STRUCTURAL DESIGN OF MASS TIMBER

A short primer on the basics of mass timber design

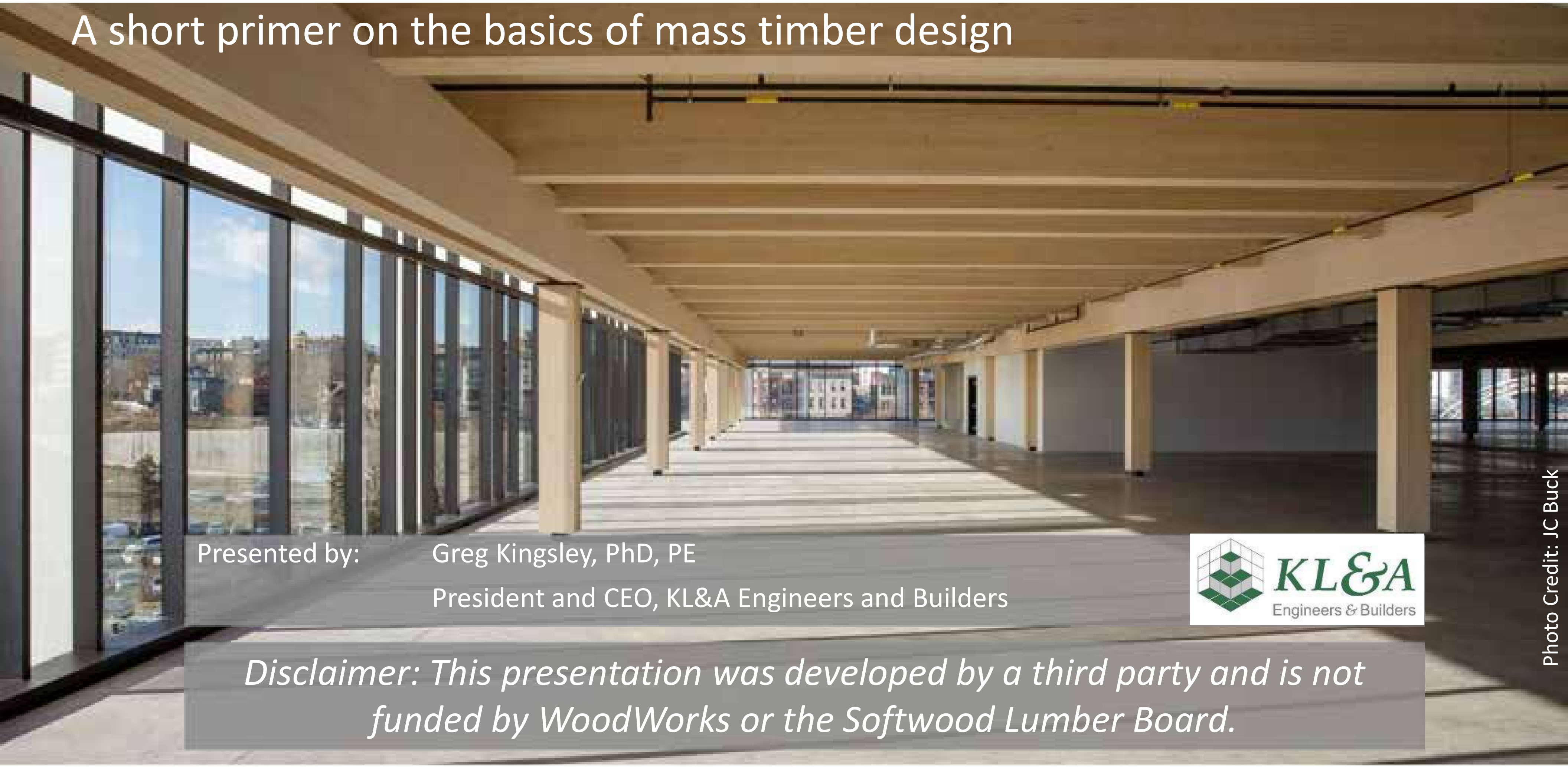

Photo Credit: JC Buck

Presented by: Greg Kingsley, PhD, PE

President and CEO, KL&A Engineers and Builders

KL&A Engineers & Builders

Disclaimer: This presentation was developed by a third party and is not funded by WoodWorks or the Softwood Lumber Board.

STRUCTURAL DESIGN OF MASS TIMBER

Outline

1. Materials
2. Gravity Load Design
3. Deflection and Vibration
4. Connections
5. Lateral Load Design
6. Fire Resistance
7. Constructability

