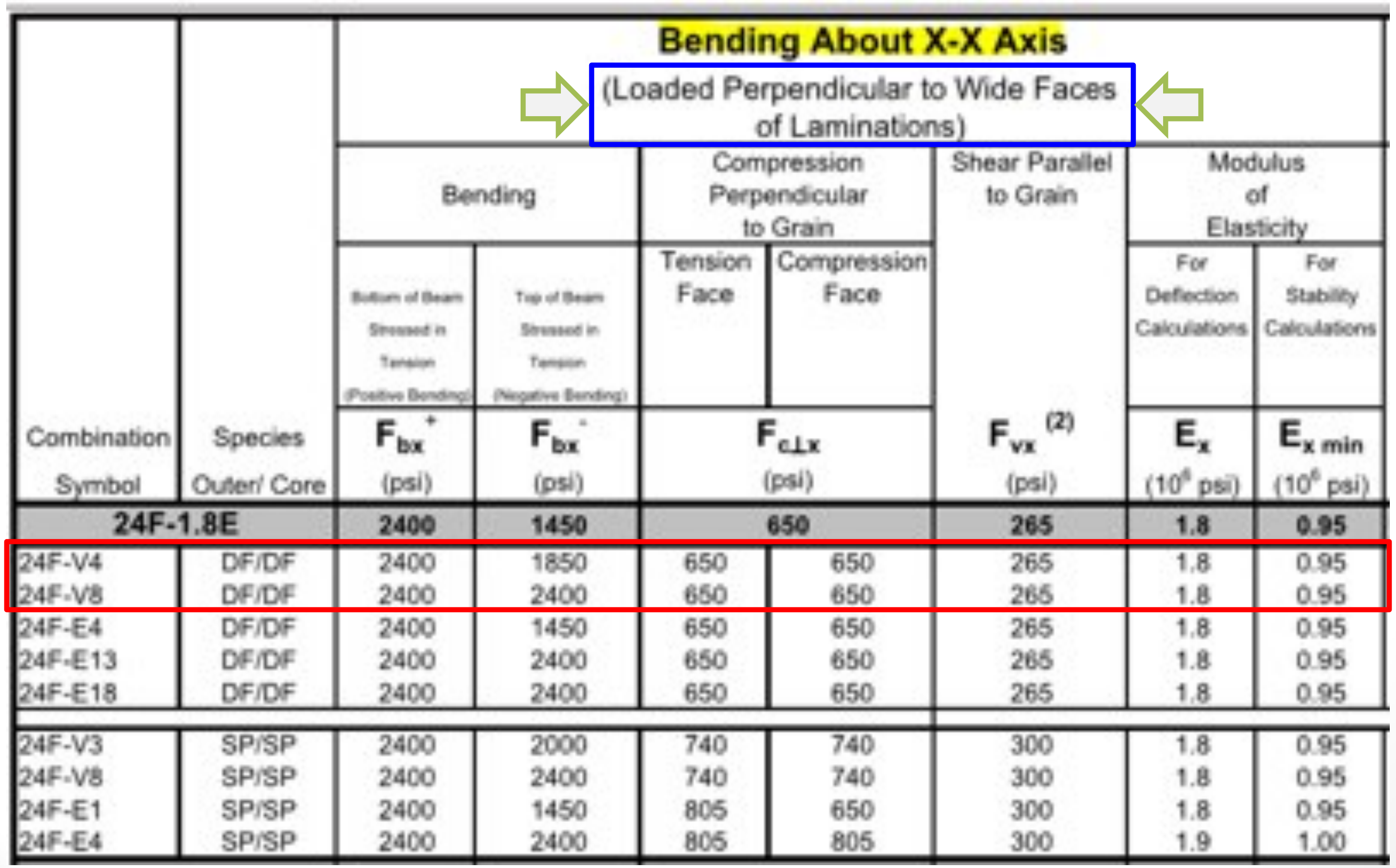
Table 5.3.1 Applicability of Adjustment Factors for Structural Glued Laminated Timber

	ASD only	ASD and LRFD										LRFD only		
	Load Duration Factor	Wet Service Factor	Temperature Factor	Beam Stability Factor[1]	Volume Factor[1]	Flat Use Factor	Curvature Factor	Stress Interaction Factor	Shear Reduction Factor	Column Stability Factor	Bearing Area Factor	Format Conversion Factor	Resistance Factor	Time Effect Factor
												K_F	ϕ	
$F_b' = F_b$ x	C_D	C_M	C_t	C_L	C_V	C_{fu}	C_c	C_I	-	-	-	2.54	0.85	λ
$F_t' = F_t$ x	C_D	C_M	C_t	-	-	-	-	-	-	-	-	2.70	0.80	λ
$F_v' = F_v$ x	C_D	C_M	C_t	-	-	-	-	-	C_{vr}	-	-	2.88	0.75	λ
$F_{rt}' = F_{rt}$ x	C_D	C_M	C_t	-	-	-	-	-	-	-	-	2.88	0.75	λ
$F_c' = F_c$ x	C_D	C_M	C_t	-	-	-	-	-	-	C_P	-	2.40	0.90	λ
$F_{c\perp}' = F_{c\perp}$ x	-	C_M	C_t	-	-	-	-	-	-	-	C_b	1.67	0.90	-
$E' = E$ x	-	C_M	C_t	-	-	-	-	-	-	-	-	-	-	-
$E_{min}' = E_{min}$ x	-	C_M	C_t	-	-	-	-	-	-	-	-	1.76	0.85	-

1. The beam stability factor, C_L, shall not apply simultaneously with the volume factor, C_V, for structural glued laminated timber bending members (see 5.3.6). Therefore, the lesser of these adjustment factors shall apply.

Glulam

- Stress Grade – NDS Supplement Table 5A

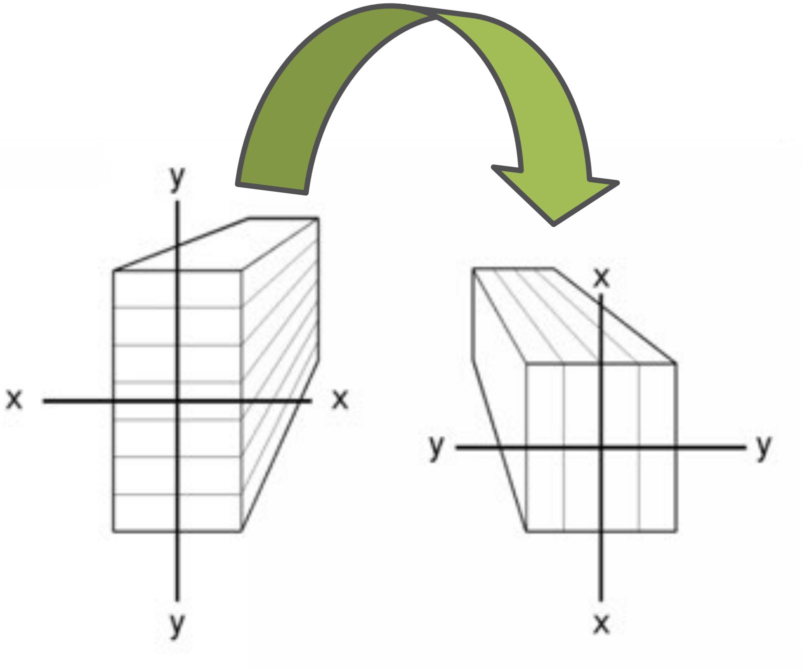


		Bending About X-X Axis (Loaded Perpendicular to Wide Faces of Laminations)						
		Bending		Compression Perpendicular to Grain		Shear Parallel to Grain	Modulus of Elasticity	
		Bottom of Beam Stressed in Tension (Positive Bending)	Top of Beam Stressed in Tension (Negative Bending)	Tension Face	Compression Face		For Deflection Calculations	For Stability Calculations
Combination Symbol	Species Outer/ Core	F_{bx}^{+} (psi)	F_{bx}^{-} (psi)	$F_{c\perp x}$ (psi)		$F_{vx}^{(2)}$ (psi)	E_x (10^6 psi)	$E_{x\,min}$ (10^6 psi)
24F-1.8E		2400	1450	650		265	1.8	0.95
24F-V4	DF/DF	2400	1850	650	650	265	1.8	0.95
24F-V8	DF/DF	2400	2400	650	650	265	1.8	0.95
24F-E4	DF/DF	2400	1450	650	650	265	1.8	0.95
24F-E13	DF/DF	2400	2400	650	650	265	1.8	0.95
24F-E18	DF/DF	2400	2400	650	650	265	1.8	0.95
24F-V3	SP/SP	2400	2000	740	740	300	1.8	0.95
24F-V8	SP/SP	2400	2400	740	740	300	1.8	0.95
24F-E1	SP/SP	2400	1450	805	650	300	1.8	0.95
24F-E4	SP/SP	2400	2400	805	805	300	1.9	1.00

Glulam Design Notes

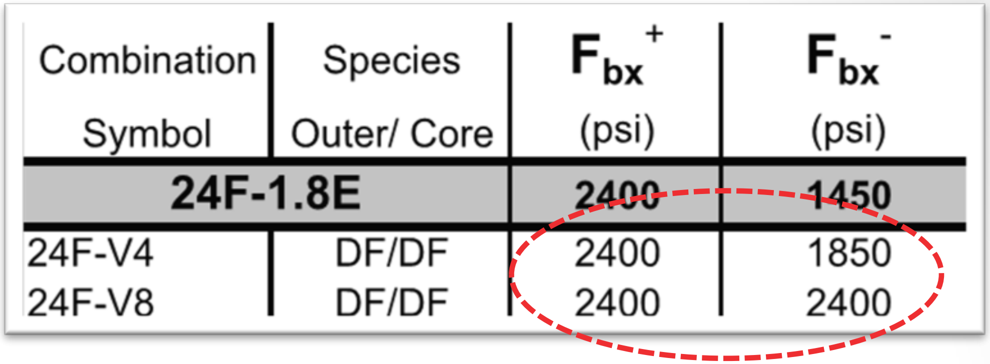
- Primary Axis Bending
  - X-X Properties
  - Lesser of C_V and C_L
- Flatwise Bending
  - Y-Y Properties
  - C_{fu}

$$C_{fu} = \left(\frac{12}{d_y}\right)^{1/9}$$

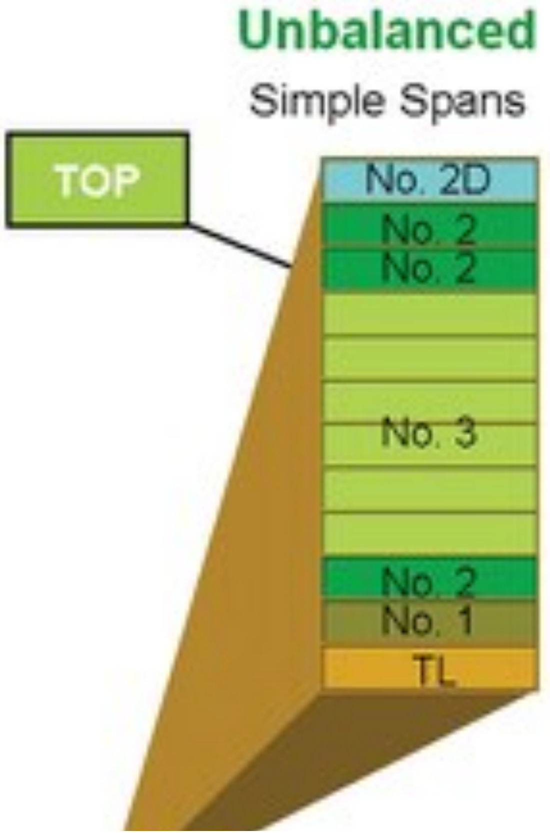


Glulam

- Beam layups

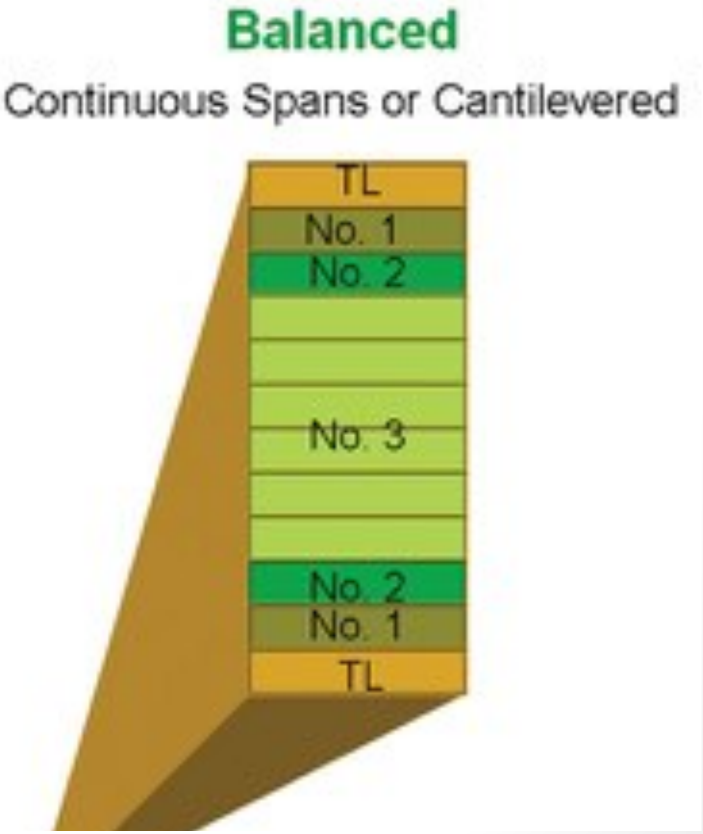


Combination Symbol	Species Outer/ Core	F_{bx}^{+} (psi)	F_{bx}^{-} (psi)
24F-1.8E		2400	1450
24F-V4	DF/DF	2400	1850
24F-V8	DF/DF	2400	2400



24F-V4

TL=Tension Lamination

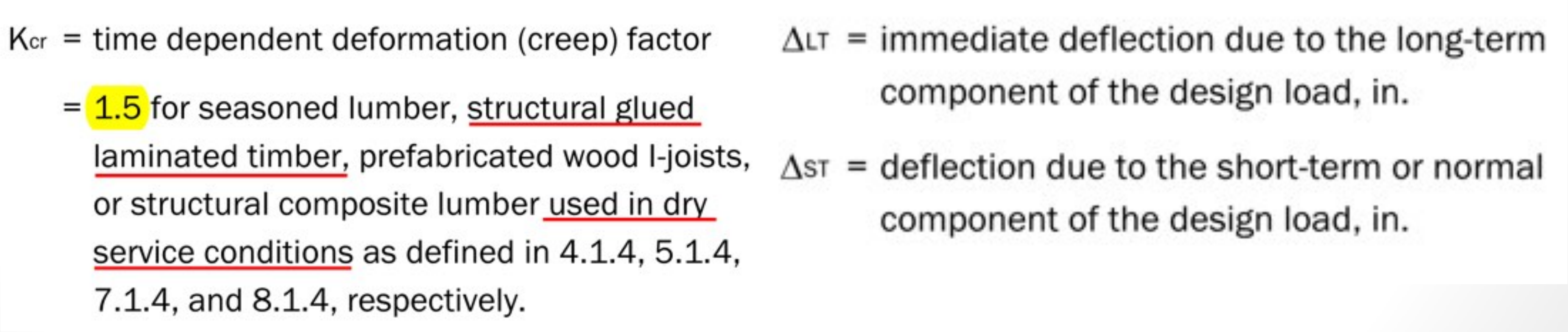


24F-V8

Special Considerations (glulam)

- Deflection
  - Deflection often governs glulam beam design in mass timber construction
  - Include long-term affects (NDS 3.5.2)

$$\Delta_T = K_{cr}\,\Delta_{LT} + \Delta_{ST}$$ (NDS eq. 3.5-1)



K_{cr} = time dependent deformation (creep) factor

= 1.5 for seasoned lumber, structural glued laminated timber, prefabricated wood I-joists, or structural composite lumber used in dry service conditions as defined in 4.1.4, 5.1.4, 7.1.4, and 8.1.4, respectively.

Δ_{LT} = immediate deflection due to the long-term component of the design load, in.

Δ_{ST} = deflection due to the short-term or normal component of the design load, in.

