Structural Design of Mass Timber Framing Systems

Presented by Paul B. Becker, PE

Thornton Tomasetti

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

Course Description

This presentation will provide a detailed look at the structural design processes associated with a variety of mass timber products, including glu-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 the use of mass timber panels as two-way spanning slabs, connection options and design considerations, and detailing and construction best practices.

Learning Objectives

1. Provide an overview of available mass timber products, design standards and structural optimization.
2. Review structural design properties and design considerations for CLT floor and roof slabs
3. Review design properties and design considerations for glulam beams and columns
4. Review connection options for CLT and glulam beams

Bath, NY circa 1880

Mass Timber Products

Albina Yards, Portland, OR circa 2016

Lever Architecture
Four-Story, 16,000 sf

Albina Yards, Portland, OR circa 2016

T3, Minneapolis, MN circa 2017

Michael Green Architecture/DLR Group
Seven-Story, 220,000 sf

photo: Hines Development

T3, Minneapolis, MN circa 2017

Michael Green Architecture/DLR Group
Seven-Story, 220,000 sf


photo: Hines Development

Candlewood Suites, Huntsville, AL, circa 2015

photo: Lend Lease

CLT Bearing Walls /Slabs
3-ply walls, 5-ply slabs
Four-stories 62,700 sf

Spaced CLT

allows for MEP chase, inlay ceiling

photo: MGA

Brock Commons, Vancouver, BC

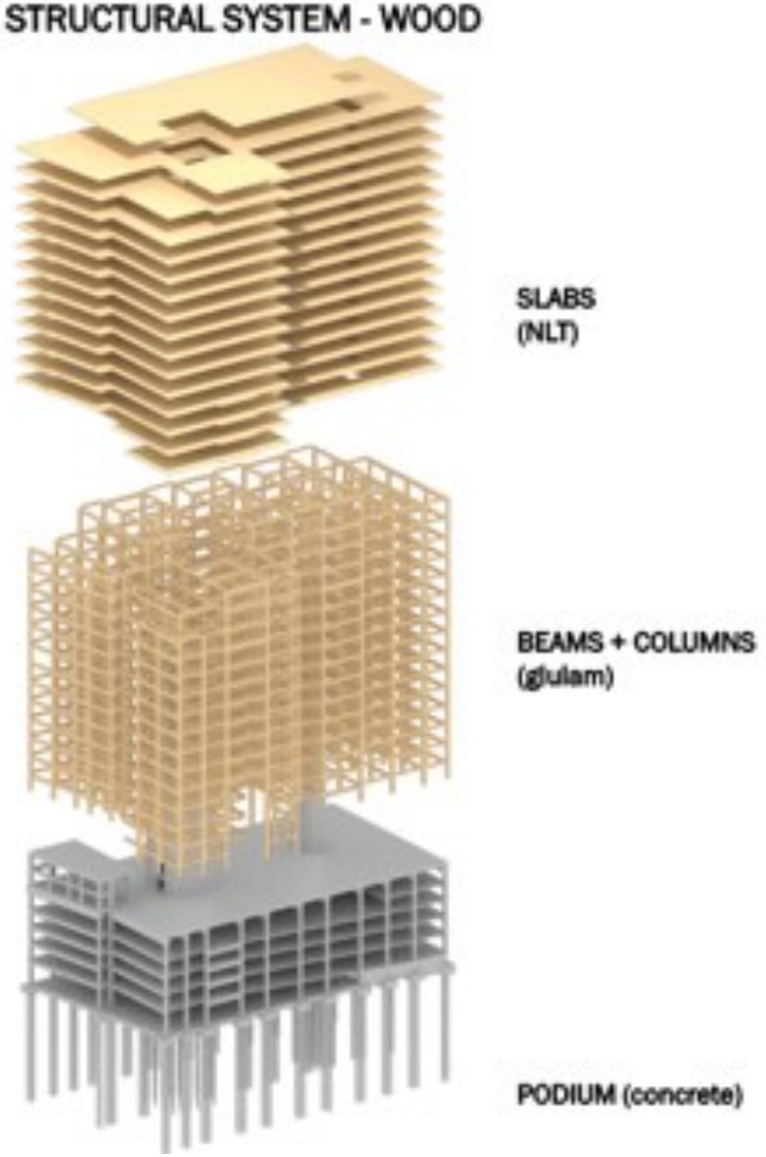
18 stories, two-way slabs, no beams

9.33’ x 13.0’ grid, 18 stories

photo: KK Law

Ascent Tower, Milwaukee, WI

21 stories (5+16) @ 238 ft

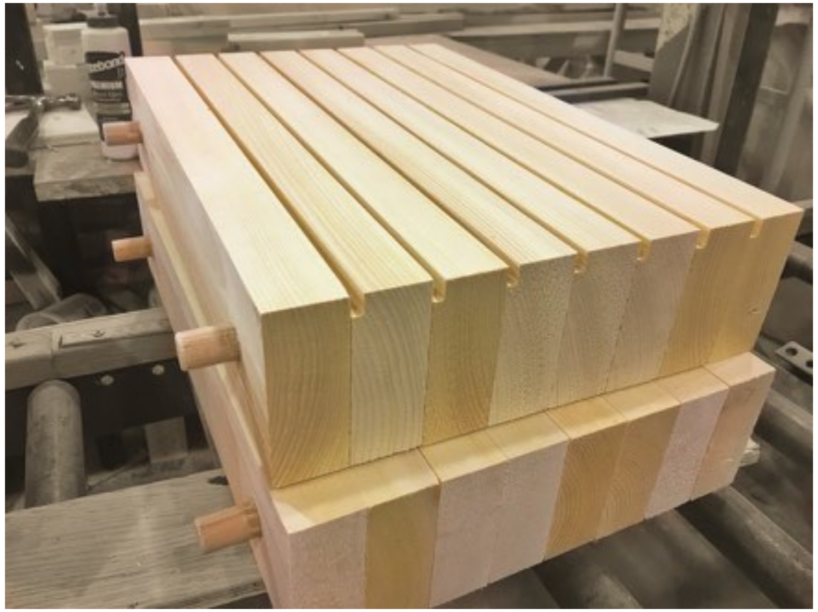


Mass Timber Products

Nail Laminated Decking

Images source: Structurecraft

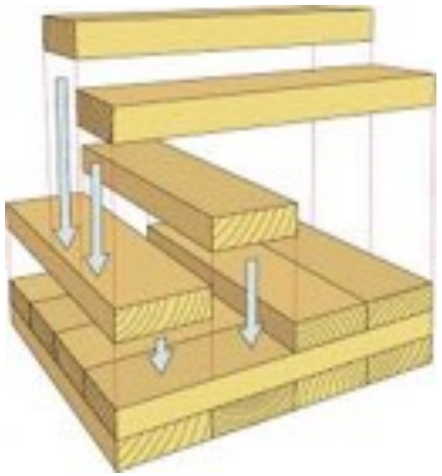
Mass Timber Products



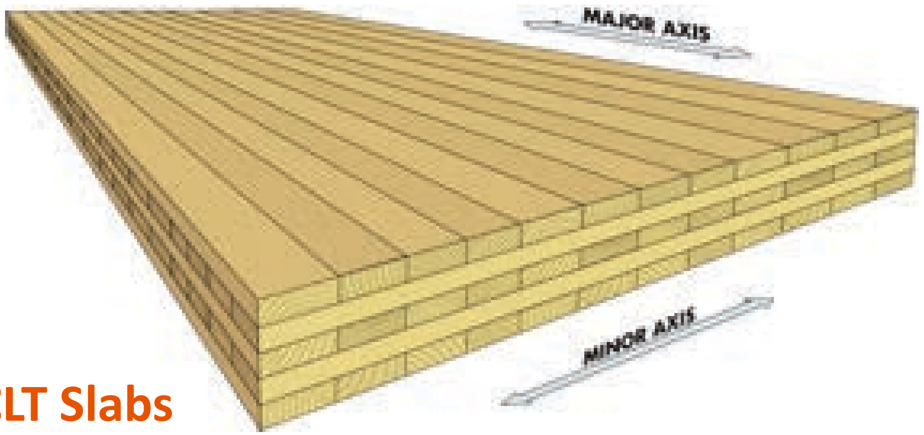
Dowel Laminated Decking

Images source: Structurecraft

Cross-Laminated Timber



Non-homogeneous, anisotropic material



CLT Slabs

Images source: CLT Handbook

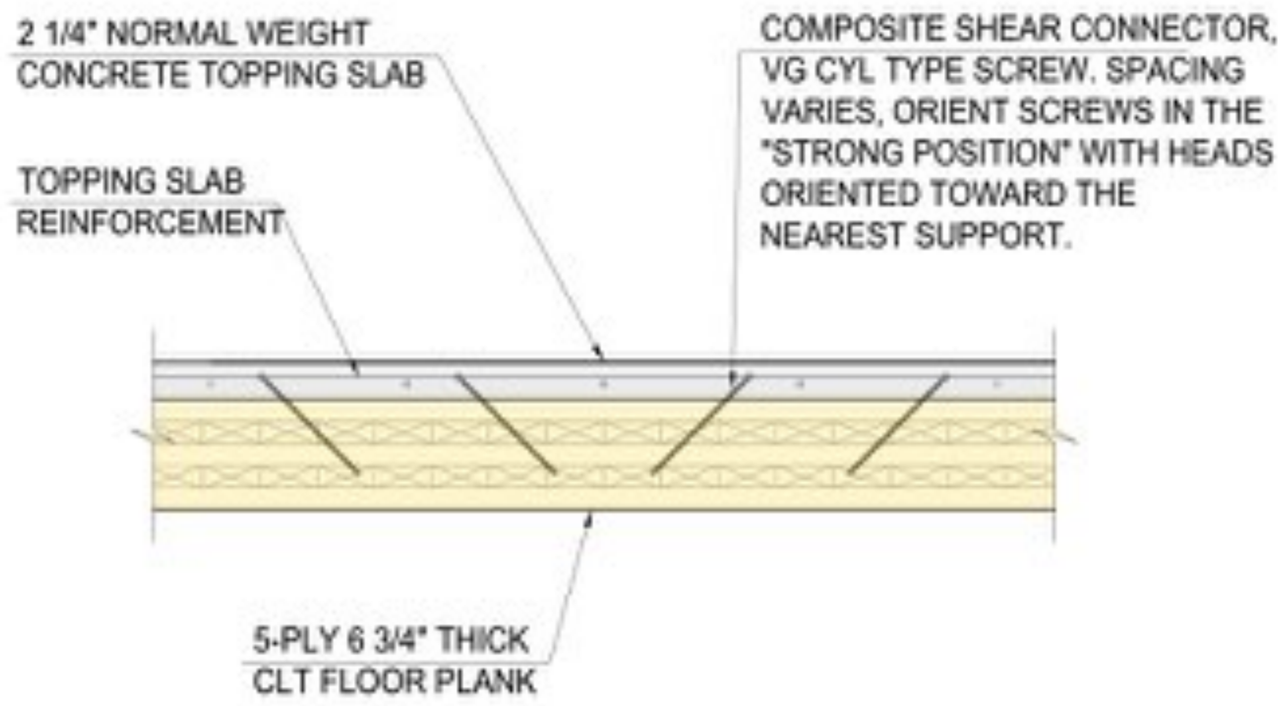
Composition

- 3-ply minimum, up to 9 ply
- Pieces 5/8" to 2 inch thick
- Pieces 2.4 inches to 9.5 inches wide
- Boards finger jointed
- MSR or visual, all kiln dried
- Width and length by manufacturer

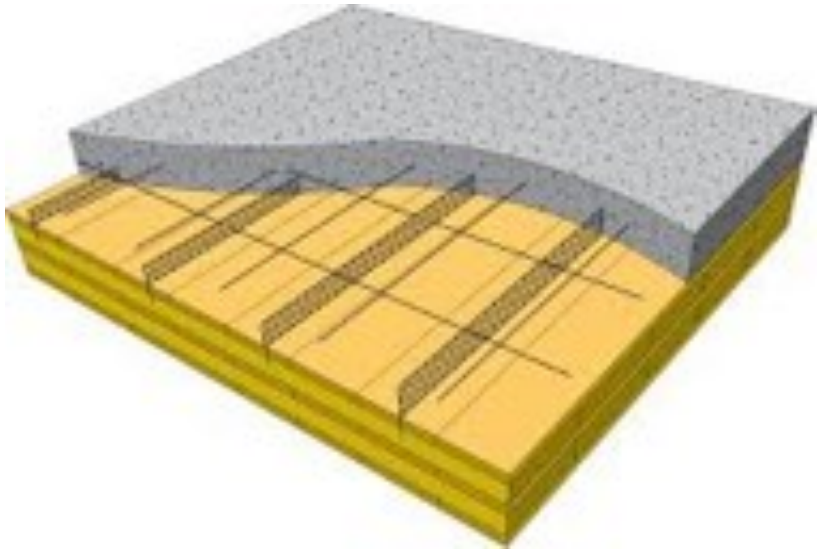
Advantages

- Dimensionally stable product
- High strength to weight ratio
- Long, wide slabs
- High in-plane, out of plane strength + stiffness
- two-way action
- Connector splitting resistance

Composite CLT



screw connector field applied

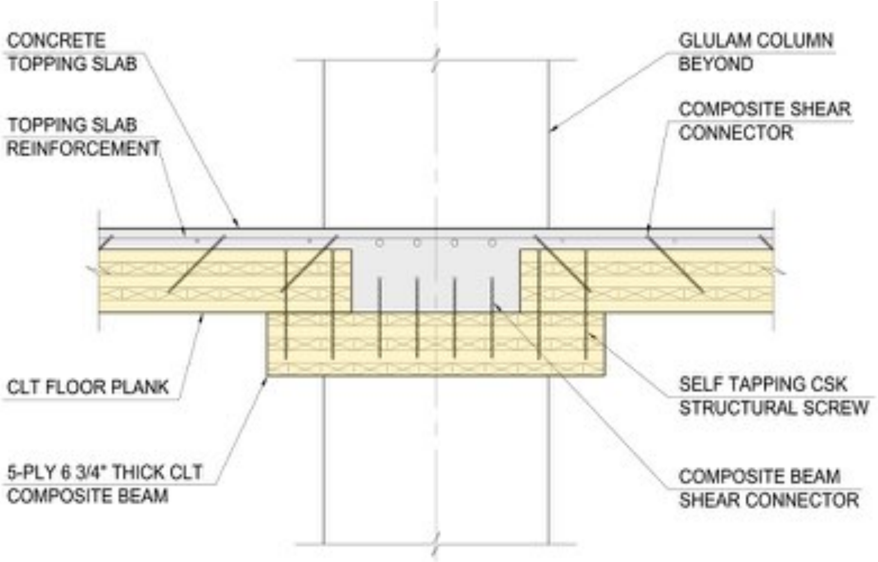


proprietary mesh connector
epoxied into CLT

Images source: SOM

Images source: Setragian/Kusuma

Composite Construction



Images source: SOM

Mass Timber Design

Design Considerations – In-Plane and Out-of-Plane

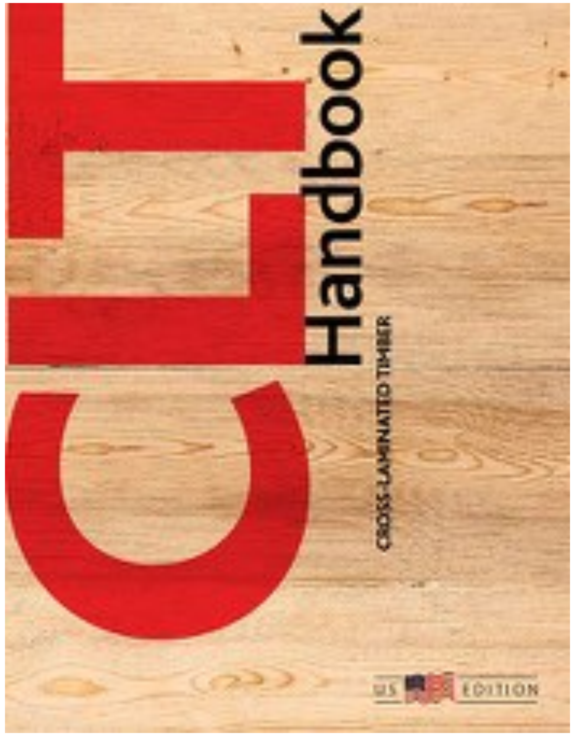
- Bending Strength
- Shear Strength

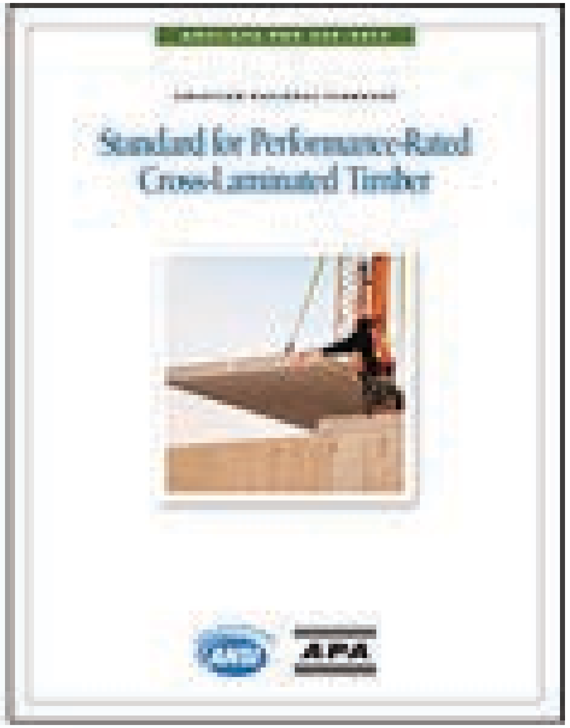
strength

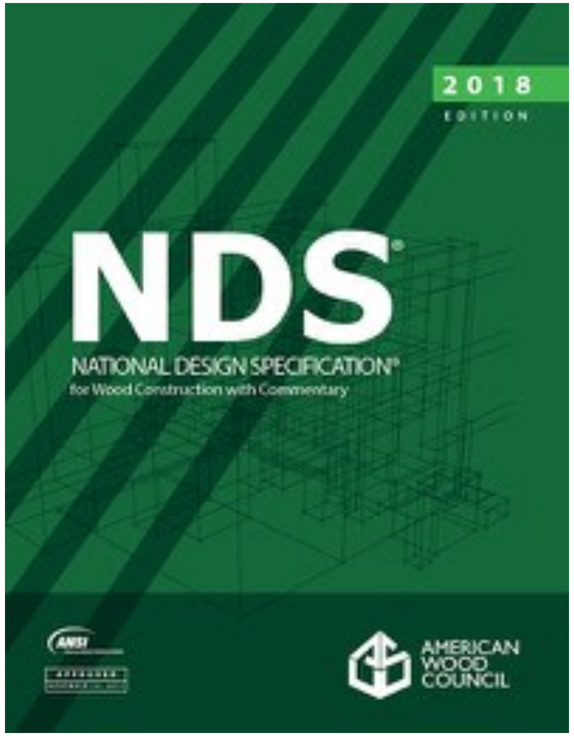
- Bending Stiffness
- Shear Stiffness
- Vibration

serviceability

Mass Timber Design Guides







Images source: CLT Handbook, PRG 320-2018, AWC NDS

Common CLT Layups

3-ply 3 layer
(3.43”-4.14”)