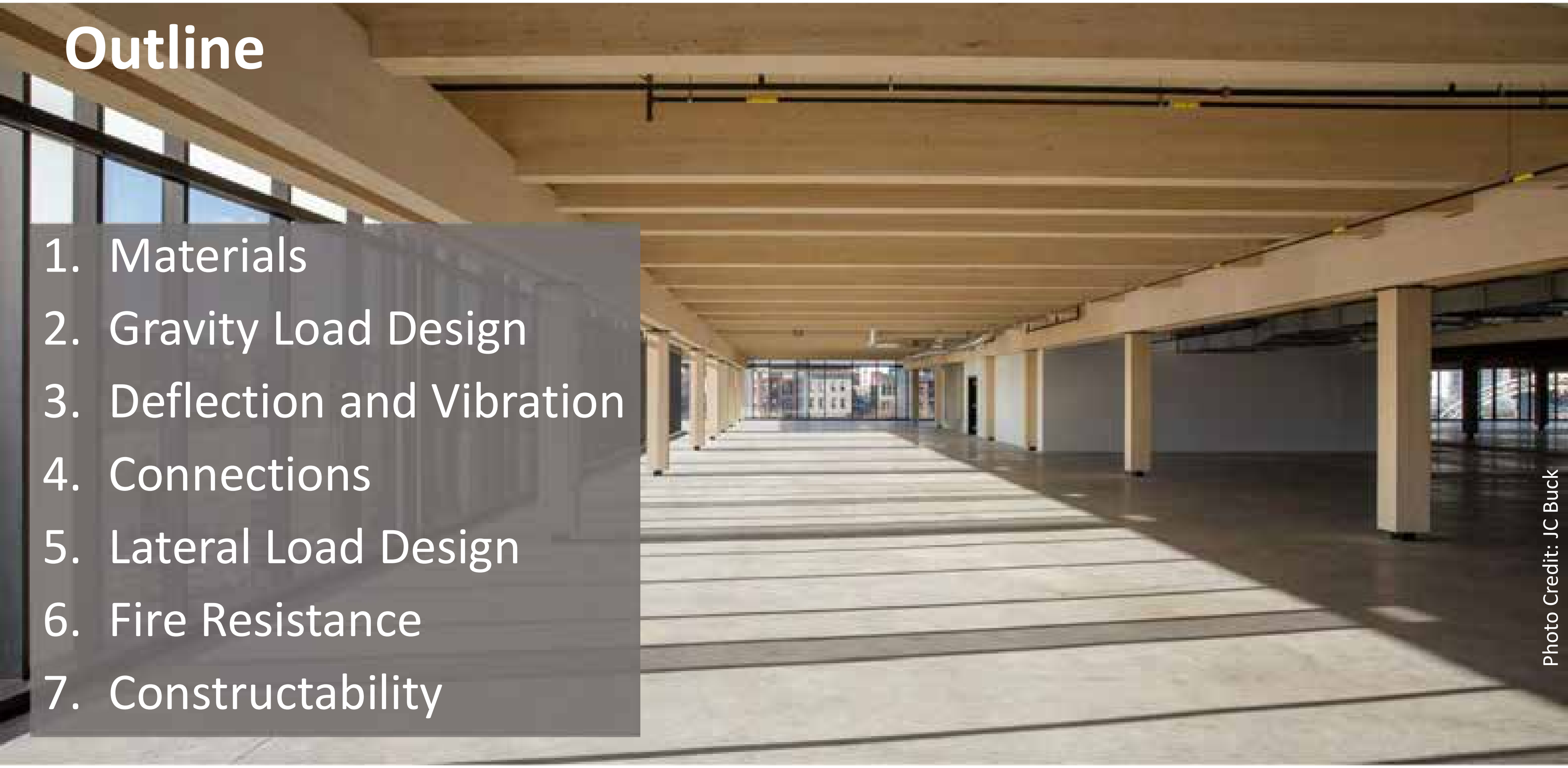

Photo Credit: JC Buck

MASS TIMBER MATERIALS

Photo Credit: KL&A

- IT’S MADE OF TREES

- IT'S MADE OF TREES
- IT'S SOLID WOOD
  (BIG PIECES MADE OUT OF LITTLE PIECES)

Nail Laminated Timber (NLT)
Dowel Laminated Timber (DLT)

Glue Laminated Timber (GLT)

Laminated Veneer Lumber (LVL)
and Mass Plywood Panels (MPP)

Cross Laminated Timber (CLT)

Images Source: Structurecraft

- IT’S MADE OF TREES
- IT’S SOLID WOOD
  (BIG PIECES MADE OUT OF
  LITTLE PIECES)
- IT’S FLAT PANELS (CLT, NLT, etc.)

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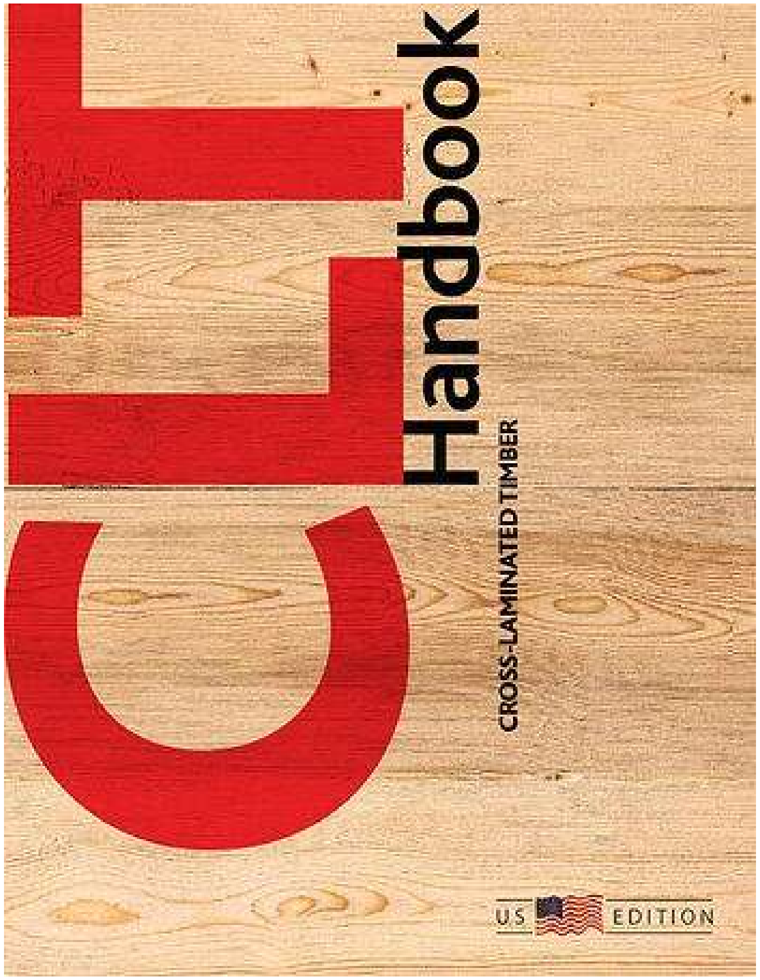
- IT'S FLAT PANELS (CLT, NLT, etc.)
- IT'S ALSO BEAMS AND COLUMNS
- IT'S PREFABRICATED