Special Considerations (glulam)

- Camber
  - APA Product Guide/APA Technical Note S550H
  - Recommend you specify a consistent camber (in feet, radius)
    - 3000 ft. for floor beams
    - 5000 ft. for roof beams
    - Do NOT camber multi-span or cantilevered members
  - Manufacturer specific camber (if available)
    - Example: Manufacturer X
      - 1310 ft., 1833 ft., 2620 ft. 3274 ft.
  - “TOP” label

Special Considerations (glulam)

- Strength Design (LRFD)
  - Timber typically designed in ASD, however using LRFD for strength controlled members may gain you **5%-15%** additional load carrying capacity
  - **NO** C_d Factor
  - Add
    - K_f (Format Conversion Factor) per NDS Table 2.3.5
    - Φ (Strength Reduction Factor) per NDS Table 2.3.6
    - λ (Time Effect Factor) per NDS Table N3 *(page 183)*
    - Use LRFD load-combinations per IBC

Special Considerations (glulam)

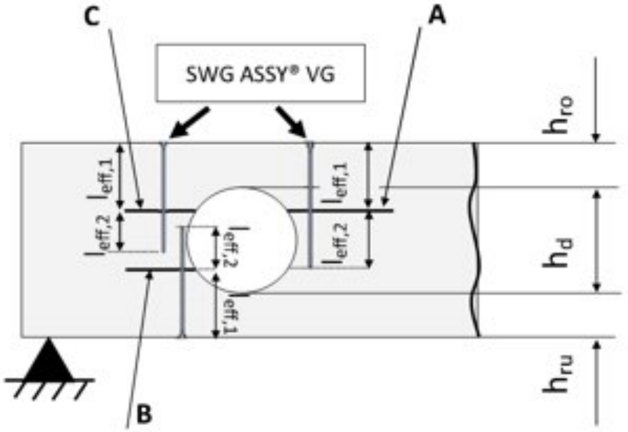
- Holes in Beams
  - APA Technical Note V700A

TECHNICAL NOTE

Effect of Large Diameter Horizontal Holes on the Bending and Shear Properties of Structural Glued Laminated Timber

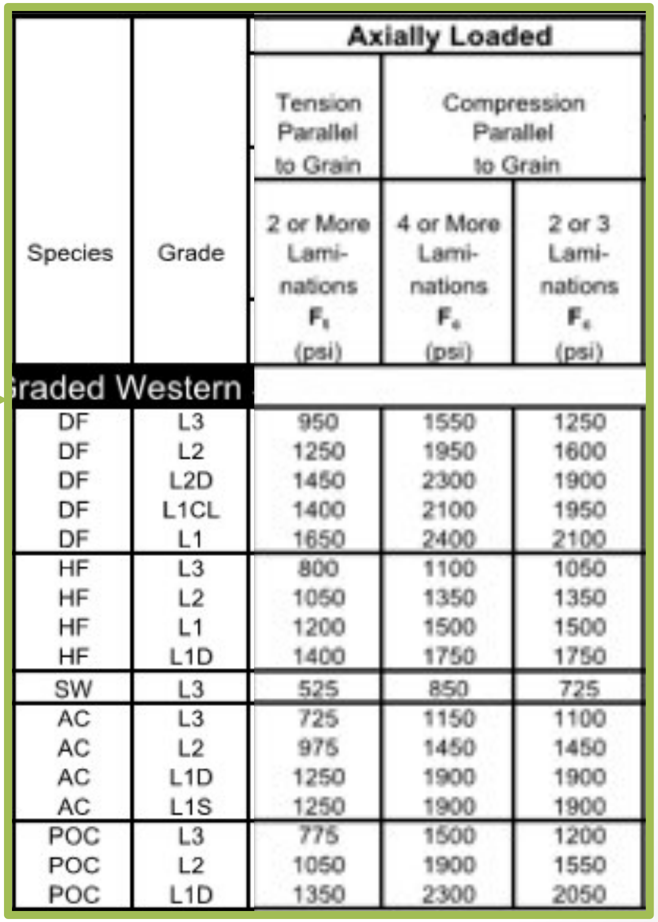
www.apawood.org

  - Reinforce Penetration with Timber Screws
    - https://mtcsolutions.com/resource/timber-reinforcement-guide/



Glulam Columns

- Adjustment Factors
  - NDS Table 5.3.1
  - C_p
- NDS Supplement
  - Table 5B
- Eccentricity
  - Not codified
  - 5% min
  - D/6?
  - Always use judgement



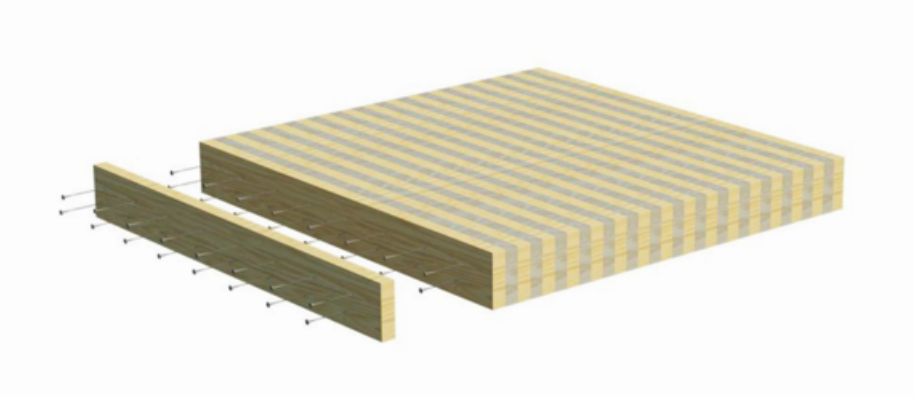
Species	Grade	Axially Loaded		
		Tension Parallel to Grain	Compression Parallel to Grain	
		2 or More Laminations F_t (psi)	4 or More Laminations F_c (psi)	2 or 3 Laminations F_c (psi)
raded Western				
DF	L3	950	1550	1250
DF	L2	1250	1950	1600
DF	L2D	1450	2300	1900
DF	L1CL	1400	2100	1950
DF	L1	1650	2400	2100
HF	L3	800	1100	1050
HF	L2	1050	1350	1350
HF	L1	1200	1500	1500
HF	L1D	1400	1750	1750
SW	L3	525	850	725
AC	L3	725	1150	1100
AC	L2	975	1450	1450
AC	L1D	1250	1900	1900
AC	L1S	1250	1900	1900
POC	L3	775	1500	1200
POC	L2	1050	1900	1550
POC	L1D	1350	2300	2050

NLT – Nail Laminated Timber

Photo: Brad Kahn

NLT – Nail Laminated Timber

- Code recognized
- Typical spans
  - 10-16 feet
- Nominal 2x on edge
- Unique aesthetics
- Floors and roofs
- Lower raw material cost
- Labor cost variable
  - More expensive if field assembled
  - Recommend panelizing



- Design Considerations
  - Fire design
  - Openings
  - High shrink/swell potential
  - Edge detailing
  - Sheathed diaphragm

NLT – Nail Laminated Timber

Photo: Elizabeth Depwe

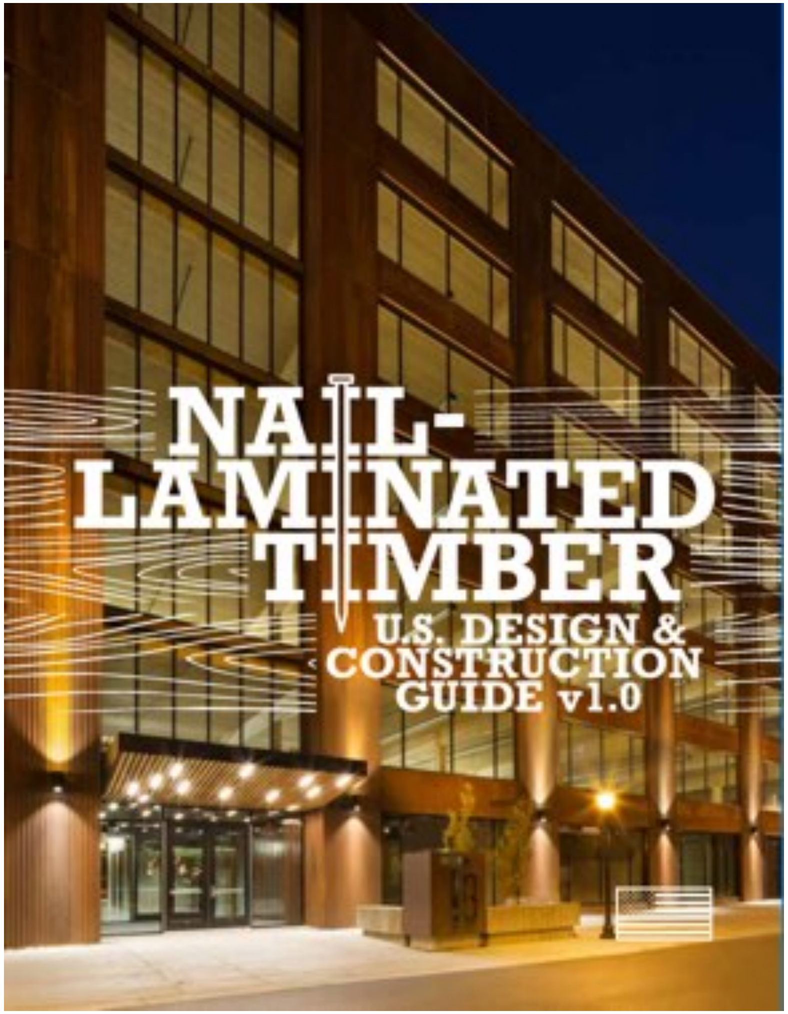
Design Codes

IBC
2304.9.3 Mechanically Laminated Decking

Specification
Chapter 4 – Sawn Lumber

Supplement
Table 4A – All species except So. Pine
Table 4B – Southern Pine
Table 4C – Mechanically Graded

Design Resources

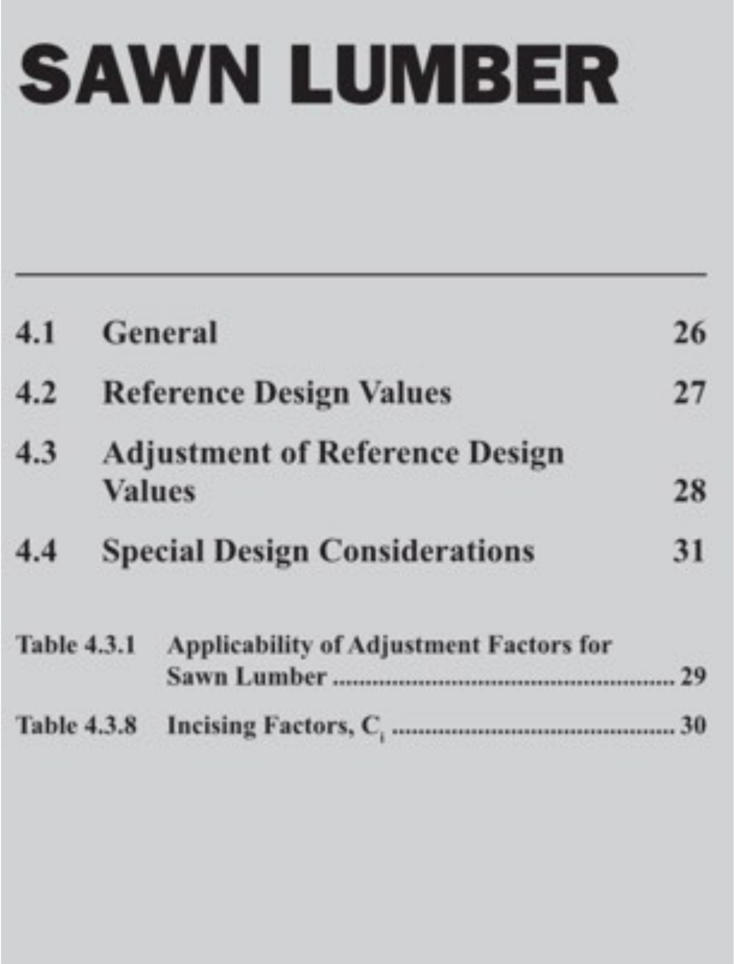


NAIL-LAMINATED TIMBER

U.S. DESIGN & CONSTRUCTION GUIDE v1.0

NLT Design Guide available at www.thinkwood.com

NLT – Nail Laminated Timber



SAWN LUMBER

Chapter 4 –

Sawn Lumber

NLT Design Notes

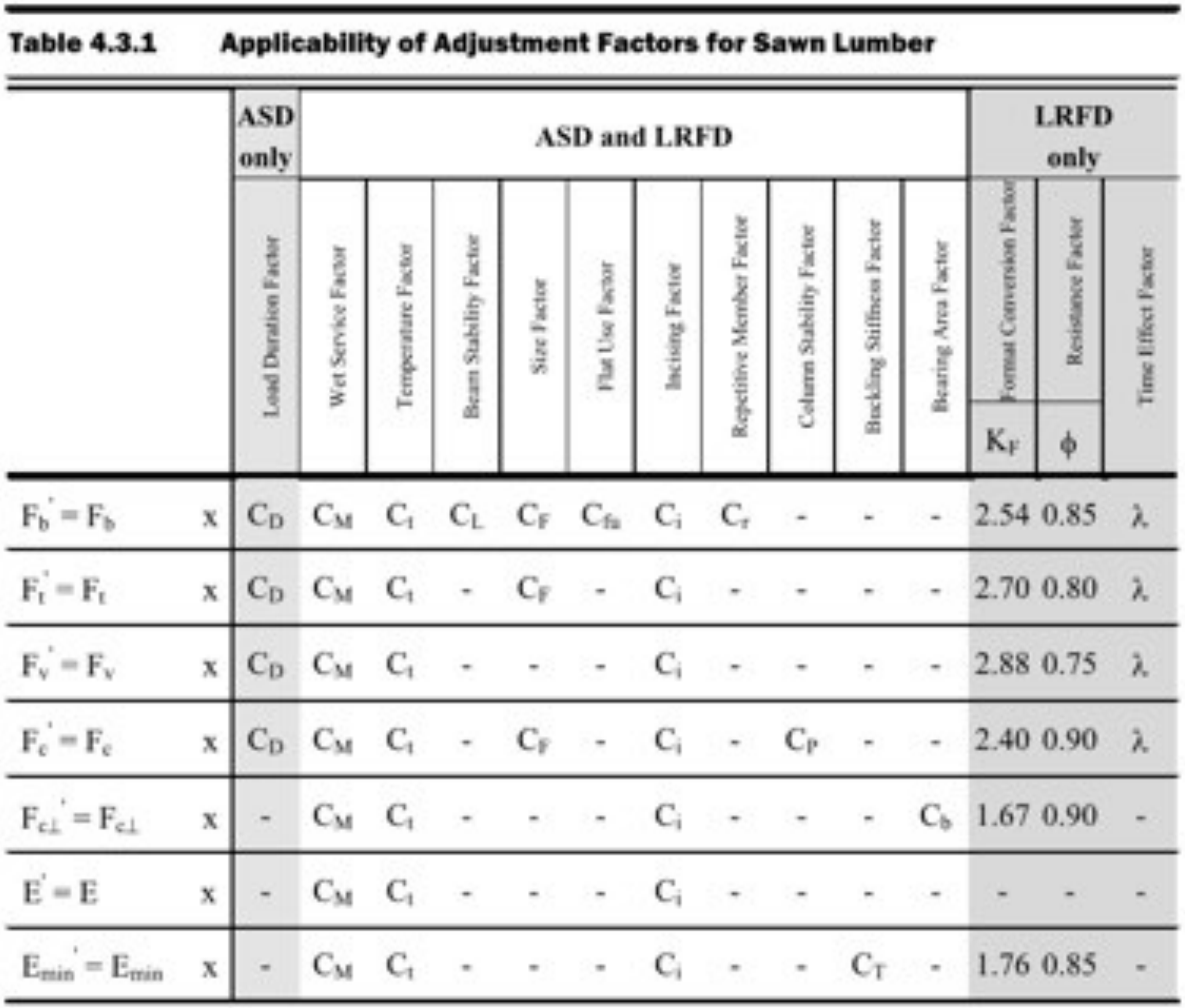
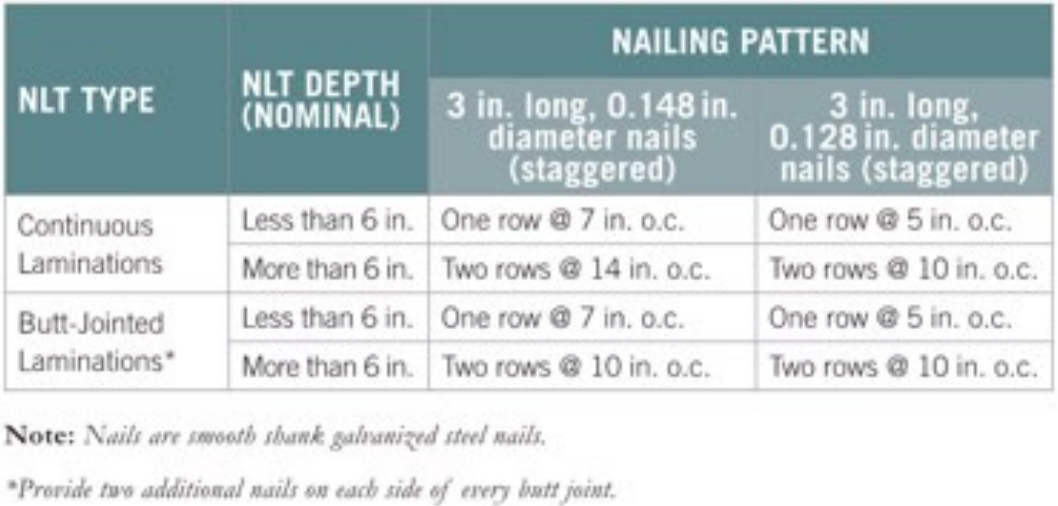


Table 4.3.1 Applicability of Adjustment Factors for Sawn Lumber

		ASD only	ASD and LRFD										LRFD only		
		Load Duration Factor	Wet Service Factor	Temperature Factor	Beam Stability Factor	Size Factor	Flat Use Factor	Incising Factor	Repetitive Member Factor	Column Stability Factor	Buckling Stiffness Factor	Bearing Area Factor	Format Conversion Factor	Resistance Factor	Time Effect Factor
													K_F	ϕ	
$F_b' = F_b$	x	C_D	C_M	C_t	C_L	C_F	C_{fu}	C_i	C_r	-	-	-	2.54	0.85	λ
$F_t' = F_t$	x	C_D	C_M	C_t	-	C_F	-	C_i	-	-	-	-	2.70	0.80	λ
$F_v' = F_v$	x	C_D	C_M	C_t	-	-	-	C_i	-	-	-	-	2.88	0.75	λ
$F_c' = F_c$	x	C_D	C_M	C_t	-	C_F	-	C_i	-	C_P	-	-	2.40	0.90	λ
$F_{c\perp}' = F_{c\perp}$	x	-	C_M	C_t	-	-	-	C_i	-	-	-	C_b	1.67	0.90	-
$E' = E$	x	-	C_M	C_t	-	-	-	C_i	-	-	-	-	-	-	-
$E_{min}' = E_{min}$	x	-	C_M	C_t	-	-	-	C_i	-	-	C_T	-	1.76	0.85	-

NLT - Lamination Nailing

- Prescriptive nailing per IBC Table 2304.9.3.2



NLT TYPE	NLT DEPTH (NOMINAL)	NAILING PATTERN	
		3 in. long, 0.148 in. diameter nails (staggered)	3 in. long, 0.128 in. diameter nails (staggered)
Continuous Laminations	Less than 6 in.	One row @ 7 in. o.c.	One row @ 5 in. o.c.
	More than 6 in.	Two rows @ 14 in. o.c.	Two rows @ 10 in. o.c.
Butt-Jointed Laminations*	Less than 6 in.	One row @ 7 in. o.c.	One row @ 5 in. o.c.
	More than 6 in.	Two rows @ 10 in. o.c.	Two rows @ 10 in. o.c.

