Structural Analysis and Design of Cross-Laminated Timber

HOOD PROL

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Presented by

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Catalyst / MGA | Michael Green Architecture / photo Andrew Giammarco

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

Course Description

As more project design teams consider using Cross-Laminated Timber (CLT) panels as floor, roof, or wall framing, there are structural design questions which arise frequently, especially for designers new to using mass timber products. This presentation provides specific design guidance on how to address common scenarios in structural analysis and design for CLT. Attendees will learn about the necessary design checks for floor and roof applications including strength and short-term and long-term deflection checks under gravity loading, as well as detailed instructions on how to calculate the structural fire resistance ratings of horizontal CLT assemblies. Particular attention will be given to the engineering implications of using multi-span CLT panels and resulting modifications to the single span design conditions. Additionally, a detailed explanation of different methods of determining horizontal diaphragm deflections will be presented.

Learning Objectives

- Review the design methods and performance checks for CLT panels used in floor and roof applications and how to use these to show code compliance.
- Understand how to calculate the structural fire resistance rating of a CLT panel using the calculated method of AWC's NDS Chapter 16.
- Discuss the types of structural analysis models which can be used in the design process and when they are needed.
- Review and understand calculation of horizontal diaphragm deflection of CLT floor and roofs

Agenda

- CLT Grades, Layups, Laminations, and Properties
- CLT Floor and Roof Analysis
- Structural Fire Design of CLT
- Design and Modeling Approaches of CLT

A collection of related topics answering real questions raised by designers.

What is Cross-Laminated Timber?

- IBC recognized structural component
- Flat panel made from 3+ layers (AKA "plys") of timber laminations
- In alternating orientations -> "Cross-Laminated"
- Assembled with specific structural adhesives



Thickness

North American CLT Product Standard



ANSI/APA PRG 320 Standard for Performance-Rated Cross-Laminated Timber

The Standard Covers:

- U.S. and Canada Use
- Panel Dimensions and Tolerances
- Component Requirements
- Structural Performance Requirements
- Panel and Manufacturing Qualification
- Marking (Stamping)
- Quality Assurance

Benefits of CLT



Considerations:

- Large light-weight panels
- Dimensionally stable
- Precise CNC machining available
- Recognized by IBC
- Dual Directional span capabilities
- Often architecturally exposed
- Fast on-site construction

Fabricated for Precise and Fast Construction

Photo: Swinerton



Major Strength Direction Bending

CLT is an Orthotropic Material

What are the layers of CLT?

Cross-Laminated Timber Solid sawn laminations



Cross-Laminated Timber SCL laminations



TIOLO. FIEles Lumber





What are the layers of CLT?

	 	_	

Visually graded lumber, such as: Doug-Fir Larch Southern (Yellow) Pine Spruce Pine Fir Hem Fir

Cross-Laminated Timber

Solid sawn laminations

Machine graded lumber

Structural lumber recognized through ASLC PS 20 Rules Cross-Laminated Timber SCL laminations



Structural Composite Lumber

Laminated Veneer Lumber (LVL) Laminated Strand Lumber (LSL) Oriented Strand Lumber (OSL) Parallel Strand Lumber (PSL)

SCL recognized through ASTM D5456

Cross-Laminated Timber Solid sawn laminations



What are the layers of CLT?

Cross-Laminated Timber SCL laminations



CLT Layup = Arrangement



CLT Grade =

Material

CLT Grade = Structural Material in the Panel

Basic grades (e.g. Examples) of solid sawn lumber in PRG 320-2019 standard

"E" grades from machine graded lumber

"V" grades from visually graded lumber

CLT Grade	Major Strength Direction	Minor Strength Direction
E1	1950f-1.7E MSR SPF	#3 Spruce Pine Fir
E2	1650f-1.5E MSR DFL	#3 Doug Fir Larch
E3	1200f-1.2E MSR Misc	#3 Misc
E4	1950f-1.7E MSR SP	#3 Southern Pine
E5	1650f-1.5E MSR Hem-Fir	#3 Hem-Fir
V1	#2 Doug Fir Larch	#3 Doug Fir Larch
V1(N)	#2 Doug-Fir Larch (North)	#3 Doug-Fir Larch (North)
V2	#1/#2 Spruce Pine Fir	#3 Spruce Pine Fir
V3	#2 Southern Pine	#3 Southern Pine
V4	#2 Spruce Pine Fir (South)	#3 Spruce Pine Fir (South)
V5	#2 Hem-Fir	#3 Hem-Fir

CLT Grade = Structural Material in the Panel

<u>Custom grades</u> by manufacturer are very common

						Table 1	. ASD F	Reference	Design V	alues ^(a) for	Lumber L	aminations	Used in	SmartLar	n CLT (for	Use in t	he U.S.)	Dimention		
				Table 2.	LSD Refe	erence De	sign Valu	La les ^(a) for Lu	minations (mber Lam	inations Us	ed in Merce	ection er CLT		<u> </u>	Laminat	Ft	F _c	F _v	F _s	Fc⊥	G
																(psi)	(psi)	(psi)	(psi)	(psi)	Ŭ
CLT	Strength	Species		Lamina	ations us	ed in Majo	r Strengt	h Direction	1	L	aminations	used in Mi	nor Streng	gth Directi	on	200	575	135	45	335	0.36
Grade	Class	opecies	Fь,0 (МРа) E	E Pa) (F _{t,0} MPa)	F _{с,0} (MPa)	F _{∨,0} (MPa)	F _{s,0} (MPa)	F _{b,90} (MPa)	E (MPa)	F _{t,90} (MPa)	F _{с,90} (MPa)	F _{∨,90} (MPa)	F _{s,90} (МРа)	200	575	135	45	335	0.36
		SPF														250	650	135	45	425	0.42
1.4V	875 ^(b)	DF-L	- 11.8	3 9,5	500	5.5	11.5	1.5	0.50	7.0	9,000	3.2	9.0	1.5	0.50	575	1,350	180	60	625	0.50
	0.100(4)	SPF					10.0		0.50						0.50	550	1,100	125	40	455	0.43
1.8M	2100(6)	DF-L	- 30.4	1 12,4	400	17.7	19.9	1.5	0.50	7.0	9,000	3.2	9.0	1.5	0.50	250	650	135	45	425	0.42
-						V2M5	SPI	F 875	1.4	450 1,150	135	45 425	0.42	SPF	875 1.4	450	1,150	135	45	425	0.42
Table 1		erence l	Desian	Values	^(a) for I	umberl	amina	ations Lle	ed in F	lement5	CLT (for	llse in t	the U.S)						565	0.55
	AOD Rei		Laminati	ions Used i	in Major St	rength Dire	ction					Lamina	tions Used	•7 in Minor St	rength Direc	tion	-			335	0.36
Grade	Grade & Species	F _b (psi)	E (10 ⁶ psi)	Ft (psi)	Fc (psi)	F _v (psi)	Fs (psi)	F _{c⊥} (psi)	G	Grade & Species	F₅ (psi)	E (10 ⁶ psi	Ft) (psi)	F₀ (psi)	F _v (psi)	Fs (psi)	F _{c⊥} (psi)	(G	405	0.43
E1M10 & E1M10.1	2100f-1.8E SPF	2,100	1.8	1,575	1,875	160	50	525	0.46	No. 1/No. SPF	² 875	1.4	450	1,150	135	45	425	0.4	42	405	0.43
E1M12, E1M12.1, & E1M12.2	1650f-1.5E SPF	1,650	1.5	1,020	1,700	135	45	425	0.42	No. 1/No. SPF	2 875	1.4	450	1,150	135	45	425	0.4	42	455	0.43
V2M7, V2M7.1, & V2M7.2	No. 1/No. 2 SPF	875	1.4	450	1,150	135	45	425	0.42	No. 1/No. SPF	2 ₈₇₅	1.4	450	1,150	135	45	425	0.4	42	405 405	0.42

Laminations

Lumber recognized by American Lumber Standards Committee under PS 20

- Min published specific gravity of 0.35
- Thickness range allowed in PRG 320 if 5/8" to 2"

1 3/8" is most common "standard" layer thickness of North American CLT

• Commodity 2" nominal lumber =

Green, Surfaced Lumber \rightarrow 1 9/16" thick

Dry, Surfaced Lumber \rightarrow 1 ½" min thick

Planed shortly before assembly into CLT \rightarrow 1 3/8" thick

- Thinner layers including 0.67", 0.75", 1.03", 1.08" used by some manufacturers
- 12% +/- 3% Moisture Content at manufacturing

Structural Composite Lumber meeting ASTM D5456

• LSL, LVL, OSL, and PSL permitted



CLT Layup = How are the layers arranged?