5-ply 5 layer
(5.47”-6.90”)

5-ply 3 layer
(5.47”-6.90”)

7-ply 7 layer
(7.52”-9.66”)

7-ply 5 layer
(7.52”-9.66”)

9-ply 9 layer
(9.57”-12.42”)

9-ply 7 layer
(9.57”-12.42”)

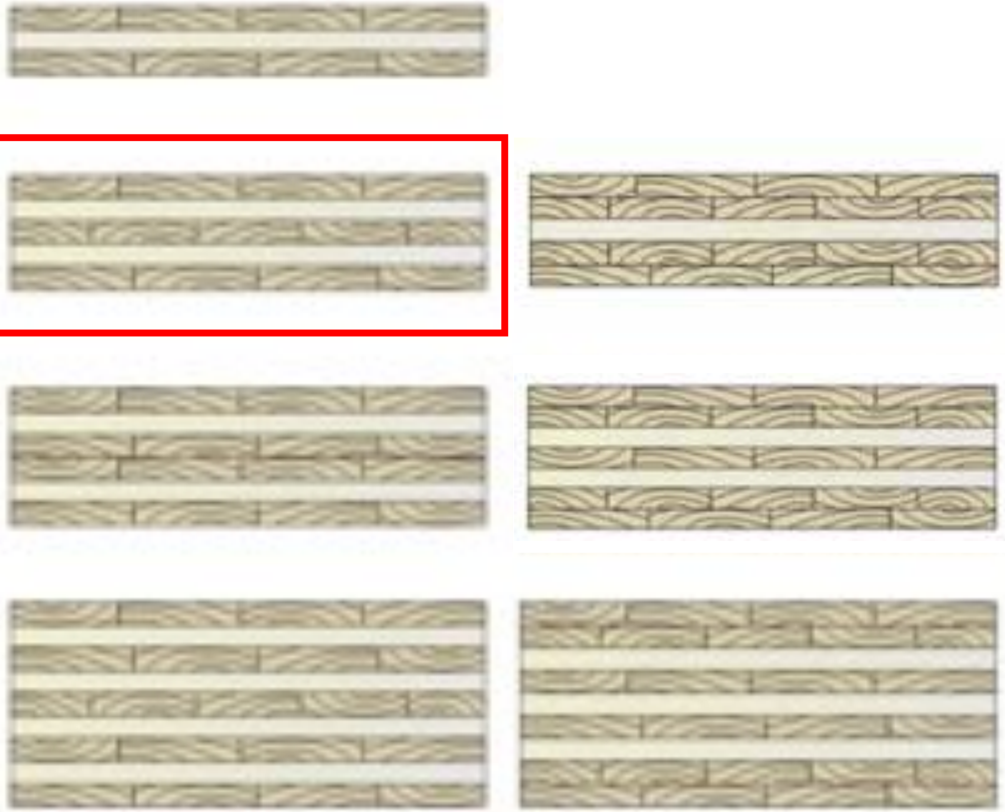


Figure 2
Examples of CLT panel cross-sections

Images source: PRG 320-2018

CLT Stress Grades

Stress Grade	Major Axis	Minor Axis
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
V1	#2 Doug Fir Larch	#3 Doug Fir Larch
V2	#1/#2 Spruce Pine Fir	#3 Spruce Pine Fir
V3	#2 Southern Pine	#3 Southern Pine

CLT Stress Grades

TABLE A1

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

CLT Layup	Laminations Used in Major Strength Direction						Laminations Used in Minor Strength Direction					
	F_b (psi)	E^d (10^6 psi)	F_t (psi)	F_c (psi)	F_v (psi)	F_s (psi)	F_b (psi)	E^d (10^6 psi)	F_t (psi)	F_c (psi)	F_v (psi)	F_s (psi)
E1	1,950	1.7	1,375	1,800	135	45	500	1.2	250	650	135	45
E2	1,650	1.5	1,020	1,700	180	60	525	1.4	325	775	180	60
E3	1,200	1.2	600	1,400	110	35	350	0.9	150	475	110	35
E4	1,950	1.7	1,375	1,800	175	55	450	1.3	250	725	175	55
V1	900	1.6	575	1,350	180	60	525	1.4	325	775	180	60
V2	875	1.4	450	1,150	135	45	500	1.2	250	650	135	45
V3	750	1.4	450	1,250	175	55	450	1.3	250	725	175	55

For SI: 1 psi = 0.006895 MPa

a. See Section 4 for symbols.

b. Tabulated values are ASD reference design values and not permitted to be increased for the lumber size and flat use adjustment factors in accordance with the NDS. The design values shall be used in conjunction with the section properties provided by the CLT manufacturer based on the actual layup used in manufacturing the CLT panel (see Table A2).

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

d. The tabulated E values are published E for lumber. For calculating the CLT design properties shown in Table A2, the transverse E of the lamination is assumed to be E/30, the longitudinal G of the lamination is assumed to be E/16, and the transverse G of the lamination is assumed to be longitudinal G/10.

Images source: PRG 320-2018

CLT Supply Options

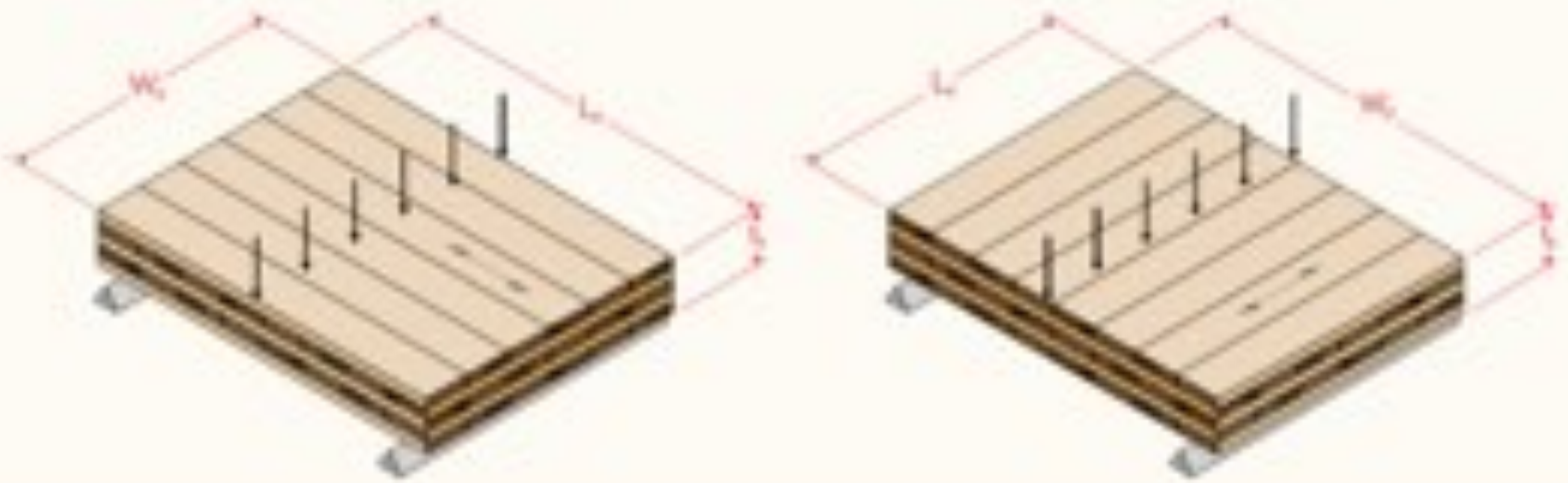
Suppliers	Location	Panel Length (ft)	Panel Width (ft)	Grades	Availability
Structurlam	British Columbia	40	8, 10	V2, E1	Available
Nordic	Quebec	64	8	E1	Available
DR Johnson	Oregon	42	8, 10	E2, V1	Available
International Beam	Alabama	52.5	8, 10, 12	V3	Available
Smartlam	Montana	40/64	8, 10	V4	Available
KLH	Austria	38	7.33		Available
Binderholz	Austria	38	11.5	Spruce, E1, V2	Available
StructureCraft	British Columbia	60	8, 10, 12		Available
Katerra	Washington	60	12	E1, V2	Available
Vaagen	Washington	60	4	E2, V1	Available
Freres (MPP)	Oregon	48	12	E2	Available
Kalesnikoff	British Columbia	-	-	-	Available 2020
Ligna Terra	Maine	-	-	-	Available 2022?

Image info: Chris Minerva, Ricky McLain

Flatwise Panel Loading

FIGURE 2

FLATWISE BENDING IN THE MAJOR (LEFT) AND MINOR (RIGHT) CLT STRENGTH DIRECTIONS



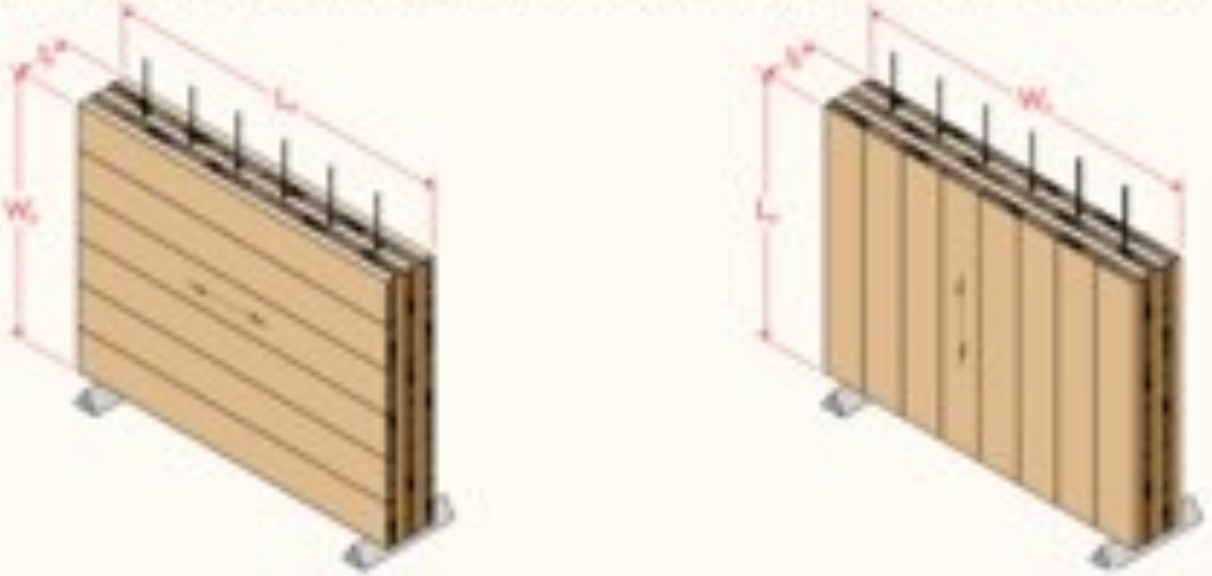
MAJOR **MINOR**

Images source: PRG 320-18

Edgewise Panel Loading

FIGURE 1

EDGEWISE BENDING IN THE MAJOR (LEFT) AND MINOR (RIGHT) CLT STRENGTH DIRECTIONS



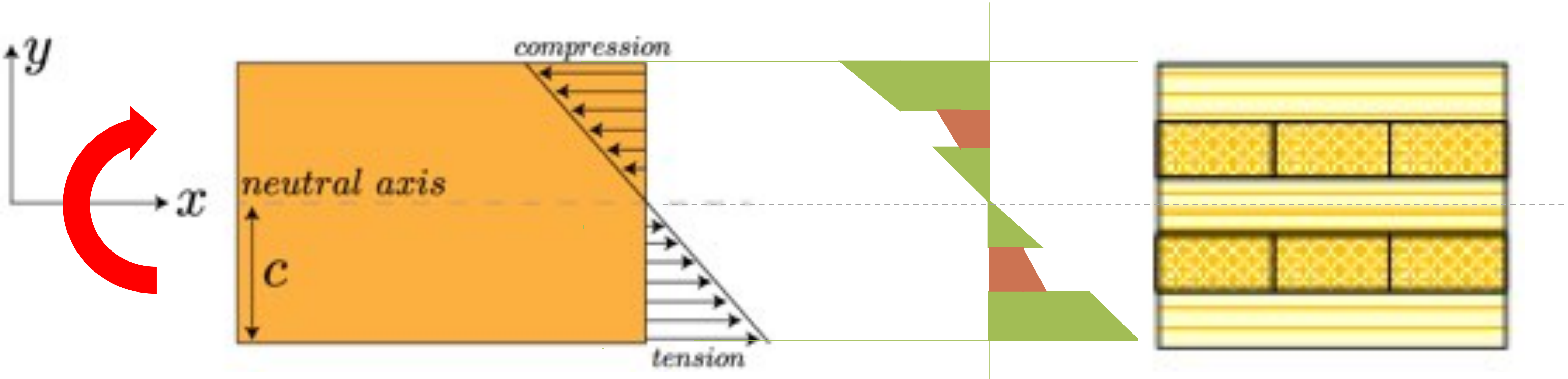
Images source: PRG 320-18

Bending Members- Flexure (out of plane)

PRG 320- calculates capacity using extreme fiber capacity approach

From Strength of Materials/Engineering Mechanics, we know

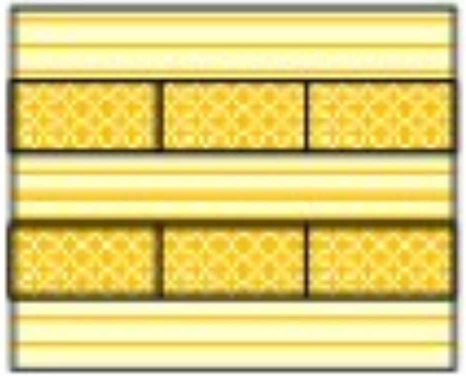
$$F_b = \frac{Mc}{I} \qquad S = \frac{I}{c} \qquad M = F_b\, S \qquad M_b \le (F_b S_{eff})'$$

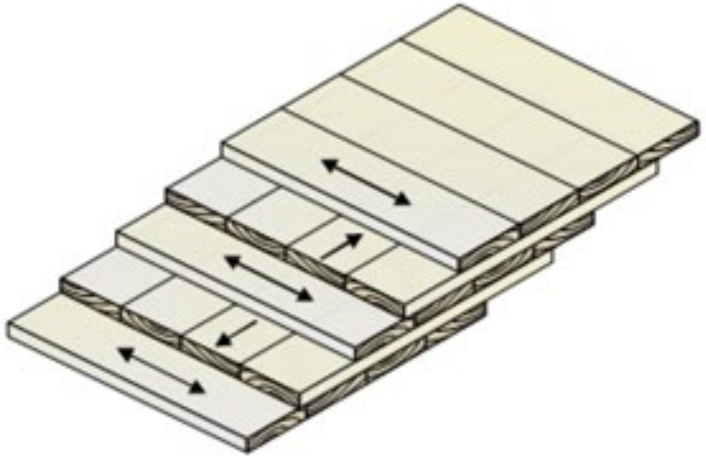


Homogeneous, isotropic material

Non-homogeneous, anisotropic material

Bending Members- Flexure (out of plane)





Flexural Capacity Check:

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

M_b = applied bending moment

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

S_{eff} = effective section modulus

F_b = reference bending design stress of outer lamination

$$S_{eff} = \frac{2EI_{eff}}{E_1 h}$$

where:

EI_{eff} = Effective bending stiffness

E_1 = Modulus of elasticity of outermost layer

h = Entire thickness of panel

Image & Reference: CLT Handbook

Bending Members- Flexure (out of plane)

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

Table 3
Parallel axis theorem calculations for EI_{eff}

Layer	E (x 10⁶ psi)	z (in.)	$Ebh^3/12$ (lb.-in.²)	EAz^2 (lb.-in.²)	Sum of Layer
1	1.7	2.75	4.4	212.1	216.5
2	1.2/30=0.04	1.375	0.1	1.2	1.4
3	1.7	0.0	4.4	0.0	4.4
4	0.04	1.375	0.1	1.2	1.4
5	1.7	2.75	4.4	212.1	216.5
				Total	**440**

Images source: CLT Handbook, Chapter 3, page 16

Bending Members- Flexure (out of plane)

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.

Note A1. The rounding rules in Table A2 are as follows:

F_bS (lbf-ft/ft) and V_s (lbf/ft)—Nearest 25 for values greater than 2,500, nearest 10 for values between 1,000 and 2,500, or nearest 5 otherwise.

EI (lbf-in.^{2}/ft) and GA (lbf/ft)—Nearest 10^6 for values greater than 10^7, nearest 10^5 for values between 10^6 and 10^7, or nearest 10^4 otherwise.

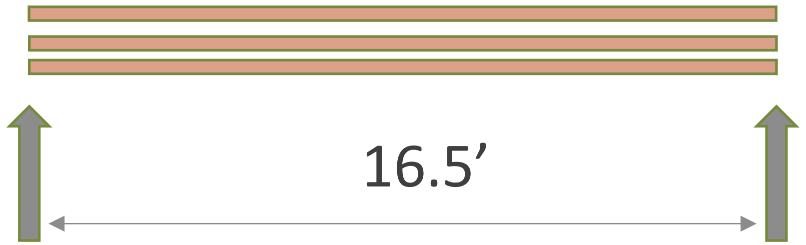
Images source: PRG 320-2018

Bending Members- Flexure Design Example

Given:

16.5 ft span

38 psf dead load, 40 psf live load



Assume:

one span along major axis of CLT

Analysis based on 1 ft width

Calculate:

ASD dead + live load applied moment

$$\mathbf{M_b = wL^2/8 = (38+40\ psf)\ (16.5\ ft)^2/8 = 2{,}655\ lb\text{-}ft/ft}$$

Reference: CLT Handbook

Bending Members- Flexure Design Example

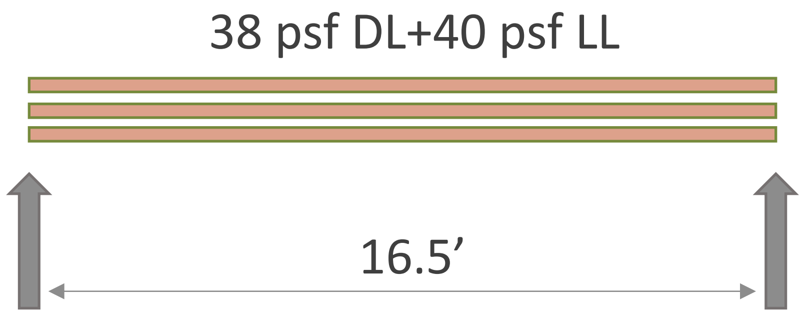
CLT GRADE	MAJOR LAYER	WEIGHT (lbs/ft²)	MAJOR STRENGTH DIRECTION					MINOR STRENGTH DIRECTION				
			$F_bS_{eff,0}$ (lbs-ft/ft)	$EI_{eff,0}$ (10^6 lbs-in²/ft)	$GA_{eff,0}$ (10^6 lbs/ft)	$M_{allow,0}$ (lbs-ft/ft)	$V_{allow,0}$ (lbs/ft)	$F_bS_{eff,90}$ (lbs-ft/ft)	$EI_{eff,90}$ (10^6 lbs-in²/ft)	$GA_{eff,90}$ (10^6 lbs/ft)	$M_{allow,90}$ (lbs-ft/ft)	$V_{allow,90}$ (lbs/ft)
V2.1	87 V	7.5	1444	56	0.5	1444	1220	37	0.4	0.30	32	240
	139 V	11.9	3329	206	1.0	3329	1770	537	21	0.60	457	850
	191 V	16.3	5917	503	1.4	5917	2290	1216	83	0.91	1034	1080
	243 V	20.8	9212	995	1.9	9219	2800	2133	209	1.20	1814	1320
V2M1.1	105 V	9.0	2042	96	0.5	2042	1440	277	3.7	0.53	235	495
	175 V	15.0	4701	[illegible]	1.1	4701	[illegible]	2403	96	1.10	2042	1440
	245 V	21.0	8315	906	1.6	8315	2500	5531	366	1.60	4701	1970
	315 V	27.0	12896	1806	2.1	12896	3025	9782	906	2.10	8315	2470

Choose 5-ply 6 7/8" (175mm) thick V2 panel,
$F_bS_{eff,0}$ = 4,701 lb-ft/ft

Reference: Structurlam Design Guide

Bending Members- Flexure Design Example

$M_b \leq (F_b S_{eff})'$ ← **Adjusted Bending Strength**



$M_b \leq \underbrace{C_D\, C_M\, C_t\, C_L}_{\text{Per NDS}} (F_b S_{eff})$

M_b = 2,655 lb-ft/ft $\leq$ (1.0) (1.0) (1.0) (1.0) 4,701 lb-ft/ft

M_b = 2,655 lb-ft/ft $\leq$ 4,701 lb-ft/ft

Flexure Strength is OK!