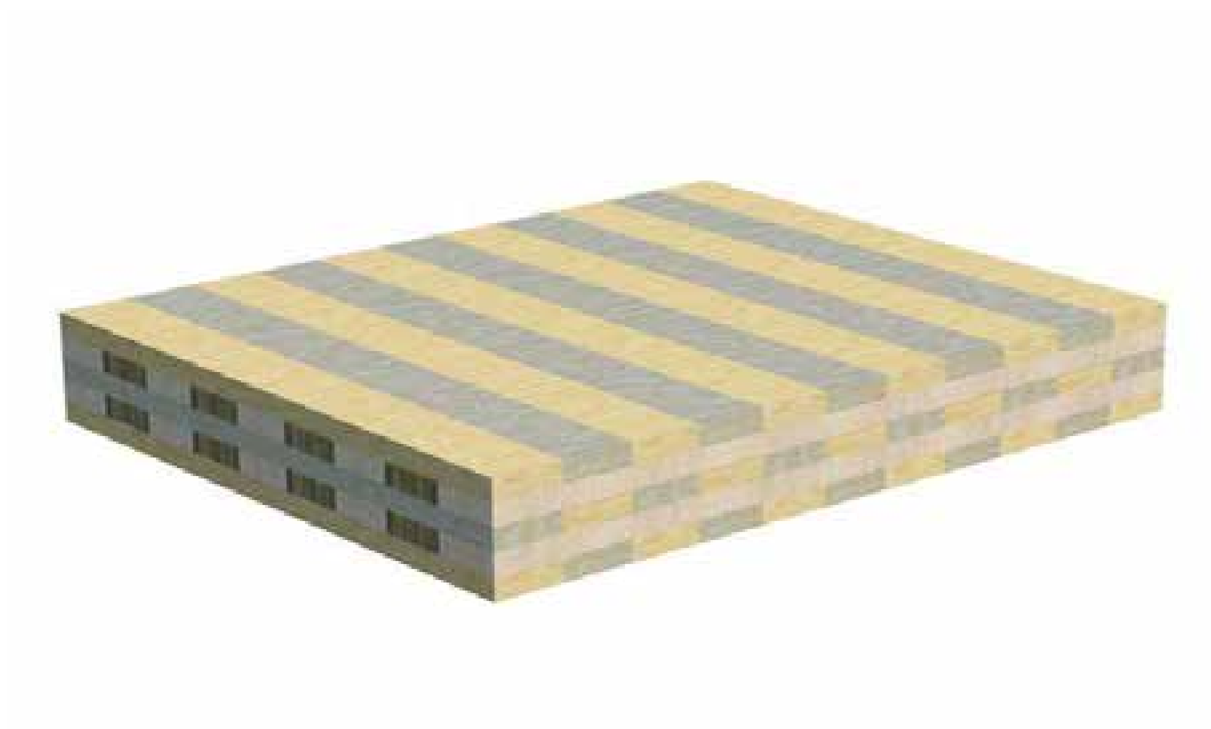
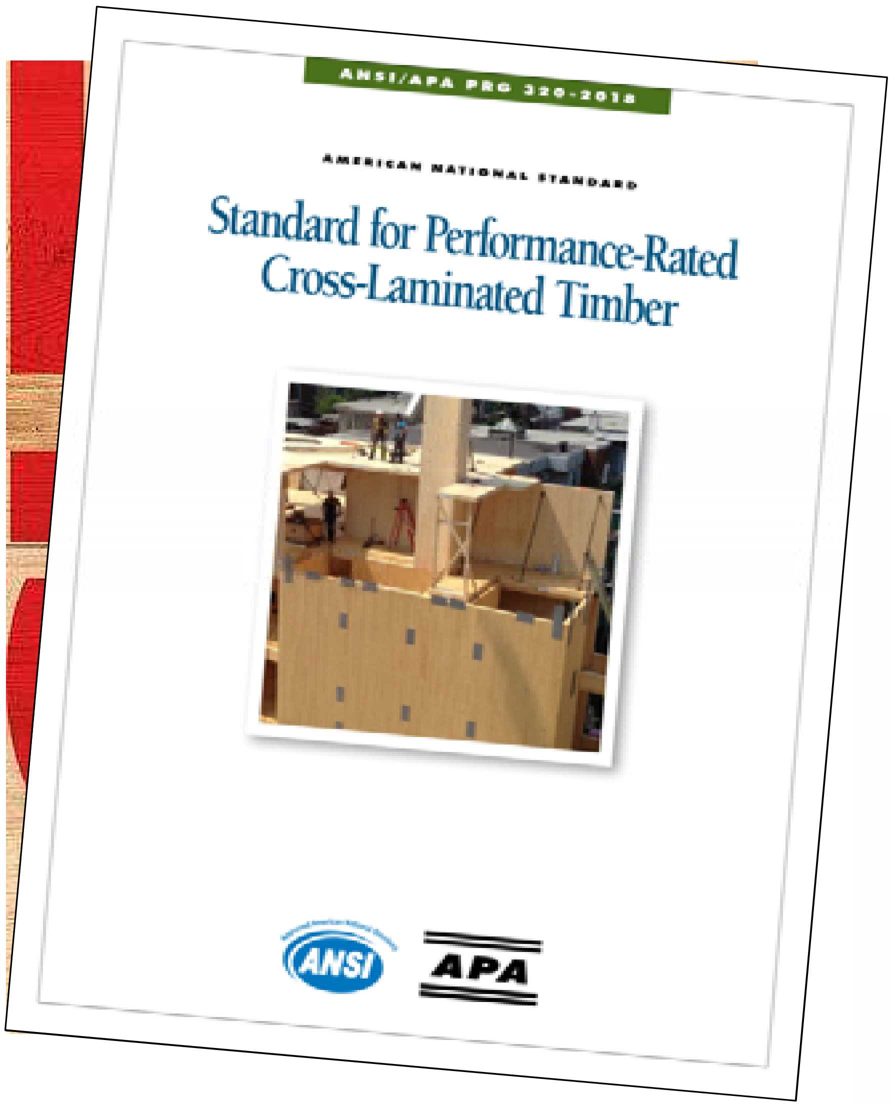
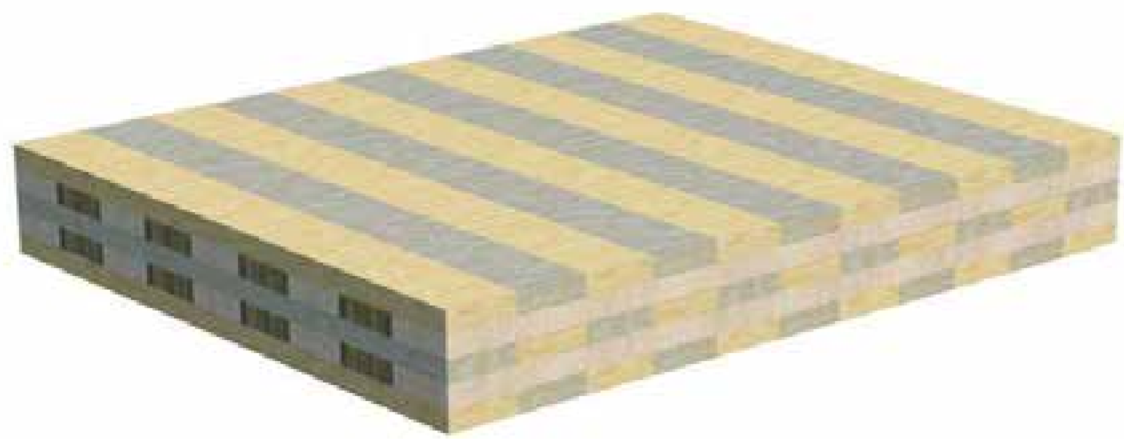