Adjacent layers in same direction

Non-uniform thickness

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7-ply





### 3rd Party Product Qualification of CLT



### **CLT Product Reports**

					Maj	or S	treng	gth D	)irec	tion l	Lami	natio	ns	٨	<i>linor</i> S	Streng	gth Dir	ection	Lamin	ations
	A	PA Prod	luct Repo ly 11, 20	ort® PR 23	-L347												Ļ		P	age 3 of 6
	Та	able 1.	ASD Ref	erence	Desig	n Valu	ies ^(a) fo	or Lum	ber La	minatio	ons Us	ed in N	Aercer Cr	ossLam	CLT (for	Use in	the U.S.	)		
	I	CLT			Lam	inations L	Jsed in Ma	ajor Streng	th Direct	on					Laminati	ions Used i	n Minor Stren	gth Direction		
		Grade	Grade & Species	Fb (psi)	E (10 ⁶ p	si) (p	¯ι si) (	Fc (psi)	F _v (psi)	Fs (psi)	Fc⊥ (psi)	G	Grade & Species	& Fb s (psi	) (10 ⁶ ps	i) (psi)	Fc (psi)	F _v (psi)	Fs Fci (psi) (psi	G
	Г	E4M1	2700f-2.2E SP	2,700	2.2	2,1	50 2	,100	190	60	805	0.57	No. 2 S	P 750	) 1.4	450	1,250	175	55 565	0.55
	Г	E4M2	2100f-1.8E SP	2,100	1.8	1,5	75 1	,875	175	55	805	0.57	No. 2 S	P 750	) 1.4	450	1,250	175	55 565	0.55
	F	E4M3 & E4M3 1	2100f-1.8E	2,100	1.8	1,5	75 1	,875	175	55	805	0.57	No. 3 S	P 450	) 1.3	250	725	175	55 565	0.55
		V3 & V3.1	No. 2 SP	750	1.4	4	50 1	.250	175	55	565	0.55	No. 3 S	P 450	) 1.3	250	725	175	55 565	0.55
	F	V3M1	No. 2 SP	750	1.4	4	50 1	.250	175	55	565	0.55	No. 2 S	P 750	) 1.4	450	1,250	175	55 565	0.55
CLT Grade (basic or <u>cust</u>	€ * <u>om</u> )					L	.ayu	q							P	anel	Prop	erties		
			$\bigcap$									γ					~ <u> </u>			
	Table 2. /	ASD Ref	ference I	Design	Value	S ^(a, b)	for Me	rcer C	rossLa	am CL'	T Liste	ed in Ta	able 1 (fo	r Use in	the U.S.	) (cont	inued)			
	V		Thick-		L	aminati	on Thic	kness (i	n.) in C	LT Layu	ıp		Ma	jor Streng	th Direction	n	M	inor Stren	gth Directio	n
	CLT Grade ^(c)	Layup ID ^(d)	ness, t _P (in.)	=	$\perp$	=	$\perp$	=	$\perp$	=	$\perp$	=	(F _b S) _{eff,0} (Ibf-ft/ft)	(EI) _{eff,0} (10 ⁶ lbf- in.²/ft)	(GA) _{eff,0} (10 ⁶ Ibf/ft)	V _{s.0} (Ibf/ft)	(F _b S) _{eft,90} (Ibf-ft/ft)	(EI) _{eff.50} (10 ⁶ lbf- in. ² /ft)	(GA) _{eff,1,90} (10 ⁶ lbf/ft)	V _{s.90} (Ibf/ft)
		87 E	3.43	1.38	0.67	1.38							3,475	72	0.53	1,510	35	0.39	0.38	295
	E4M3 1	139 E	5.47	1.38	0.67	1.38	0.67	1.38					7,975	264	1.1	2,410	485	23	0.77	1,200
	E4110.1	191 E	7.52	1.38	0.67	1.38	0.67	1.38	0.67	1.38			14,200	646	1.6	3,300	1,100	91	1.2	2,100
		243 E	9.57	1.38	0.67	1.38	0.67	1.38	0.67	1.38	0.67	1.38	22,075	1,278	2.1	4,200	1,940	229	1.5	3,000

### **FLATWISE** Panel Properties







**MAJOR Strength Direction** "Parallel" Direction Use subscript '0' in Notation

**MINOR Strength Direction** "Perpendicular" Direction Use subscript '90' in Notation

	bending	shear	bending	shear
strength	$(F_bS)_{eff,f,0}$	V _{s,0}	(F _b S) _{eff,f,90}	<b>V</b> _{s,90}
stiffness	(EI) _{efff0}	(GA) _{eff,f,0}	(EI) _{eff,f,90}	(GA) _{eff,f,90}

*Reference: ANSI/APA PRG 320 and Product Reports* 

### Structural Grades vs Appearance?

How does the selection of a CLT grade impact visual appearance of final product?

**Major Strength Direction Minor Strength Direction** CLT Grade #3 Spruce Pine Fir E1 1950f-1.7E MSR SPF E2 1650f-1.5E MSR DFL #3 Doug Fir Larch "E" grades from E3 1200f-1.2E MSR Misc #3 Misc machine graded lumber 1950f-1.7E MSR SP #3 Southern Pine E4 E5 1650f-1.5E MSR Hem-Fir #3 Hem-Fir V1 #2 Doug Fir Larch #3 Doug Fir Larch V1(N) #2 Doug-Fir Larch (North) #3 Doug-Fir Larch (North) V2 #1/#2 Spruce Pine Fir #3 Spruce Pine Fir "V" grades from visually graded lumber V3 #2 Southern Pine #3 Southern Pine V4 #2 Spruce Pine Fir (South) #3 Spruce Pine Fir (South) V5 #2 Hem-Fir #3 Hem-Fir

V Grades of CLT <u>ARE NOT</u> better visually than E grades of CLT

### Impacts on Final Aesthetic of CLT

#### Lumber is a natural product with variations and character



Spruce-Pine-Fir (SPF) & Spruce-Pine-Fir South (SPF-S)



Hem-Fir (HF)



**Douglas Fir-Larch** 

(DF)



Courtesy SMARTLAM

Southern Yellow Pine (SYP)

What can impact final look?

- Species or Species Group (DFL, SPF, HF, SP)
- Structural Grade (Select Structural, #1, #2, etc)
- Manufacturers process to control natural variation
- Construction process: moisture management & remedies
- Applied stains and finishes

**CLT Grade** 

### Impacts on Final Aesthetic of CLT

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Spruce-Pine-Fir (SPF) & Spruce-Pine-Fir South (SPF-S)



Hem-Fir (HF)



(DF)



Courtesy SMARTLAM

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____ Appearance Classification

### PRG 320 defines <u>example</u> CLT Appearance Classifications



**Architectural Appearance –** where appearance is important but not overriding consideration

#### Architectural Douglas Fir

**Industrial Appearance** – for use in applications where appearance is not a primary concern

Industrial Southern Pine



Consult with manufacturers for options available and cost impacts

Photos courtesy SMARTLAM

CLT Floor and Roof Analysis and Design

### Generic Mass Timber Floor System (girder & purlin)



(4) Girders Spans of 30 ft

### **Major Span Direction Analysis**



For actions resisted by primarily 1-way spanning behavior, common to analyze as a beam. 1 ft strip a very convenient width.