Note: *Nails are smooth shank galvanized steel nails.*

**Provide two additional nails on each side of every butt joint.*

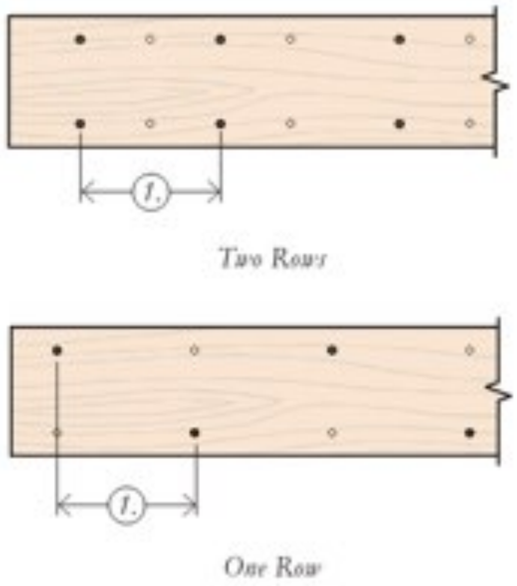


Figure 4.9: *Lamination Nailing*

Key

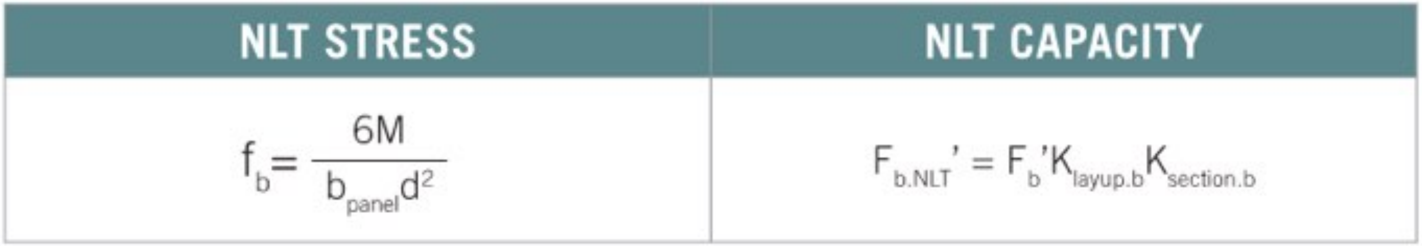
1. Nailing spacing

• Nailing in face layer

◦ Nailing in layer beyond

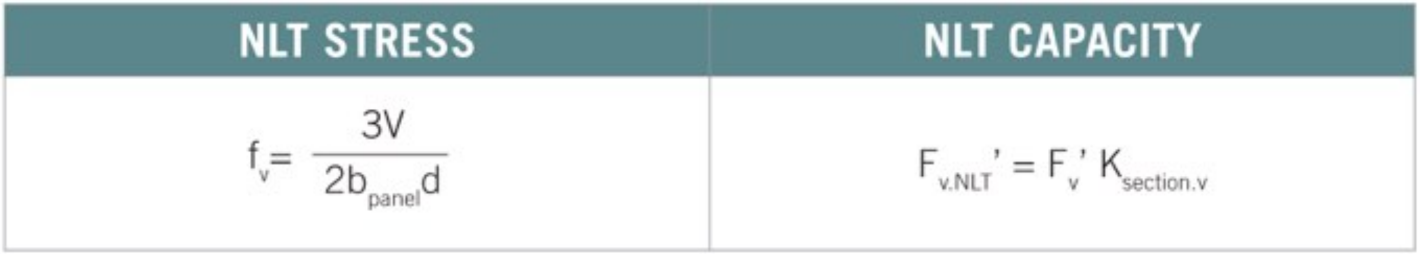
NLT Design Notes

- Flexure



NLT STRESS	NLT CAPACITY
$f_b = \frac{6M}{b_{panel} d^2}$	$F_{b.NLT}' = F_b' K_{layup.b} K_{section.b}$

  - F_b' includes all applicable adjustment factors per NDS Table 4.3.1
- Shear



NLT STRESS	NLT CAPACITY
$f_v = \frac{3V}{2 b_{panel} d}$	$F_{v.NLT}' = F_v' K_{section.v}$

  - F_V' includes all applicable adjustment factors per NDS Table 4.3.1

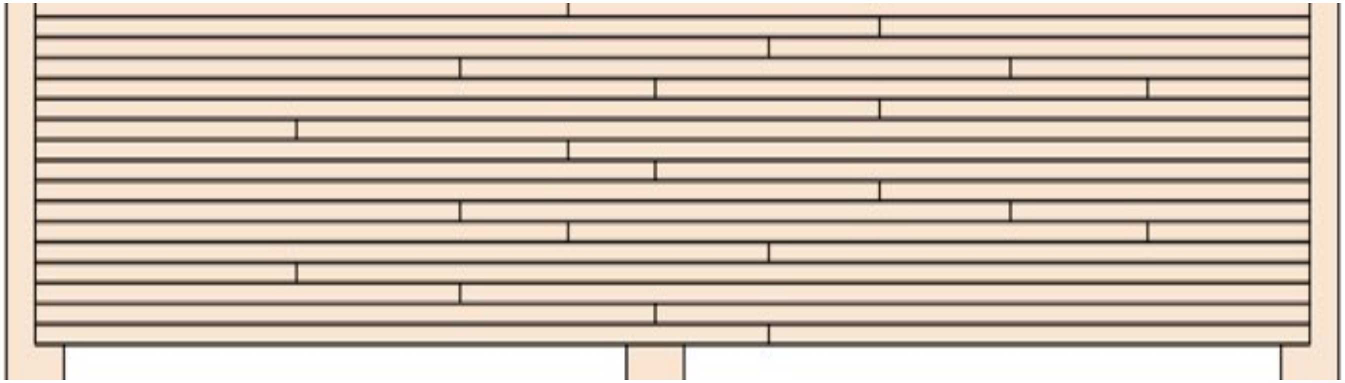
NLT Design Notes

- NDS Adjustment Factors per NDS Table 4.3.1
  - Design NLT as fully braced (C_L=1.0)
  - Size Factor (C_F) based on single lamination
  - Repetitive Factor (C_R) applies = 1.15
- Additional adjustment factors required when NLT laminations are *not* butt jointed at supports (K_{LAYUP}) *and* when mixing laminations of varying depths ($K_{SECTION}$)

NLT Design Notes

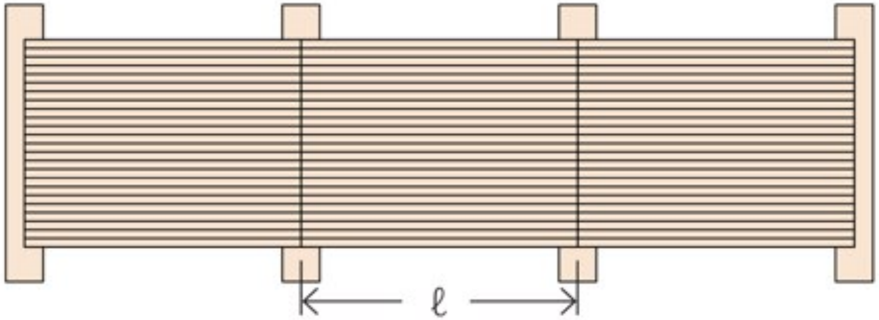
Layup Factor (K_{layup}) - IBC 2304.9.3

- Less than 1.0 when “controlled” layups place lamination joints between supports
- May produce less lumber waste
- Reduced strength and stiffness



NLT Design Notes

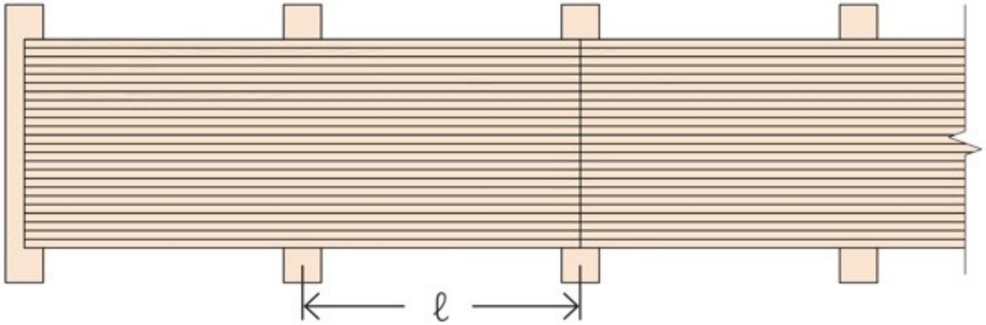
Continuous (single span)



$$K_{\text{layup.b}} = 1.0 \qquad K_{\text{layup.E}} = 1.0$$

$$M = \frac{w\ell^2}{8} \qquad \Delta = \frac{5w\ell^4}{384E\,(d^3/12)}$$

Continuous (multi-span)

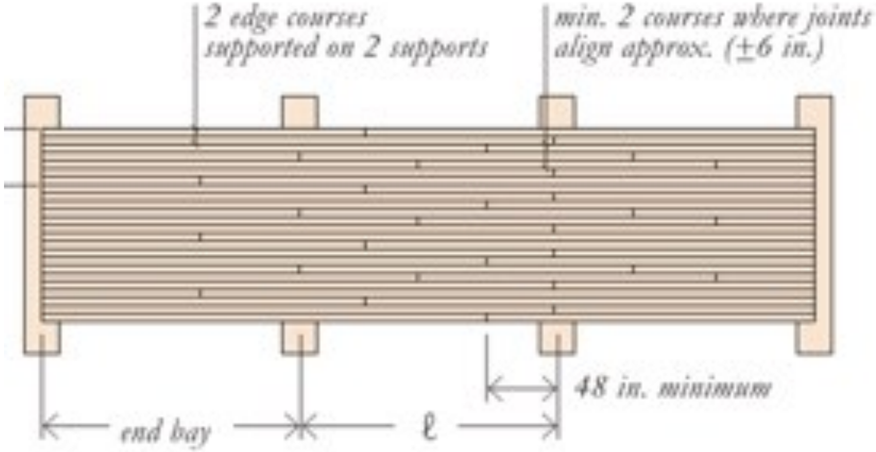


$$K_{\text{layup.b}} = 1.0 \qquad K_{\text{layup.E}} = 1.0$$

$$M = \frac{w\ell^2}{8} \qquad \Delta = \frac{w\ell^4}{185E\,(d^3/12)}$$

NLT Design Notes

Random Controlled Layup (Not permitted in Type IV Construction)



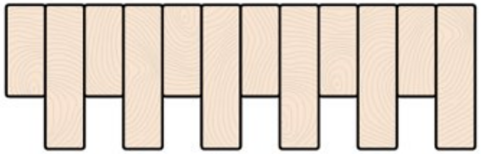
$$K_{layup.b} = 0.67 \qquad K_{layup.E} = 0.69$$

$$M = 0.10w\ell^2 \qquad \Delta = \frac{0.0069w\ell^4}{E\,(d^3/12)}$$

Layup rules per IBC 2304.9.2.5 and 2304.9.3.3

$$EI = E_{NLT}'\ I = E'\ K_{layup.E} K_{section.E} \frac{b_{panel} d^3}{12}$$

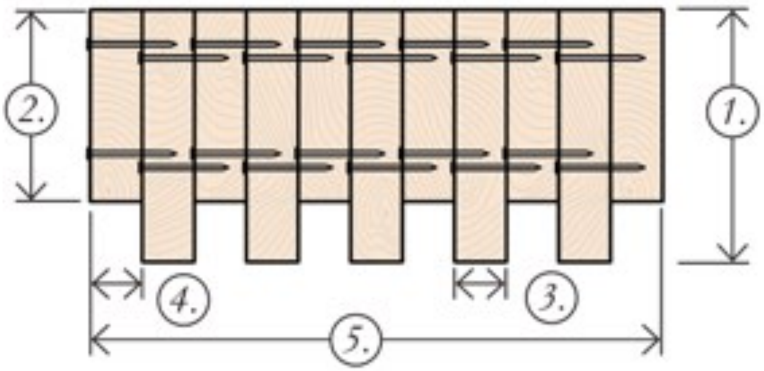
NLT Design Notes



Layup Factor ($K_{SECTION}$)

- Staggered lamination depth for aesthetic or acoustic purposes
- Reduced efficiency
  - Not a fully composite section
  - Modifying deeper lamination stiffness across full width
    - +/-33% strength & stiffness loss
  - Shear based on only contribution from deeper laminations

NLT Design Notes



$$⑥ \quad x_i = \frac{n_i b_{lam\,i}}{b_{panel}}$$

Key

1. *NLT deep lamination depth* (d_1)
2. *NLT shallow lamination depth* (d_2)
3. *NLT deep lamination thickness* (b_{lam1})
4. *NLT shallow lamination thickness* (b_{lam2})
5. *NLT panel width* (b)
6. *Ratio of lamination depths* (x_i), *where* n_i = *the number of laminations of depth* d_i

STIFFNESS ($K_{section.E}$)	BENDING ($K_{section.b}$)	SHEAR ($K_{section.v}$)
$K_{section.E} = X_1 + X_2\left[\frac{d_2}{d_1}\right]^3$	$K_{section.b} = X_1 + X_2\left[\frac{d_2}{d_1}\right]^3$	$K_{section.v} = X_1$

Special Considerations (NLT)

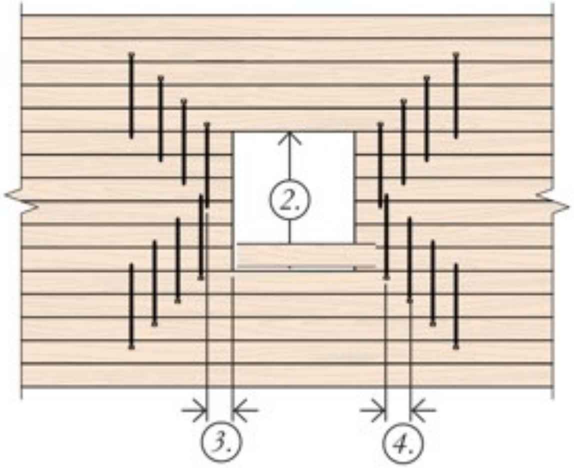
- Penetrations and openings

Opening Size	Action
Up to 2” diameter	Okay, 6” minimum spacing, stagger (reinforce groups of (3) or more as opening)
2” to 6” diameter	Provide local reinforcement screws
6” to 18” opening	Provide reinforcement angle
Greater than 18”	Provide supplemental framing

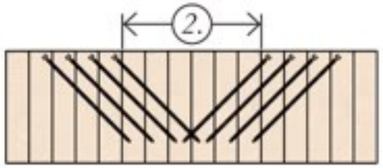
- Penetrations larger than 2” should avoid NLT panel joint/spline
- Require penetration submittal for openings greater than 6”

Special Considerations (NLT)

- Penetrations and Openings

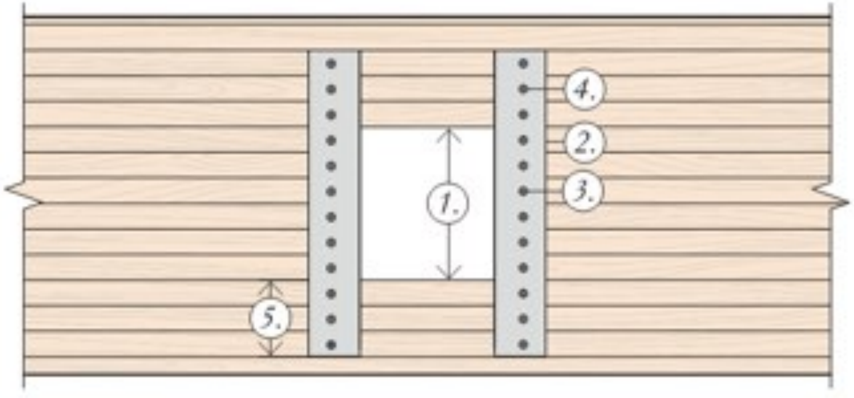


Plan View of Opening

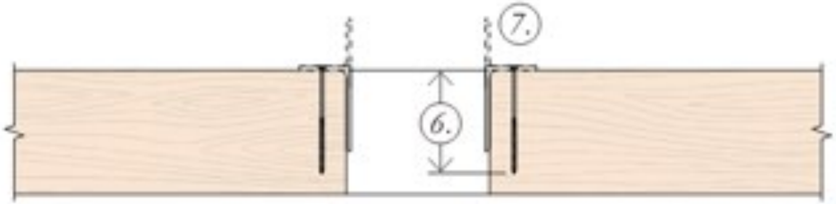


Section Beyond Opening

Up to 6”



Plan View of Opening with Steel Angle Framing



Section of Opening with Steel Angle Framing

6” to 18” Opening

Special Considerations (NLT)

- Consider long-term deflection effects per NDS 3.5.2
- Vibration options
  - Limit elastic live load deflection (L/480+)
  - AISC Design Guide 11 - Vibrations of Steel-Framed Structural Systems Due to Human Activity
- Weak-axis overhang
  - Up to 6" (4 laminations) with supplemental nailing and reinforcement screws or provide outrigger framing

Tips For Success (NLT)

- Panelize NLT (on-site or off-site)
  - Use timber screws to achieve equivalent toe-nailing requirements per IBC 2304.9.3.2
  - Provide spline type connection at panel-to-panel connections

- Moisture Management Plan
  - Sheath to restrain as soon as possible
  - Introduce gaps to allow for swell
    - ¾” every 10 feet
  - Tape joints
  - Protect wood end grain

CLT – Cross Laminated Timber

Photo: Michael Dupras

CLT – Cross Laminated Timber

- Code recognized (2015 IBC)
- Prefabricated/non-commodity
  - Floors and roofs
  - Load-bearing walls
  - Shear walls
  - Bi-directional span
- Dimensionally stable
- Typical spans
  - 12’-20’ spans (non-composite)
  - 16’-24’ spans (composite)
  - Typically vibration or shear governed

Versatile!