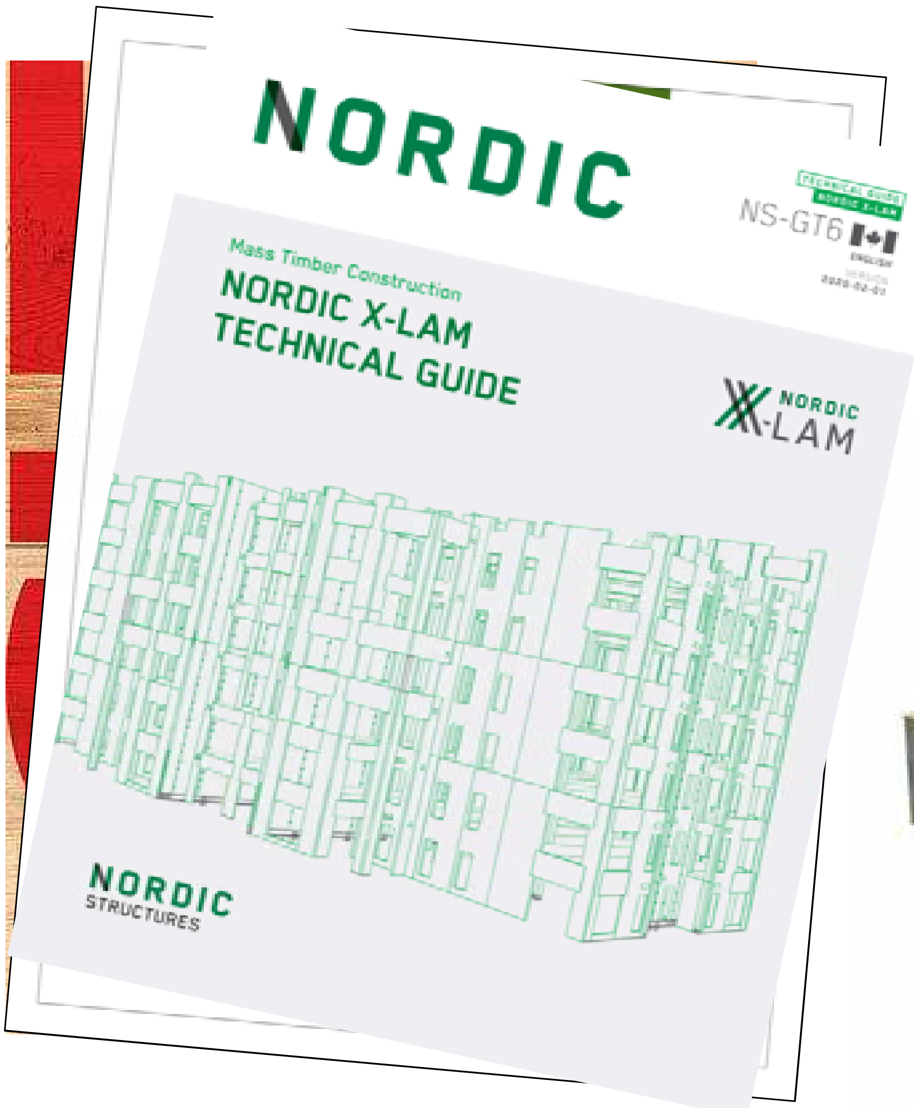
Image Courtesy of Fast and Epp

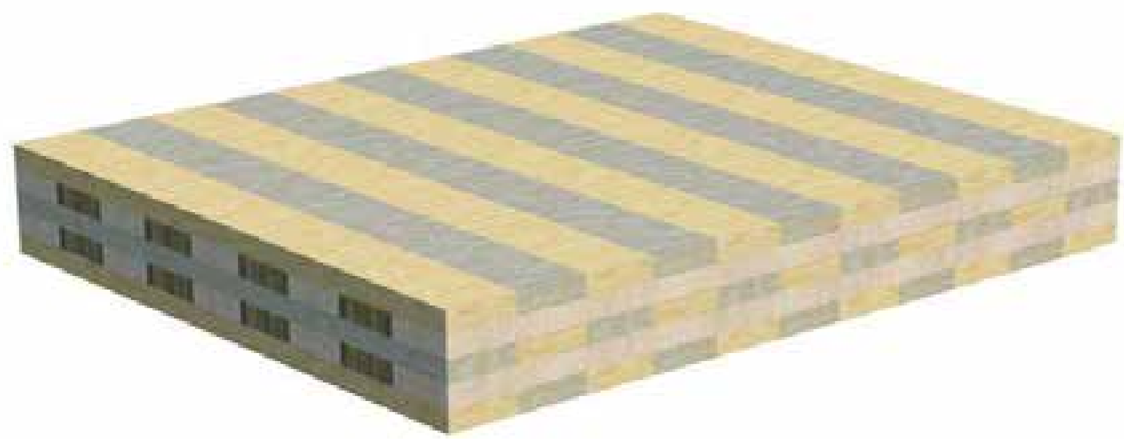




Cross Laminated Timber

Image Courtesy of Fast and Epp





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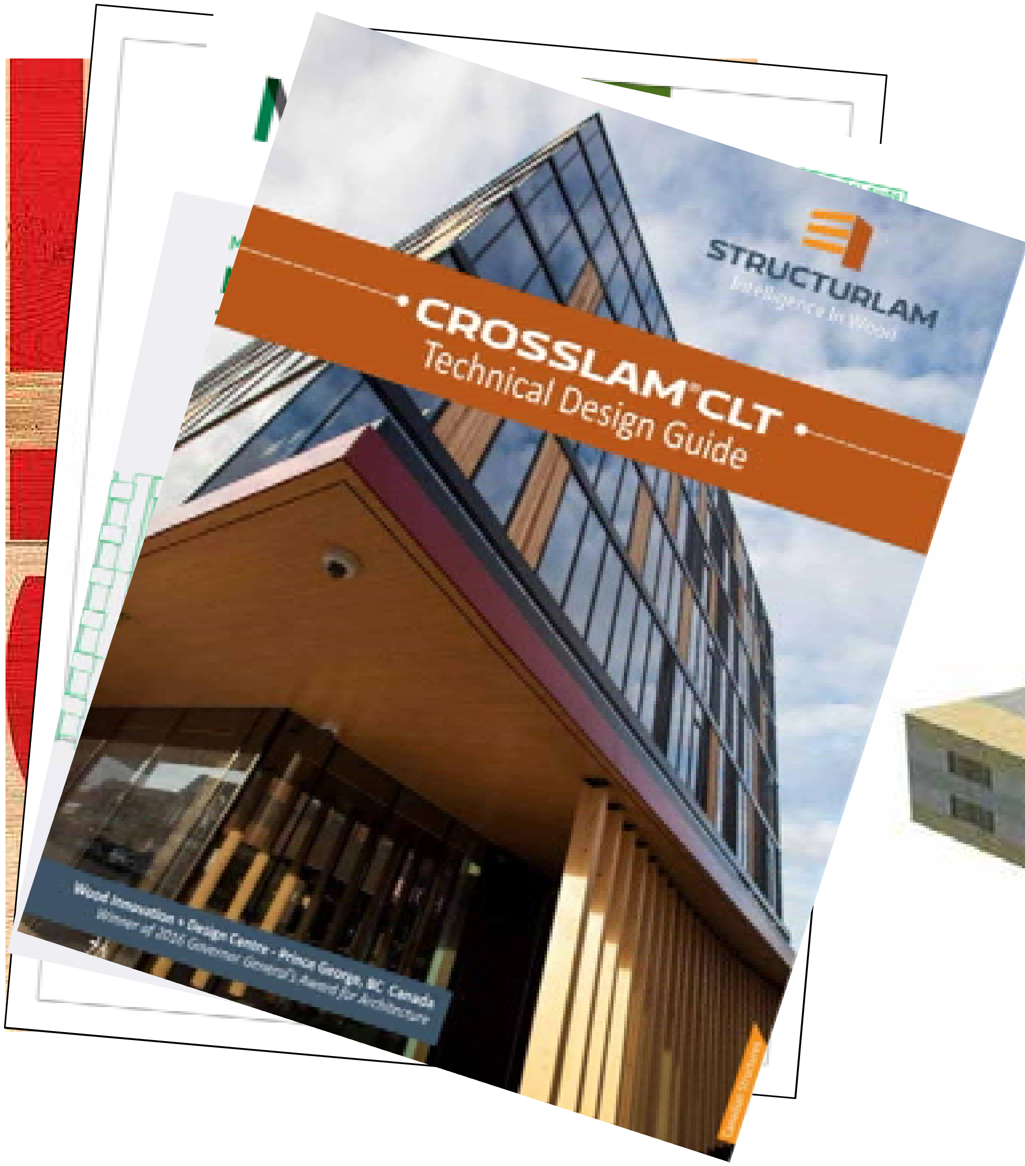