Can use this approach for multiple spans, cantilevers, etc.

### PRG 320 Basic Layup Properties

1 3/8

1 3/8

4 1/8

6 7/8

E4

1 3/8

1 3/8

1 3/8

13/8 13/8 13/8

#### Flatwise Panel Properties provided per foot of width of panel Layup CLT Grade TABLE A2 ASD REFERENCE DESIGN VALUES^o FOR BASIC CLT GRADES AND LAYUPS (FOR USE IN THE U.S.) Lamination Thicknes (in.) in CLT Layup **Major Strength Direction Minor Strength Direction** (F_bS)_{eff,f,0} (lbf-ft/ (EI)_{eff,f,0} (10° lbf-(GA)_{eff,f,0} (10⁶ lbf/ (EI)_{eff,f,90} V_{s,90} V____ $(F_{b}S)_{eff,f,90}$ (10° lbf-(GA)_{eff,f,90} CLT ft of in.²/ft of ft of (lbf/ft of (lbf-ft/ft in.²/ft of (10⁶ lbf/ft (lbf/ft of t_p (in.) width) width) width) width) of width) width) of width) width) Grade = = 4 1/8 1 3/8 3/8 1 3/8 4,525 115 3.1 0.61 1,490 0.46 160 495 1 3/8 E1 6 7/8 3/8 1 3/8 1 3/8 1 3/8 10,400 440 0.92 2,480 1,370 81 1.2 1,490 9 5/8 13/8 13/8 1 3/8 1 3/8 1 3/8 13/8 13/8 18,375 1.089 3,475 3,150 313 1.8 2,480 1.4 1 3/8 1 3/8 102 0.56 4 1/8 1 3/8 3,825 0.53 1.980 3.6 660 165 E2 6 7/8 3/8 3/8 1 3/8 1 3/8 1 3/8 8,825 389 1.1 3,300 1,440 95 1.1 1,980 9 5/8 1 3/8 1 3/8 1 3/8 1 3/8 13/8 13/8 13/8 15,600 963 4,625 3,300 364 3,300 1.6 1.7 1 3/8 1 3/8 1 3/8 2,800 81 2.3 0.44 4 1/8 0.35 1,160 110 385 6 7/8 1 3/8 1 3/8 1 3/8 1 3/8 1 3/8 6,400 311 0.69 1,930 955 0.87 1,160 E3 61 1 3/8 1 3/8 13/8 13/8 13/8 13/8 13/8 11,325 2,700 2,210 1,930 9 5/8 769 1.0 234 1.3 0.62

115

440

0.50

1.0

1,820

3.025

140

1.230

3.4

88

1.2

605

1.820

4,525

10.400

### Flatwise Flexural Strength Design Example

Select acceptable CLT section

Given:

15 foot span floor50 psf live load75 psf total dead load (includes 15 psf partition load)



15 foot span

#### Assume:

one-way spanning action in major strength axis of CLT Analysis of a 1 ft strip of panel as beam

Calculate ASD Applied Moment using load combo 1.0DL + 1.0LL

M_b = w L² / 8 = (75plf+50plf) (15ft)² / 8 = 3,516 lb-ft/ft

### Flatwise Flexural Strength

Design properties based on an Extreme Fiber Model:

Flexural Capacity Check:

$$M_a \leq (F_b S_{eff})'$$



M_a = applied bending moment

 $(F_b S_{eff})'$  = adjusted bending capacity

S_{eff} = effective section modulus

= reference bending design stress of outer lamination

Separate values for most components

*Reference: NDS* 

**F**_b

### Flatwise Flexural Capacity Check (ASD)



 $M_a \leq C_D (1.0) (F_b S_{eff})$ 

*Reference: NDS Table 10.3.1* 

### Flatwise Flexural Strength Design Example

Look for Acceptable CLT Grade from PRG 320:  $F_b S_{eff,0} > 3516 \text{ lb-ft/ft}$ 

		La	minatio	on Thick	ness (i	n.) in C	LT Lay	up	Major Strength Direction				Minor Strength Direction			
CLT Grade	t _p (in.)	=	1	=		=	, 	=	(F _b S) _{eff,f,0} (Ibf-ft/ ft of width)	(EI) _{eff,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 _b S) _{eff,f,90} (Ibf-ft/ft of width)	(EI) _{eff,f,90} (10 ⁶ lbf- in.²/ft of width)	(GA) _{eff.f.90} (10° lbf/ft of width)	V _{s 20} (Ibf/ft of width)
_	4 1/8	1 3/8	1 3/8	1 3/8					1,740	95	0.49	1,820	140	3.4	0.52	605
V3	6 7/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8			4,000	363	0.98	3,025	1,230	88	1.0	1,820
	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	4,225	2,825	338	1.6	3,025
	4 1/8	1 3/8	1 3/8	1 3/8					1,800	74	0.38	1,490	140	2.6	0.41	495
V4	6 7/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8			4,150	285	0.76	2,480	1,230	68	0.82	1,490
	9 5/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	7,325	706	1.1	3,475	2,825	260	1.2	2,480

Select 5-Ply 6 7/8" Thick V3 Panel with F_bS_{eff,0} = 4000 lb-ft/ft V3 uses Southern Pine #2 & #3

Reference: ANSI/APA PRG 320 Table A2

### Flatwise Flexural Strength Design Example

#### **ASD Flexural Capacity:**

Dead + Live load,  $C_D = 1.0$ 

 $(F_b S_{eff})' = C_D (1.0) (F_b S_{eff})$ = 1.0 (1.0) (4000 lb-ft/ft)

= 4000 lb-ft/ft

 $M_a = 3516 \text{ lb-ft/ft} \leq (F_b S_{eff})' = 4000 \text{ lb-ft/ft}$ 

**Flexural Strength OK** 





### Flatwise Shear Strength

"Fiber Stress Check"

 $V_a \leq F_s(Ib/Q)_{eff}'$   $V_a$  = applied shear  $F_s(IbQ)_{eff}'$  = adjusted shear strength



Jargon Alert! AKA "Planar Shear", "Out-of-Plane Shear", or "Rolling Shear" Strength



Reference: NDS 2018

### Flatwise Shear Strength





**Rolling Shear**
## Flatwise Shear Check (ASD)



 $V_{a} \le (1.0) V_{s}$ 

Duration of Load Effects (Cd and λ) NOT applicable to Flatwise Shear Strength of CLT in the NDS

*Reference: NDS & Product Reports* 

# Flatwise Shear Strength

#### TABLE A2 (continued)

#### ASD REFERENCE DESIGN VALUES[®] FOR BASIC CLT GRADES AND LAYUPS (FOR USE IN HE U.S.)

		La	minatio	on Thick	ness (i	in.) in C	CLT Lay	υp	Major Strength Direction			Minor Strength Direction				1
CLT Grade	t _p (in.)	=	Ť	=	$\perp$	=	T	=	(F _b S) _{eff,f,0} (Ibf-ft/ ft of width)	(EI) _{eff,f,0} (10 ⁶ lbf- in.²/ft of width)	(GA) _{eff,f,0} (10 [¢] lbf/ ft of width)	V _{ş,0} (lbf/ft of width)	(F _b S) _{eff,f,90} (Ibf-ft/ft of width)	(EI) _{eff,f,90} (10 ⁶ lbf- in.²/ft of width)	(GA) _{eff.f.90} (10° lbf/ft of width)	V _{₅90} (Ibf/ft of width)
	4 1/8	1 3/8	1 3/8	1 3/8					1,740	95	0.49	1.820	140	3.4	0.52	605
٧3	6 7/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8			4,000	363	0.98	3,025	1,230	88	1.0	1,820
	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	4,225	2,825	338	1.6	3,025
	4 1/8	1 3/8	1 3/8	1 3/8					1,800	74	0.38	1,490	140	2.6	0.41	495
V4	6 7/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8			4,150	285	0.76	2,480	1,230	68	0.82	1,490
	9 5/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	7,325	706	1.1	3,475	2,825	260	1.2	2,480