CLT – Cross Laminated Timber

Photo: Michael Dupras

Design Codes & Standards

2018
INTERNATIONAL CODES

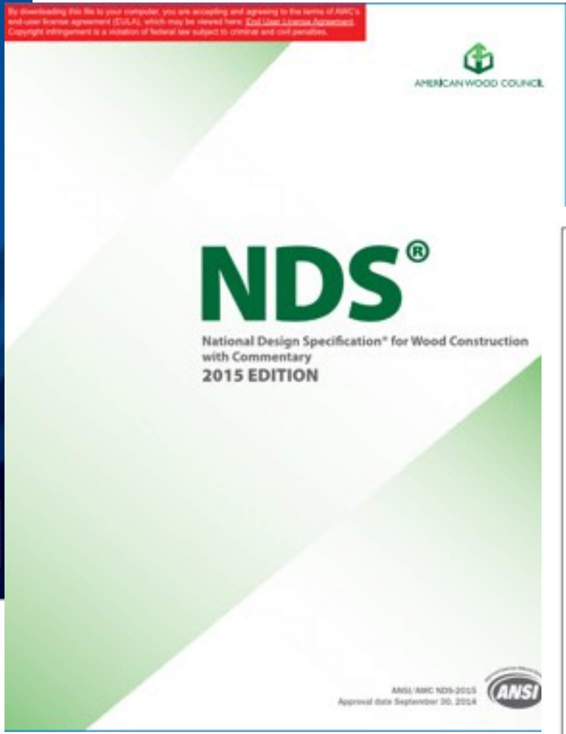
IBC®

A Member of the International Code Family®

INTERNATIONAL
BUILDING CODE®

IBC

2303.1.4 - Structural Glued Cross Laminated Timber



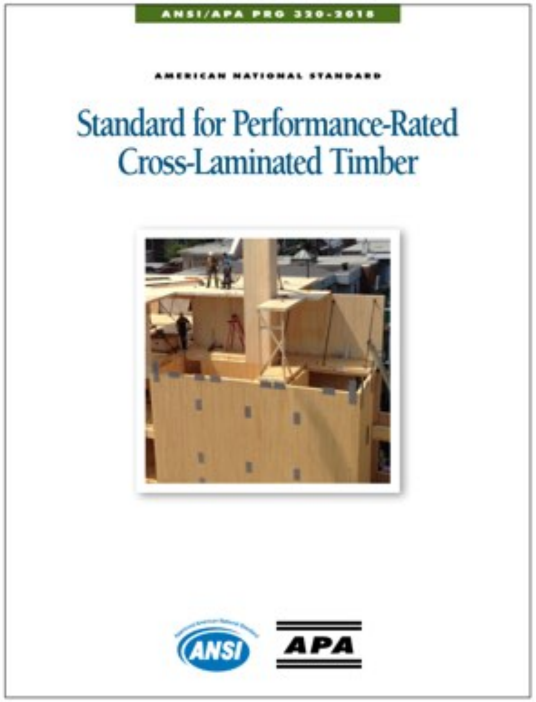
AMERICAN WOOD COUNCIL

NDS®

National Design Specification® for Wood Construction
with Commentary
2015 EDITION

ANSI/AWC NDS-2015
Approval date September 30, 2014

Specification
Chapter 10 – Cross
Laminated Timber



ANSI/APA PRG 320-2018

AMERICAN NATIONAL STANDARD

Standard for Performance-Rated
Cross-Laminated Timber

ANSI APA

PRG-320
Table 4A – All species except So. Pine
Table 4B – Southern Pine
Table 4C – Mechanically Graded

CLT Design Notes

- Minimum Performance Standards for layups outlined in PRG-320

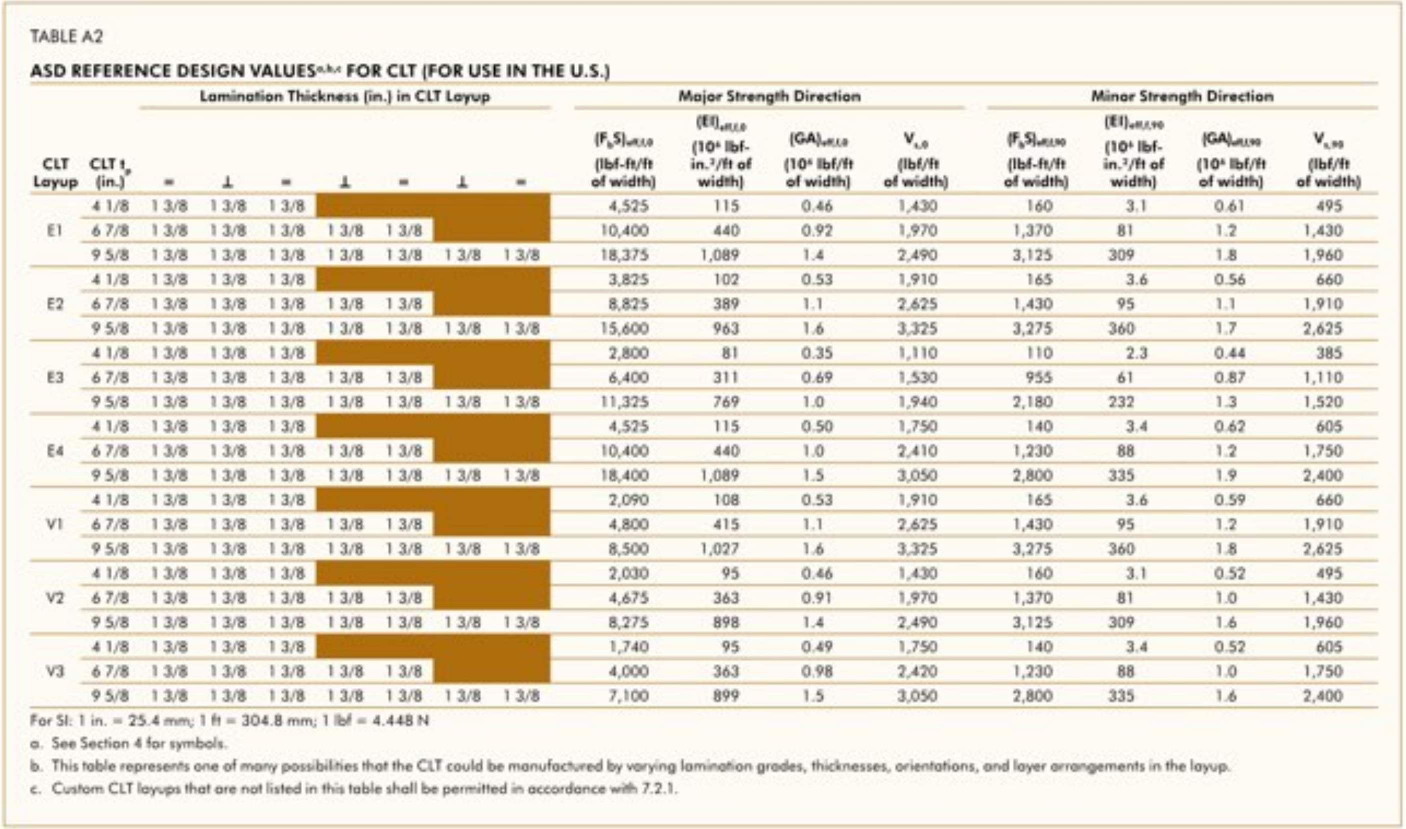


TABLE A2

ASD REFERENCE DESIGN VALUES[a,b,c] FOR CLT (FOR USE IN THE U.S.)

		Lamination Thickness (in.) in CLT Layup							Major Strength Direction				Minor Strength Direction			
CLT Layup	CLT t_p (in.)	=	⊥	=	⊥	=	⊥	=	$(F_bS)_{eff,f,0}$ (lbf-ft/ft of width)	$(EI)_{eff,f,0}$ (10^6 lbf-in.^{2}/ft of width)	$(GA)_{eff,f,0}$ (10^6 lbf/ft of width)	$V_{s,0}$ (lbf/ft of width)	$(F_bS)_{eff,f,90}$ (lbf-ft/ft of width)	$(EI)_{eff,f,90}$ (10^6 lbf-in.^{2}/ft of width)	$(GA)_{eff,f,90}$ (10^6 lbf/ft of width)	$V_{s,90}$ (lbf/ft of width)
E1	4 1/8	1 3/8	1 3/8	1 3/8					4,525	115	0.46	1,430	160	3.1	0.61	495
	6 7/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8			10,400	440	0.92	1,970	1,370	81	1.2	1,430
	9 5/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	18,375	1,089	1.4	2,490	3,125	309	1.8	1,960
E2	4 1/8	1 3/8	1 3/8	1 3/8					3,825	102	0.53	1,910	165	3.6	0.56	660
	6 7/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8			8,825	389	1.1	2,625	1,430	95	1.1	1,910
	9 5/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	15,600	963	1.6	3,325	3,275	360	1.7	2,625
E3	4 1/8	1 3/8	1 3/8	1 3/8					2,800	81	0.35	1,110	110	2.3	0.44	385
	6 7/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8			6,400	311	0.69	1,530	955	61	0.87	1,110
	9 5/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	11,325	769	1.0	1,940	2,180	232	1.3	1,520
E4	4 1/8	1 3/8	1 3/8	1 3/8					4,525	115	0.50	1,750	140	3.4	0.62	605
	6 7/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8			10,400	440	1.0	2,410	1,230	88	1.2	1,750
	9 5/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	18,400	1,089	1.5	3,050	2,800	335	1.9	2,400
V1	4 1/8	1 3/8	1 3/8	1 3/8					2,090	108	0.53	1,910	165	3.6	0.59	660
	6 7/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8			4,800	415	1.1	2,625	1,430	95	1.2	1,910
	9 5/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	8,500	1,027	1.6	3,325	3,275	360	1.8	2,625
V2	4 1/8	1 3/8	1 3/8	1 3/8					2,030	95	0.46	1,430	160	3.1	0.52	495
	6 7/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8			4,675	363	0.91	1,970	1,370	81	1.0	1,430
	9 5/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	8,275	898	1.4	2,490	3,125	309	1.6	1,960
V3	4 1/8	1 3/8	1 3/8	1 3/8					1,740	95	0.49	1,750	140	3.4	0.52	605
	6 7/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8			4,000	363	0.98	2,420	1,230	88	1.0	1,750
	9 5/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	7,100	899	1.5	3,050	2,800	335	1.6	2,400

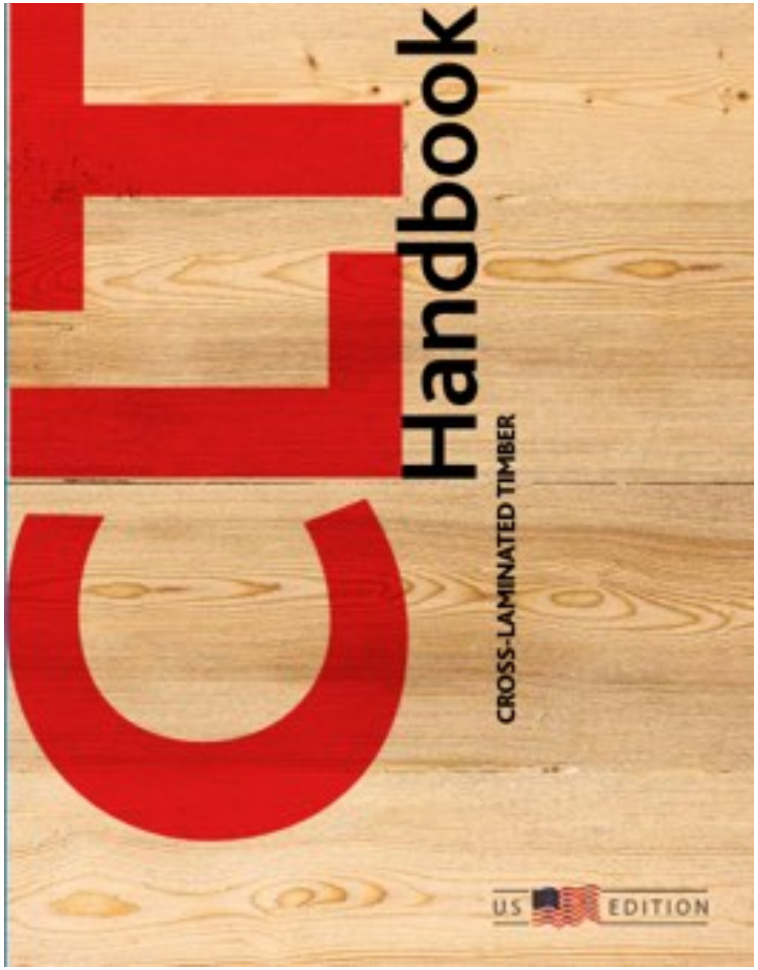
For SI: 1 in. = 25.4 mm; 1 ft = 304.8 mm; 1 lbf = 4.448 N

a. See Section 4 for symbols.

b. This table represents one of many possibilities that the CLT could be manufactured by varying lamination grades, thicknesses, orientations, and layer arrangements in the layup.

c. Custom CLT layups that are not listed in this table shall be permitted in accordance with 7.2.1.

Design Resources



CLT Handbook

CROSS-LAMINATED TIMBER

US EDITION

CLT Handbook available at www.thinkwood.com

CLT – Cross Laminated Timber

CROSS-LAMINATED TIMBER

Chapter 10 –

Cross Laminated Timber

CLT Design Notes

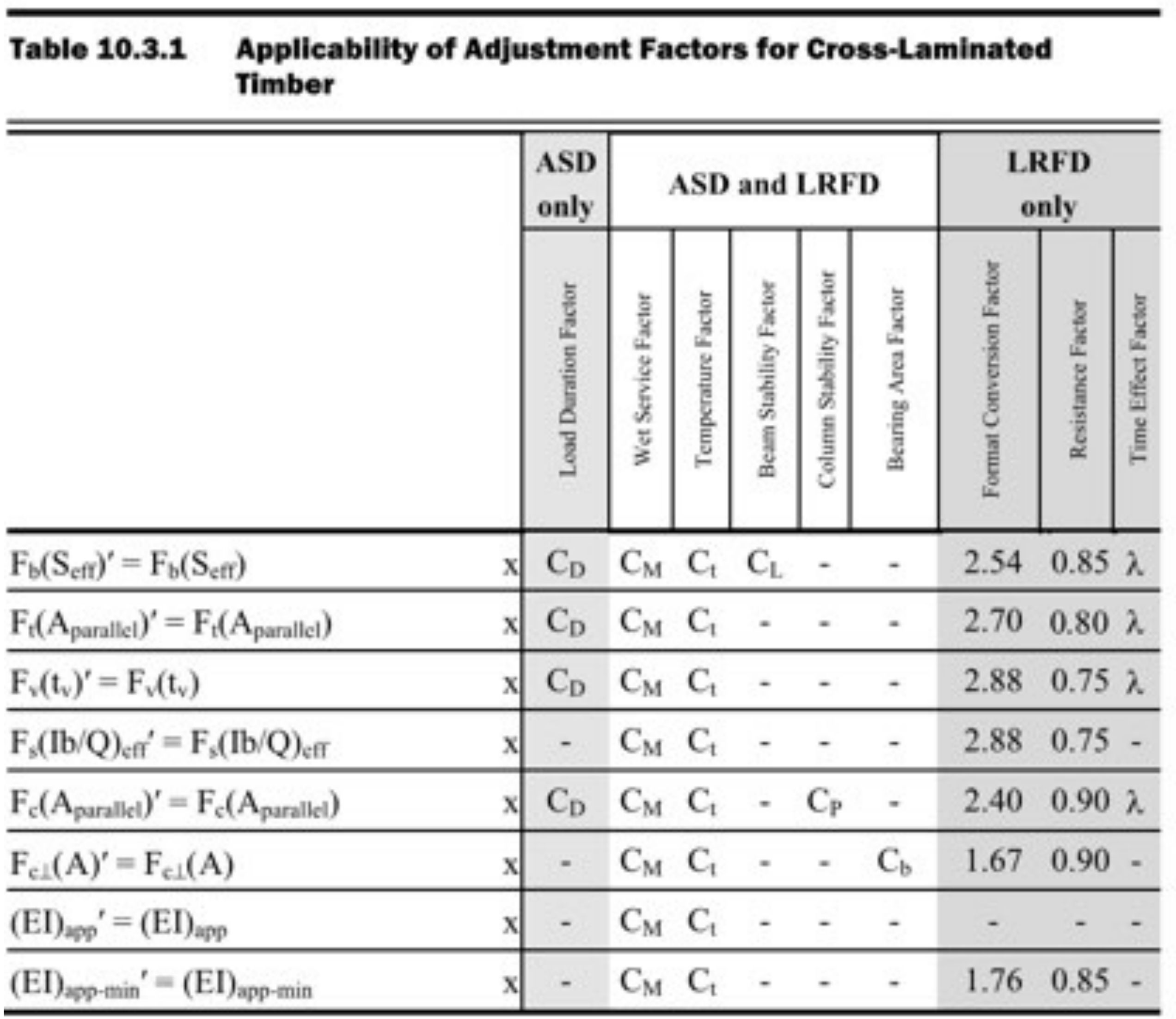


Table 10.3.1 Applicability of Adjustment Factors for Cross-Laminated Timber

			ASD only	ASD and LRFD					LRFD only		
			Load Duration Factor	Wet Service Factor	Temperature Factor	Beam Stability Factor	Column Stability Factor	Bearing Area Factor	Format Conversion Factor	Resistance Factor	Time Effect Factor
Bending	$F_b(S_{eff})' = F_b(S_{eff})$	x	C_D	C_M	C_t	C_L	-	-	2.54	0.85	λ
Tension	$F_t(A_{parallel})' = F_t(A_{parallel})$	x	C_D	C_M	C_t	-	-	-	2.70	0.80	λ
Shear	$F_v(t_v)' = F_v(t_v)$	x	C_D	C_M	C_t	-	-	-	2.88	0.75	λ
	$F_s(Ib/Q)_{eff}' = F_s(Ib/Q)_{eff}$	x	-	C_M	C_t	-	-	-	2.88	0.75	-
Comp.	$F_c(A_{parallel})' = F_c(A_{parallel})$	x	C_D	C_M	C_t	-	C_P	-	2.40	0.90	λ
Bearing	$F_{c\perp}(A)' = F_{c\perp}(A)$	x	-	C_M	C_t	-	-	C_b	1.67	0.90	-
Stiffness	$(EI)_{app}' = (EI)_{app}$	x	-	C_M	C_t	-	-	-	-	-	-
	$(EI)_{app-min}' = (EI)_{app-min}$	x	-	C_M	C_t	-	-	-	1.76	0.85	-