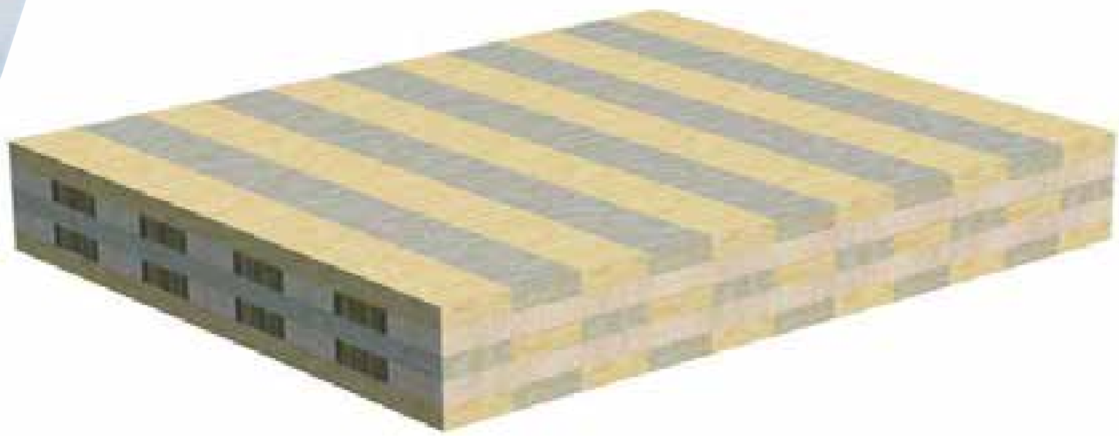

Cross Laminated Timber

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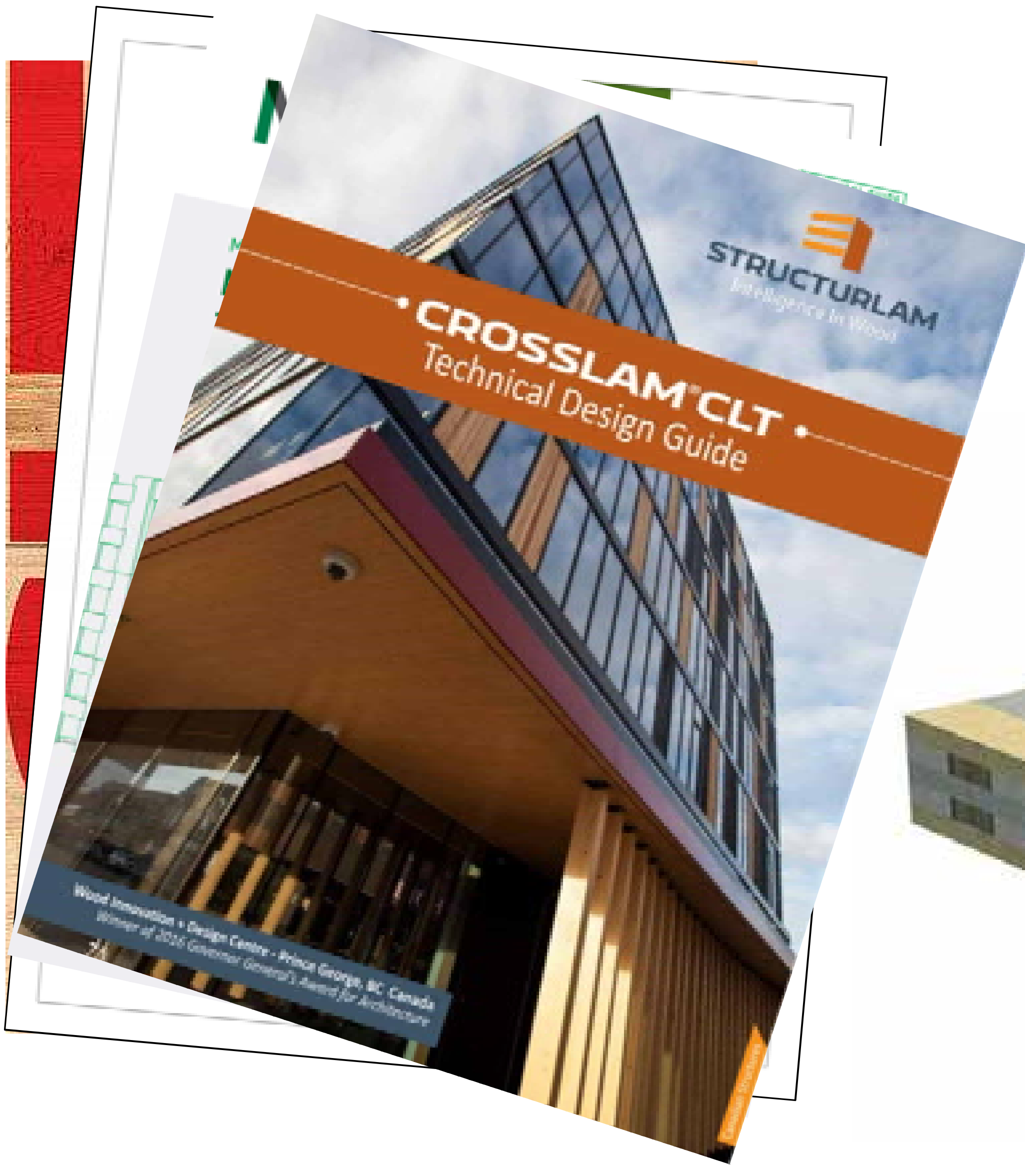
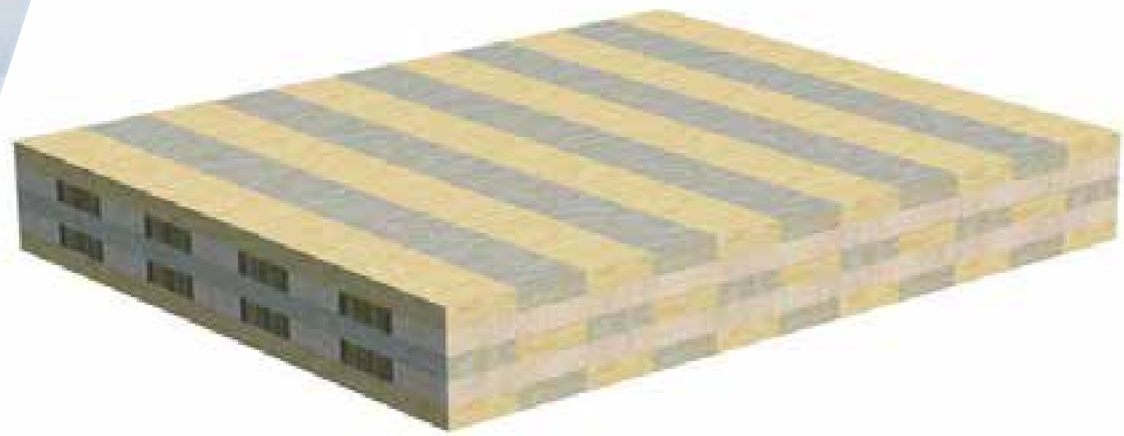


- Structurlam
- Nordic
- DR Johnson
- Smartlam
- Freres Lumber Co
- Katerra
- Vaagen Timber
- Kalesnikoff
- …

Not a commodity!