For 5-Ply 6 7/8" Thick V3 Panel  $V_{s,0} = 3,025$  lb/ft of width

# Flatwise Shear Strength (ASD)

**Applied Shear Force** 

V_a = w L / 2 = (75+50psf) (15ft) / 2 = 938 lb/ft

#### **Reference Shear Capacity**

 $F_{s}(IbQ)_{eff} = V_{s,0} = 3,025 \text{ lb/ft}$ 

#### **Adjusted Shear Capacity**

 $F_{s}(IbQ)_{eff}' = C_{M}C_{t}V_{s,0}$ 

#### **Demand to Capacity Check**

 $V_a \le (1.0) V_{s,0} = 3,025 \text{ lb/ft}$ 938 lb/ft  $\le 3,025 \text{ lb/ft}$  ok for shear.



15 foot span



Calculation deflection midspan using uniformly loaded simply span beam equation:

$$\Delta_{max} = \frac{5}{384} \frac{wL^4}{EI}$$
W = D + L = 125 psf  

$$\Delta_{max} = \frac{5}{384} \frac{wL^4}{EI} \quad \leftarrow \text{ from common beam tables}$$
For V3 5-ply (6 7/8") EI_{eff,0} = 363x10⁶ lbf-in²/ft  

$$= \frac{5}{384} \frac{125 \frac{lb}{ft^2} \left(1ft / 12\frac{in}{ft}\right) \left(15 ft * 12\frac{in}{ft}\right)^4}{363 * 10^6 \frac{lb in^2}{ft}} = 0.39 in$$

## Flatwise Deflection Example

• For selected 6 7/8" 5-Ply V3, lookup major strength stiffness values

TABLE A2 (continued)

#### ASD REFERENCE DESIGN VALUES^a FOR BASIC CLT GRADES AND LAYUPS (FOR USE IN THE U.S.)

		La	minatio	on Thick	mess (i	n.) in C	CLT Lay	up	Major Strength Direction				Minor Strength Direction			
CLT Grade	t _p (in.)	=	Ţ	=	$\perp$	=	Ţ	=	(F _b S) _{eff,f,0} (Ibf-ft/ ft of width)	(EI) _{eff,f,0} (10° lbf- in.²/ft of width)	(GA) _{eff,f,0} (10 [¢] lbf/ ft of width)	V _{s.0} bf/ft of width)	(F _b S) _{eff,f,90} (Ibf-ft/ft of width)	(EI) _{eff,f,90} (10° lbf- in.²/ft of width)	(GA) _{eff,f,90} (10° lbf/ft of width)	V _{s90} (lbf∕ft of width)
	4 1/8	1 3/8	1 3/8	1 3/8					1,740	95	0.49	1,820	140	3.4	0.52	605
V3	6 7/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8			4,000	363	0.98	3,025	1,230	88	1.0	1,820
	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	4,225	2,825	338	1.6	3,025
	4 1/8	1 3/8	1 3/8	1 3/8					1,800	74	0.38	1,490	140	2.6	0.41	495
V4	6 7/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8			4,150	285	0.76	2,480	1,230	68	0.82	1,490
	9 5/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	7,325	706	1.1	3,475	2,825	260	1.2	2,480

#### Reference: ANSI/APA PRG 320

# Simple Span Deflection Calculation

Major strength direction stiffness

- Flexural Stiffness: El_{eff,0}
- Shear Stiffness: GA_{eff,0} ??

W = 75 psf DL, 50 psf LL

15 foot span

El_{eff,0} "true" <u>flexural</u> stiffness, however shear deformations can be significant:

Uniformly loaded, single span, simply supported rectangular beam deflection *with shear stiffness*:

$$\Delta_{max} = \frac{5}{384} * \frac{wL^4}{EI_{eff}} + \frac{1}{8} * \frac{wL^2}{5/6 \ GA_{eff}} \qquad \Delta_{max} = 0.39 \ in + 0.05 \ in = 0.44 \ in = L/409$$

For V3 5-ply (6 7/8")  $GA_{eff.0} = 0.98 \times 10^6 \, lbf - in^2 / ft$ 

For common spans & loading, shear deflections often 10% to 20% of flexural

# **Deflection Creep Factor**

• Deformation to Long Term Loads

$$\Delta_T = K_{cr} \, \Delta_{LT} + \Delta_{ST} \qquad \text{NDS Eq 3.5-1}$$

 $\Delta_{ST}$  Deflection due to short-term loading

 $\Delta_{LT}$  Immediate deflection due to long term loading

 $K_{cr}$  2.0 for CLT in dry service conditions

#### **Design Example:**

- $\Delta_{\rm ST}$  from 50psf = 0.177 in
- $\Delta_{LT}$  from 75psf = 0.266 in
- $\Delta_{\rm T}$  = 2.0 (0.266) + 0.177 = 0.709 in
- = L / 254

#### Reference: NDS 2018 Section 3.5

Do NOT overlook checking acceptable <u>total</u> <u>deformations</u> to the building performance including visual perceptions of deformations. Your project may want to be better than code minimum.

w plf

15 foot span

## **Deflection Calculations**

For single span, simply supported uniform load

$$\Delta_{max} = \frac{5}{384} * \frac{wL^4}{EI_{eff}} + \frac{1}{8} * \frac{wL^2}{5/6 \ GA_{eff}}$$



Uniform load, w

Span, L

What is *Apparent* Flexural Stiffness, El_{app}, such that

$$\Delta_{\max} = \frac{5}{384} \cdot \frac{wL^4}{El_{app}}$$

Set equal to each other and solve for El_{app}

$$EI_{app} = \frac{EI_{eff}}{1 + \frac{11.5EI_{eff}}{GA_{eff}L^2}}$$

Reference: NDS Chapter 10 and Commentary

## **Deflection Calculations**

Apparent Flexural Stiffness depends on Span Length



Apparent Flexural Stiffness depends on Load Shape and Support Conditions

		-			
	Loading	End Fixity	k _b	ks	Ks
	Lifemal, Distributed	Pinned	5/384	1/8	11.5
	Uniformly Distributed	Fixed	1/384	1/8	57.6
		Pinned	1/48	1/4	14.4
NDS 2018	Line Load at midspan	Fixed	1/192	1/4	57.6
	Line Load at quarter points	Pinned	11/768	1/8	10.5
	Constant Moment	-	1/12	0	0
	Uniformly Distributed	Cantilevered	1/8	1/2	4.8
	Line Load at free-end	Cantilevered	1/3	1	3.6
	Calumn Bushling	Pinned	А	$A\pi^2$	11.8
	Column Buckling	Fixed	В	$4B\pi^2$	47.4

Table C10.4.1.1 Shear Deformation Adjustment Factors

# Vibration Criteria for CLT Floor Span

CLT Floor Span Limit (base value) from FPInnovations method

$$L_{lim} \le \frac{1}{12.05} \frac{\left(EI_{eff}\right)^{0.293}}{(\overline{\rho}A)^{0.122}}$$
 [ft]

Where, for 12 in wide strip:  $EI_{eff}$  = effective flexural stiffness (lbf-in²)  $\overline{\rho}$  = in-service specific gravity of the CLT, unitless e.g. weight normalized by weight of water A = the cross-section area (in²) = thickness * 12 in

$$L_{lim} \le \frac{1}{13.34} \frac{\left(EI_{eff}\right)^{0.293}}{(w)^{0.122}}$$
 [ft]

Where, for 12 in wide strip:  $EI_{eff}$  = effective flexural stiffness (lbf-in²) w = CLT weight per area (lbf/ft²)

Reference "US Mass Timber Floor Vibration Design Guide" Chapter 4

# Vibration Criteria for CLT Floor Span

Recommended CLT Floor Span Limit (base value)

$$L_{lim} \le \frac{1}{13.34} \frac{(363 \times 10^6 \, \text{lbf in}^2/\text{ft})^{0.293}}{(20.8 \, lbf/ft^2)^{0.122}} \, \text{[ft]} = 16.7 \, \text{ft}$$

15 ft span in plan < 16.7 ft recommended span limit

This is only a check of the CLT panel span for common occupancies and sensitivities. Additional checks need to be performed on the supporting frame!