CLT Design Notes

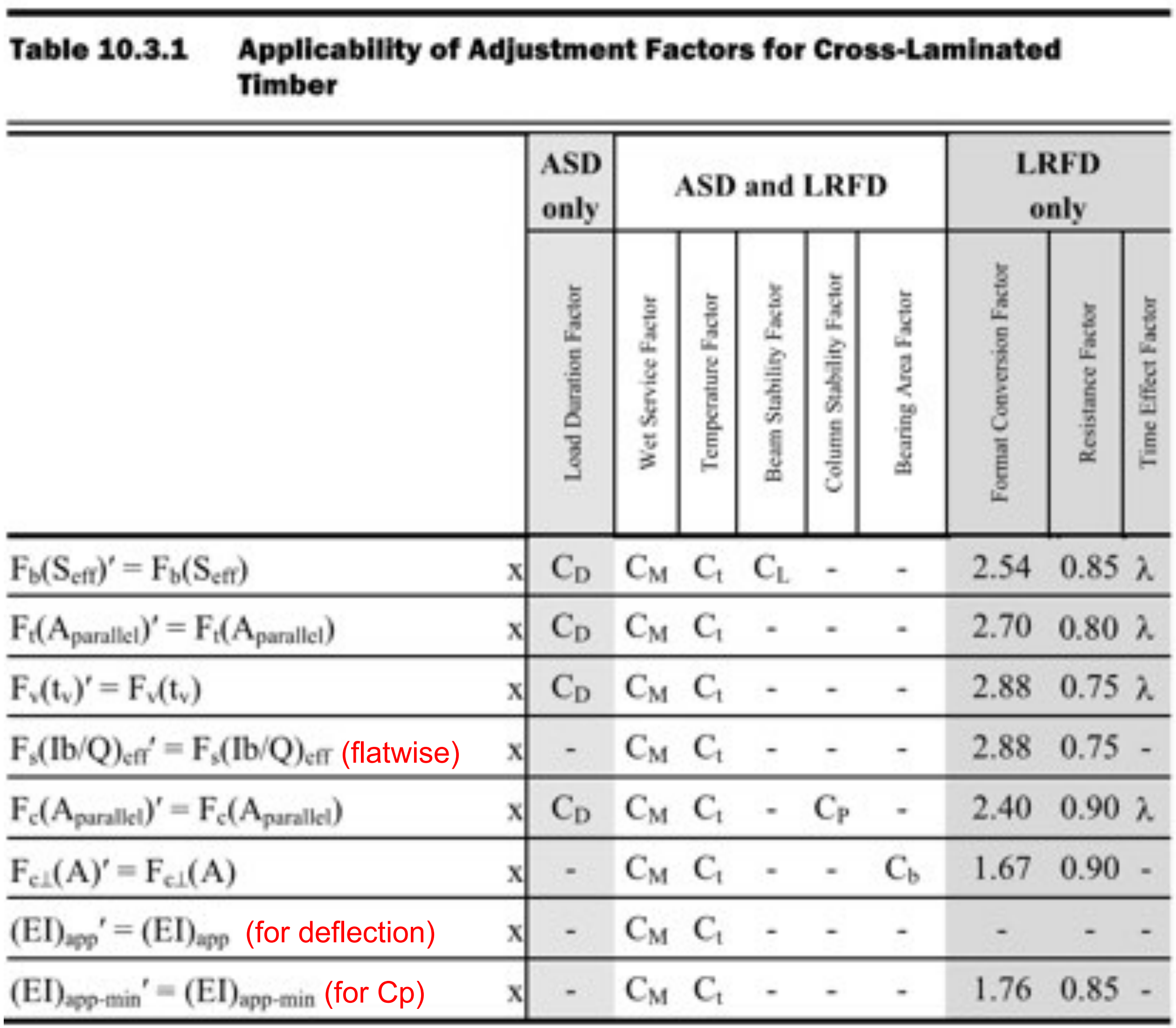


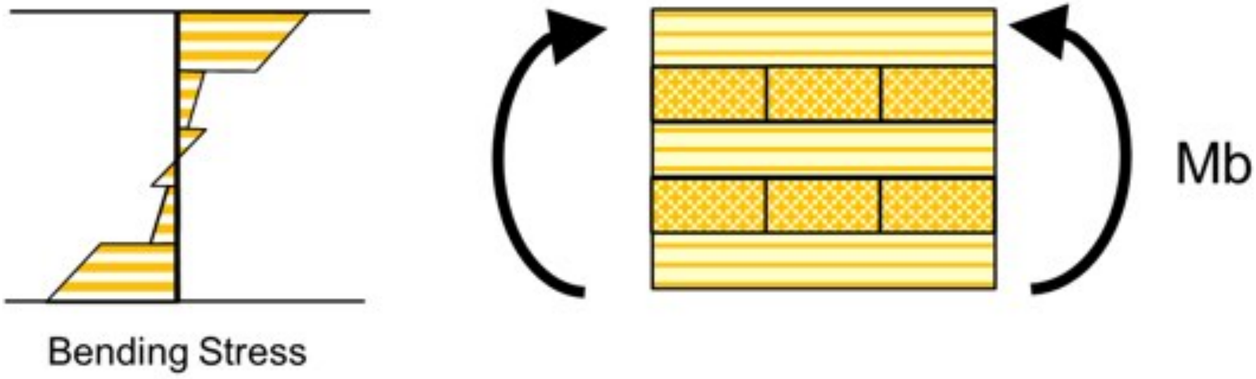
Table 10.3.1 Applicability of Adjustment Factors for Cross-Laminated Timber

			ASD only	ASD and LRFD					LRFD only		
			Load Duration Factor	Wet Service Factor	Temperature Factor	Beam Stability Factor	Column Stability Factor	Bearing Area Factor	Format Conversion Factor	Resistance Factor	Time Effect Factor
Bending	$F_b(S_{eff})' = F_b(S_{eff})$	x	C_D	C_M	C_t	C_L	-	-	2.54	0.85	λ
Tension	$F_t(A_{parallel})' = F_t(A_{parallel})$	x	C_D	C_M	C_t	-	-	-	2.70	0.80	λ
Shear	$F_v(t_v)' = F_v(t_v)$	x	C_D	C_M	C_t	-	-	-	2.88	0.75	λ
	$F_s(Ib/Q)_{eff}' = F_s(Ib/Q)_{eff}$ (flatwise)	x	-	C_M	C_t	-	-	-	2.88	0.75	-
Comp.	$F_c(A_{parallel})' = F_c(A_{parallel})$	x	C_D	C_M	C_t	-	C_P	-	2.40	0.90	λ
Bearing	$F_{c\perp}(A)' = F_{c\perp}(A)$	x	-	C_M	C_t	-	-	C_b	1.67	0.90	-
Stiffness	$(EI)_{app}' = (EI)_{app}$ (for deflection)	x	-	C_M	C_t	-	-	-	-	-	-
	$(EI)_{app\text{-}min}' = (EI)_{app\text{-}min}$ (for Cp)	x	-	C_M	C_t	-	-	-	1.76	0.85	-

CLT Design Notes

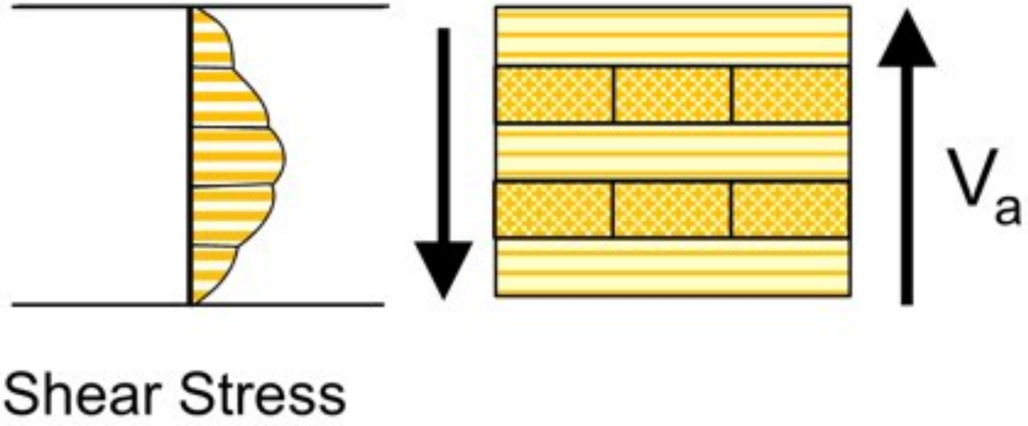
- Bending (ASD)
  - $F_b(S_{eff})' = \underbrace{F_b(S_{eff})}_{\text{PER MFR.}}\underbrace{(C_d)(C_m)(C_T)(C_L)}_{\text{PER NDS}}$

$C_L = 1.0$*



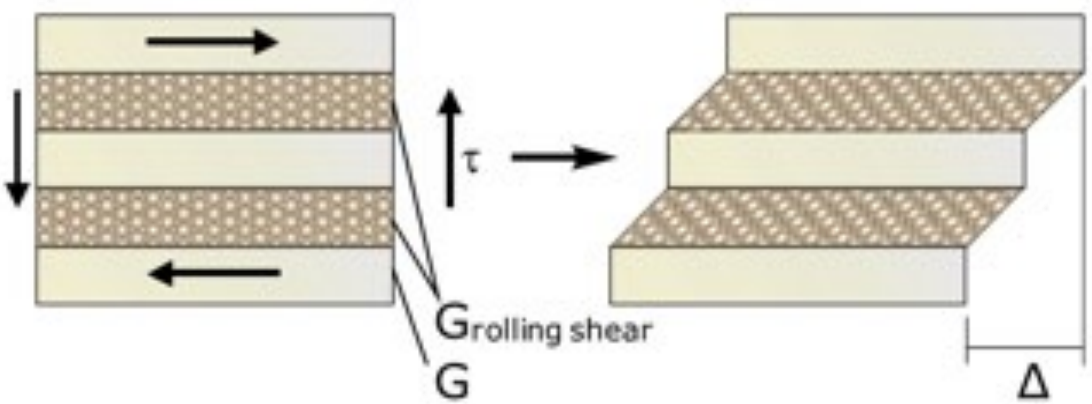
CLT Design Notes

- Shear (ASD)
  - $F_S(IbQ_{eff})' = \underbrace{F_S(IbQ_{eff})}_{\substack{\text{PER}\\ \text{MFR.}\\ \downarrow \\ \boxed{V_s}}}\underbrace{(C_m)(C_T)}_{\substack{\text{PER}\\ \text{NDS}}} \longleftarrow$ **No** C_d



CLT Design Notes

- "Rolling Shear"
  - $G_R \approx G_0/10$
  - Produces high shear deformations
  - Accounted for in CLT properties
    - $F_b(S_{eff})$
    - $F_S(IbQ_{eff})$



Special Considerations (CLT)

- Deflection
  - CLT deflection to account for shear deformations (mandatory)

$$(EI)_{app} = \frac{EI_{eff}}{1 + \frac{K_s EI_{eff}}{GA_{eff} L^2}} \quad (C10.4.1\text{-}1)$$

  - L = span
  - K_s per Table 10.4.1.1 (next slide)
  - Provided by CLT Mfr.
    - EI_{eff}, GA_{eff}

Special Considerations (CLT)

- Shear Deformation Adjustment Factor (K_s)

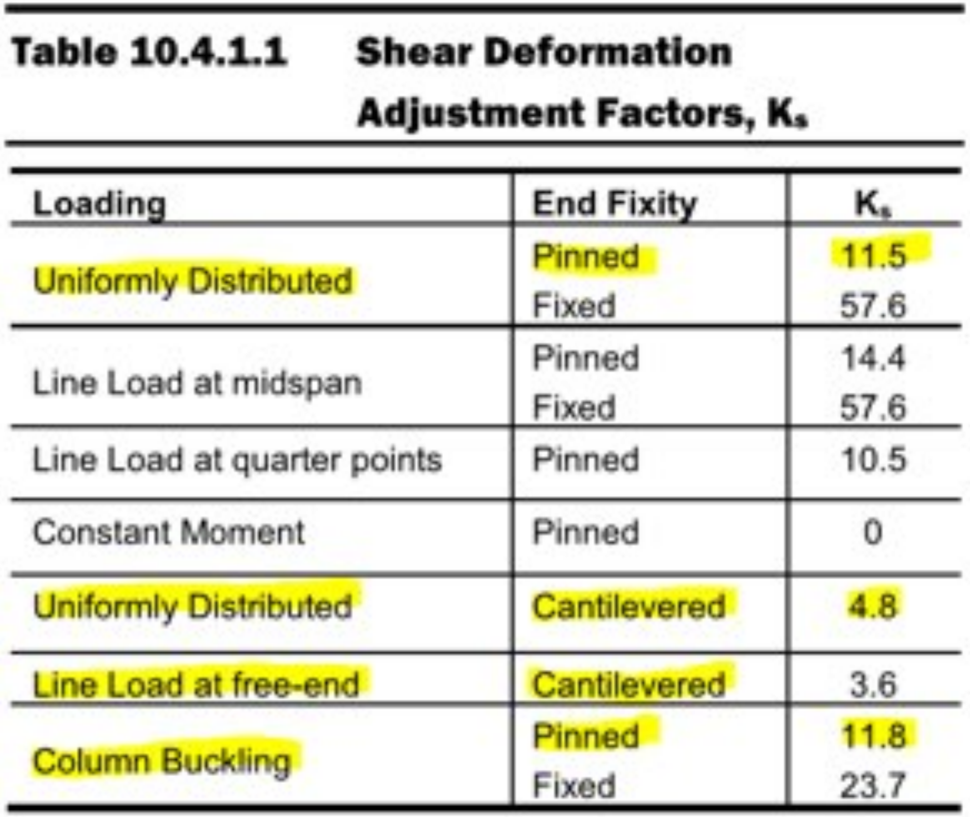


Table 10.4.1.1 Shear Deformation Adjustment Factors, K_s

Loading	End Fixity	K_s
Uniformly Distributed	Pinned	11.5
	Fixed	57.6
Line Load at midspan	Pinned	14.4
	Fixed	57.6
Line Load at quarter points	Pinned	10.5
Constant Moment	Pinned	0
Uniformly Distributed	Cantilevered	4.8
Line Load at free-end	Cantilevered	3.6
Column Buckling	Pinned	11.8
	Fixed	23.7

Special Considerations (CLT)

- Vibration
  - Often controls CLT spans
  - Vibration controlled spans provided by CLT mfr.

  - Simplified Approach (for spans < 15 ft.)
    - Limit elastic live load deflection (L/600)
    - Limit elastic total load deflection (L/400)

  - CLT Handbook (FPInnovation), Chapter 7

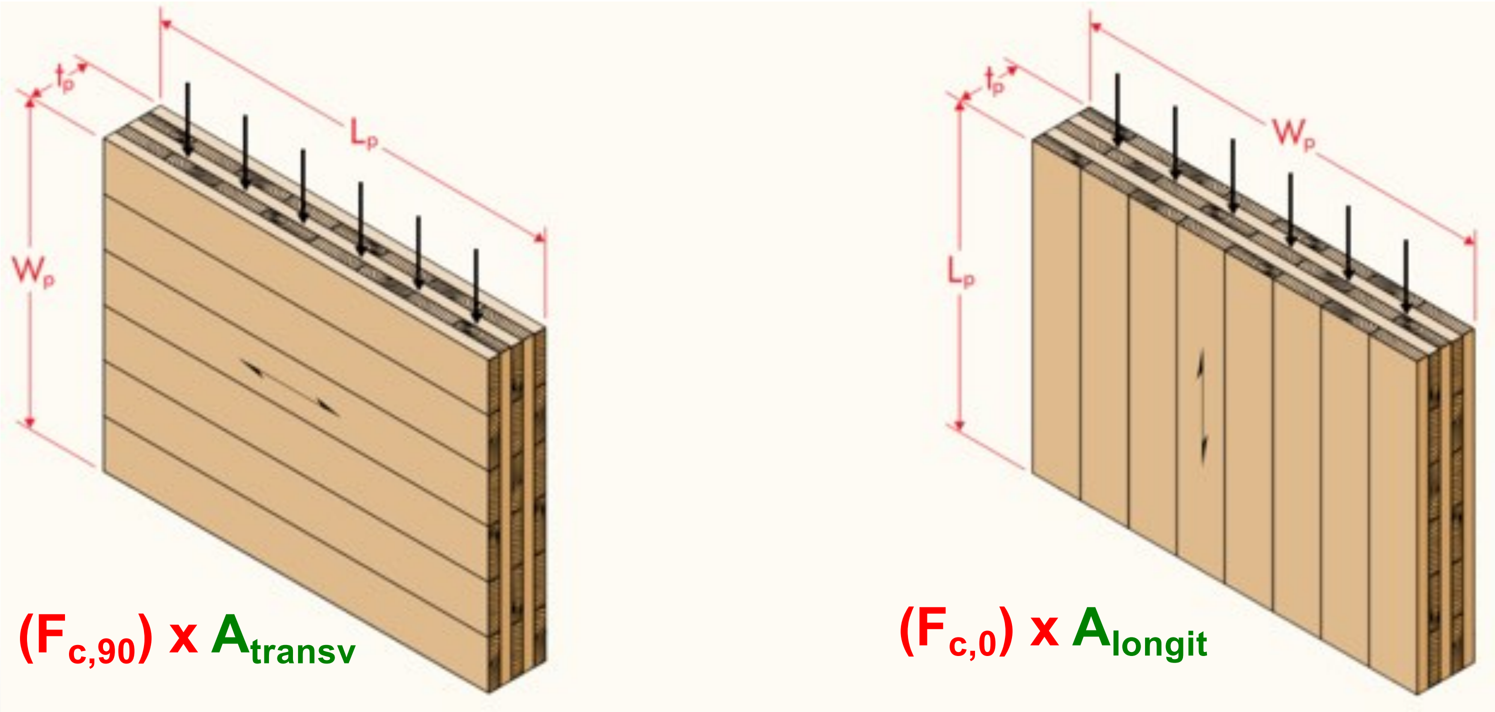
$$l \leq \frac{1}{12.05} \frac{(EI_{app})^{0.293}}{(\rho A)^{0.122}}$$

Special Considerations (CLT)

- Vibration
  - Performance variables not accounted for
    - Continuous/multi-span benefits
    - Ceilings (increased damping)
    - Topping slab stiffness (non-composite)
    - Stiffness of supports
    - Other interstitial elements
      - Acoustic mat
      - Raised access floor
  - US Mass Timber Floor Vibration Design Guide
    - Release expected early 2020

CLT Design Notes

- Compression
  - $F_C(A_{parallel})' = \underbrace{F_C(A_{parallel})}_{\text{PER MFR.}}\underbrace{(C_d)(C_m)(C_T)(C_P)}_{\text{PER NDS}}$



Texas Wood Design Symposium
Houston, Texas
February 25, 2020

CLT Design Notes

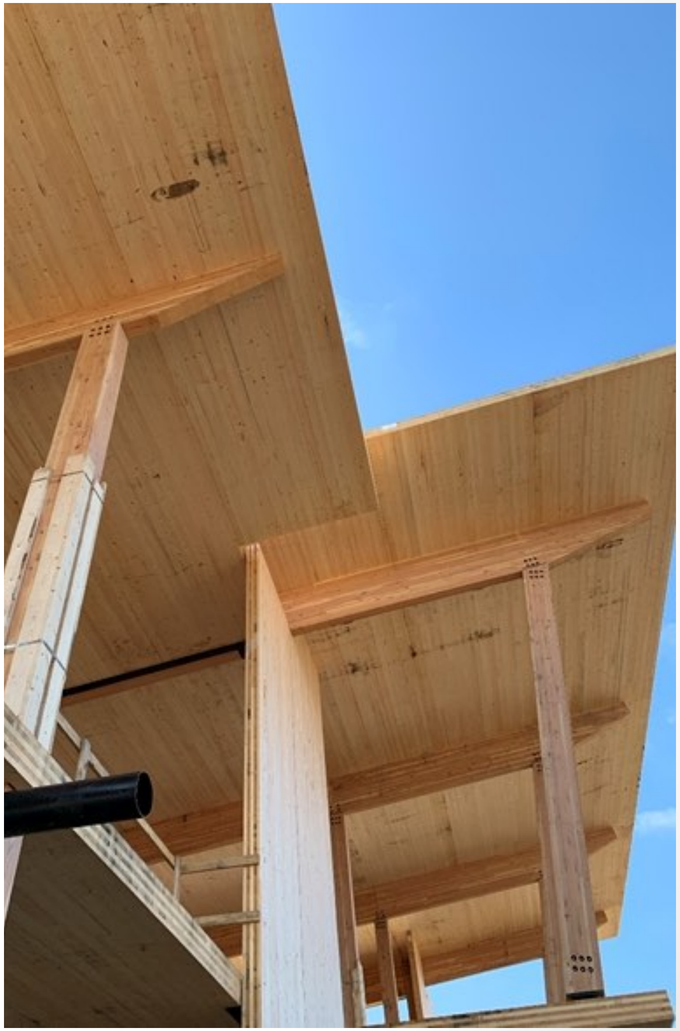
- Compression
  - Columns Stability Factor, $\mathbf{C_P}$

$$C_P = \frac{1+\left(F_{cE}/F_c^*\right)}{2c} - \sqrt{\left[\frac{1+\left(F_{cE}/F_c^*\right)}{2c}\right]^2 - \frac{F_{cE}/F_c^*}{c}} \quad (3.7\text{-}1)$$