Flatwise Shear Strength

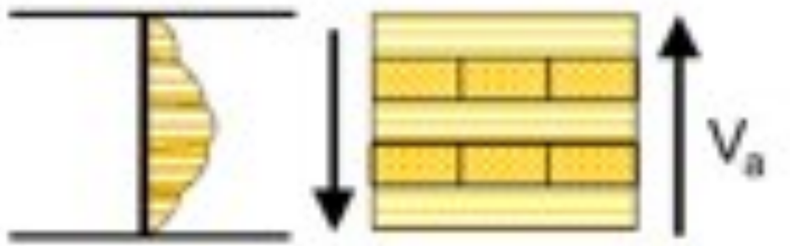
Design Properties based on Extreme Fiber Model:

Shear Capacity Check:

$V_a \leq F_s(Ib/Q)_{eff}'$

V_a = applied shear

$F_s(Ib/Q_{eff})'$ = adjusted shear strength



Shear Stress

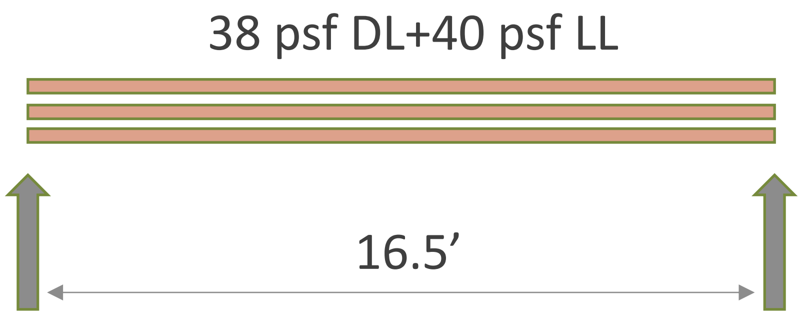
From Strength of Materials

$v_s = \dfrac{V\,Q}{I\,t}$ $\qquad$ $V = \dfrac{v_s\,I\,t}{Q}$

Reference: CLT Handbook, Images source: Scott Breneman, PE

Flatwise Shear Strength

$$(Ib/Q)_{eff} = \frac{EI_{eff}}{\sum_{i=1}^{n/2} E_i h_i z_i}$$



Non-homogeneous, anisotropic material

where:

EI_{eff} = Effective bending stiffness

E_i = Modulus of elasticity of an individual layer

h_i = Thickness of an individual layer, except the middle layer, which is half its thickness

z_i = Distance from the centroid of the layer to the neutral axis, except for the middle layer, where it is to the centroid of the top half of that layer.

Reference: NDS / CLT Handbook

Flatwise Shear Strength

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

where:

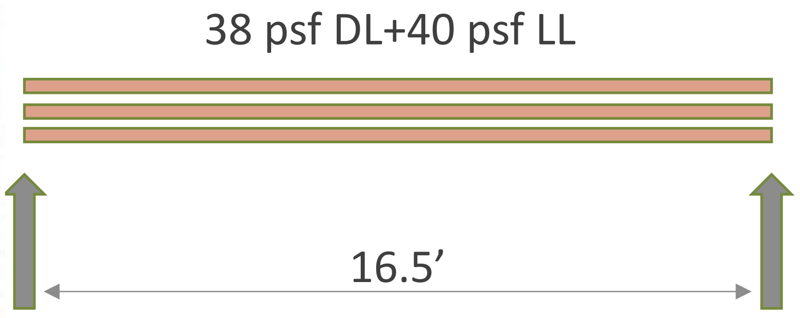
V_{planar} = induced shear due to loads

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

$$V_{planar} \le C_d C_m C_t (F_s(IbQ)_{eff})$$

Flatwise Shear Strength

CLT GRADE	MAJOR LAYER	WEIGHT (lbs/ft²)	MAJOR STRENGTH DIRECTION					MINOR STRENGTH DIRECTION				
			$F_bS_{eff,0}$ (lbs-ft/ft)	$EI_{eff,0}$ (10^6 lbs-in²/ft)	$GA_{eff,0}$ (10^6 lbs/ft)	$M_{allow,0}$ (lbs-ft/ft)	$V_{allow,0}$ (lbs/ft)	$F_bS_{eff,90}$ (lbs-ft/ft)	$EI_{eff,90}$ (10^6 lbs-in²/ft)	$GA_{eff,90}$ (10^6 lbs/ft)	$M_{allow,90}$ (lbs-ft/ft)	$V_{allow,90}$ (lbs/ft)
V2.1	87 V	7.5	1444	56	0.5	1444	1220	37	0.4	0.30	32	240
	139 V	11.9	3329	206	1.0	3329	1770	537	21	0.60	457	850
	191 V	16.3	5917	503	1.4	5917	2290	1216	83	0.91	1034	1080
	243 V	20.8	9212	995	1.9	9219	2800	2133	209	1.20	1814	1320
V2M1.1	105 V	9.0	2042	96	0.5	2042	1440	277	3.7	0.53	235	495
	175 V	15.0	4701	366	1.1	4701	1980	[illegible]	96	1.10	2042	1440
	245 V	21.0	8315	906	1.6	8315	2500	5531	366	[illegible]	[illegible]	1970
	315 V	27.0	12896	1806	2.1	12896	3025	9782	906	2.10	8315	2470



R = 644 lb

Choose 5-ply 6 7/8” (175mm) thick V2 panel

V_{allow} = 1,980 lb > 644 lb OK!

Reference: Structurlam Design Guide

Flatwise Flexural Stiffness (Deflection)

- Bending Stiffness
- Shear Stiffness

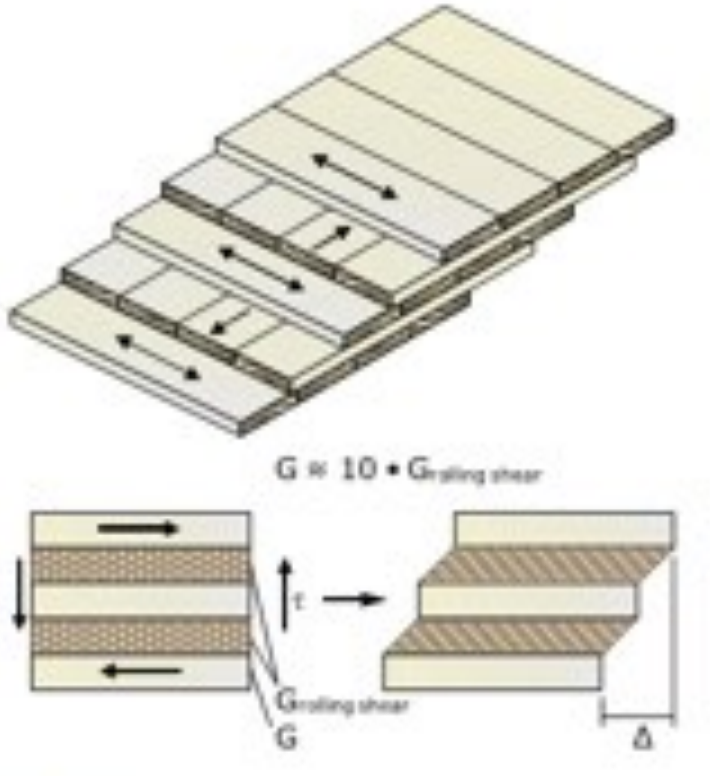
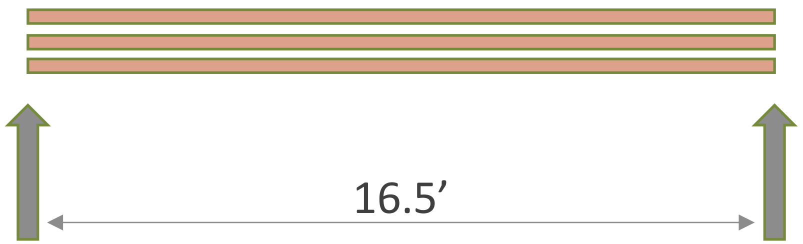


Figure 1
Rolling shear deformation of a 5-layer CLT panel



R = 644 lb

G = Shear Modulus

Reference: CLT Handbook

Flatwise Flexural Stiffness (Deflection)

Using Shear Analogy Method

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

Because Shear deflections can be a significant in CLTs, adjust the effective bending stiffness to an apparent bending stiffness.

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

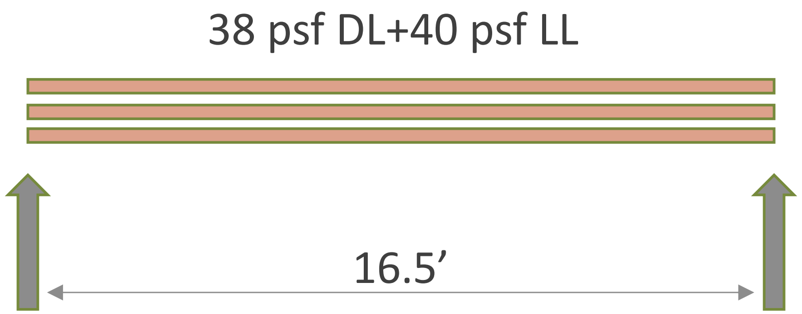
K_s = constant based on loading and end conditions per Table 2, Chapter 3 CLT Handbook (simple, pinned K_s = 11.5)

Images source: CLT Handbook

Deflection Under Long-Term Loading

Design Example

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



Δ_{DL} = from 38 psf = 0.19 in

Δ_{LL} = from 40 psf = 0.20 in

Δ_{max} = (.19) + (.20) = 0.39 in (L/507)

reference: CLT Handbook Chapter 3

Deflection Under Long-Term Loading

$$\Delta_T = K_{cr}\,\Delta_{LT} + \Delta_{ST}$$

K_{cr} = Time Dependent Creep Factor, 2.0 for dry service CLT

Δ_{LT} = Immediate Deflection Due to Long Term Component of load

Δ_{ST} = Deflection due to Short Term or Normal Component of load

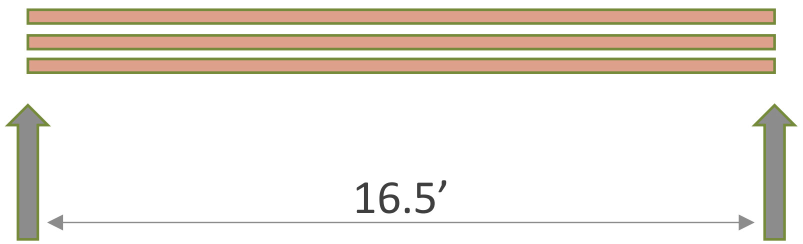
$$\Delta_T = 2.0\,(\Delta_{LT}) + (\Delta_{ST})$$

Images source: CLT Handbook Chapter 6

Deflection Under Long-Term Loading

Design Example

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



Δ_{LT} = from 38 psf = 0.19 in

Δ_{ST} = from 40 psf = 0.20 in

Δ_{total} = 2.0 (0.19) + (0.20) = 0.58 in (L/341)

Images source: CLT Handbook Chapter 6

Floor Vibration

Occupant perception of vibration is significant design consideration,
Human sensitivity to vibration @ frequency between 4 – 8Hz

Natural Frequency not best measure of vibration performance; accelerations felt is better measure but difficult to calculate accurately given the variability of inputs esp, damping

Vibration response to footfall is dependent on natural frequency and damping

Mass Timber Floors – 2.5% to 3.5% modal damping

Ignore composite action of concrete topping unless floor designed and detailed as such

Simplified Analysis per CLT Handbook, AISC Design Guide 11, CSA 086 Annex A, ISO 10137

Floor Vibration

Human sensitivity to Vibration - frequency between 4 – 8Hz

`

One approach: US CLT Handbook, Chapter 7 (FPI Method)

Calculated natural frequency of simple span of bare CLT:

$$f = \frac{2.188}{2L^2}\sqrt{\frac{EI_{app}}{\rho A}}$$

Where:

EI_{app} = apparent stiffness for 1 foot strip, pinned supported, uniformly loaded, simple span (K_s = 11.5) (lb-in^2)

ρ = specific gravity of the CLT

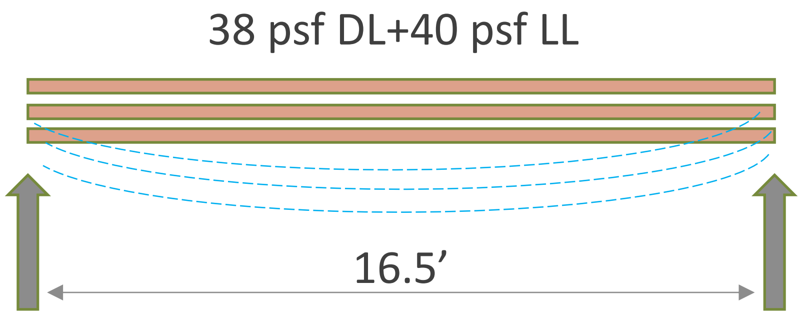
A = the cross section area (thickness x 12 inches) (in^2)

Images source: Scott Breneman, PE, reference CLT Handbook Chapter 7

Floor Vibration – Span Limitations

Human sensitivity to Vibration - frequency between 4 – 8Hz

FPI Method Floor Span Limitations



Frequency f > 9.0 Hz

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

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

<u>Using Spreadsheet and Iterate</u>

1. Estimate L
2. Calculate EI_{app}
3. Calculate L limit
4. Repeat until convergence

reference: CLT Handbook Chapter 7

Floor Vibration Controlled Span - Example

- Grade = E1
- Thickness = 6 7/8 in. (0.175 m)
- Specific gravity = 0.56 (560.66 kg/m³)
- EI_{eff} = 440 x 10^6 lb.-in.²/ft. (4.140 x 10^6 N-m²/m)
- GA_{eff} = 0.92 x 10^6 lb./ft. (1.343 x 10^7 N/m)
- l = vibration controlled span (ft.)

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

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

Table 5
Excel calculation for the example

Thickness (in.)	Trial Span (ft.)	EI_{eff} ($\times 10^6$ lb.-in.²/ft.)	GA_{eff} ($\times 10^6$ lb./ft.)	EI_{app} Equation [5] ($\times 10^6$ lb.-in.²/ft.)	Specific Gravity	New Span Equation [4] (ft.)
6.875	17.188	440	0.92	389.5	0.56	17.10
6.875	17.100	440	0.92	389.1	0.56	17.09
6.875	17.090	440	0.92	389.0	0.56	17.09

reference: CLT Handbook Chapter 7

FPI Vibration Span Limits for Std Grades / Layups

Grade	Layup	Thickness	FPI Span Limit
E1	3ply	4 1/8"	12' 5"
	5ply	6 7/8"	17' 4"
	7ply	9 5/8"	21' 8"
E2	3ply	4 1/8"	12' 0"
	5ply	6 7/8"	16' 8"
	7ply	9 5/8"	20' 10"
E3	3ply	4 1/8"	11' 7"
	5ply	6 7/8"	16' 1"
	7ply	9 5/8"	20' 1"
E4	3ply	4 1/8"	12' 2"
	5ply	6 7/8"	17' 0"
	7ply	9 5/8"	21' 3"

Grade	Layup	Thickness	FPI Span Limit
V1	3ply	4 1/8"	12' 2"
	5ply	6 7/8"	17' 0"
	7ply	9 5/8"	21' 3"
V2	3ply	4 1/8"	11' 11"
	5ply	6 7/8"	16' 8"
	7ply	9 5/8"	20' 10"
V3	3ply	4 1/8"	12' 0"
	5ply	6 7/8"	16' 9"
	7ply	9 5/8"	21' 0"

- These are approximate only!
- Verify based on manufactures properties
- Verify based on project specifics
- Check strength and deflection

reference: Woodworks

Floor Vibration

4.4 CLT Floor with a Heavy Topping [>20 lb./ft.^{2} (100 kg/m^2)]

It is known that without a suspended ceiling, a heavy topping is normally necessary for CLT floor to achieve the satisfactory airborne and impact sound insulation. The heavy topping adds significant mass to the floor system, and reduces the fundamental natural frequency to below 9 Hz. Based on the experience of the authors, even though the topping increases the floor stiffness, the low first natural frequency makes the floor susceptible to annoying vibrations (Hu, 2007). For lightweight wood-joisted floor systems, the design method requires to reduce the spans of the joisted floors after a heavy cementitious topping is added (Hu, 2007). A similar approach should be applied to CLT floors with a heavy topping. As an interim measure, it is recommended that the span be calculated using equation [4] for vibration controlled design of such heavy topping CLT floor system, assuming the bare CLT floor mass and stiffness be reduced by 10%. This interim recommendation will be further refined through laboratory study.