Cross Laminated Timber

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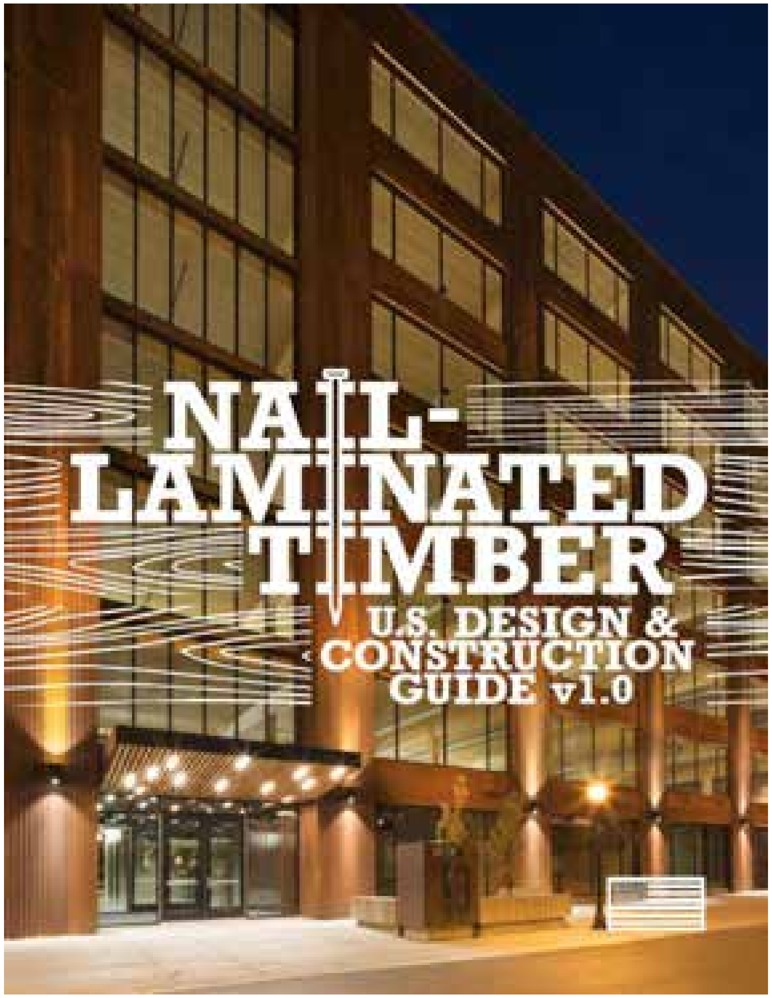
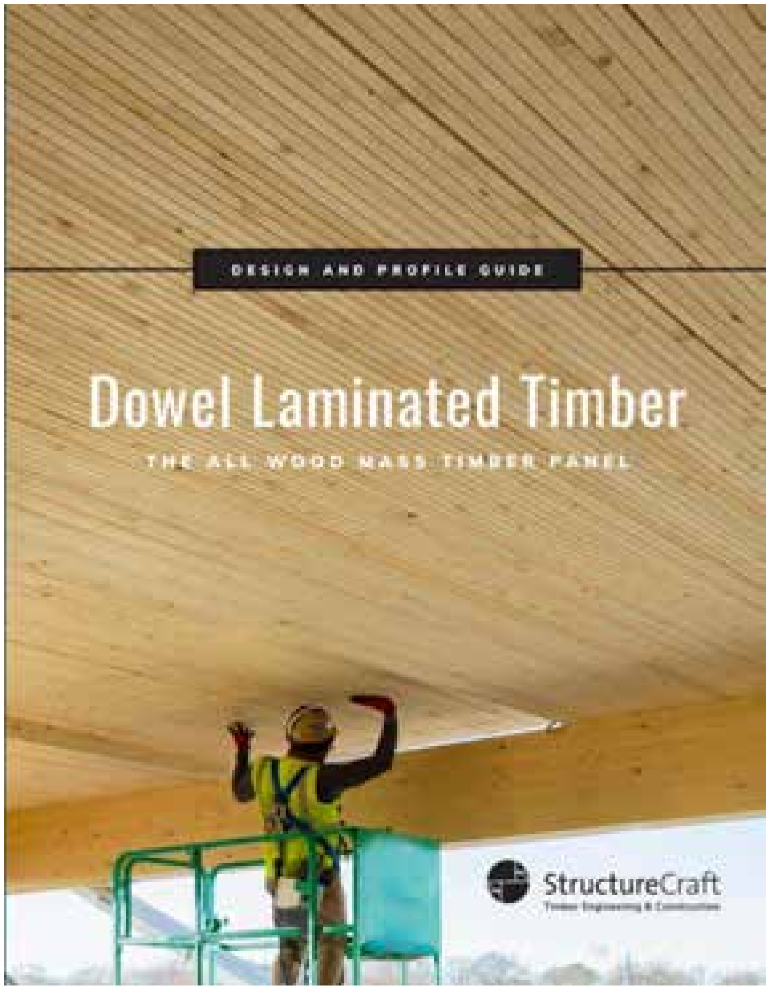
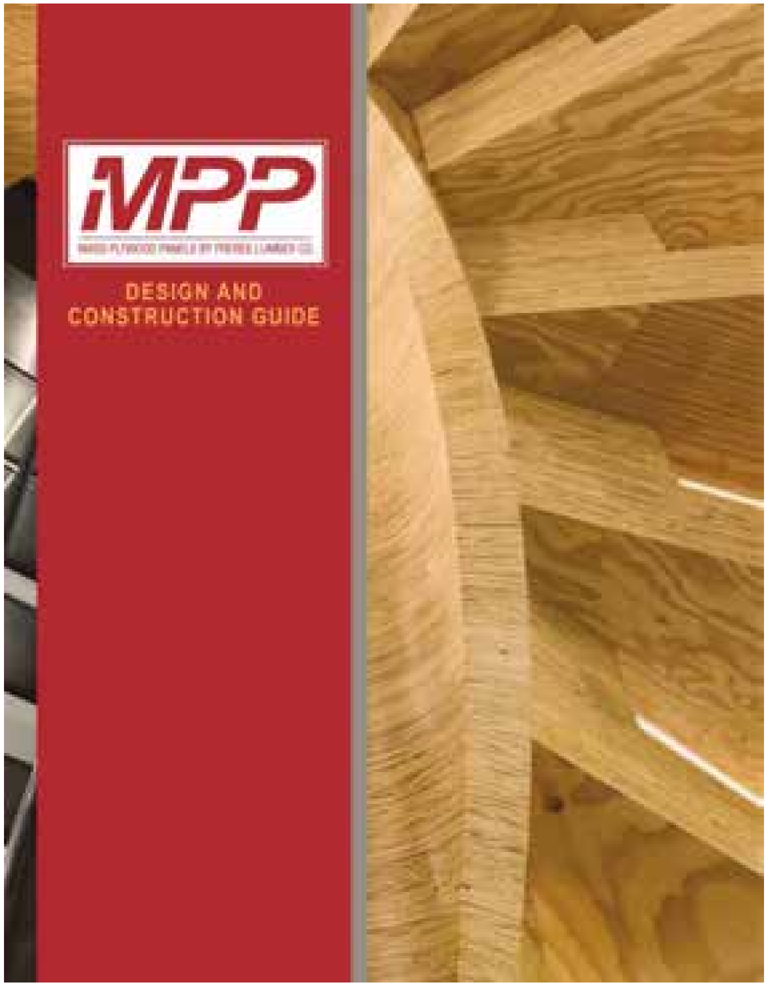