- c=0.9 per NDS 3.7.1
- $F^*_c = \underbrace{(F_{c,0})}_{\text{PER MFR.}}\underbrace{(C_d)(C_M)(C_t)}_{\text{PER NDS}}$
- $F_{cE} = \frac{0.822\,(EI)'_{app\text{-}min}}{(L_e/d)^2} \longrightarrow \mathbf{(EI)'_{app\text{-}min} = 0.5184(EI)'_{app}}$

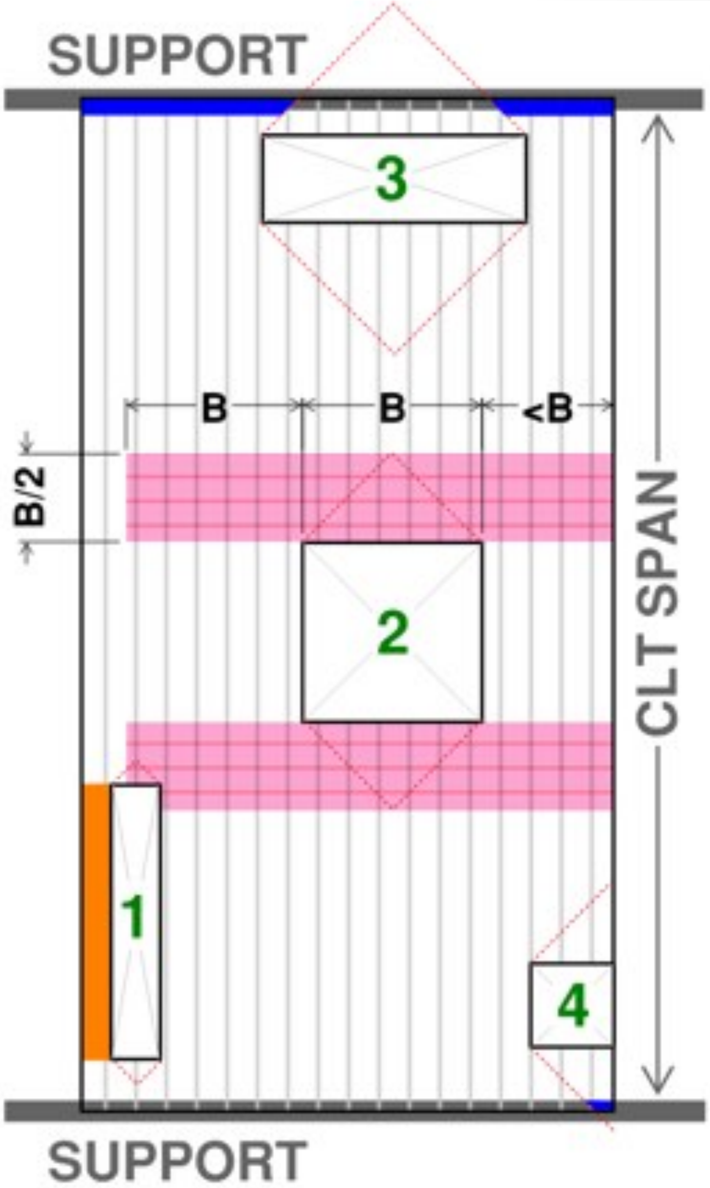
Special Considerations (CLT)

- Cantilevers
  - Analyze each direction independently
  - Distribute load each direction relative to stiffness, $(EI)_{app}$
- Deflection by superposition



Special Considerations (CLT)

- Openings
  - Distribute load around openings equally (trib)
    - Consider opening relationship with panel edge (load sharing?)
  - **Analyze weak-axis "strips"**
  - **Identify critical sections**
  - **Reduced shear/bearing near supports**
  - **Reduced stability at long narrow sections (C_L<1.0)**



Tips for Success (CLT)

- Optimization
  - Adopt a timber friendly grid size
    - i.e. 16x30, 20x28
    - 50%+ cost from wood fiber (commodity)
  - Glulam most expensive fiber (on a ft^3 basis)
  - On-board CLT supplier/manufacturer
    - Optimize panel layout/spans to fabricator
  - Minimize pieces
  - Connection influence
  - 3-ply considerations

- BIM for fabrication
  - Panel layout plan – who controls?

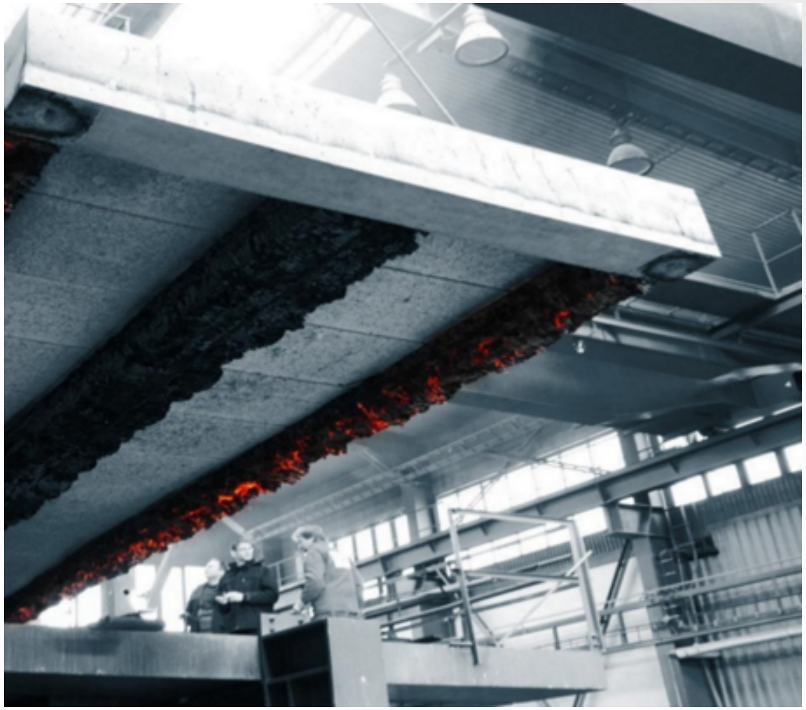
Tips for Success (CLT)

- Jurisdictional approval
  - Early involvement
  - Leverage resources

- Special inspection

- Understanding out of scope items
  - Acoustics/ acoustic mats
  - Site moisture management
  - Site timber protection

- FEA tools (openings, cantilevers, vibration)
  - Dlubal



Fire Design

Fire Design Basic Concepts

Char Rate

Char Depth

Fire Design Checks

Special Considerations

Fire Design

- Construction Types (IBC Table 601)

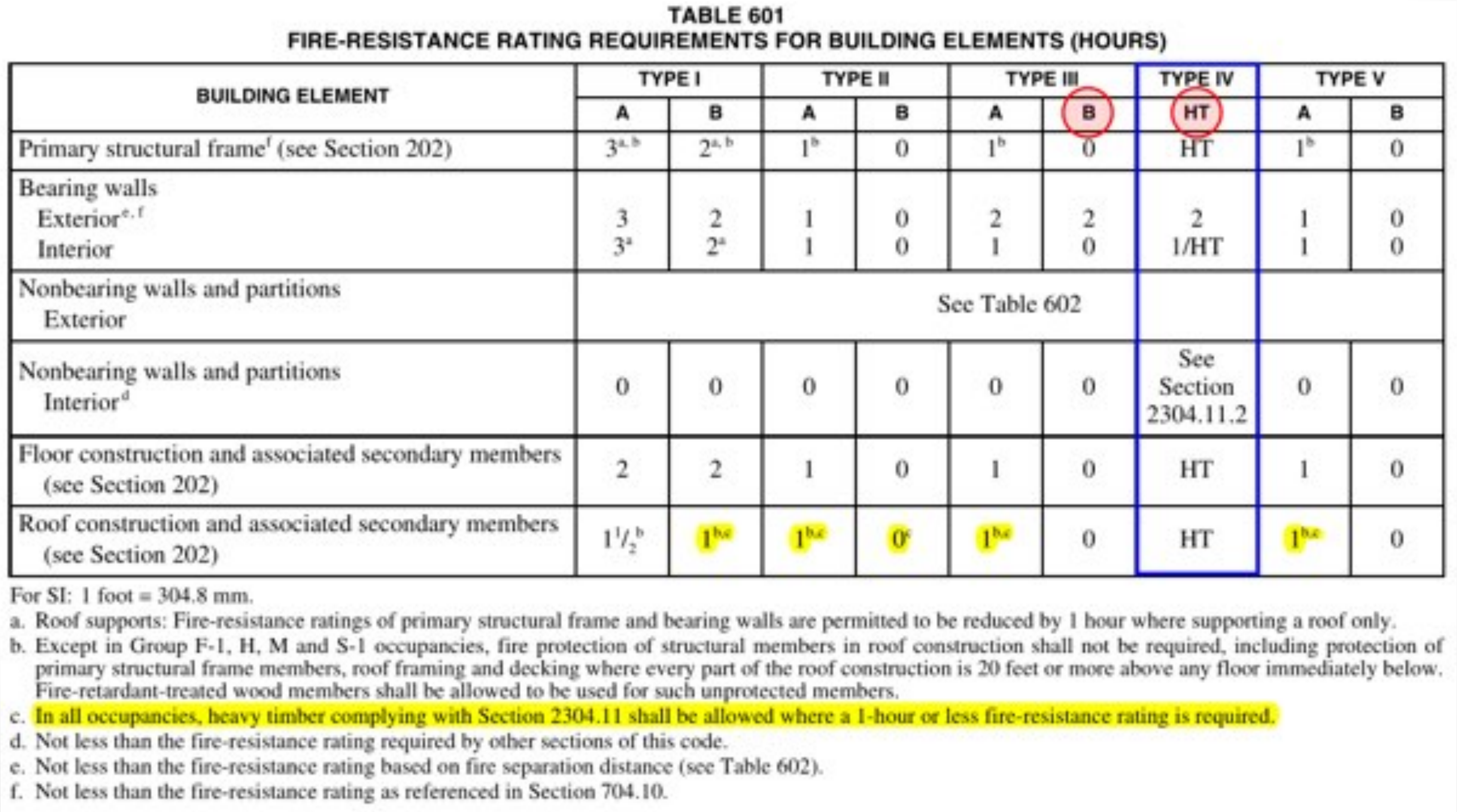


TABLE 601
FIRE-RESISTANCE RATING REQUIREMENTS FOR BUILDING ELEMENTS (HOURS)

BUILDING ELEMENT	TYPE I		TYPE II		TYPE III		TYPE IV	TYPE V	
	A	B	A	B	A	B	HT	A	B
Primary structural frame[f] (see Section 202)	3[a, b]	2[a, b]	1[b]	0	1[b]	0	HT	1[b]	0
Bearing walls Exterior[e, f] Interior	 3 3[a]	 2 2[a]	 1 1	 0 0	 2 1	 2 0	 2 1/HT	 1 1	 0 0
Nonbearing walls and partitions Exterior	See Table 602								
Nonbearing walls and partitions Interior[d]	0	0	0	0	0	0	See Section 2304.11.2	0	0
Floor construction and associated secondary members (see Section 202)	2	2	1	0	1	0	HT	1	0
Roof construction and associated secondary members (see Section 202)	1½[b]	1[b,c]	1[b,c]	0[c]	1[b,c]	0	HT	1[b,c]	0

For SI: 1 foot = 304.8 mm.

a. Roof supports: Fire-resistance ratings of primary structural frame and bearing walls are permitted to be reduced by 1 hour where supporting a roof only.

b. Except in Group F-1, H, M and S-1 occupancies, fire protection of structural members in roof construction shall not be required, including protection of primary structural frame members, roof framing and decking where every part of the roof construction is 20 feet or more above any floor immediately below. Fire-retardant-treated wood members shall be allowed to be used for such unprotected members.

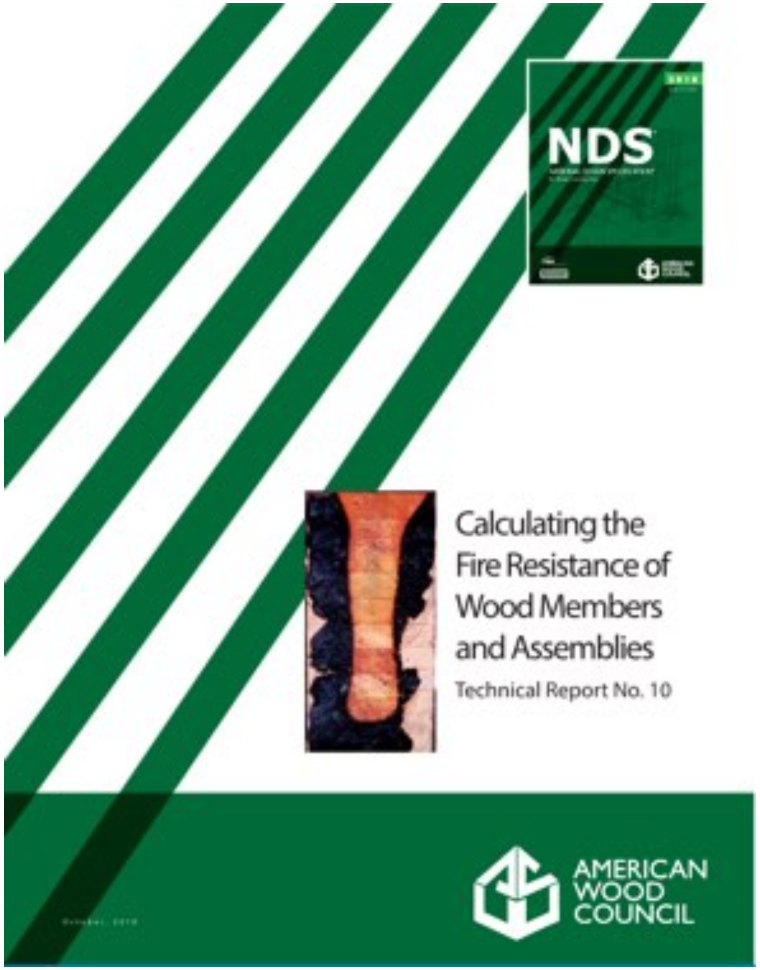
c. In all occupancies, heavy timber complying with Section 2304.11 shall be allowed where a 1-hour or less fire-resistance rating is required.

d. Not less than the fire-resistance rating required by other sections of this code.

e. Not less than the fire-resistance rating based on fire separation distance (see Table 602).

f. Not less than the fire-resistance rating as referenced in Section 704.10.