Recommendation seems conservative

Mass Timber Floor Vibration Guide coming 2020 – more specific design info

reference: CLT Handbook Chapter 7

Two-Way Action

Flexure

- Manufactures provide flexure and shear capacity in both major axis
- NDS 2018 Chapter 10 (CLT) - Adjustment factors to check capacity against the design code using ASD / LRFD design checks
- NDS 2018 C3.9.2-2 could check the combined loading condition - very conservative approach
- Laminations in orthogonal directions share load based upon their relative stiffness
- Treat the major / minor direction flexural and shear checks independently. This is the common state of practice in European design

Two-Way Action

Bearing Capacity at Supports

NDS 2018 Chapter 10 includes design provisions for the bearing capacity of CLT panels to loads on the surface

Local Punching Shear at Supports

This limit state is critical for point supported CLT panels.

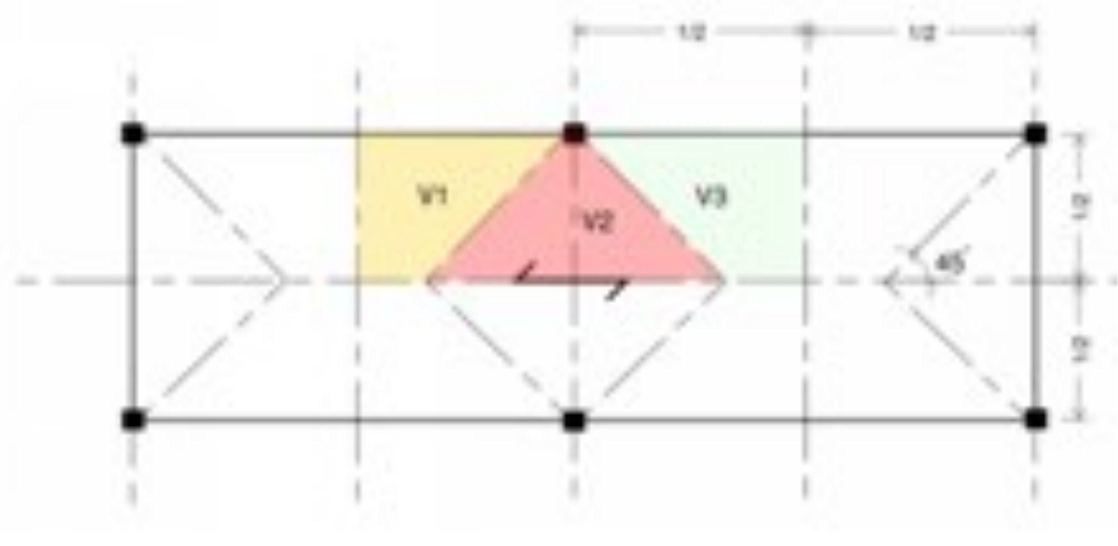


Figure 5: Plan View of CLT Panel – Shear Approximation

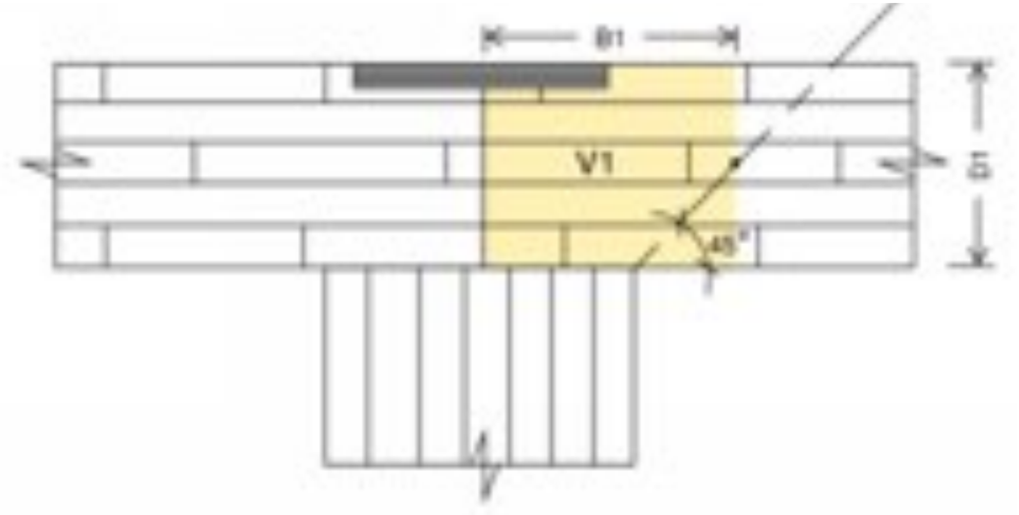
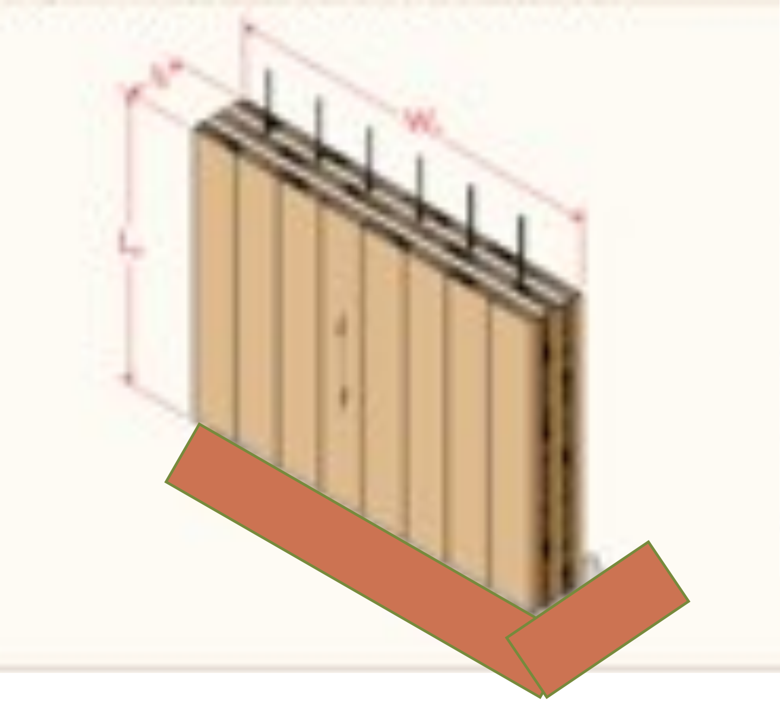


Figure 6: V1 or V3 Shear Area

Image: Gafner, Jackson WCTE 2016

Bearing Walls



$$P_{parallel} \leq F'_c A_{parallel}$$

where:

$P_{parallel}$ = Load applied parallel to the direction of the fibers
F_c' = Adjusted compression strength
$A_{parallel}$ = Area of layers with fibers running parallel to the direction of the load

$$F_c' A_{parallel} = F_c^* A_{parallel} = F_c C_p A_{parallel}$$

Image: PRG 320-2018

Bearing Walls

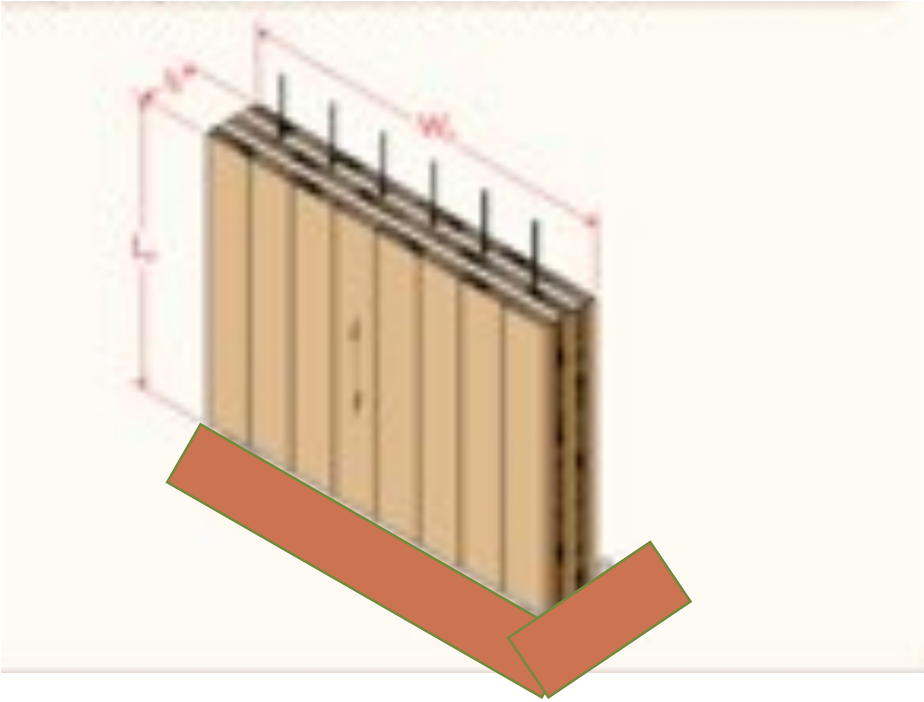


Image: PRG 320-2018

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

where:

F_c^* = reference compression design value parallel to grain multiplied by all applicable adjustment factors except C_P (see 2.3), psi

$$F_{cE} = \frac{0.822\ E_{min}'}{(\ell_e/d)^2}$$

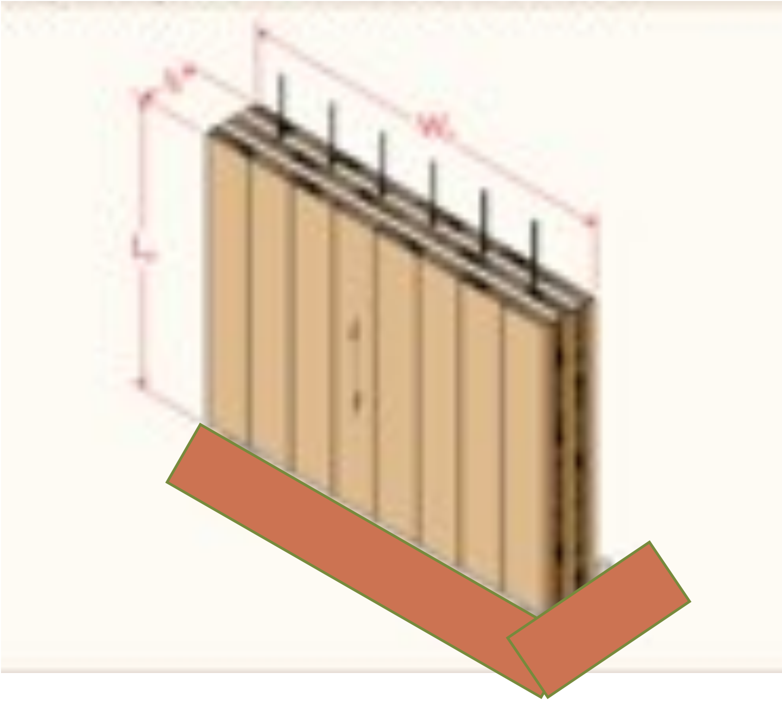
c = 0.8 for sawn lumber

c = 0.85 for round timber poles and piles

c = 0.9 for structural glued laminated timber, structural composite lumber, and cross-laminated timber

Source: NDS 2018

Bearing Walls



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

where:

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

c = 0.9 for CLT

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

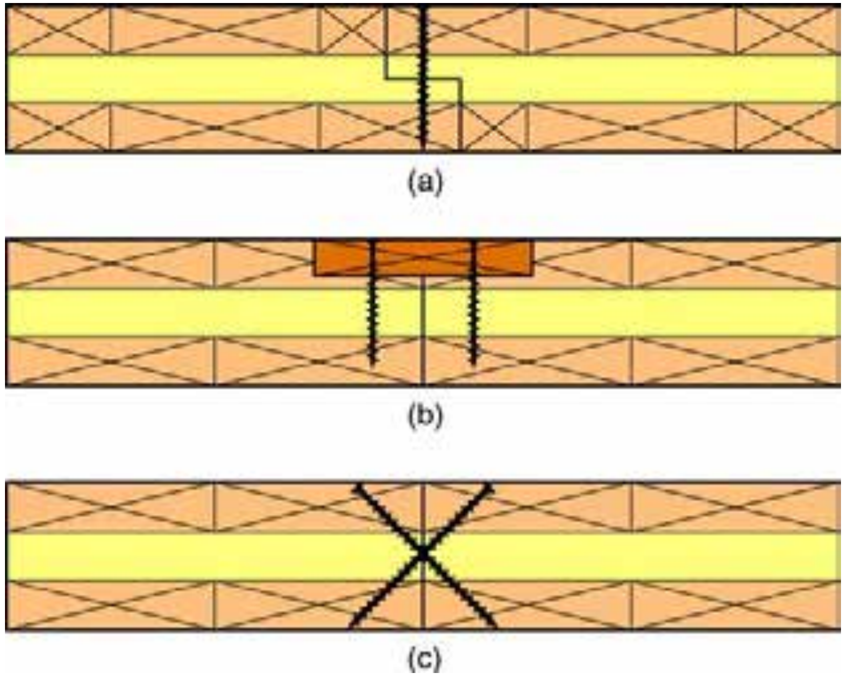
$$EI_{app\text{-}min} = 0.5184\ EI_{app}$$

$$P_{parallel} \leq P_c C_p A_{parallel}$$

Source: PRG 320-2018

Connections

Panel to Panel at floors, walls and roof



Proposed Design

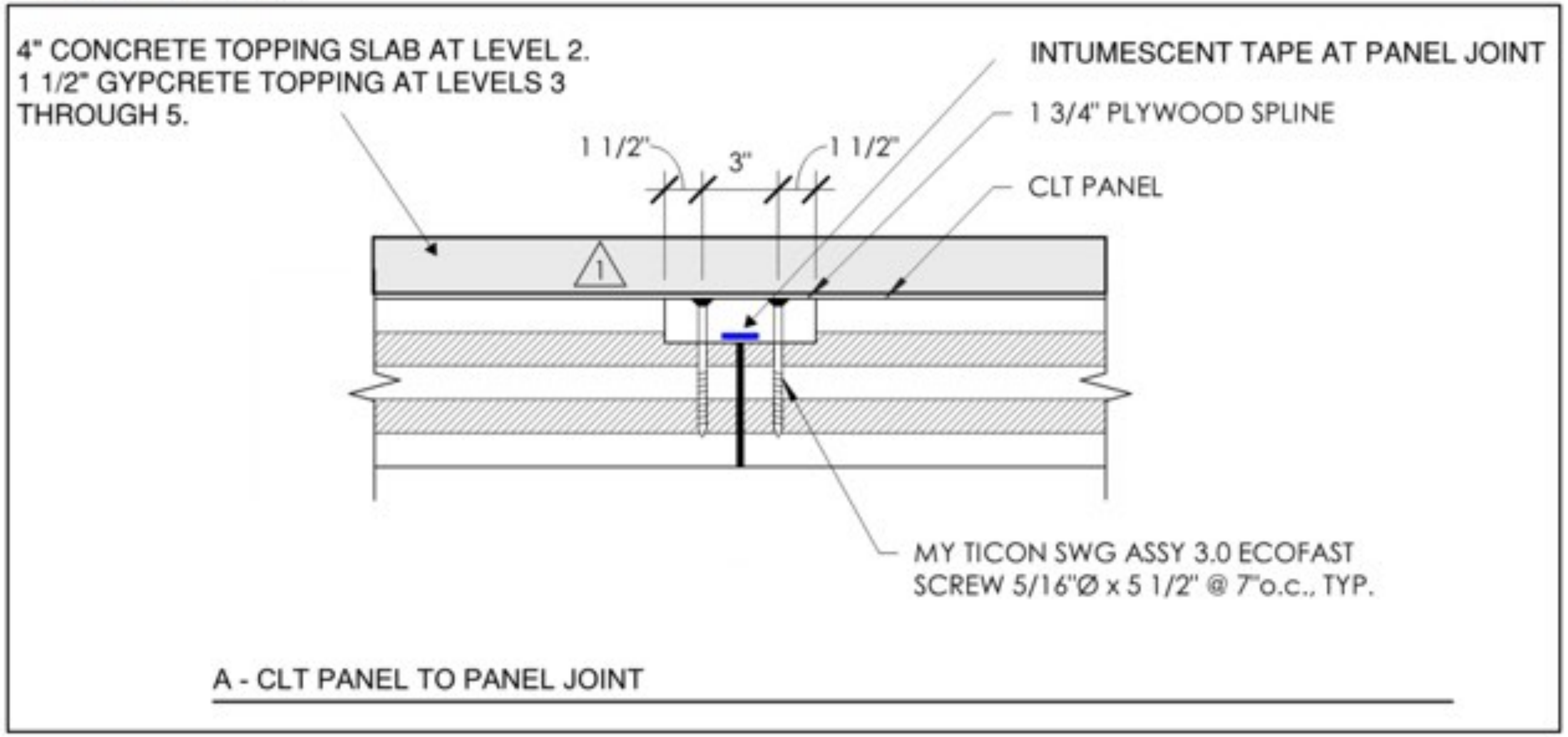
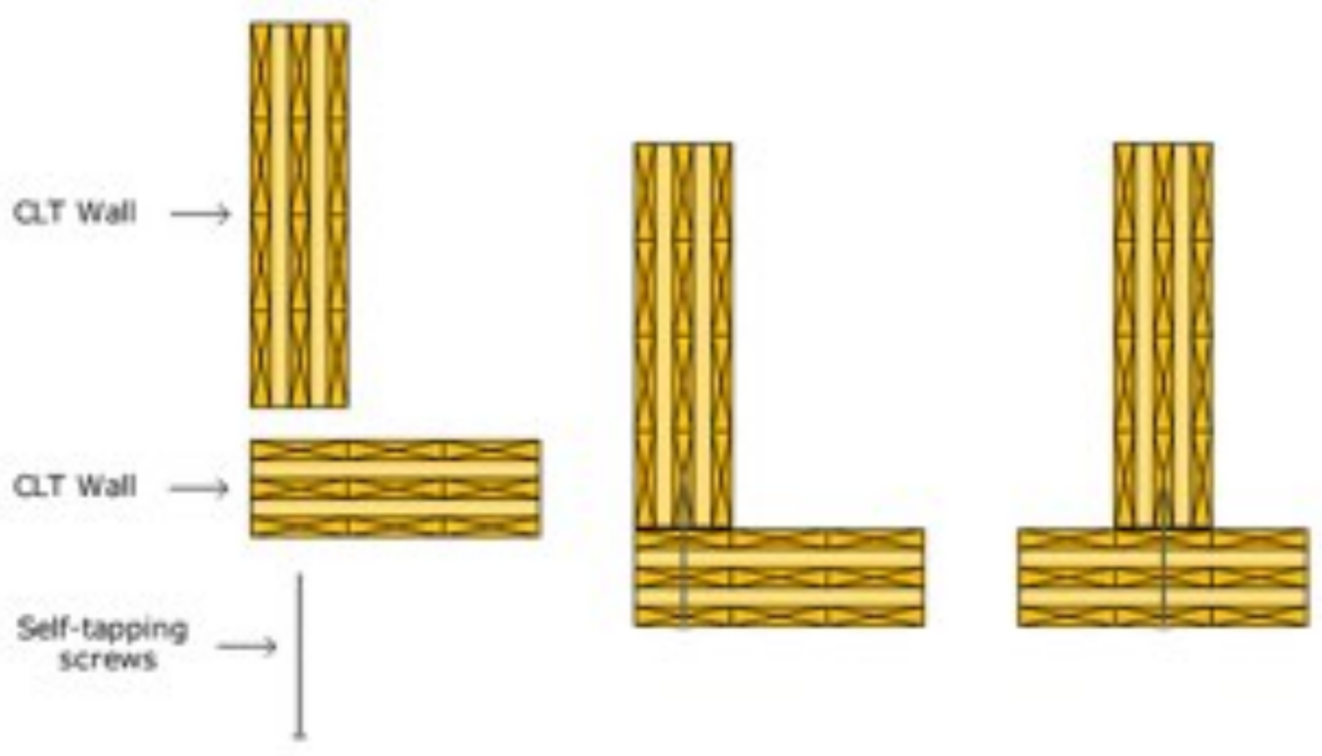