Nail Laminated Timber



Dowel Laminated Timber

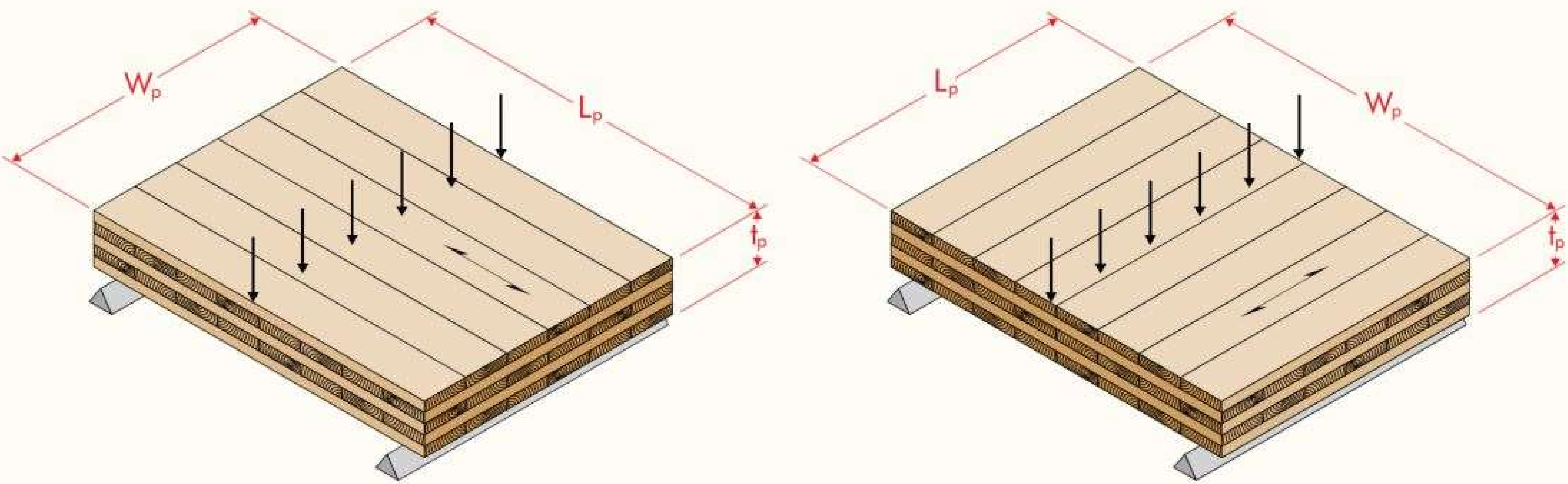


Mass Plywood Panel

GRAVITY DESIGN OF CLT

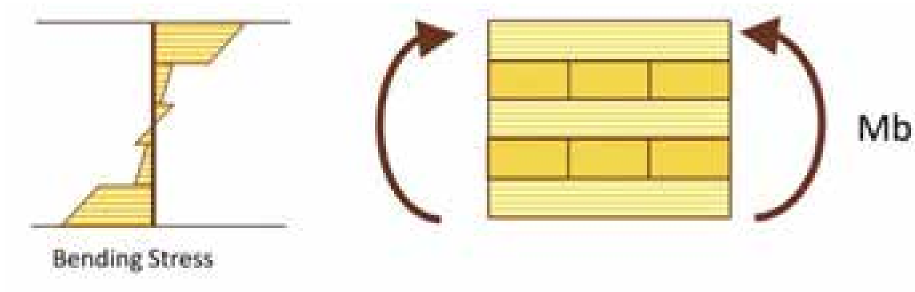
Strong Axis vs Weak Axis: CLT is Orthotropic

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



Source: ANSI/APA PRG 320

FLEXURAL STRENGTH



$$M_b \leq C_D C_M C_t C_L \left(F_b S_{eff} \right)$$

Per NDS

Typically = 1

Provided as combined value by manufacturer

$$M_b \leq C_D \left(F_b S_{eff} \right)$$

FLEXURAL STRENGTH

TABLE A2

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

CLT Layup	CLT t_p (in.)	Lamination Thickness (in.) in CLT Layup: =	⊥	=	⊥	=	⊥	=	Major Strength Direction: $(F_bS)_{eff,f,0}$ (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)	Minor Strength Direction: $(F_bS)_{eff,f,90}$ (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

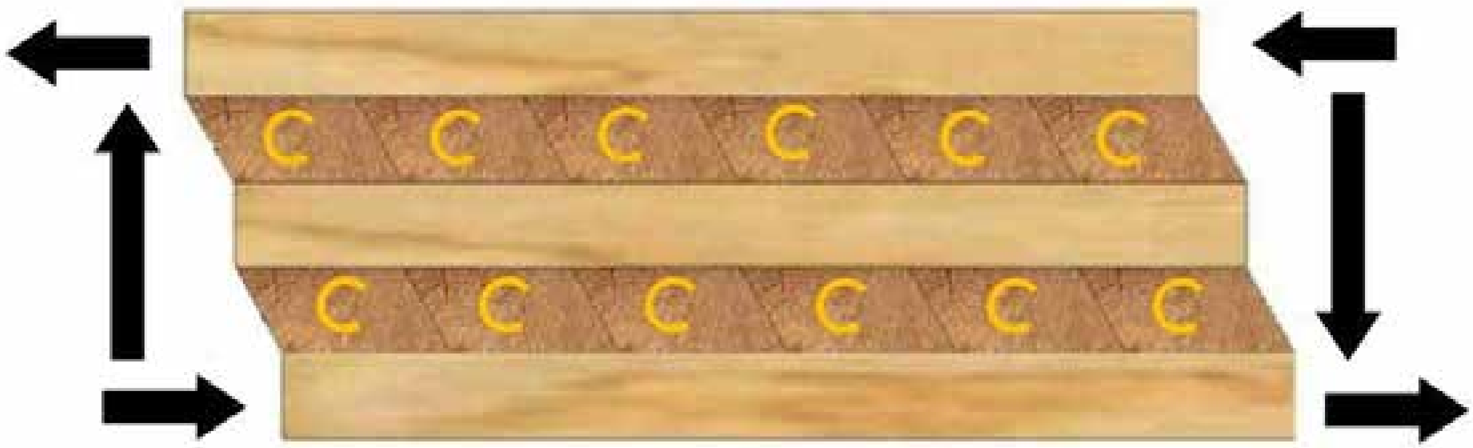
For SI: 1 in. = 25.4 mm; 1 ft = 304.8 mm; 1 lbf = 4.448 N

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.

SHEAR STRENGTH



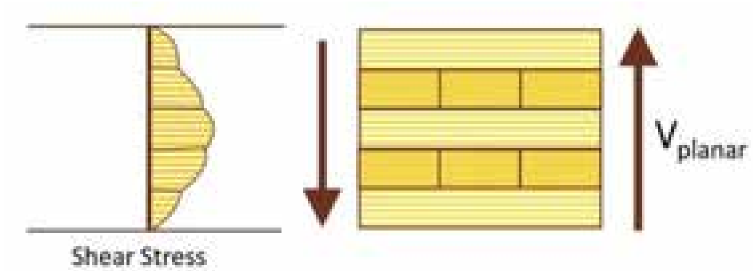
“Planar Shear” = “Out-of-plane Shear” = “Rolling Shear”

Wood Structural Panel Term

Structural Engineering Term

CLT Term

SHEAR STRENGTH



$$V_{planar} \leq C_M C_t \left(F_s (I_b Q)_{eff} \right) = 1.0\, V_s$$

$C_M C_t$: Typically = 1

$F_s (I_b Q)_{eff}$: Provided as combined value by manufacturer

$$V_{planar} \leq V_s$$

SHEAR STRENGTH

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	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
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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
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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
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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.