# Natural Frequency of Uniform Beam





 $f_n = \frac{\pi}{2L^2} \sqrt{\frac{EI}{m}} = \frac{\pi}{2L^2} \sqrt{\frac{gEI}{w}}$ 

Uniform simple span beam

- Span, L
- Flexural stiffness, El
- Mass per length, m, or w/g
- $\Delta$  is deflection to expected weight, e.g.  $\Delta_{LT}$

$$f_n = 0.18 \sqrt{\frac{g}{\Delta}} = \frac{3.54 \, Hz \, \sqrt{in}}{\sqrt{\Delta}}$$

Our 15 ft floor example:  $f_n = \frac{3.54 \text{ Hz} \sqrt{in}}{\sqrt{0.266 \text{ in}}} = 6.86 \text{ Hz}$ 

Reference "US Mass Timber Floor Vibration Design Guide" Chapter 4

### Generic Mass Timber Floor System (girder & purlin)



⁽⁴⁾ Girders Spans of 30 ft

## Understand Manufacturer's Capabilities









Credit: Tanya Luthi, Entuitive

### Multi-span CLT Panels as Simple Beams Single span $M_{max} = \frac{1}{8}wL^2$ $V_{max} = \frac{1}{2}wL$ $R_{max} = wL$ $\delta_{max} = \frac{5wL^4}{385 EI}$ W W **Double span** $M_{max} = \frac{1}{8}wL^2$ $V_{max} = \frac{5}{8}wL$ $R_{max} = \frac{5}{4}wL$ $\delta_{max} = \frac{wL^4}{185 EL}$ W W W **Triple span**

* Skip loading can be higher

 $L \qquad L \qquad L \qquad L \qquad L \qquad M_{max} = \frac{1}{10} w L^2 * \qquad V_{max} = \frac{6}{10} w L * \qquad R_{max} = \frac{11}{10} w L^* \qquad \delta_{max} = 0.0069 \frac{w L^4}{EI} *$ 

### Uniform Load, Equal Spans, Comparison of Critical Design Values

	Moment $M_{max}$	Shear V _{max}	Deflection $\delta_{max}$	Reaction R _{max}
Single span	.125 $wL^2$	.500 wL	.0130 $\frac{wL^4}{EI}$	1.00 <i>wL</i>
Double span	.125 $wL^2$	.625 wL	.0054 $\frac{wL^4}{EI}$	1.25 wL
Triple span	$.100 wL^2$	.600 wL	.0069 $\frac{wL^4}{EI}$	1.10 wL
Triple span Skip load (2 of 3)	.117 $wL^2$	.617 wL	.0099 $\frac{wL^4}{EI}$	1.20 <i>wL</i>

Sources of span tables:

- AWC Design Aid No. 6 Beam Design Formulas with Shear and Moment Diagrams
- AISC Manual of Steel Construction

### Uniform Load, Equal Spans, Comparison of Critical Design Values

	Moment $M_{max}$	Shear V _{max}	Deflection $\delta_{max}$	Reaction R _{max}
Single span	$.125 wL^{2}$	.500 wL	$.0130 \ \frac{wL^4}{EI}$	1.00 wL
Double span	$.125 wL^{2}$	.625 wL	.0054 $\frac{wL^4}{EI}$	1.25 wL
Triple span	$.100 wL^2$	.600 wL	.0069 $\frac{wL^4}{EI}$	1.10 <i>wL</i>
Triple span Skip load (2 of 3)	.117 $wL^2$	.617 wL	.0099 $\frac{wL^4}{EI}$	1.20 <i>wL</i>

What if the number of spans per panel is unknown?

Often the case in design before a manufacturer is selected.

### Uniform Load, Equal Spans, Comparison of Critical Design Values

	Moment $M_{max}$	Shear V _{max}	Deflection $\delta_{max}$	Reaction R _{max}
Single span	$.125 wL^{2}$	.500 wL	$.0130 \ \frac{wL^4}{EI}$	1.00 wL
Double span	$.125 wL^{2}$	.625 wL	.0054 $\frac{wL^4}{EI}$	1.25 wL
Triple span	.100 $wL^2$	.600 wL	.0069 $\frac{wL^4}{EI}$	1.10 wL
Triple span Skip load (2 of 3)	.117 $wL^2$	.617 wL	.0099 $\frac{wL^4}{EI}$	1.20 wL

A panel design strategy for <u>unknown</u> panel layout of regular 1-way span lengths:

- Design CLT panels as single span
- Design interior support points for potential 25% increase in reaction

# 5-Ply V3 Panel 15' Example– Single vs Multi Span

	<i>Moment</i> M _{max} (ft-lbs/ft)	Shear ${V}_{max}$ (lbs)	Total Deflection $\delta_{max}$ (in)	Reaction $R_{max}$ (lbs)
Single span	<b>3, 516</b> (DCR = 0.88)	<b>936</b> (DCR= 0.31)	0.71	1,875
Double span	<b>3</b> , <b>516</b> (DCR= 0.88)	<b>1</b> , <b>172</b> ( <i>DCR = 0.39</i> )	0.34	2,344
Triple span	<b>2,813</b> (DCR = 0.70)	<b>1</b> , <b>125</b> ( <i>DCR= 0.37</i> )	0.41	2,063

- Same design loads and span(s) from previous example
- Simple span reaction assumes (2) panels at support point (1.0wl)
- Multi-span values do not include skip loading
- Total deflection includes creep

# Vibration Criteria for CLT Floor Span

What's the impact of multi-span panels on floor vibrations?

• Check the longest span, if unequal

 Recommend a 20% increase in the Base Span Limit when non-structural elements are present which provide enhanced stiffening effect*

*Partition walls, finishes, ceilings

In example: 15 ft span in plan < (1.2) 16.7 = 20 ft



Reference "US Mass Timber Floor Vibration Design Guide" Chapter 4

# Multi-span CLT Panels – Complex Cases



A more careful analysis may be appropriate:

- Euler beam analysis using Elapp to approximate shear deformations
- Timoshenko beam analysis with explicit shear deformations
- Thick plate/laminate plate FEA (can also pick up two-directional behavior)

Structural Fire Design of CLT

# What about fire resistance ratings?

#### Mass Timber: Up to 18 Stories in Construction Types IV-A, IV-B or IV-C



TABLE 601—FIRE	RESIST	ANCE RA	TING R	EQUIRE	MENTS	FOR BU	JILDING	ELEME	NTS (HO	OURS)		
	TYPE I		TYPE II		TYPE III		TYPE IV				TYPE V	
BUILDING ELEMENT		В	Α	В	A	В	A	В	с	нт	Α	В
Primary structural frame ^f (see Section 202)	3 ^{a, b}	2 ^{a, b, c}	1 ^{b, c}	0 ^c	1 ^{b, c}	0	3ª	2ª	2ª	нт	1 ^{b, c}	0
Bearing walls												
Exterior ^{e, f}	3	2	1	0	2	2	3	2	2	2	1	0
Interior	3ª	2 ^a	1	0	1	0	3	2	2	1/HT ^g	1	0
Nonbearing walls and partitions Exterior	See Table 705.5											
Nonbearing walls and partitions Interior ^d	0	0	0	0	0	0	0	0	0	See Section 2304.11.2	0	0
Floor construction and associated secondary structural members (see Section 202)	2	2	1	0	1	0	2	2	2	нт	1	0
Roof construction and associated secondary structural members (see Section 202)	1 ¹ / ₂ ^b	1 ^{b, c}	1 ^{b, c}	0 ^c	1 ^{b, c}	0	1 ¹ / ₂	1	1	нт	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 or mezzanine immediately below. Fire-retardanttreated 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 for roof construction, including primary structural frame members, 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 705.5).

f. Not less than the fire-resistance rating as referenced in Section 704.9.

g. Heavy timber bearing walls supporting more than two floors or more than a floor and a roof shall have a fire-resistance rating of not less than 1 hour.