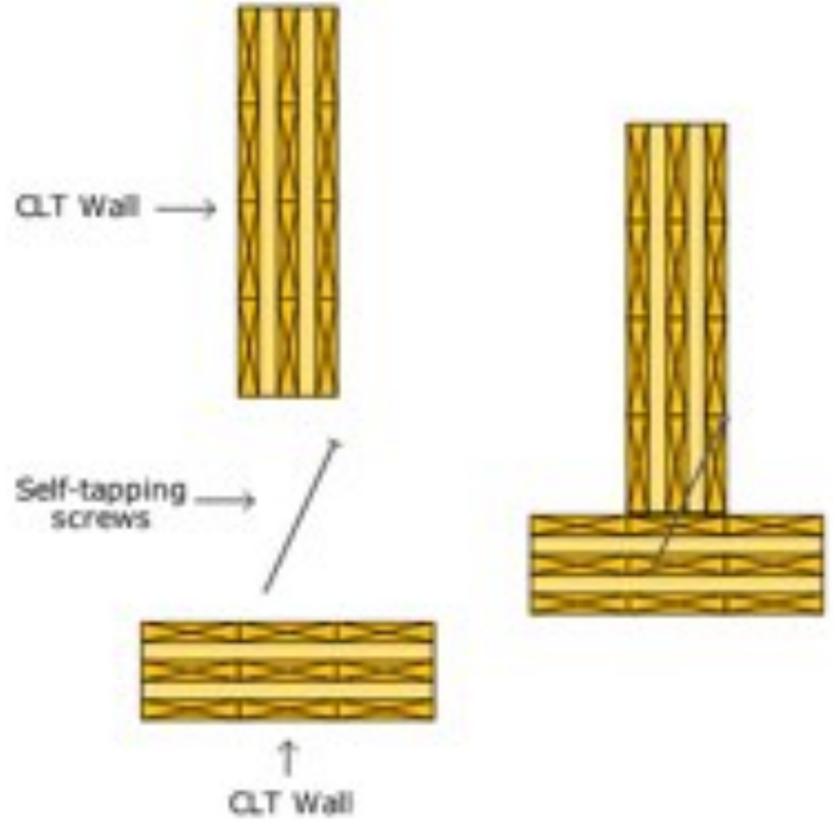
Image: Code Unlimited-Block 76W CLT Connections Engineering Judgement Report