Fire Design Codes

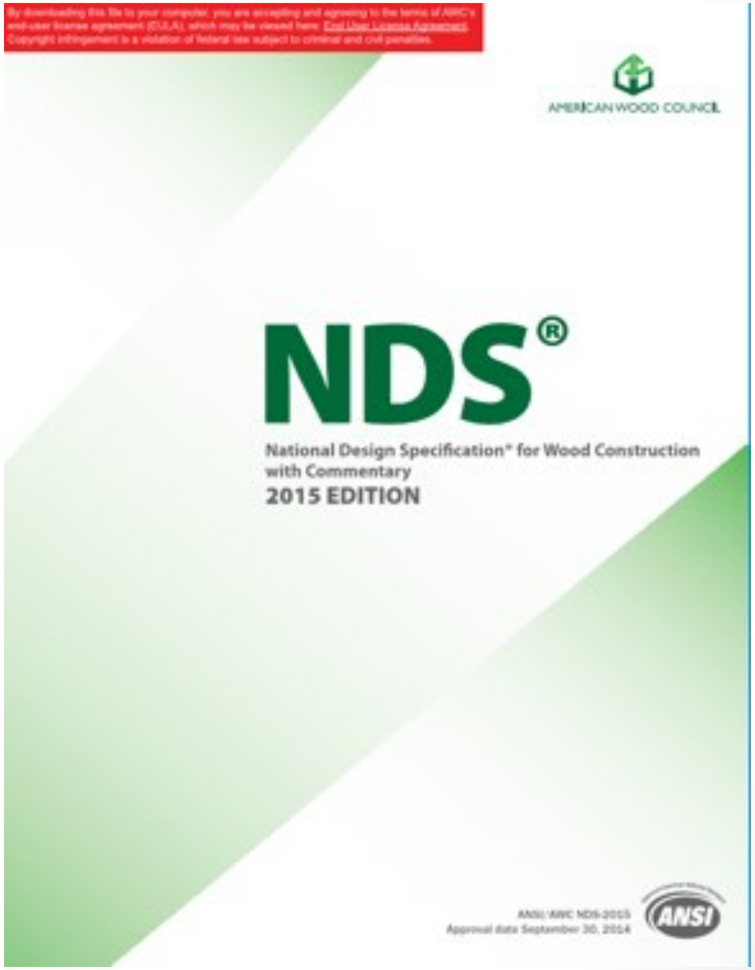


Calculating the Fire Resistance of Wood Members and Assemblies

Technical Report No. 10

AMERICAN WOOD COUNCIL

AWC TR-10



AMERICAN WOOD COUNCIL

NDS®

National Design Specification® for Wood Construction with Commentary

2015 EDITION

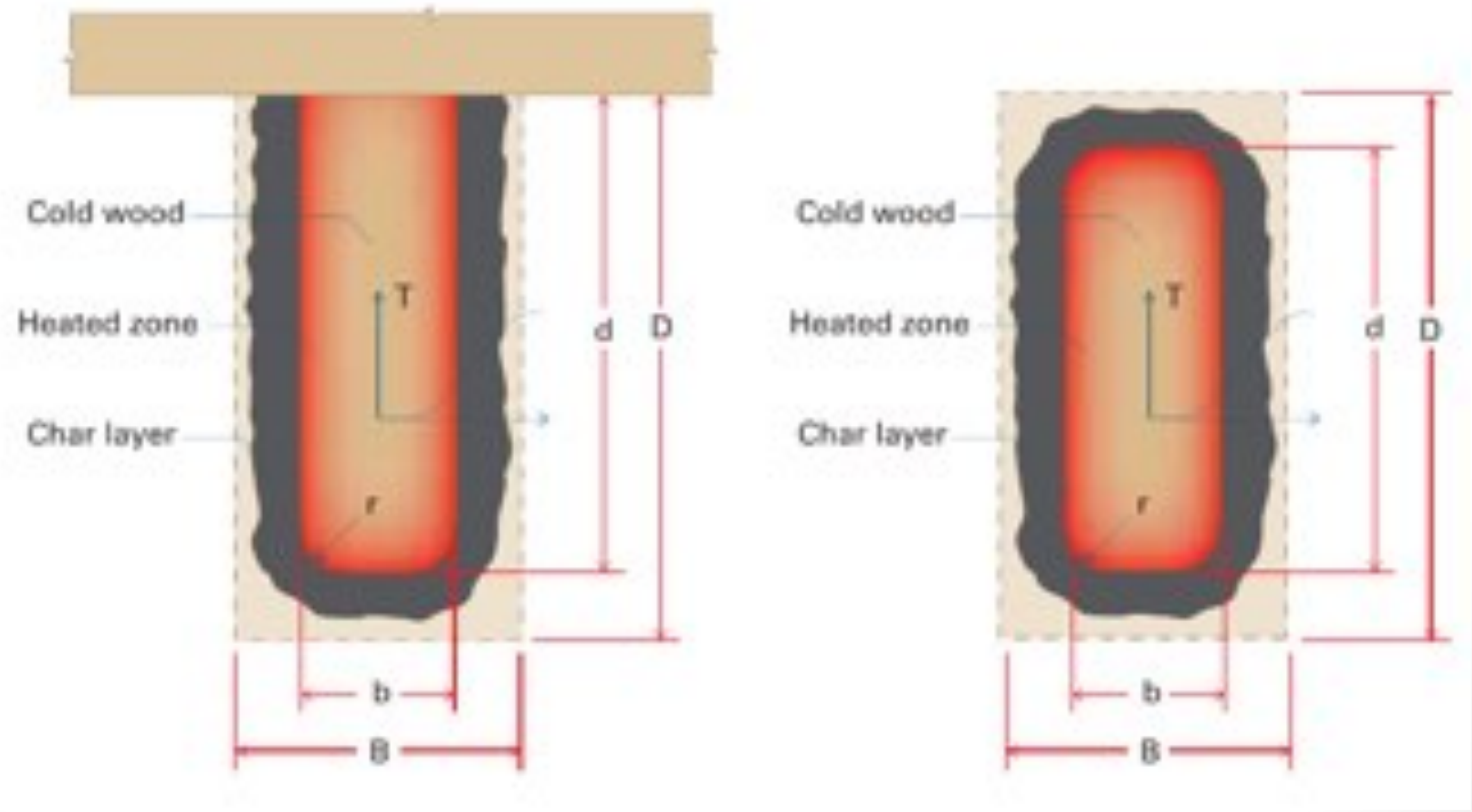
ANSI/AWC NDS-2015
Approval date September 30, 2014

NDS – Chapter 16
+ commentary

Fire Design Basics

- Wood burns → char is formed on all exposed surfaces
- Charred areas of exposed member are assumed to have no strength and no stiffness
- Sectional properties of member are reduced by char depth
- Reduced (remaining) section stresses are checked against average ultimate strength

Fire Design Basics



Char Rate

- Char depth (a) based on non-linear char rate (β)
- A researched based *nominal* char rate (β_n) of 1.5 in/hr. is used for wood design and adjusted for time to determine an *effective* char rate (β_{eff})

$$\beta_{eff} = \frac{1.2\beta_n}{t^{0.187}}$$

(NDS 16.2-1)

t (hr.)	β_{eff} (in/hr.)
1 hr.	1.8 in/hr.
1.5 hr.	1.67 in/hr.
2 hr.	1.58 in/hr.

β_{eff} = *Effective* char rate (in./hr.), adjusted for exposure time, t

1.2 Factor – 20% increase factor to account for reduced strength in heated zone and reduced section at corners (accelerated charring)

β_n = *Nominal* char rate (in./hr.) based on 1-hour exposure (1.5 in/hr. for wood design)

t = exposure time (hr.) as required by IBC

Char Depth

- Effective char depth (a_{char})
  - Depth to be subtracted from each exposed side
  - a_{char} = Effective char rate (β_{eff}) x exposure time (t)

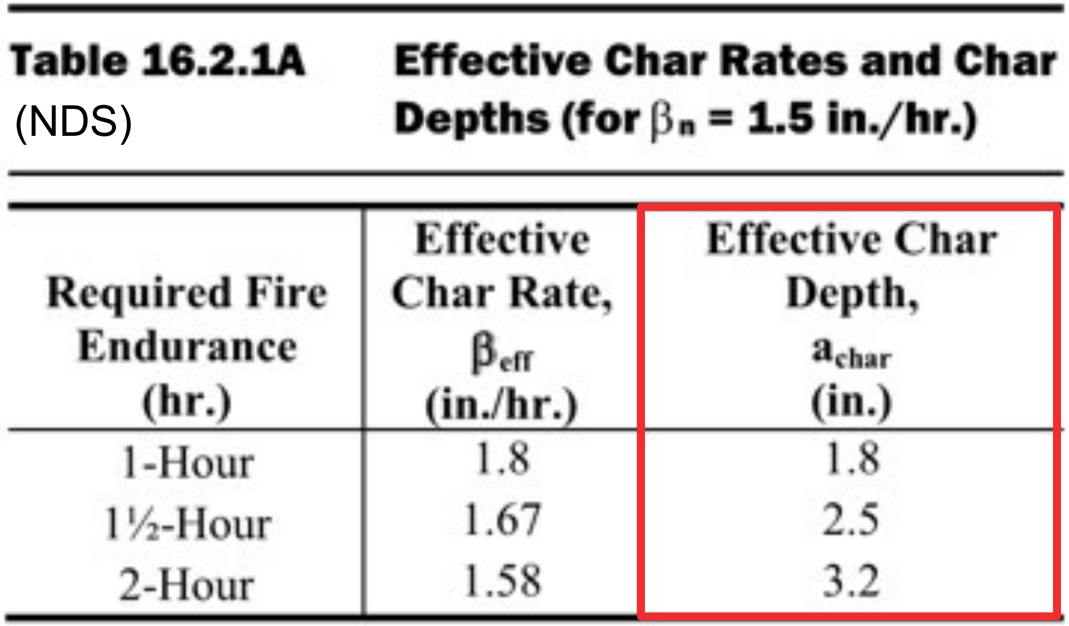
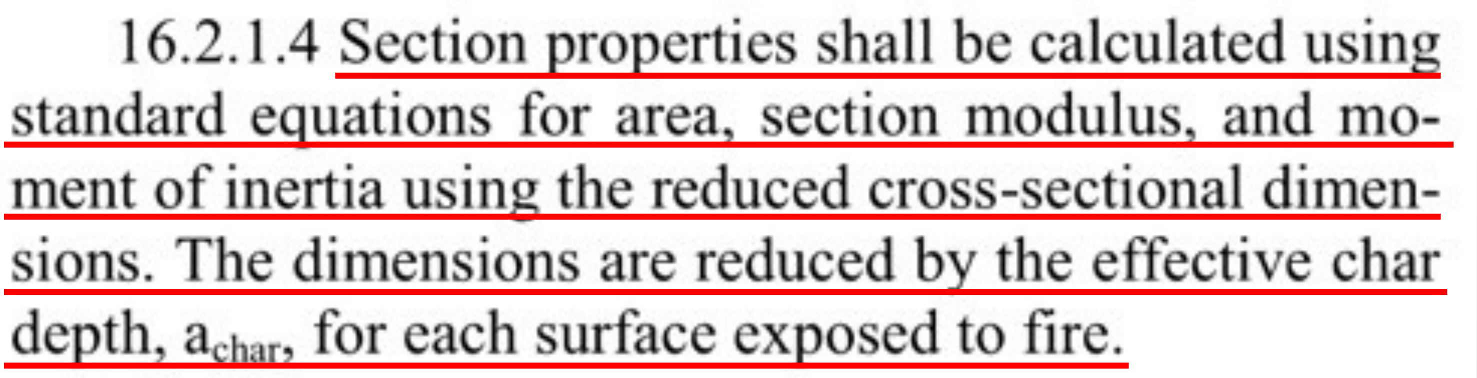


Table 16.2.1A (NDS) **Effective Char Rates and Char Depths (for β_n = 1.5 in./hr.)**

Required Fire Endurance (hr.)	Effective Char Rate, β_{eff} (in./hr.)	Effective Char Depth, a_{char} (in.)
1-Hour	1.8	1.8
1½-Hour	1.67	2.5
2-Hour	1.58	3.2

Fire Design Checks

- Applicable design values (from supplement)
  - F_b, F_t , F_c, F_{bE}, F_{cE}
- Applicable adjustment factors
  - *K* – Average strength per table 16.2.2 (next slide)
  - C_f, C_v, C_{fu}



16.2.1.4 Section properties shall be calculated using standard equations for area, section modulus, and moment of inertia using the reduced cross-sectional dimensions. The dimensions are reduced by the effective char depth, a_{char}, for each surface exposed to fire.

Fire Design Checks

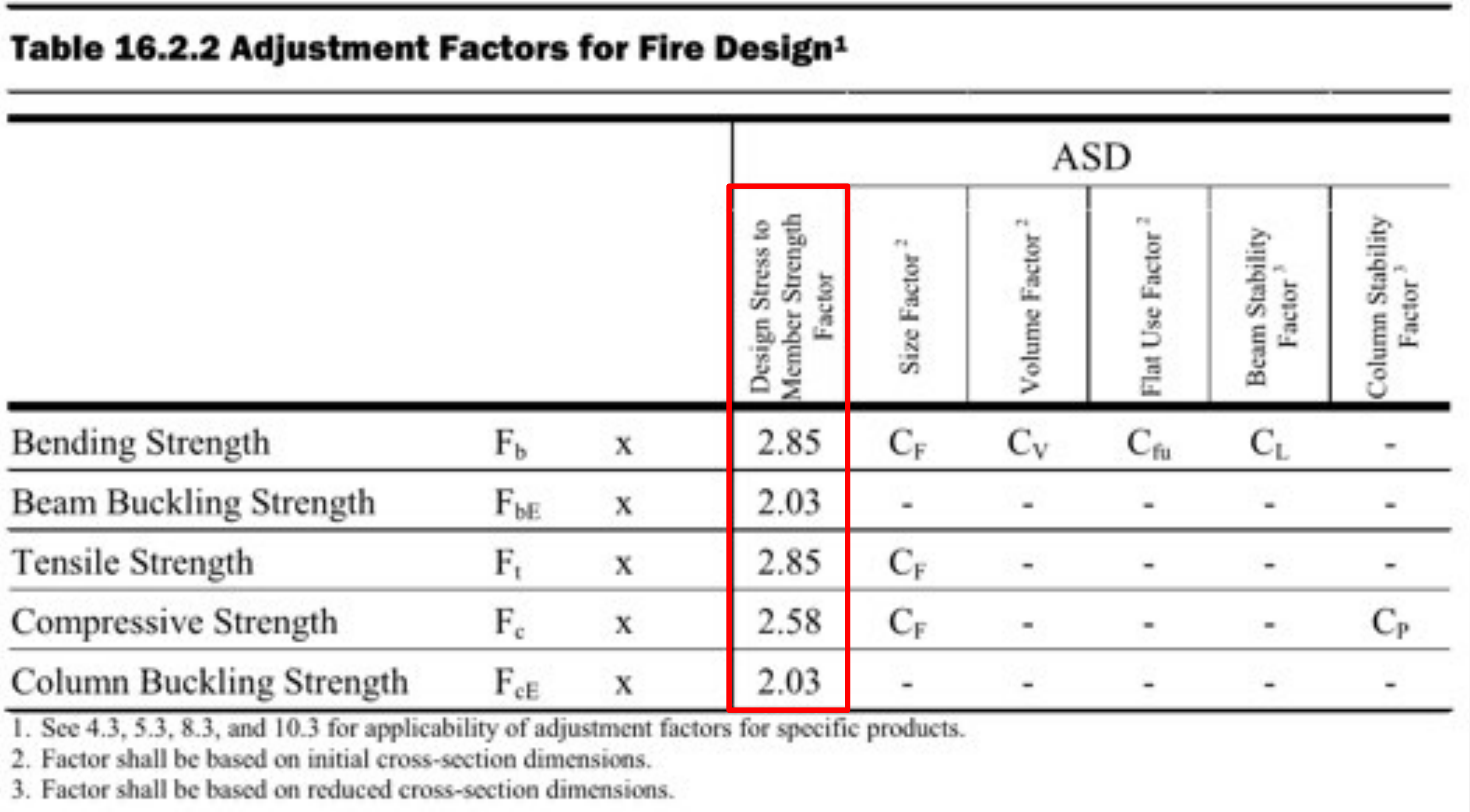


Table 16.2.2 Adjustment Factors for Fire Design[1]

			ASD					
			Design Stress to Member Strength Factor	Size Factor[2]	Volume Factor[2]	Flat Use Factor[2]	Beam Stability Factor[3]	Column Stability Factor[3]
Bending Strength	F_b	x	2.85	C_F	C_V	C_{fu}	C_L	-
Beam Buckling Strength	F_{bE}	x	2.03	-	-	-	-	-
Tensile Strength	F_t	x	2.85	C_F	-	-	-	-
Compressive Strength	F_c	x	2.58	C_F	-	-	-	C_P
Column Buckling Strength	F_{cE}	x	2.03	-	-	-	-	-

1. See 4.3, 5.3, 8.3, and 10.3 for applicability of adjustment factors for specific products.
2. Factor shall be based on initial cross-section dimensions.
3. Factor shall be based on reduced cross-section dimensions.

Special Considerations

- CLT
  - Varying effective char rate based on lamination thickness (NDS 16.2.1.3)

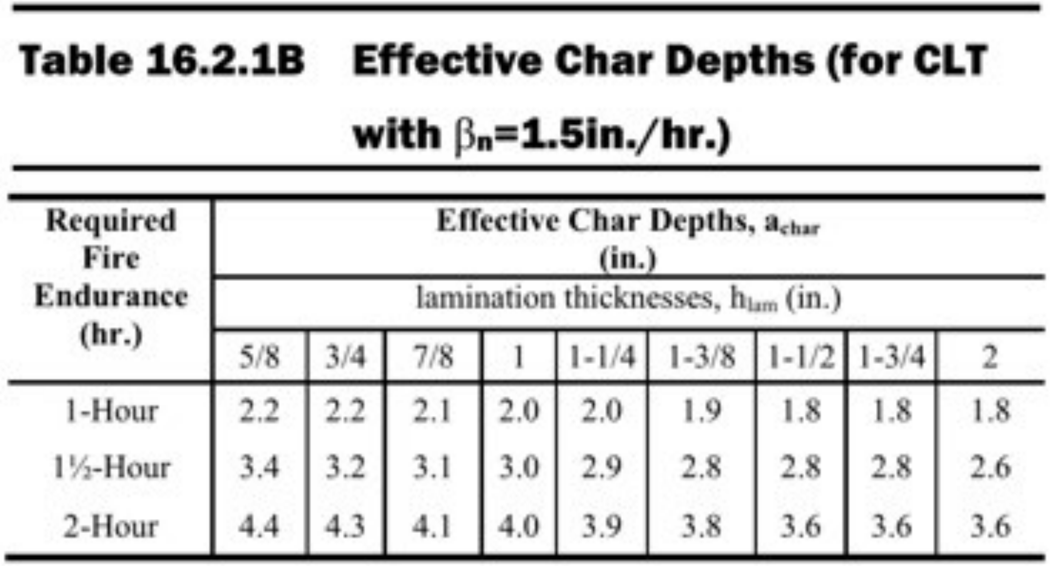
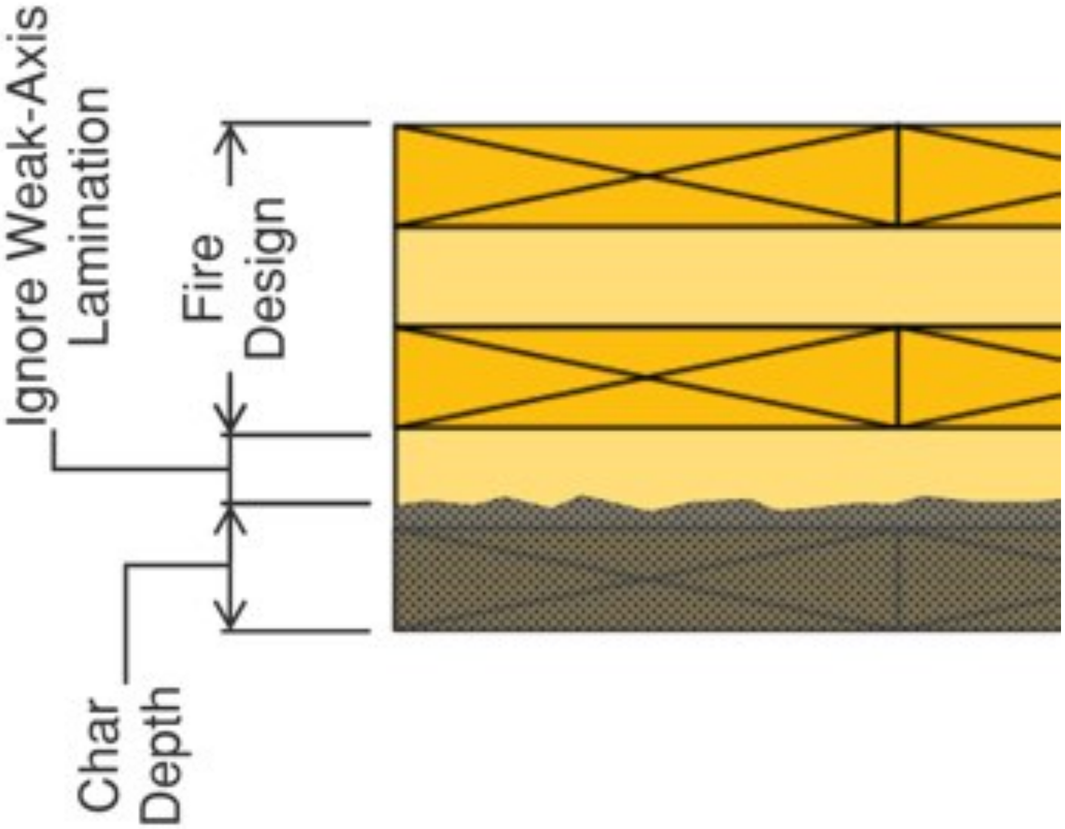


Table 16.2.1B Effective Char Depths (for CLT with β_n=1.5in./hr.)