## Fire Design of CLT

CLT structural capacity

CLT char depth

Original CLT depth

Credit: David Barber, ARUP

### Fire Resistance Ratings Based on ASTM E119 Testing



#### ASTM E119 Time Temperature Curve

- Tested Assemblies (IBC 703.2)
- Analytical Methods (IBC 703.3):
  - 1. Fire-resistance designs in "approved sources"
  - 2. Prescriptive assemblies in IBC 721
  - 3. Calculations per IBC 722
  - 4. Engineering analysis based on tested assemblies
  - 5. Alternative methods per IBC 104.11
  - 6. Fire-resistance design certified by approved agency

### Fire Resistance Ratings Based on ASTM E119 Testing



ASTM E119 Time Temperature Curve

- Tested Assemblies (IBC 703.2)
- Analytical Methods (IBC 703.3):
  - 1. Fire-resistance designs in "approved sources"
  - 2. Prescriptive assemblies in IBC 721
  - 3. Calculations per IBC 722
  - 4. Engineering analysis based on tested assemblies
  - 5. Alternative methods per IBC 104.11
  - 6. Fire-resistance design certified by approved agency

### Test reports from approved 3rd party fire test labs

### Inventory of Fire Resistance Tests of Mass Timber

https://www.woodworks.org/resources/inventory-of-fire-resistance-tested-mass-timber-assemblies-penetrations/

#### Table 1: North American Fire Resistance Tests of Mass Timber Floor / Roof Assemblies





### Fire Resistance Ratings Based on ASTM E119 Testing



ASTM E119 Time Temperature Curve

- Tested Assemblies (IBC 703.2)
- Analytical Methods (IBC 703.3):
  - 1. Fire-resistance designs in "approved sources"
  - 2. Prescriptive assemblies in IBC 721
  - 3. Calculations per IBC 722
  - 4. Engineering analysis based on tested assemblies
  - 5. Alternative methods per IBC 104.11
  - 6. Fire-resistance design certified by approved agency

### **3rd-party references such as UL Listings**

### Fire Resistance Ratings Based on ASTM E119 Testing



ASTM E119 Time Temperature Curve

- Tested Assemblies (IBC 703.2)
- Analytical Methods (IBC 703.3):
  - 1. Fire-resistance designs in "approved sources"
  - 2. Prescriptive assemblies in IBC 721
  - 3. Calculations per IBC 722
  - 4. Engineering analysis based on tested assemblies
  - 5. Alternative methods per IBC 104.11
  - 6. Fire-resistance design certified by approved agency

### **Engineering based extrapolations from tested assemblies**

### Fire Resistance Ratings Based on ASTM E119 Testing



#### ASTM E119 Time Temperature Curve

- Tested Assemblies (IBC 703.2)
- Analytical Methods (IBC 703.3):
  - 1. Fire-resistance designs in "approved sources"
  - 2. Prescriptive assemblies in IBC 721
  - 3. Calculations per IBC 722
  - 4. Engineering analysis based on tested assemblies
  - 5. Alternative methods per IBC 104.11
  - 6. Fire-resistance design certified by approved agency

### **Calculation method per NDS Chapter 16**

### Calculated FRR of Exposed Timber: IBC to NDS code compliance path



Code Path for Exposed Wood Fire-Resistance Calculations

#### IBC 703.3

#### Methods for determining fire resistance

- Prescriptive designs per IBC 721.1
- Calculations in accordance with IBC 722
- Fire-resistance designs documented in sources
- · Engineering analysis based on a comparison
- Alternate protection methods as allowed by 104.11



#### Calculated Fire Resistance

"The calculated *fire resistance* of exposed wood members and wood decking shall be permitted in accordance with **Chapter 16 of ANSI/AWC National Design Specification for Wood Construction (NDS)** 

#### NDS Chapter 16 Fire Design of Wood Members

- · Limited to calculating fire resistance up to 2 hours
- Char depth varies based on exposure time (i.e., fire-resistance rating), product type and lamination thickness. Equations and tables are provided.
- TR 10 and NDS commentary are helpful in implementing permitted calculations.

### Calculated Structural Fire Resistance of CLT

Step 1: Calculated Char depth



### Step 3: Compare adjusted capacity to applied design loads

 $M_a \leq K(F_bS_{eff})$ 



 $\mathrm{F_{b}S_{eff}}$ 

Nominal char rate of 1.5"/hour is recognized in NDS for solid sawn, glulam, CLT, SCL and decking wood products.



Photo Credit: FPInnovations

Char depth  $a_{char} = 1.5 t^{0.813}$ 

Calculated char depth is non-linear, with char rate slowing down

Table 16.2.1AChar Depth and Effective CharDepth (for  $\beta_n = 1.5$  in./hr.)

Required Fire Resistance (hr.)	Char Depth, a _{char} (in.)	Effective Char Depth, a _{eff} (in.)
1-Hour	1.5	1.8
1 ¹ / ₂ -Hour	2.1	2.5
2-Hour	2.6	3.2

Not 3.0



Glue lines in CLT

Calculated char depth is non-linear in the NDS. In CLT, char rate assumed to <u>restart</u> at each glue line

Char depth  $a_{char} = 1.5 t^{0.813}$ 

 $h_{lam} = 1.5 t_{gi}^{0.813}$ Time for char to traverse lamination:

 $t_{gi} = \left(\frac{h_{lam}}{1.5}\right)^{1.23}$ 

h _{lam}	5/8"	3/4"	1″	1 3/8"
t _{gi}	0.341 hr	0.426 hr	0.607 hr	0.899 hr
	20.4 min	25.6 min	36.4 min	53.9 min

**Char time vs CLT lamination thickness** 



Reference NDS Chapter 16.2.1

For exposure time to fire, t

Equal Layer Thicknesses





Number of fully charred layers:  $n_{lam} = \frac{t}{t_{gi}}$  (round down) Time for those layers to char:  $n_{lam}t_{gi}$ 

Time to partially char the last charred layer

 $t - n_{lam} t_{gi}$ 

Depth of char in the last charred layer:

 $1.5 (t - n_{lam} t_{gi})^{0.813}$ 

Total depth of char at time t:

$$a_{char} = n_{lam} h_{lam} + 1.5 (t - n_{lam} t_{gi})^{0.813}$$

Reference NDS Chapter 16.2.1

Exposure time, t = 2 hours

Equal Layer Thicknesses



**Fire Exposed Side** 

Reference NDS Chapter 16.2.1

 $n_{lam} = \frac{t}{t_{ai}} = \frac{2 hr}{0.899 hr} = 2.22 \Rightarrow 2$ Time for those layers to char:

 $n_{lam}t_{gi} = 2(0.899 hr) = 1.798 hr$ 

Time to partially char the last charred layer

 $t - n_{lam} t_{gi} = 2 - 1.798 = .202 hr$ 

Depth of char in the last charred layer:

 $h_{lam} = 1.375''$  1.5  $(t - n_{lam}t_{gi})^{0.813} = 1.5(0.202)^{0.813} = 0.409$  in

Total depth of char at time t:

$$a_{char} = n_{lam} h_{lam} + 1.5 \ (t - n_{lam} t_{gi})^{0.813}$$

= 2(1.375) + 0.409 = 3.159 in
### Calculated Structural Fire Resistance of CLT – Char Depth

Exposure time, t = 2 hours



Calc effective "char" depth, adding heat effected zone

$$a_{eff} = 1.2a_{char} = 1.2(3.159") = 3.791"$$

 Table 16.2.1B
 Effective Char Depths (for CLT

with  $\beta_n$  = 1.5in./hr.)