Connections

Wall to Wall



End Screw

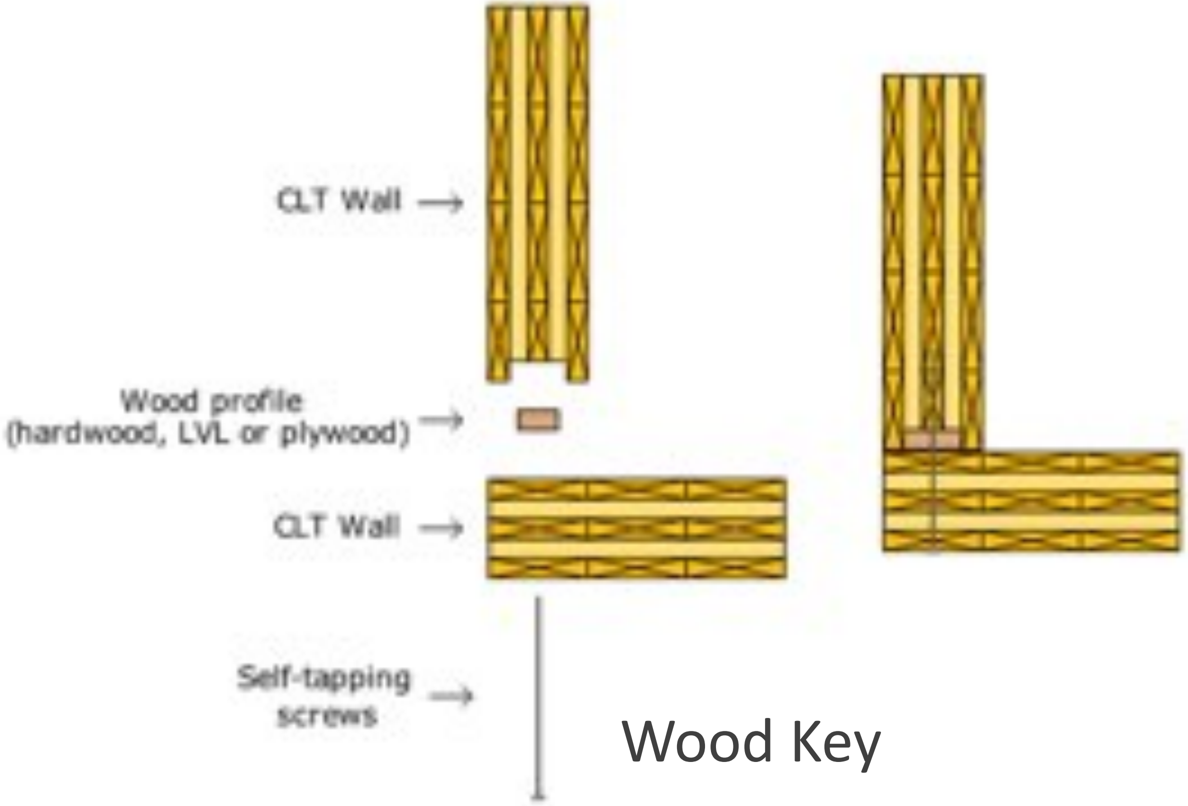


Toe Screw

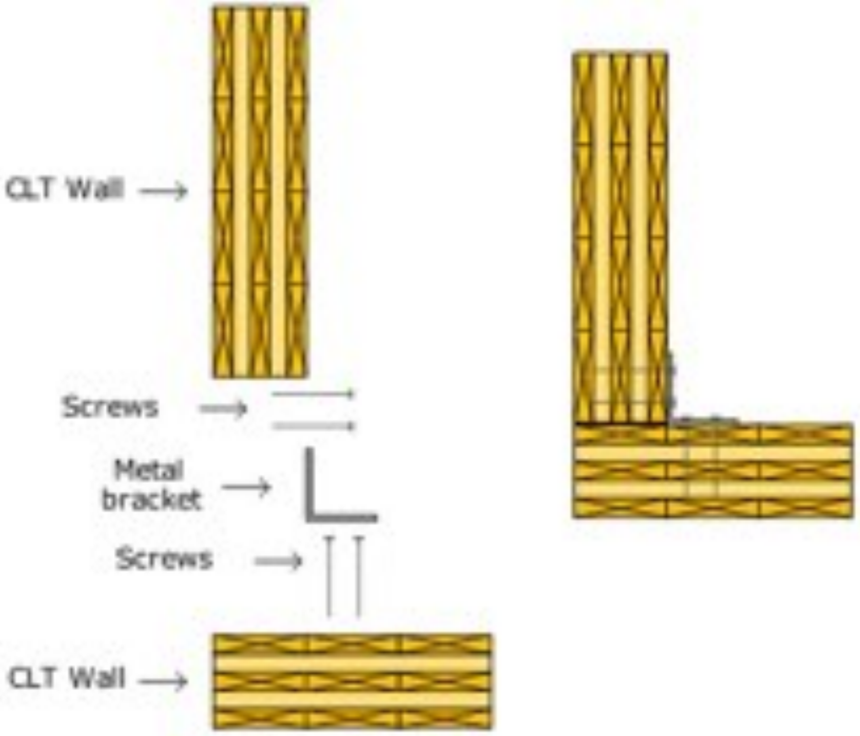
Image: CLT Handbook Chapter 5

Connections

Wall to Wall



Wood Key

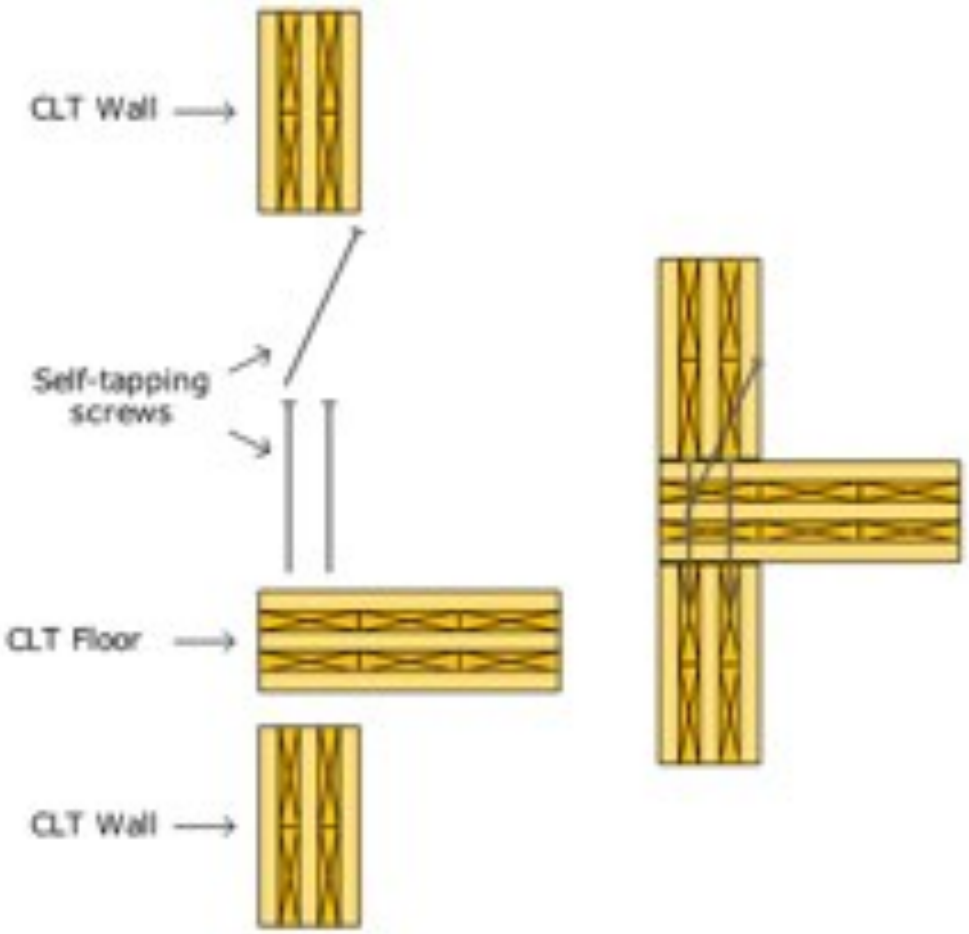


Steel Bracket

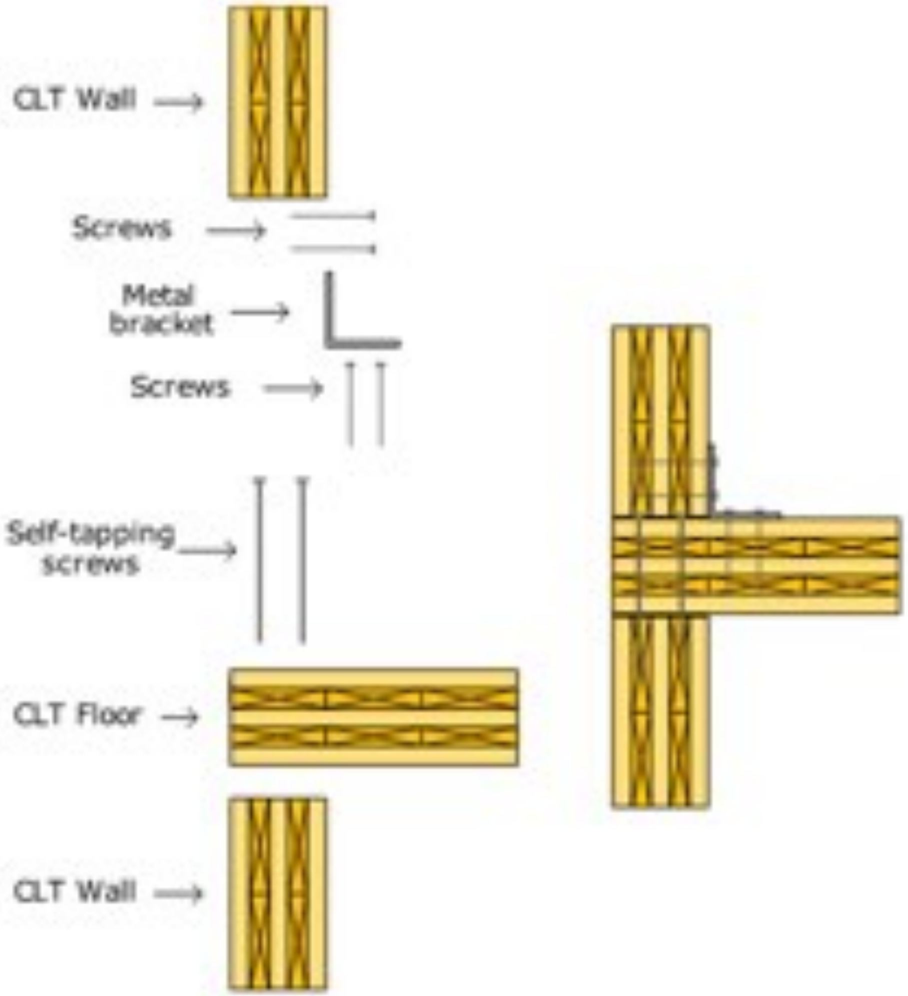
Image: CLT Handbook Chapter 5

Connections

Wall to Wall



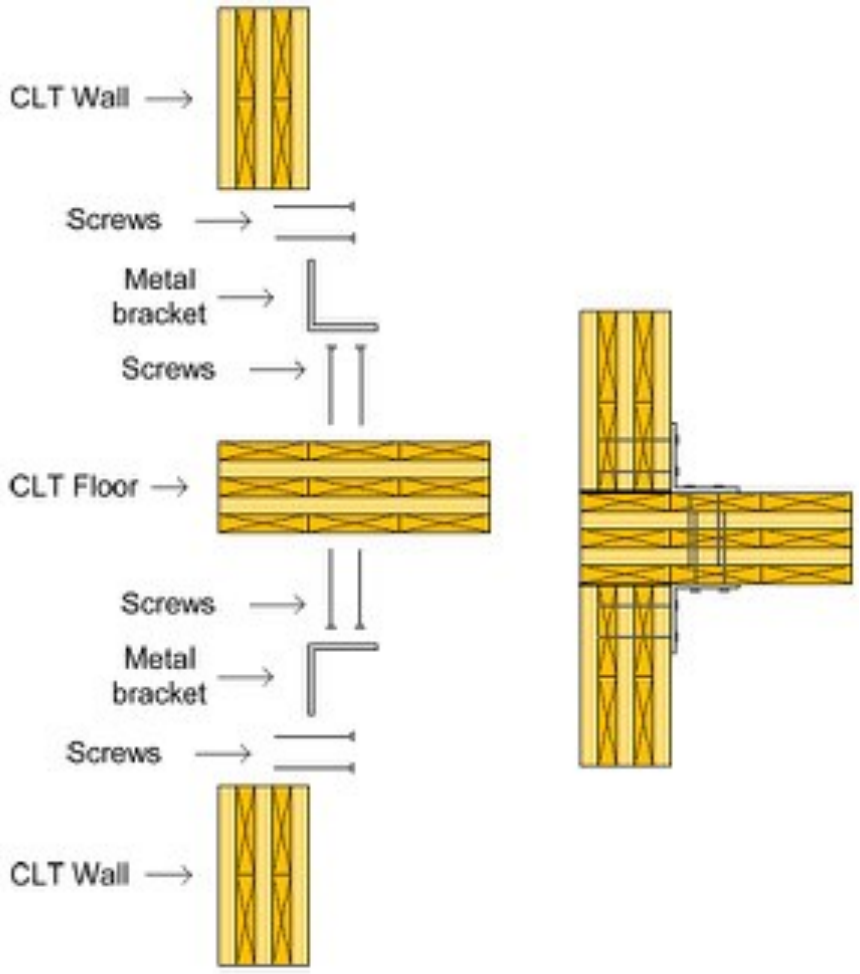
End Screw, Toe Screw



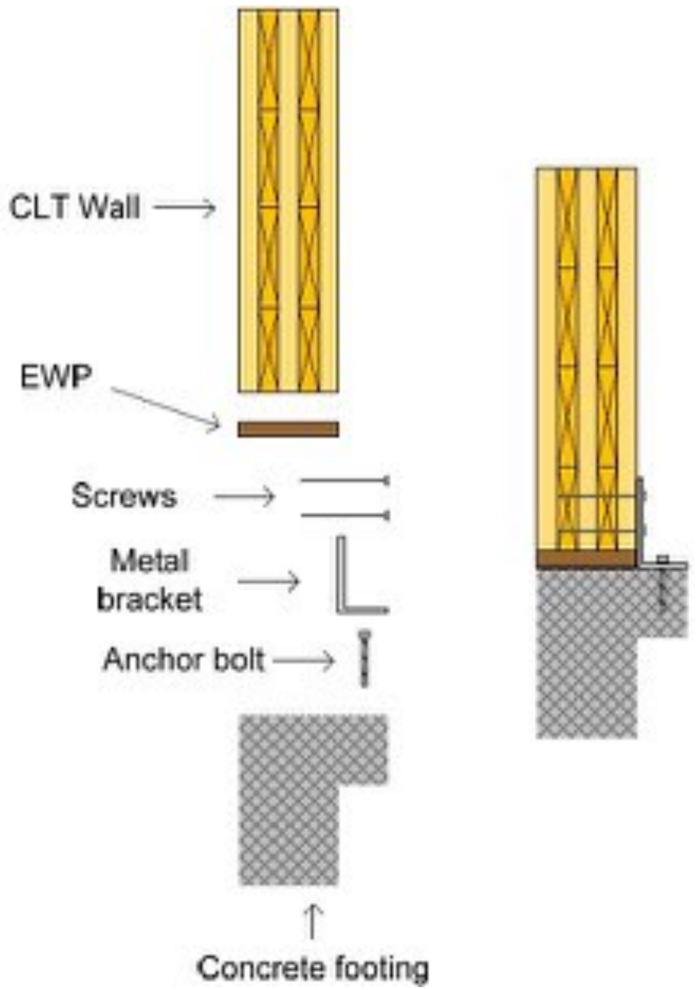
Steel Bracket

Image: CLT Handbook Chapter 5

Connections   Panel to Panel at floors, walls and roof



Double Steel Bracket



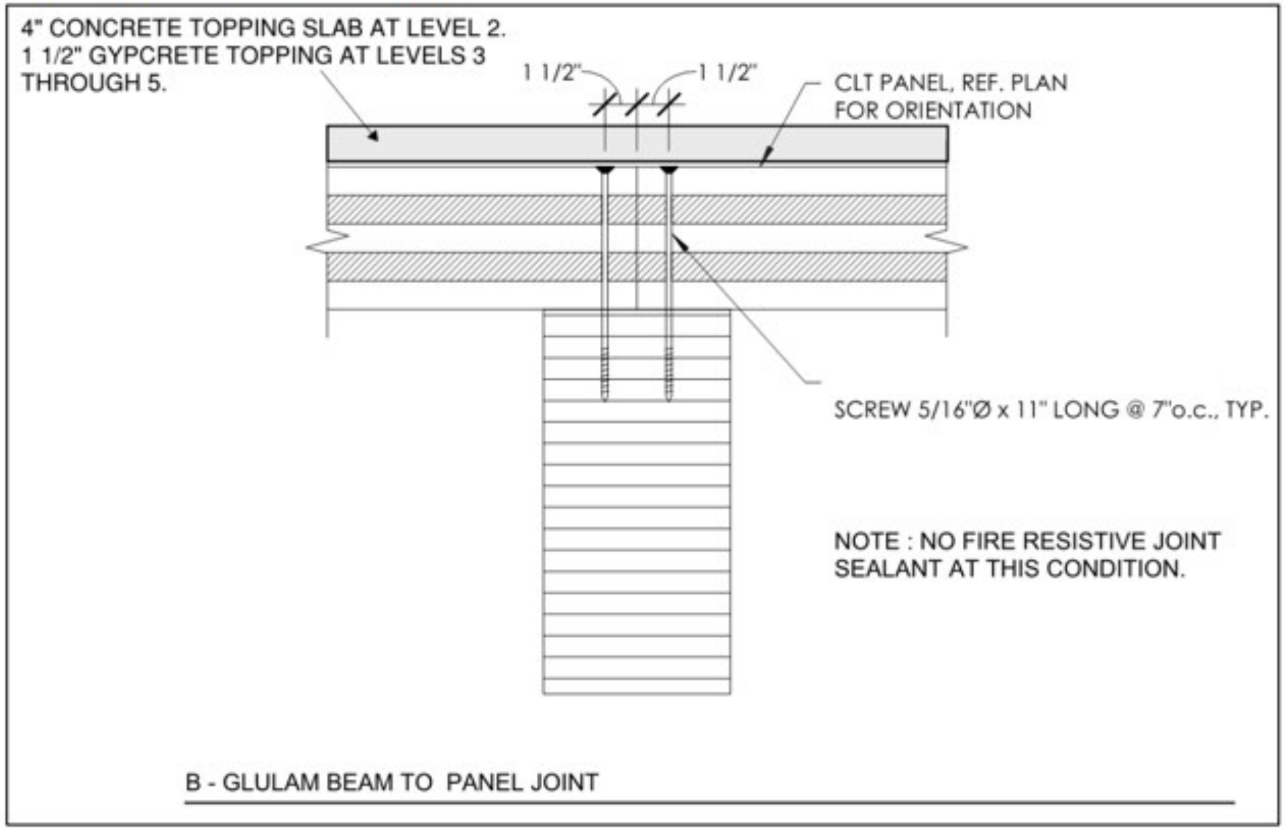
Steel Bracket

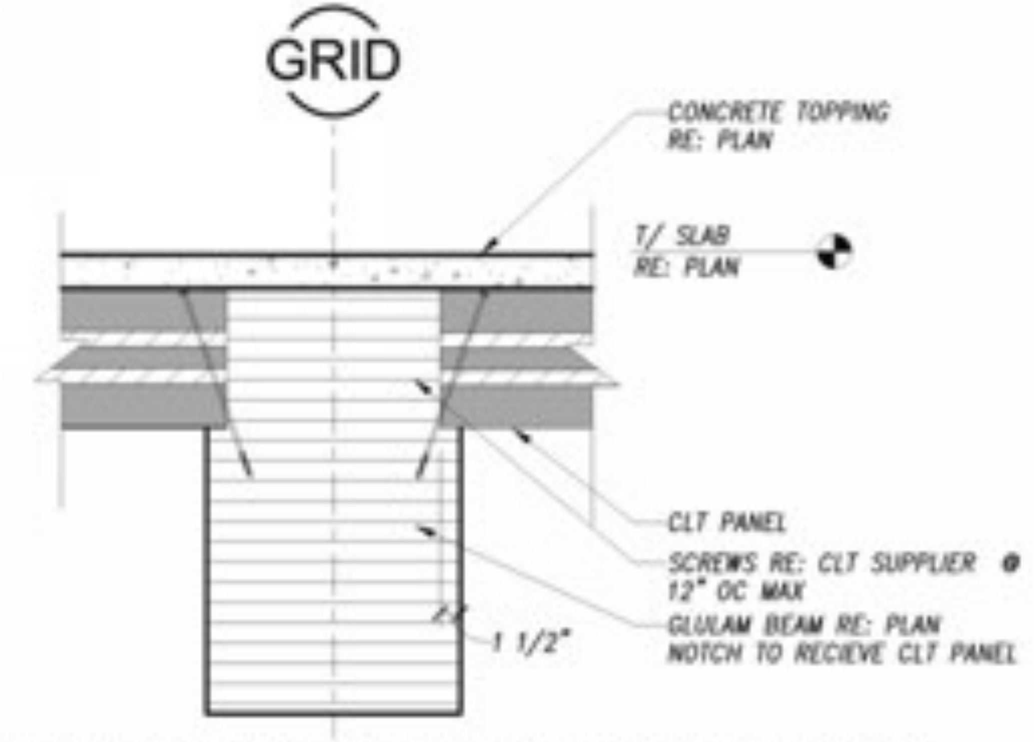
reference: CLT Handbook Chapter 5

Connections

Panel to GLB

Glulam beam to panel joint



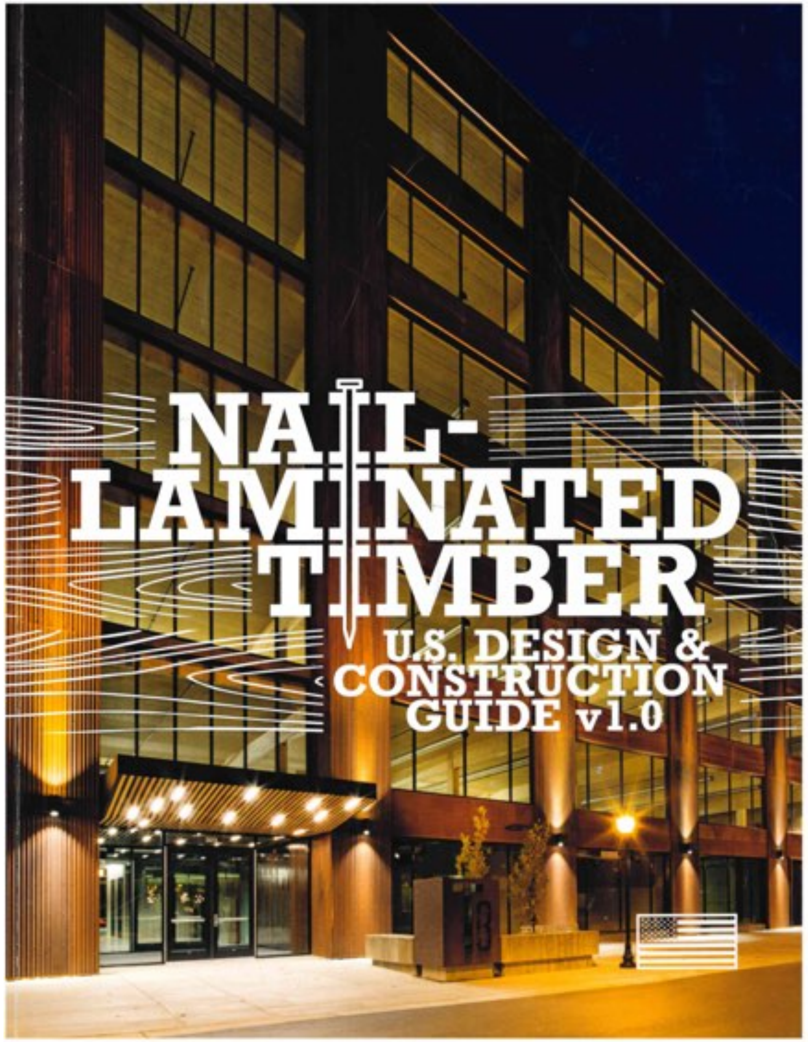


CLT TO INTERIOR BEAM CONNECTION

Image: Code Unlimited Block 76W CLT Connections Engineering Judgement Report

Images source: Greg Kingsley, PhD, PE, KL&A Engineers and Builders

Mass Timber Products - NLT



download –rethinkwood.com

Images source: Structurecraft

NLT Design

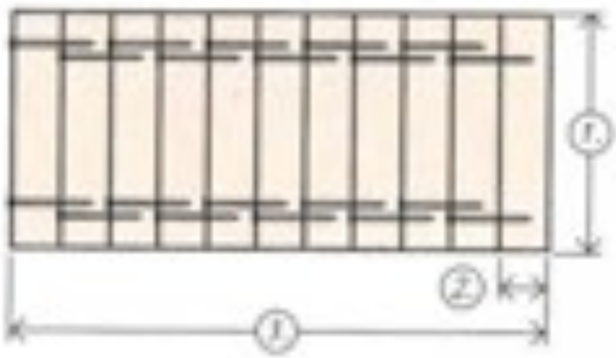


Figure 4.1: *NLT Cross Section*

Key

1. *NLT depth (d)*
2. *Lamination thickness (b_{lam})*
3. *NLT panel width (b)*

Treat NLT as built-up beam per NDS provisions

Beam Stability Factor (C_L) =1

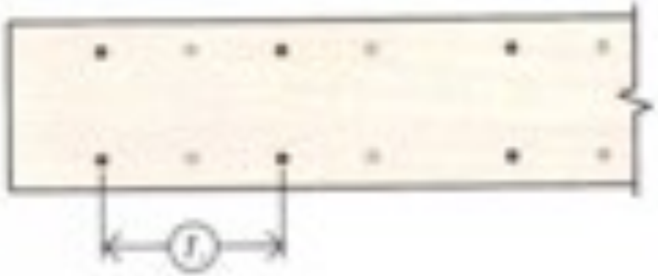
Size factor (C_F) based on individual lam thickness (b_{lam})

Repetitive Member (C_r) =1.15

Layup Factor (K_{layup}) adjusts bending and stiffness

Images source: NLT Guide V1.0

NLT Design



Two Rows

One Row

TABLE 4.6 MINIMUM LAMINATION NAILING

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.

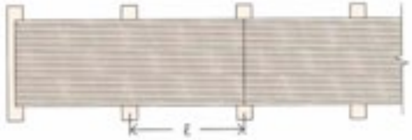
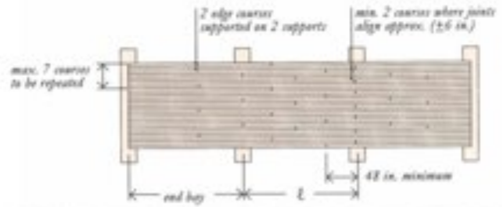
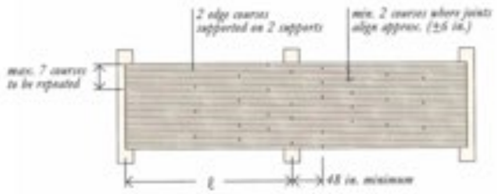
Note: *Nails are smooth shank galvanized steel nails.*

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

Images source: NLT Guide V1.0

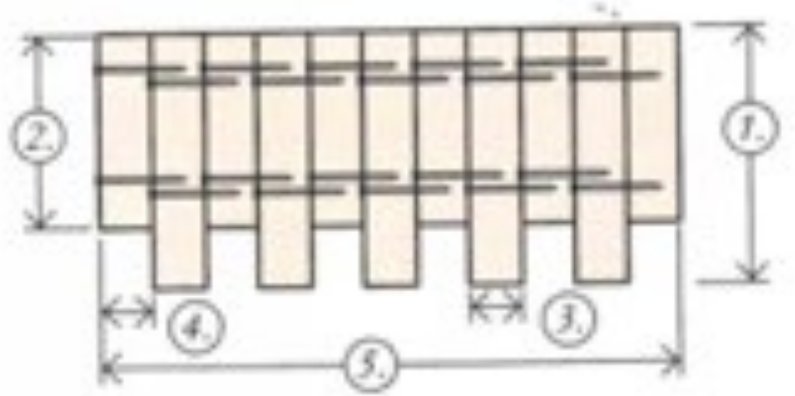
NLT Design – Butt Joints – (K_{layup})

TABLE 4.1: NLT LAYUP TYPES AND ADJUSTMENT FACTORS

LAYUP TYPE		ADJUSTMENT FACTOR: Bending Strength ($K_{layup,b}$)	ADJUSTMENT FACTOR: Stiffness ($K_{layup,E}$)	NOTES
Laminations continuous and single span		$K_{layup,b} = 1.0$ $M = \frac{w\ell^2}{8}$	$K_{layup,E} = 1.0$ $\Delta = \frac{5w\ell^4}{384E\,(d^3/12)}$	Maximum strength for a given depth. Typical maximum length for laminations of 16 to 20 feet. Longer laminations can be fabricated with structural finger joints (certified exterior joints or certified end joints).
Laminations continuous and multi-span		$K_{layup,b} = 1.0$ $M = \frac{w\ell^2}{8}$	$K_{layup,E} = 1.0$ $\Delta = \frac{w\ell^4}{185E\,(d^3/12)}$	Maximum strength and stiffness for a given depth. Typical maximum length for laminations of 16 to 20 feet. Longer laminations can be fabricated with structural finger joints (certified exterior joints or certified end joints).
Laminations with controlled random butt joints over 4 or more supports		$K_{layup,b} = 0.67$ $M = 0.10w\ell^2$	$K_{layup,E} = 0.69$ $\Delta = \frac{0.0069w\ell^4}{E\,(d^3/12)}$	Maximum stiffness for a butt-jointed system. Rules for joint locations are given in IBC 2304.9.2.5 and 2304.9.3.3, and illustrated in the adjacent figure.
Laminations with controlled random butt joints over fewer than 4 supports		$K_{layup,b}$=0.202 $\frac{(\ell/d)^{[illegible]}}{s^{[illegible]}}$ $M = \frac{w\ell^2}{8}$ $K_{layup,E}$=0.0436 $\frac{(\ell/d)^{[illegible]}}{s^{[illegible]}}$	for single span: $\Delta = \frac{5w\ell^4}{384E\,(d^3/12)}$ for double span: $\Delta = \frac{w\ell^4}{185E\,(d^3/12)}$	Based on European research, rules for joint locations per IBC should be amended as follows: • Where butt joints occur in the same general line (±6 in.), they must be separated by a minimum of three intervening laminations. • Each lamination must extend over a minimum of one support. • See Section 4.3.1 for minimum nailing requirements.

Images source: NLT Guide V1.0

NLT Design - Variable Depth Members ($K_{section}$)



6. $X_i = \frac{n_i b_{lam\,i}}{b_{panel}}$

- Nails do not provide necessary stiffness for full composite
- All lams do not reach maximum bending capacity

- Deeper lams reach full capacity first
- Shallow lams reach only a portion of their capacity
- Based on relative stiffness

TABLE 4.2 STAGGERED NLT ADJUSTMENT FACTORS

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

Images source: NLT Guide V1.0

NLT Design - Variable Depth Members ($K_{section}$)

TABLE 4.3 BENDING DESIGN EQUATIONS

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

TABLE 4.4 SHEAR DESIGN EQUATIONS

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

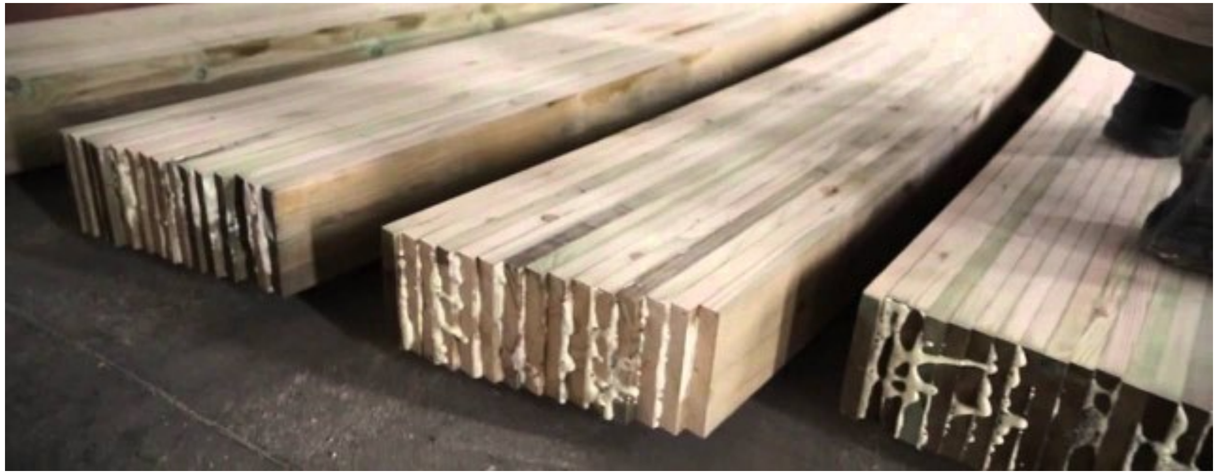
Deflection

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

Images source: NLT Guide V1.0

Glu-Lams

- Fabricated from conventional sawn lumber
- Laminations glued together to create a built-up beam
- Typically Southern Pine or Douglas Fir– high architectural quality