Required Fire Endurance (hr.)	Effective Char Depths, a_{char} (in.)								
	lamination thicknesses, h_{lam} (in.)								
	5/8	3/4	7/8	1	1-1/4	1-3/8	1-1/2	1-3/4	2
1-Hour	2.2	2.2	2.1	2.0	2.0	1.9	1.8	1.8	1.8
1½-Hour	3.4	3.2	3.1	3.0	2.9	2.8	2.8	2.8	2.6
2-Hour	4.4	4.3	4.1	4.0	3.9	3.8	3.6	3.6	3.6

Special Considerations

- CLT



Special Considerations

- NLT
  - Continuous/monolithic Topping present?

YES	NO
Char as solid member	Char individual laminations
One-dimensional charring	Two-dimensional charring
Char bottom-side to depth a_{char} only	Char bottom-side to depth a_{char} + 1/3 a_{char} depth on (2) sides

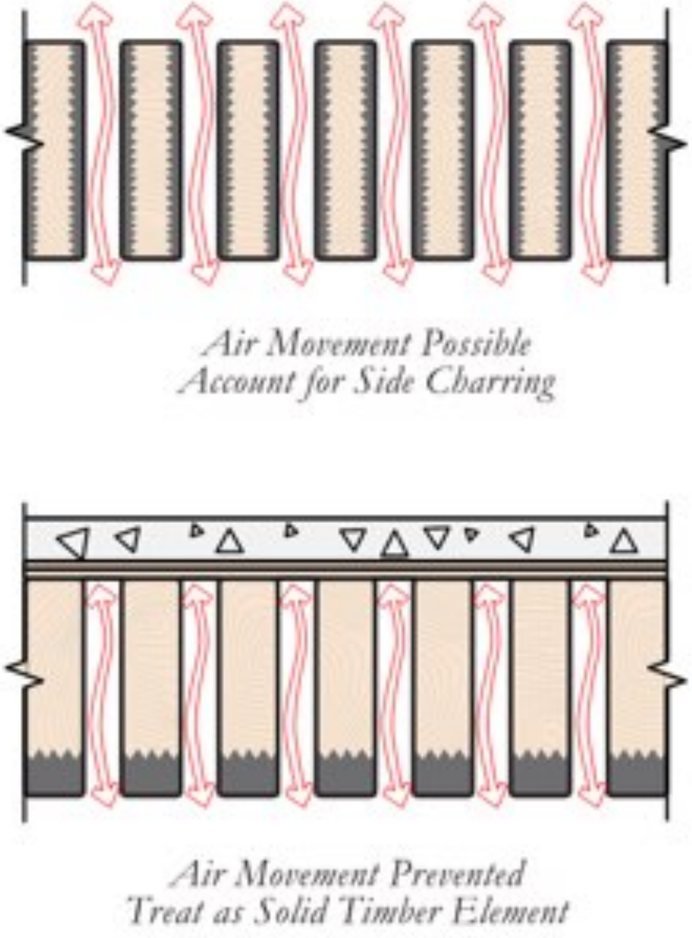
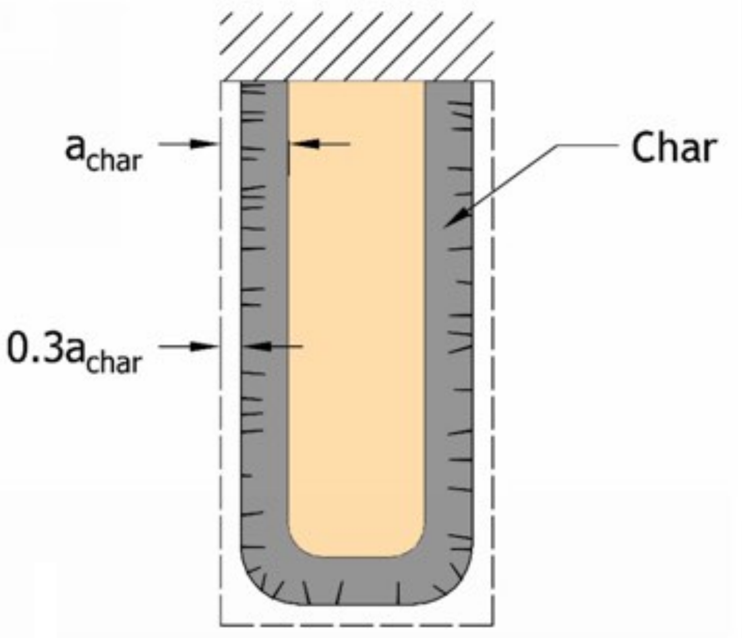
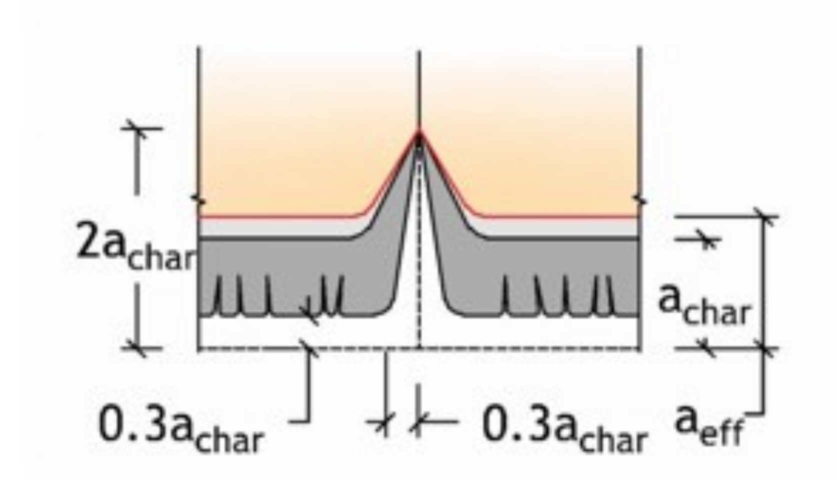


Figure 3.5: *Air Movement Through NLT*

Special Considerations

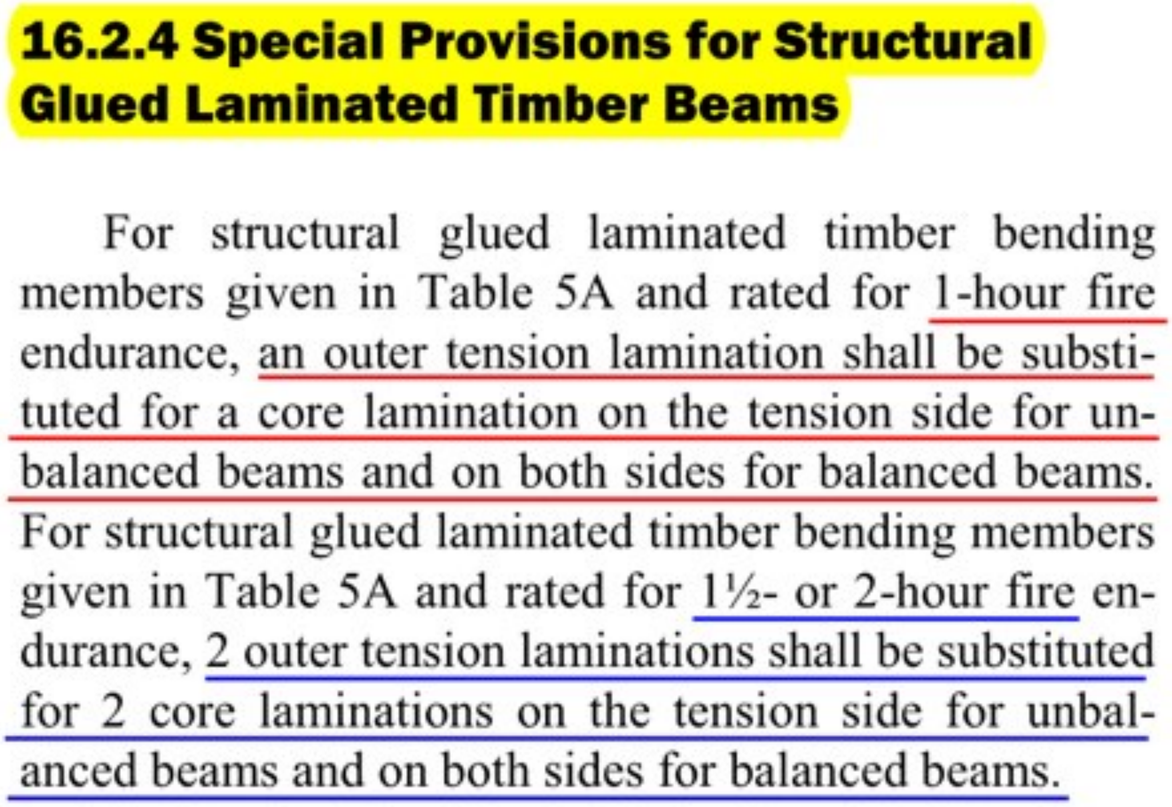
- Char Contraction
  - Needs to be considered when wood is used as a protective element
  - Refer to AWC TR-10 section 1.5.1





Fire Design Notes

- Glulam Beams

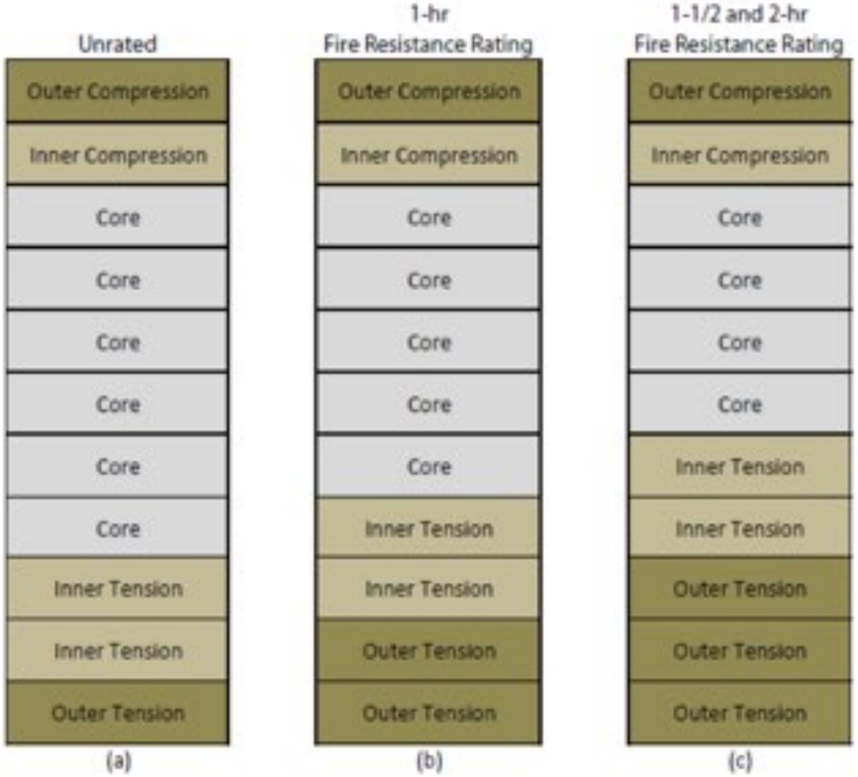


16.2.4 Special Provisions for Structural Glued Laminated Timber Beams

For structural glued laminated timber bending members given in Table 5A and rated for 1-hour fire endurance, an outer tension lamination shall be substituted for a core lamination on the tension side for unbalanced beams and on both sides for balanced beams. For structural glued laminated timber bending members given in Table 5A and rated for 1½- or 2-hour fire endurance, 2 outer tension laminations shall be substituted for 2 core laminations on the tension side for unbalanced beams and on both sides for balanced beams.

Fire Design Notes

- Glulam Beams (unbalanced shown)



Unrated	1-hr Fire Resistance Rating	1-1/2 and 2-hr Fire Resistance Rating
Outer Compression	Outer Compression	Outer Compression
Inner Compression	Inner Compression	Inner Compression
Core	Core	Core
Core	Core	Core
Core	Core	Core
Core	Core	Core
Core	Core	Inner Tension
Core	Inner Tension	Inner Tension
Inner Tension	Inner Tension	Outer Tension
Inner Tension	Outer Tension	Outer Tension
Outer Tension	Outer Tension	Outer Tension
(a)	(b)	(c)

*Similar for balanced layup

Fire Design Notes

- No serviceability requirements for fire case

- Connections require same fire resistance rating as primary structural frame
  - Conceal connection beyond char depth or protect by other means

- Fire design may not require larger members but will still add cost:
  - Connection protection
  - Oversizing members to conceal connections
  - Fire beam layups
  - Fire caulking
  - Special inspection
  - Penetrations

Mass Timber Connections

- Considerations
  - Aesthetics (Architect)
  - Cost (Owner)
  - Project Delivery (Contractor)
  - Fire Requirements

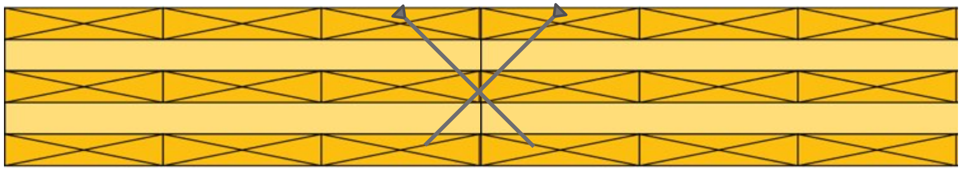
Mass Timber Connections

- Considerations
  - Aesthetics (Architect)
  - Cost (Owner)
  - Project Delivery (Contractor)
  - Fire Requirements

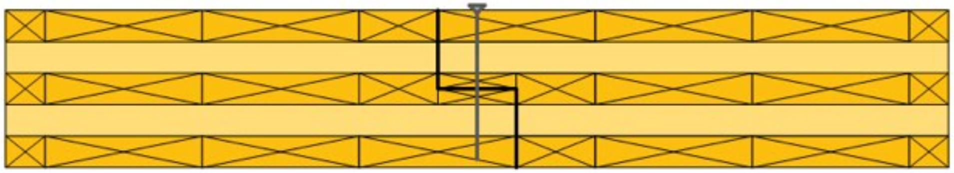
Mass Timber Connections

- CLT Panel Connections

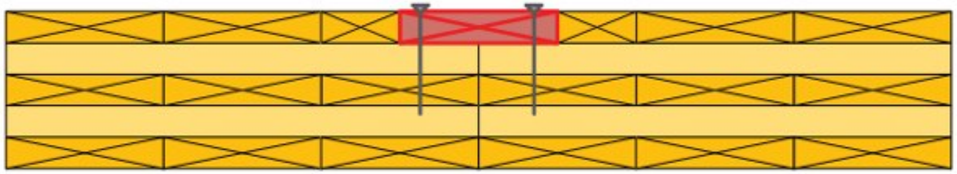
Butt Joint



Half-lap



Spline



Mass Timber Connections

Engineered Timber Screws

SIMPSON Strong-Tie®

MTC SOLUTIONS

Formerly MyTiCon

Eurotec®

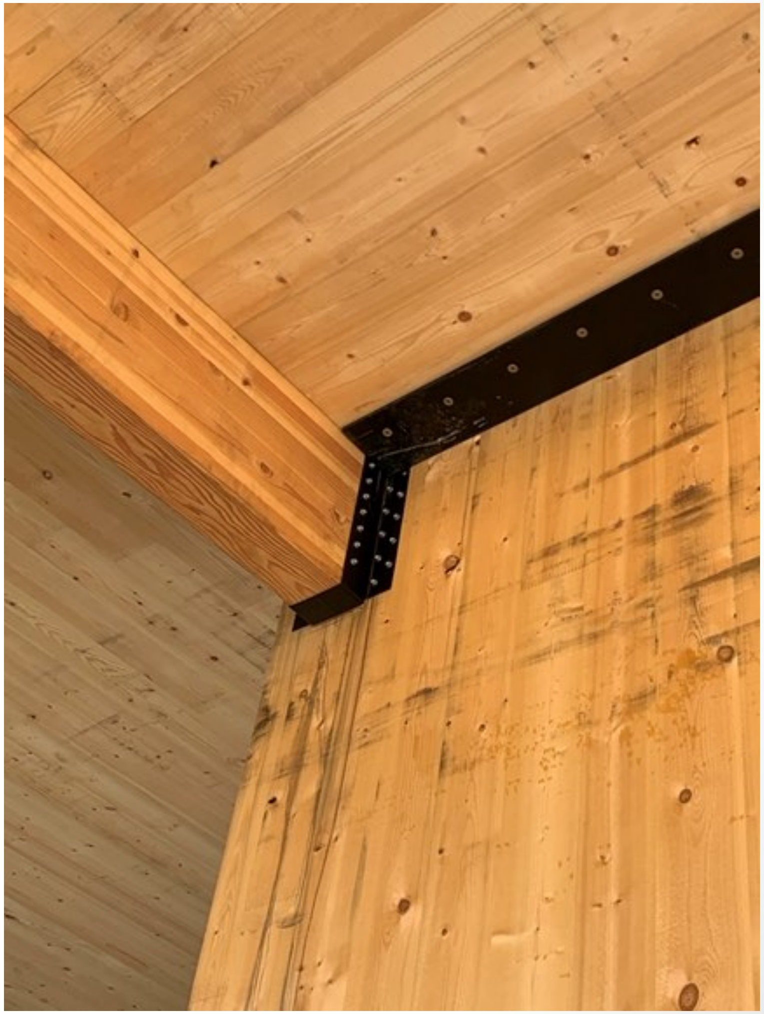
rothoblaas

TimberLOK®

Structural Wood Screw

Tips For Success (Connections)

- Make inclusive design process
- Avoid field welding
- Specify timber screws in lieu of lag screws
  - No/limited pre-drilling
  - More ductile
  - Faster installation



Additional Resources

- woodworks.org
  - Project Support
  - Educational Resources
  - White Papers
  - Design Tools

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(512) 947-4787

sherry.mundell@woodworks.org

- thinkwood.com
  - CLT Handbook
  - NLT Design Guide
- awc.org
  - Software
  - Free Calculators
  - Design Examples

Thank you!

This concludes The American Institute of Architects Continuing Education Systems Course

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