Required Fire	Effective Char Depths, a _{eff} (in.)								
Resistance (hr.)	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
1 ¹ / ₂ -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



### Calculated Structural Fire Resistance of CLT – Char Depth

#### Exposure time, t = 2 hours





t_{gi}  $\sum t_{gi}$ .899 hr .899 hr .899 hr .899 hr 2.113 > 2 1.215 .607*hr* .607*hr* .607

Number of fully charred layers:

 $n_{lam} \Rightarrow 2$ Time for those layers to char:  $"n_{lam}t_{gi}" = \sum t_{gi} = 1.215 hr$  of bottom 2 layers Time to partially char the last charred layer = 2 - 1.215 = .785 hrDepth of char in the last charred layer:  $= 1.5(0.785)^{0.813} = 1.232$  in Total depth of char at time t:  $a_{char} = "n_{lam}h_{lam}" + 1.5 (t - n_{lam}t_{gi})^{0.813}$ 

= (1.0 + 1.0) + 1.232 = 3.232 in

### Calculated Structural Fire Resistance of CLT – Char Depth

#### Exposure time, t = 2 hours



Calc effective "char" depth, adding heat effected zone

$$a_{eff} = 1.2a_{char} = 1.2(3.232'') = 3.878''$$

No table in the NDS for unequal layer thicknesses. Use a spreadsheet



Fire Exposed Side

### Calculated Structural Fire Resistance of CLT – Capacity Exposure time, *t* = 2 hours



Given effective char depth, what is the capacity of the remaining structurally effective CLT?



### Calculated Structural Fire Resistance of CLT – Capacity

Use Shear Analogy Model to calculate design capacities of remaining section.



PRG 320-2019 Appendix X3 provides equations for <u>balanced</u> layups.

Canadian CLT Handbook Section 8.5 demonstrates how to modify this for <u>unbalanced</u> layups.

Critical difference is the neutral axis is not at the center of the layup

Model calculates a single bending capacity for positive and negative bending, based on F_b of outer laminations

Reference PRG 320 Appendix X3 and Canadian CLT Handbook Ch 8

### Calculated Structural Fire Resistance of CLT – Capacity

For an example of this implemented, see the free CLT Spreadsheet calculator "CLT Design Tools" published by Equilibrium:

https://eqcanada.com/design-resources/







Wood Innovation Grant recipient





Shear Analogy Model calcs result in residual reference bending and shear strength:

 $(F_b S_{eff})_{frr=2hr}$ 

 $V_{s,frr=2hr} = (F_s(IbQ)_{eff})_{frr=2hr}$ 

NDS Ch 16 ASD load check (D+L):

 $M_a \le 2.85 (F_b S_{eff})_{frr=2hr}$ 

2.85 bending stress increase factor from NDS 2018 Table 16.2.2

 $V_a \le 2.75 V_{s,frr=2hr}$ 

2.75 shear stress increase factor from AWC's TR-10 2021 Table 1.4.2 and FDS 2022 Table 3.2.5





For (5) 1 3/8" layers, 6 7/8" thick CLT with 2-hour FRR:

 $M_a \le 35\% (F_b S_{eff}) \le 2.85 (F_b S_{eff})_{frr=2hr}$ 

 $V_a \leq 100\% V_s \leq 2.75 V_{s,frr=2hr}$ 

Major direction bending critical under 2hour FRR case, but have a preliminary check for 6 7/8″ 5-ply => ASD D+L DCR ≤ 35%

Major direction shear not going to control the 2-hr FRR case for 6 7/8" 5-ply



For (5) 1 3/8" layers, 6 7/8" thick CLT with 1-hour FRR:  $M_a \le 100\% (F_b S_{eff}) \le 2.85 (F_b S_{eff})_{frr=1hr}$  $V_a \le 100\% V_s \le 2.75 V_{s,frr=1hr}$ 

Fire Exposed Side

Major direction bending and shear not going to control the 1-hr FRR case for 6 7/8" 5-ply

For (3) 1 3/8" layers, 4 1/8" thick CLT with 1-hour FRR:





## Strength Check at 2 Hour FRR

#### 15' floor span example

D+L:  $M_a = 3516 \text{ lb-ft/ft}$  (single span).

Non-fire Demand / Capacity Ratio = 0.88 for 5 ply 6 7/8" V3 CLT

6 7/8" V3 CLT @ 2 Hrs?

 $a_{eff} = 3.79"$ Calc'ed in "CLT Design Tools" spreadsheet
2.85 (F_bS_{eff})_{frr=2hr} = 1436 lb-ft/ft. Much less than M_a= 3516 lb-ft/ft
67/8" E4 CLT @ 2 Hrs?
2.85 (F_bS_{eff})_{frr=2hr} = 3735 lb-ft/ft. > M_a= 3516 lb-ft/ft. OK
Non-fire Demand / Capacity Ratio = 0.34 for 5 ply 6 7/8" E4 CLT

W = 75 psf DL, 50 psf LL

15 foot span

Ma

#### "E" grades of CLT likely have a cost premium relative to "V" grades

# Design and Modeling Approaches for CLT

## Two-way CLT design





Cooley Landing Project in East Palo Alto. Photo: WoodWorks

Photo: Swinterton

Brock Commons in Vancouver, BC. Photo: Acton Ostry Architects

## CLT is an Othrotropic Material





**Minor Strength Direction** Bending

**Major Strength Direction** Bending

~1.2 to ~240x  $(EI)_{eff,f,0} =$ (EI)_{eff,f,90} more common 2.4 to 40x

## Flatwise Two-Way CLT Analysis



Finite Element Model

Grillage Model

Image from proHolz Cross-Laminated Timber Structural Design, Vol 2

Approximate Strip Analysis

### CLT Finite Element Modelling – Plate Models

#### Method 1: Plate Modelling using CLT section properties.

For flatwise behavior, need <u>asymmetric plates</u>. Isotropic plates just won't represent behavior properly.

Just as with beam analysis, plate modeling can be done with or without consideration of shear deformations.

- "Thin plate" models following Kirchhoff theories without shear deformations. Like Euler-Bernoulli beams
- "Thick plate" models following Mindlin-Reissner theories with shear deformations. Like Timoshenko beams.

Different methods of defining plate properties...

- Indirect definition of plate properties using isotropic material and asymmetric stiffness modifiers.
- Direct definition of plate properties/stiffness values

Explicitly match model stiffness with manufacturers stiffness values

Good at "full span" and similar type of geometries



Input orthotropic plate properties in CSI SAP 2000

### CLT Finite Element Modelling–Laminate Models

#### Method 2: Laminate modeling using CLT lamination properties

2nd order laminate theory (thick laminate) models can capture shear deformations.

The analysis package calculates the CLT section stiffness values.

- Resulting stiffness values don't exactly match recognized/published stiffness properties of CLT.
- Good at "full span" dimensions
- Maybe better than plate models capture small scale behaviors... but in a way not matching design standards.
- Not going to capture connection type behaviors such as perp to grain bearing and stress increases at notches, etc.



Input laminate properties in RFEM DLUBAL

3-D Solids modeling? Fracture mechanics?

## **CLT Finite Element Models**



#### Finite Element Model

Goal in Flatwise CLT model: Get suitable stiffness in major and minor bending directions.

Test simple spans of model to compare FEA deflections vs hand calcs....

Make sure you can model a simple span before getting complex.