reference: CLT Handbook Chapter 7

Glu-lams

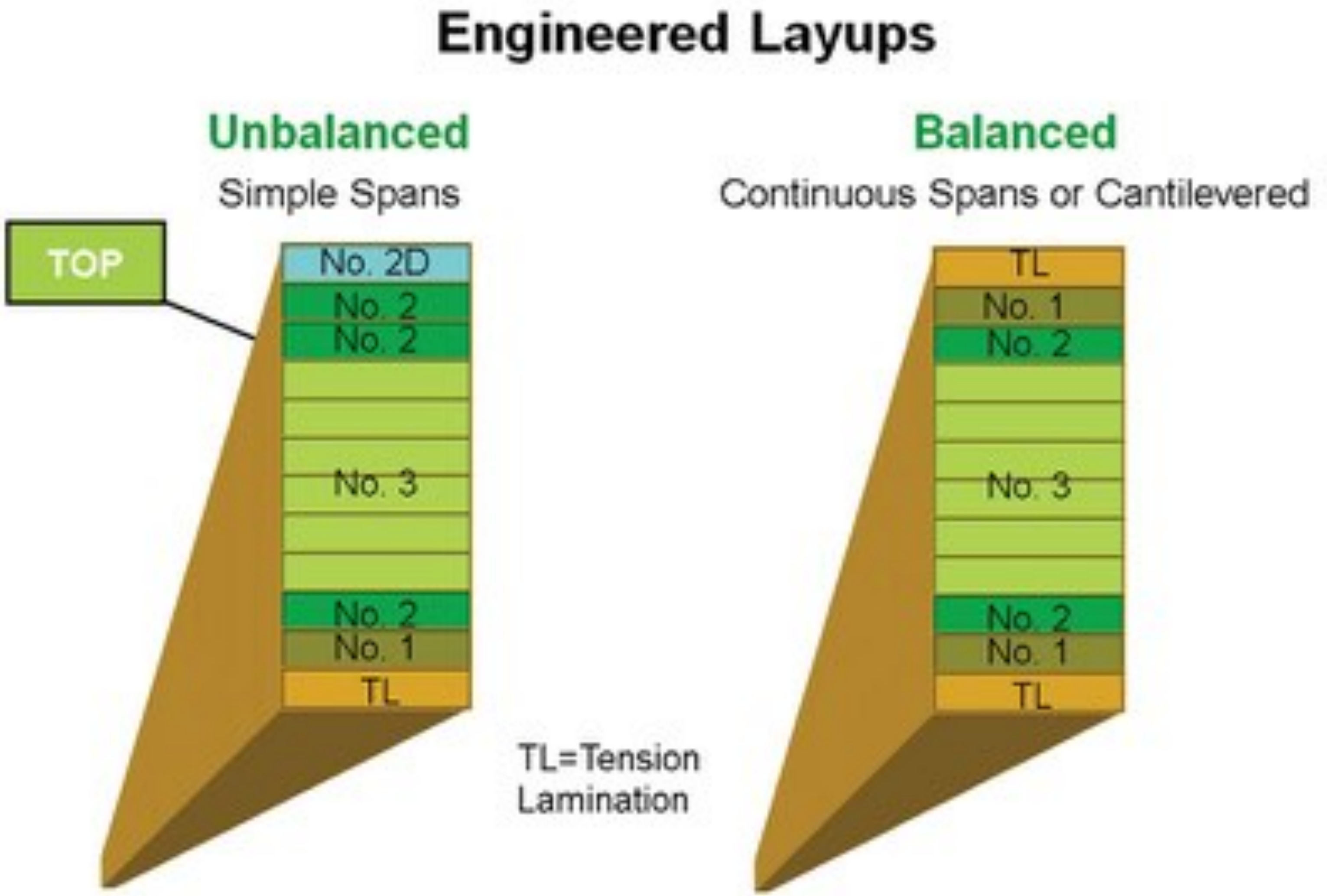
- Specified by size, grade and finish (architectural versus industrial)

- Beam design
  - Unbalanced layup – 24F-V3 or 24F-1.8E
    - Higher grade laminations at bottom, weaker grade laminations at middle and top
    - Conventional layup - works for simple spans

  - Balanced layups – 24F-E4 or 24F-1.8E balanced
    - Same grade laminations at top and bottom
    - Cantilevers and continuous beams

reference: CLT Handbook Chapter 7

Glu-lams



reference: APA Glulam Design Guide

Balanced vs. Unbalanced Layup

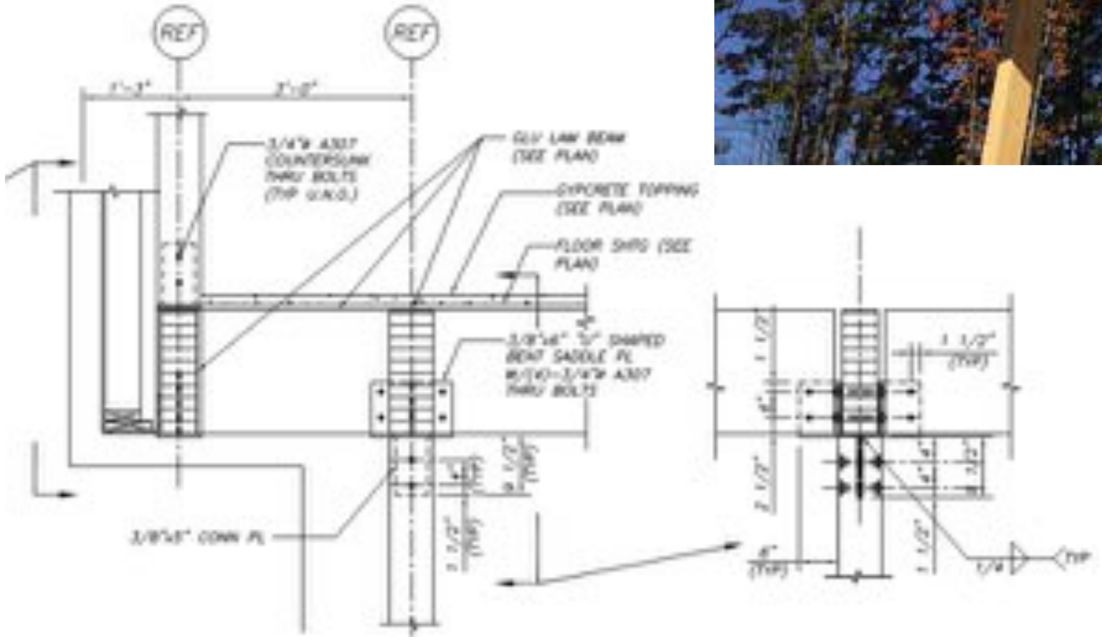


Image: Thornton Tomasetti

Glulam – Manufacturer options

- “Off the shelf”
  - Stock beams: Power Beams by Anthony Forest Product, X-beam by Rosboro, etc..
  - Size up to 7”x28 7/8” (Anthony Powers); 8 ¾”x30” (Rosboro)
  - Available as architectural grade and treated for exterior
  - Connection made in the field
- Specialized manufacturer
  - High quality, custom product: Unalam, CLT list of Manuf
  - Shop fabricated, connection design, CNC
  - Curved!
  - Can be treated for exterior
  - Cost is a function of width - 2 beams cheaper?

Glulam Beams – Design (NDS Chapter 5)

- Values included for width (Table 5.1.3), Section Properties (Supplement Table 1C and 1D) and Reference Design Values (Supplement Table 5a)

- Check with local manufacturer

Table 5A (Cont.) **Expanded - Reference Design Values for Structural Glued Laminated Softwood Timber Combinations[1]**
(Members stressed primarily in bending) (Tabulated design values are for normal load duration and dry service conditions. See NDS 5.3 for a comprehensive description of design value adjustment factors.)

Use with Table 5A Adjustment Factors

Combination Symbol	Species Outer/ Core	Bending About X-X Axis (Loaded Perpendicular to Wide Faces of Laminations): Bending – Bottom of Beam Stressed in Tension (Positive Bending) F_{bx}^{+} (psi)	Bending – Top of Beam Stressed in Tension (Negative Bending) F_{bx}^{-} (psi)	Compression Perpendicular to Grain – Tension Face $F_{c\perp x}$ (psi)	Compression Perpendicular to Grain – Compression Face $F_{c\perp x}$ (psi)	Shear Parallel to Grain F_{vx} (2) (psi)	Modulus of Elasticity – For Deflection Calculations E_x (10^6 psi)	Modulus of Elasticity – For Stability Calculations $E_{x\,min}$ (10^6 psi)	Bending About Y-Y Axis (Loaded Parallel to Wide Faces of Laminations): Bending F_{by} (psi)	Compression Perpendicular to Grain $F_{c\perp y}$ (psi)	Shear Parallel to Grain F_{vy} (2)(3) (psi)	Modulus of Elasticity – For Deflection Calculations E_y (10^6 psi)	Modulus of Elasticity – For Stability Calculations $E_{y\,min}$ (10^6 psi)	Axially Loaded: Tension Parallel to Grain F_t (psi)	Axially Loaded: Compression Parallel to Grain F_c (psi)	Fasteners: Specific Gravity for Fastener Design – Top or Bottom Face G	Fasteners: Specific Gravity for Fastener Design – Side Face G
24F-1.8E		**2400**	**1450**	**650**		**265**	**1.8**	**0.95**	**1450**	**560**	**230**	**1.6**	**0.85**	**1100**	**1600**	**0.50**	
24F-V4	DF/DF	2400	1850	650	650	265	1.8	0.95	1450	560	230	1.6	0.85	1100	1650	0.50	0.50
24F-V8	DF/DF	2400	2400	650	650	265	1.8	0.95	1550	560	230	1.6	0.85	1100	1650	0.50	0.50
24F-E4	DF/DF	2400	1450	650	650	265	1.8	0.95	1400	560	230	1.7	0.90	1100	1700	0.50	0.50
24F-E13	DF/DF	2400	2400	650	650	265	1.8	0.95	1750	560	230	1.7	0.90	1250	1700	0.50	0.50
24F-E18	DF/DF	2400	2400	650	650	265	1.8	0.95	1550	560	230	1.7	0.90	975	1700	0.50	0.50
24F-V3	SP/SP	2400	2000	740	740	300	1.8	0.95	1700	650	260	1.6	0.85	1150	1650	0.55	0.55
24F-V8	SP/SP	2400	2400	740	740	300	1.8	0.95	1700	650	260	1.6	0.85	1150	1650	0.55	0.55
24F-E1	SP/SP	2400	1450	805	650	300	1.8	0.95	1550	650	260	1.7	0.90	1150	1600	0.55	0.55
24F-E4	SP/SP	2400	2400	805	805	300	1.9	1.00	1850	650	260	1.8	0.95	1450	1750	0.55	0.55

Table 5.1.3 **Net Finished Widths of Structural Glued Laminated Timbers**

Nominal Width of Laminations (in.)	3	4	6	8	10	12	14	16
Net Finished Width (in.) – Western Species	2-½	3-1/8	5-1/8	6-¾	8-¾	10-¾	12-¼	14-¼
Net Finished Width (in.) – Southern Pine	2-½	3	5	6-¾	8-½	10-½	12	14

Images: American Wood Council

Glulam Beams – Design

- Design as standard wood member using NDS Table 5.3.1 adjustment factors

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.

Image: American Wood Council

Glulam Columns - Design

APA design guide for “first pass” tables

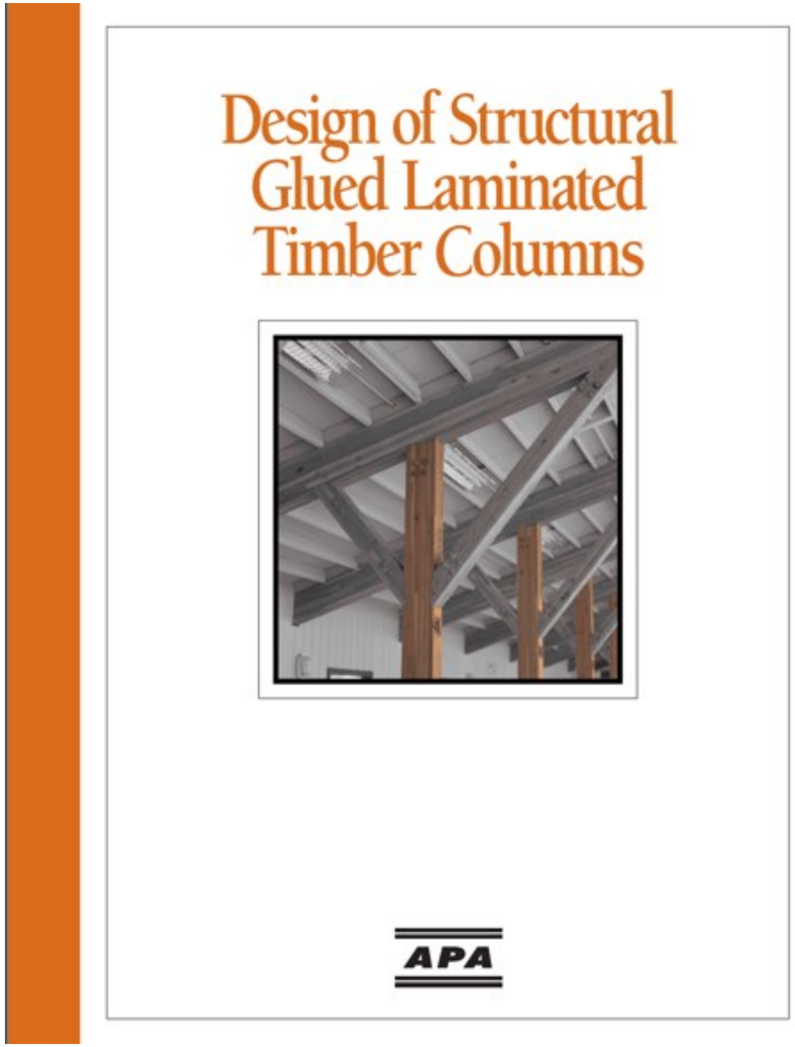
TABLE 5

ALLOWABLE AXIAL LOADS (POUNDS) FOR COMBINATION NO. 2 DOUGLAS-FIR GLULAM COLUMNS
Side loads are not permitted. End loads are limited to a maximum eccentricity of either 1/6 column width or depth, whichever is worse.

Effective Column Length (ft)	Lamination Net Width = 3-1/2 in.								
	Net Depth = 4-1/2 in. (3 lams)			Net Depth = 6 in. (4 lams)			Net Depth = 7-1/2 in. (5 lams)		
	Load Duration Factor			Load Duration Factor			Load Duration Factor		
	1.00	1.15	1.25	1.00	1.15	1.25	1.00	1.15	1.25
8	7,283	7,611	7,799	10,108	10,523	10,762	12,635	13,154	13,453
9	6,184	6,424	6,561	8,531	8,836	9,010	10,664	11,044	11,263
10	5,298	5,479	5,582	7,278	7,507	7,639	9,097	9,384	9,548
11	4,580	4,720	4,800	6,271	6,448	6,550	7,839	8,060	8,187
12	3,994	4,104	4,167	5,454	5,594	5,673	6,817	6,992	7,092
13	3,510	3,598	3,649	4,783	4,895	4,959	5,979	6,119	6,199
14	3,107	3,179	3,220	4,226	4,318	4,370	5,283	5,397	5,462

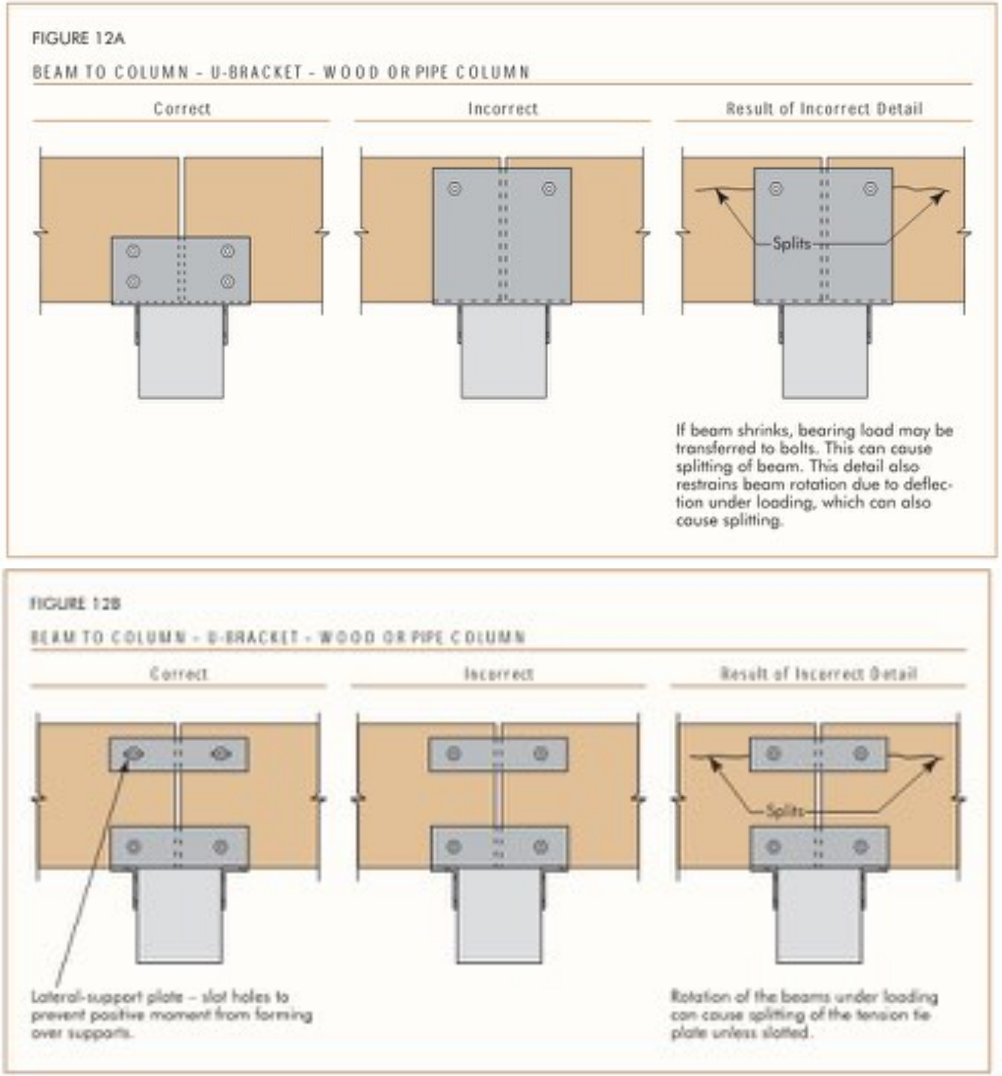
Notes:

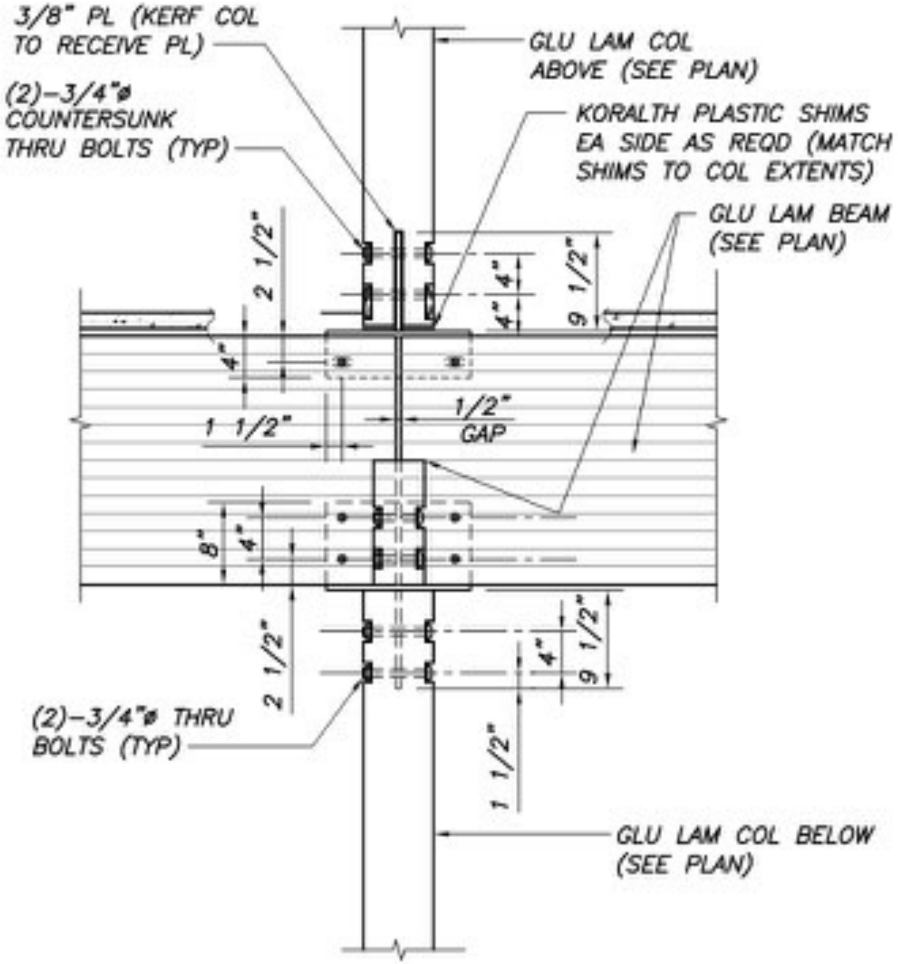
1. The tabulated allowable loads apply only to one-piece glulam members made with all L2 laminations (Combination 2) without special tension laminations.
2. Applicable service conditions = dry.
3. The tabulated allowable loads are based on axially loaded columns subjected to a maximum eccentricity of either 1/6 column width or 1/6 column depth, whichever is worse. For side loads, other eccentric end loads, or other combined axial and flexural loads, see NDS.
4. The column is assumed to be unbraced, except at the column ends, and the effective column length is equal to the actual column length.
5. Design properties for normal load duration and dry-use service conditions:
   Compression parallel to grain (F_c) = 1,950 psi for 4 or more lams, or 1,600 psi for 2 or 3 lams.
   Modulus of elasticity (E) = 1.6×10^6 psi.
   Flexural stress when loaded parallel to wide faces of lamination (F_{byy}) = 1,800 psi for 4 or more lams, or 1,600 psi for 3 lams.
   Flexural stress when loaded perpendicular to wide faces of lamination (F_{bxx}) = 1,700 psi for 2 lams to 15 in. deep without special tension laminations.
   Volume factor for F_{bx} is in accordance with NDS. Size factor for F_{by} is $(12/d)^{1/9}$, where d is equal to the lamination width in inches.
6. These values are for preliminary design use only. Final design should include a complete analysis, including bearing capacity of the foundation supporting the column.



reference: APA Glulam Design Guide

Glu-Lam Connections per AITC / APA





reference: APA Glulam Design Guide

Glu-Lam Connection Details

Photos: Chris Williams

Glu-lam Connection Details

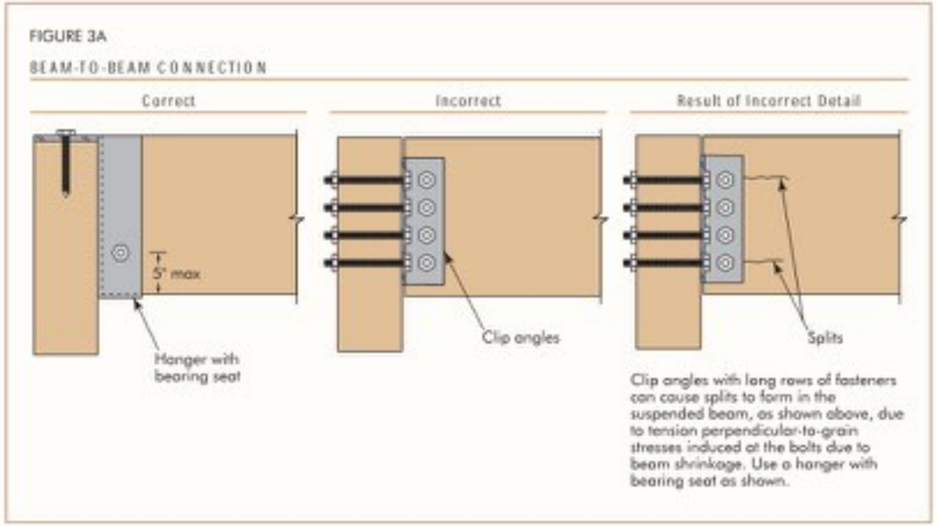
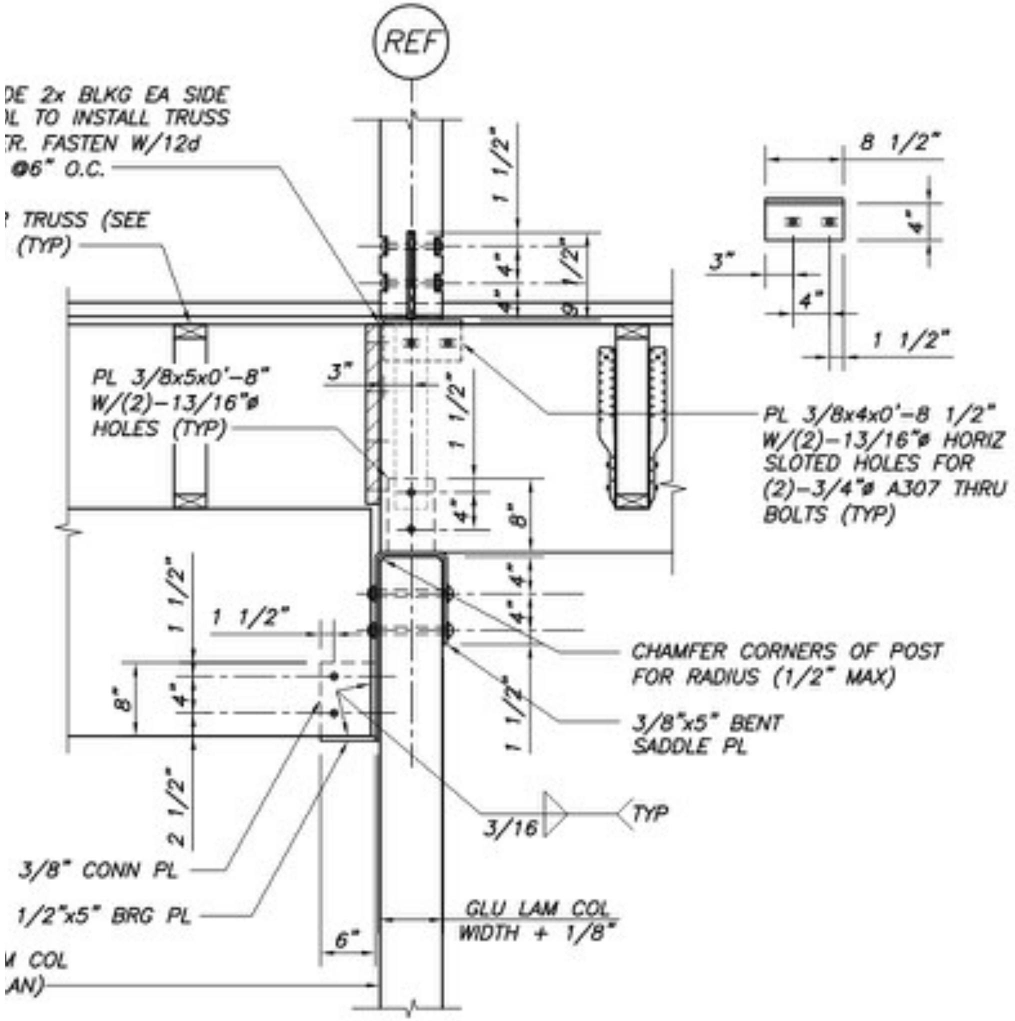


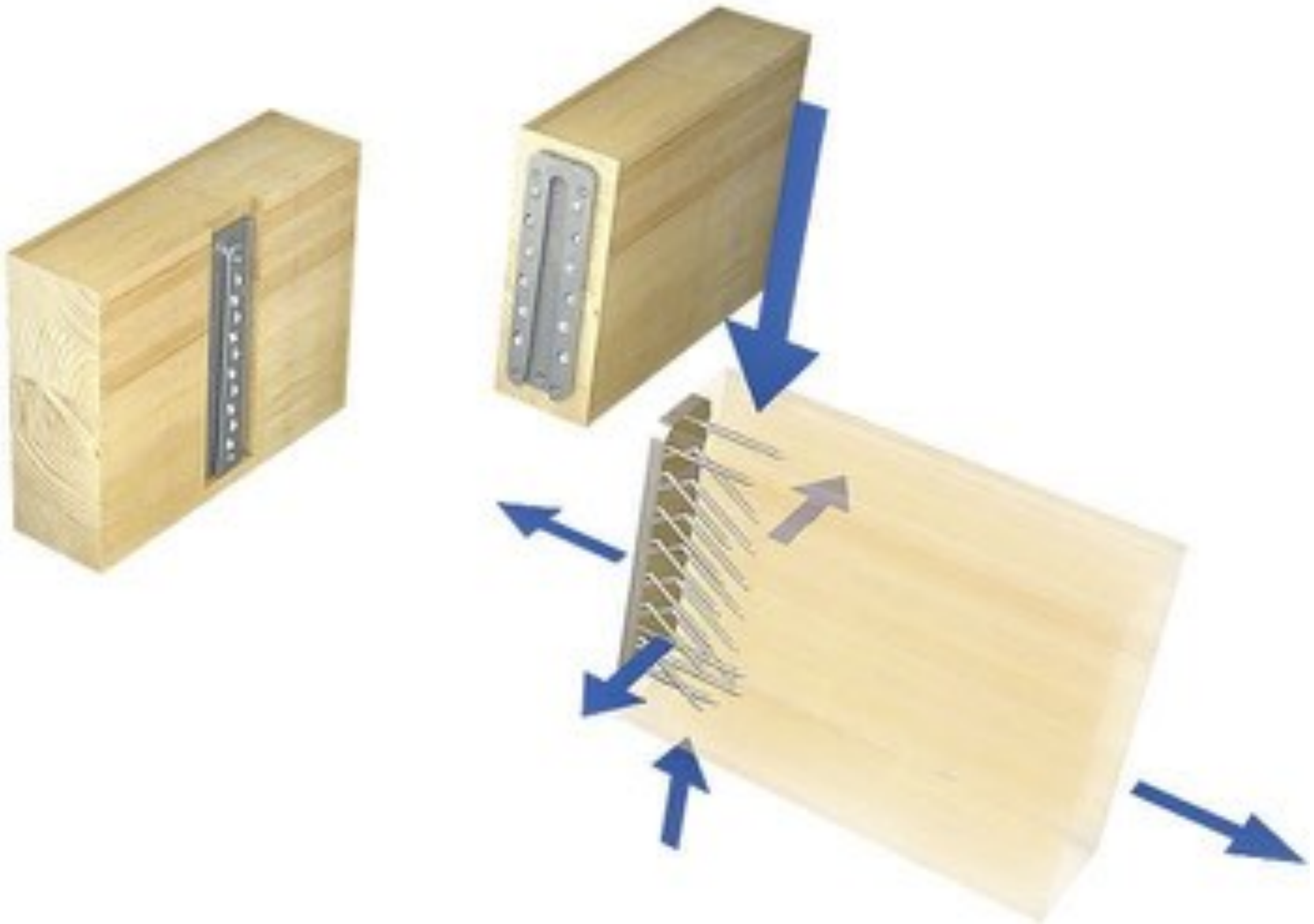
Photo Chris Williams



reference: APA Glulam Design Guide

Glu-lam Connection Details

Beam - Beam



5,800-29,400 lb capacity

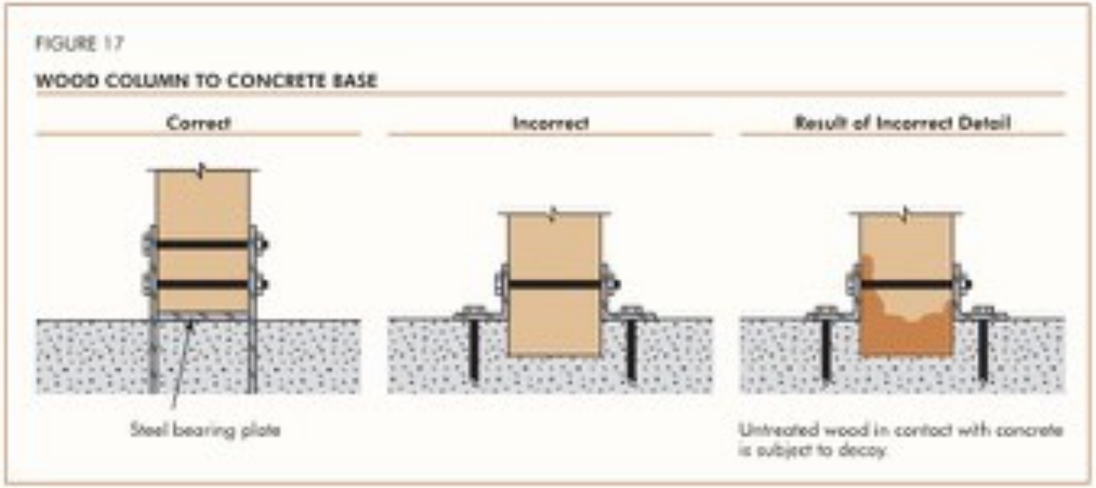
reference: MiTiCon

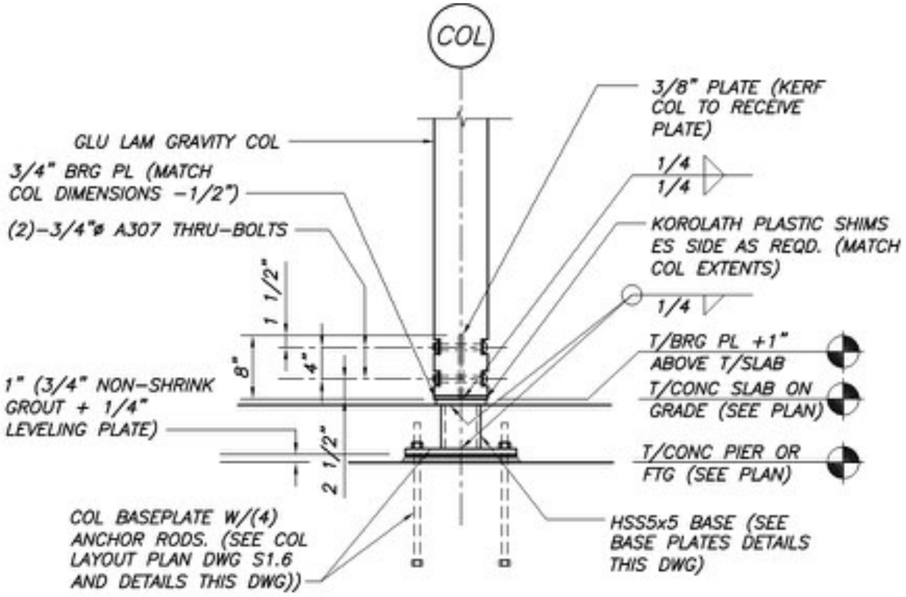
Glu-lam Connection Details

Beam - Column

Photo: structurlam

Glu-lam Connection Details





Detail: Thornton Tomasetti   image: APA Glulam Design Guide   Photos: Chris Williams

Glu-lam Connection Details

Column-column connections

concealed steel connection

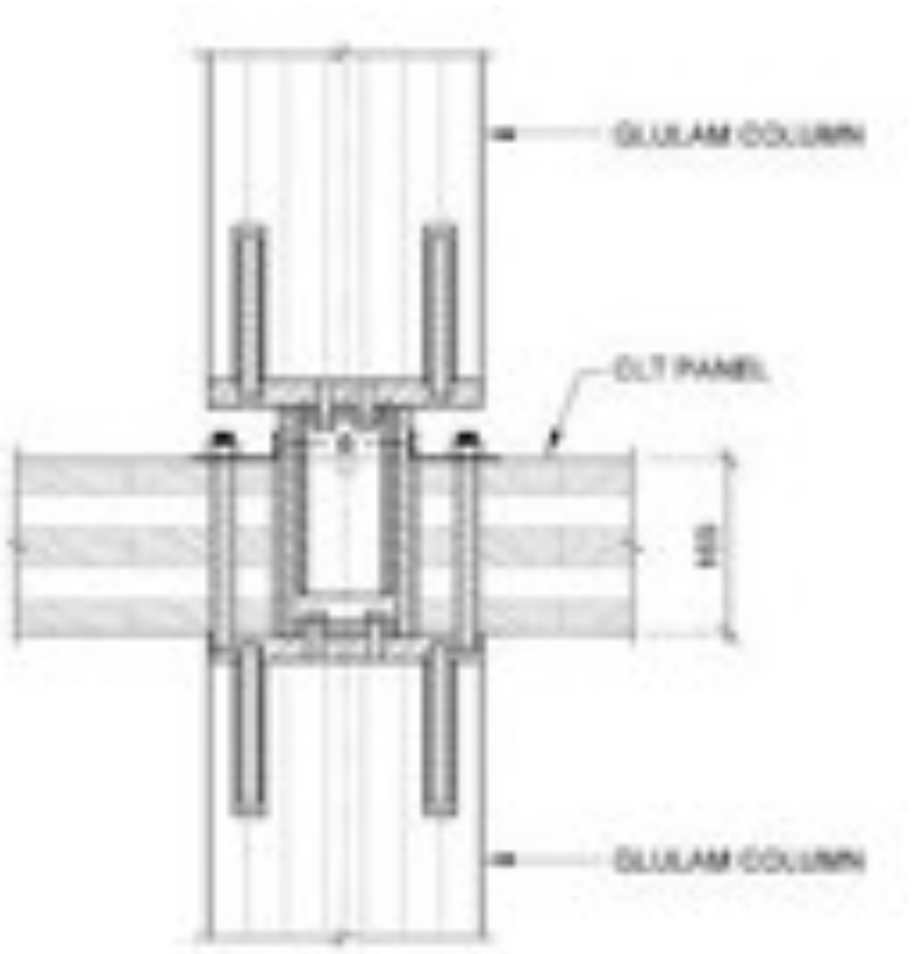


image: Structurecraft

Glu-lam Connection Details

Column-column connections

concealed steel connection

Brock Commons, Vancouver, BC

images: Structurecraft

What’s Possible?

image: Sidewalk Labs

QUESTIONS?

This concludes The American Institute of Architects Continuing Education Systems Course

Paul B. Becker, PE

Thornton Tomasetti

pbecker@thorntontomasetti.com