## Flatwise Two-Way CLT Analysis



Figure 9.7 Cross-laminated timber plane (a) as grillage model (b) with longitudinal members (L) and transverse members (Q)

Image from proHolz Cross-Laminated Timber Structural Design, Vol 2

#### Grillage Model

A general grillage of representative interconnected beams... isn't very practical compared to a FE plate or laminate model.

A simple grillage of substitute beams around an opening can be a useful design tool

"Openings with their largest dimension below ten percent of the span are considered small openings and normally can be executed without verification"



#### Approximate Strip Analysis

Download Cross-Laminated Timber Structural Design, Vol 2 from <a href="https://www.proholz.at/publikationen/cross-laminated-timber-structural-design-volume-ii">https://www.proholz.at/publikationen/cross-laminated-timber-structural-design-volume-ii</a>



## Flatwise Two-way CLT Design

How do we check simultaneous flatwise two-way loading of CLT?



## Flatwise Two-way CLT Design

How do we check simultaneous flatwise two-way loading of CLT?

Consistent agreement by CLT experts:



#### Flatwise bending and Flatwise shear in the two orthogonal directions can be checked independently

Reference Cross-Laminated Timber Structural Design (Vol 1) Section 5.11 Combined Stresses from <a href="https://www.proholz.at/publikationen/cross-laminated-timber-structural-design">https://www.proholz.at/publikationen/cross-laminated-timber-structural-design</a>

Image from Fast+Epp Timber Bay Design Tool





14.3

13.2

12.1

9.9 8.8 7.7

6.6

2.2

Image from "<u>An Approach to CLT Diaphragm Modeling for</u> <u>Seismic Design with Application to a U.S High-Rise Project</u>"



"All models are wrong, but some are useful". - George Box, British Statistician

Image from Fast+Epp Timber Bay Design Tool





#### Gravity Models:

- Are component-based models and design acceptable?
- Do you need a full 3D building gravity model?
- Boundary conditions and member continuity as appropriate for code-based strength and deflection checks
   e.g. gravity connections idealized as pins

#### Vibration Models:

- Floor and bay studies to understand design choices or achieve high performance floors
- Multi-story models for unusual structural configurations
- Boundary conditions and member continuity as appropriate for low amplitude vibrations

#### e.g. gravity connections idealized as fixed

Reference US Mass Timber Floor Vibration Design Guide for Discussion



Image from "<u>An Approach to CLT Diaphragm Modeling for</u> Seismic Design with Application to a U.S High-Rise Project"

#### Diaphragm Models:

- Commonly used to justify idealize diaphragm as rigid or flexible. (Can a hand calc suffice?)
- Used to explore complicated diaphragm designs

#### Vertical Force Resisting System Models:

- Commonly used to analyze and design multi-story vertical force resisting systems.
- Used to verify drift limits

### *Full 3-D Lateral System Models of diaphragm and vertical systems:*

• Used when needed to do semi-rigid diaphragm analysis



#### Full 3D BIM Models:

- Valuable in mass timber framing planning, MEPF coordination (class detection), manufacturing, fabrication and erection
- Integration with structural design models valuable but not necessary
- Development of 3D BIM model a different scope than structural design

Photos: Swinerton

# Diaphragm Models





CLT Diaphragm often combined with non-mass timber vertical lateral force resisting system.

- Wood Structural Panel shear walls
- Concrete shear walls
- Steel braced frames
- Steel moment frames





Lateral load, w

#### **Homogenous Model**

Uniform diaphragm membrane model with no explicit modeling of connection joints with properties approximating effective system behavior



Lateral load, w

#### **Discrete Panel with Spaced Connections**

Explicit model of CLT panel layout with regular discretized model of connections. Multi directional springs to model connections.

Few types of connection elements. MANY connection elements.



#### **Discrete Panel with Corner Connections**

Explicit model of CLT panel layout with connection in limited locations. Multi directional springs to model connections.

Different connection elements types per panel length. Few connection elements.





Area of a connection detail represented by discrete element to element MDOF springs





Areas of a connection detail represented by discrete element to element MDOF springs



Lateral load, w

#### **Discrete Panel with Connection Zones**

Explicit model of CLT panel layout with smoothed model of connections. For example, with "line springs" or equivalent 2-D membrane elements

> Use of meshing capabilities of commercial FEM software to discretize.



Lateral load, w

#### **Homogenous Model**

Uniform diaphragm membrane model with no explicit modeling of connection joints with properties approximating effective system behavior

Possible source of homogenous properties



## **CLT** Diaphragm Deflection Equations

WSP 4-Term Diaphragm Deflection Equation



Generalized equation by Lawson, et al (2023)

$$\delta_{\text{dia}} = \left(\frac{12 \text{ in}}{1 \text{ ft}}\right) \frac{5vWL^3}{96EAd^2} + \frac{vL}{4G_v t_v} + \frac{L}{4} \left(\frac{n_{\parallel}e_{f\parallel}}{P_{\perp}} + \frac{n_{\perp}e_{f\perp}}{P_{\parallel}}\right) + \frac{\Sigma(x\Delta_c)}{2d}$$

## **CLT Diaphragm Deflection Equations**







Generalized equation by Lawson, et al (2023)

$$\delta_{\text{dia}} = \left(\frac{12 \text{ in}}{1 \text{ ft}}\right) \frac{5\nu W L^3}{96EAd^2} + \frac{\nu L}{4G_{\nu}t_{\nu}} + \frac{L}{4} \left(\frac{n_{\parallel}e_{\text{f}\parallel}}{P_{\perp}} + \frac{n_{\perp}e_{\text{f}\perp}}{P_{\parallel}}\right) + \frac{\Sigma(x\Delta_{\text{c}})}{2d}$$

## **CLT Diaphragm Deflection Equations**

CLT specific equations by Lawson, et al

$$\delta_{\text{dia}} = \left(\frac{12 \text{ in}}{1 \text{ ft}}\right) \frac{5vWL^3}{96EAd^2} + \frac{vL}{4G_v t_v} + \frac{L}{4} \left(\frac{n_{\parallel}e_{f\parallel}}{P_{\perp}} + \frac{n_{\perp}e_{f\perp}}{P_{\parallel}}\right) + \frac{\Sigma(x\Delta_c)}{2d}$$
$$\delta_{\text{cant,u}} = \left(\frac{12 \text{ in}}{1 \text{ ft}}\right) \frac{vW'L'^3}{4EAd^2} + \frac{vL'}{2G_v t_v} + \frac{L'}{2} \left(\frac{n_{\parallel}e_{f\parallel}}{P_{\perp}} + \frac{n_{\perp}e_{f\perp}}{P_{\parallel}}\right) + \frac{\Sigma(x'\Delta_c)}{d}$$

Journal of Architectural Engineering / Archive / Vol. 29, No. 3

#### PREVIOUS ARTICLE

Technical Papers | May 29, 2023



Fig. 1. Deflection parameters of a simple span diaphragm.

NEXT ARTICLE

Check for updates

#### Wood Diaphragm Deflections. I: Generalizing Standard Equations Using Mechanics-Based Derivations for Panel Construction


# CLT Diaphragm Design Guide based on SDPWS 2021

### CLT Diaphragm Design Guide

BASED ON SDPWS 2021



### **Chapter Organization**

- 1. Introduction
- 2. Codes and Standards
- 3. Methodology of CLT Diaphragm Design
- 4. Diaphragm Shear Components
- 5. Diaphragm Boundary Elements
- 6. Diaphragm Deflection and Stiffness
- 7. Special Design Considerations
- 8. Example 12-Story Office with Distributed Frames
- 9. Example 12-Story Office with Reinforced Concrete Cores
  10. Example 5-Story Residence with Wood-Frame Shear walls
  Appendix A Precalculated Design Capacities
  Appendix B Literature Review

# Additional Resources – WoodWorks.org





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