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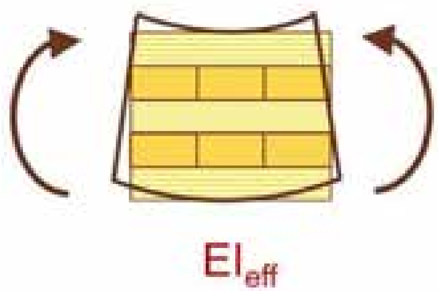
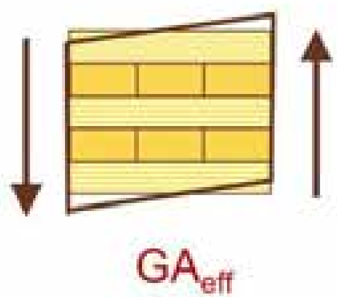
FLEXURE AND SHEAR DFFORMATIONS



$$(EI)_{eff,f,0} = \sum_{i=1}^{n} E_i b_0 \frac{t_i^3}{12} + \sum_{i=1}^{n} E_i b_0 t_i z_i^2$$



$$(GA)_{eff,f,0} = \frac{(t_p - \frac{t_1}{2} - \frac{t_n}{2})^2}{\left[\left(\frac{t_1}{2G_1 b_0}\right) + \left(\sum_{i=2}^{n-1} \frac{t_i}{G_i b_0}\right) + \left(\frac{t_n}{2G_n b_0}\right)\right]}$$

FLEXURE AND SHEAR DFFORMATIONS

TABLE A2

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

CLT Layup	CLT t_p (in.)	Lamination Thickness (in.) in CLT Layup							Major Strength Direction				Minor Strength Direction			
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	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
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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
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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.

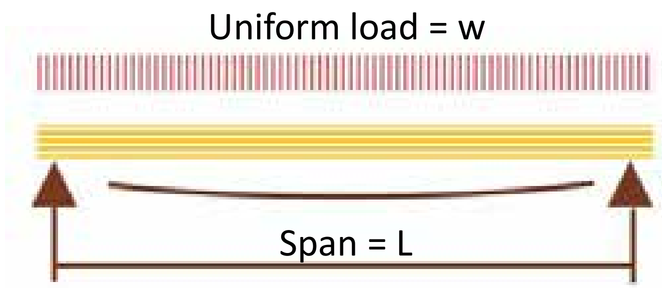
c. Custom CLT layups that are not listed in this table shall be permitted in accordance with 7.2.1.

FLEXURE AND SHEAR DEFORMATIONS

Example:

Short-term mid-span deflection of a uniformly loaded one-way slab

$$\Delta_{ST} = \frac{5}{384} \cdot \frac{wL^4}{EI_{eff}} + \frac{1}{8} \cdot \frac{wL^2}{{}^5/_6\, GA_{eff}}$$



FLEXURE AND SHEAR DEFORMATIONS

Example:

Short-term mid-span deflection of a uniformly loaded one-way slab

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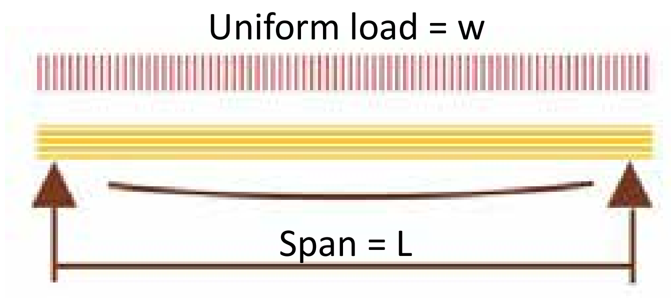


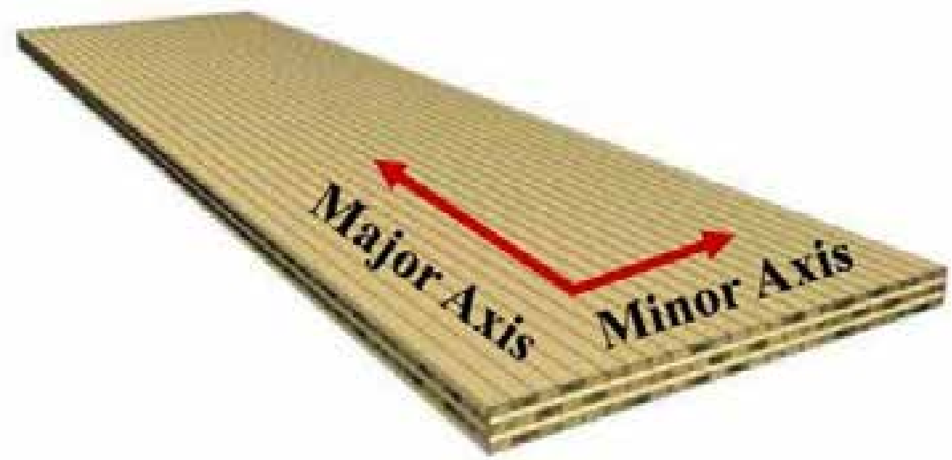
Long-term deflection

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

NDS Eq 3.5-1

Δ_{ST}	Deflection due to short term loading
Δ_{LT}	Immediate deflection due to long term loading
K_{cr}	Creep factor for CLT = 2.0 for dry service conditions

PROPERTIES FOR STRENGTH AND DEFORMATION



Flexural Strength:	$F_b S_{eff,0}$	$F_b S_{eff,90}$
Flexural Stiffness:	$EI_{eff,0}$	$EI_{eff,90}$
Shear Strength:	$V_{s,0}$	$V_{s,90}$
Shear Stiffness:	$GA_{eff,0}$	$GA_{eff,90}$

Values in RED provided by CLT manufacturer

DESIGN FOR VIBRATION

U.S. Building Code Requirements for Vibration:

NONE

Barely discussed in IBC, NDS, etc.
ASCE 7 Commentary Appendix C has some discussion, no requirements

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Floor Vibration Design Methods

Rules of Thumb → Empirical Methods → Simplified Analytical → FEM/Modal → FEM/Time History

- $\Delta < L/480$
- $f_n > 14$ Hz
- FPI / CLT Handbook
- New Mass Timber Design Guide (2020)
- AISC Design Guide 11 (Steel)
- SCI P354 (Steel)
- CCIP 016 (Concrete)
- CRSI Design Guide 10 (Concrete)

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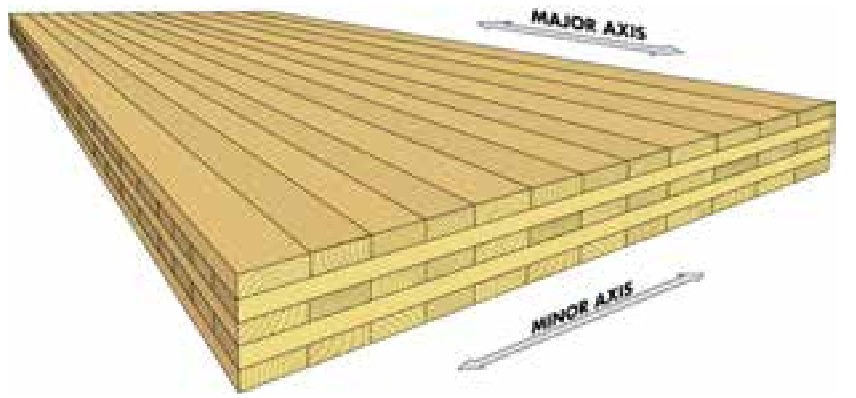
One possible approach to vibration analysis:
U.S. CLT Handbook, Chapter 7 (FPI Method)

Limit CLT Floor Span such that:

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



Based on:
- Un-topped CLT
- Single, simple span
- Bearing wall supports

FPI Span Limits for Basic CLT Grades / Layups

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"

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"

Approximate rules of thumb based on FPI Span Limits:

- **3-ply: 11 to 12 ft**
- **5-ply: 16 to 17 ft**
- **7-ply: 20 to 21 ft**

These span limits do not account for:

- **Strength or deflection limits**
- **Effect of beam flexibility on vibration**
- **Effect of panel continuity on vibration**

Slide content by Scott Breneman and WoodWorks

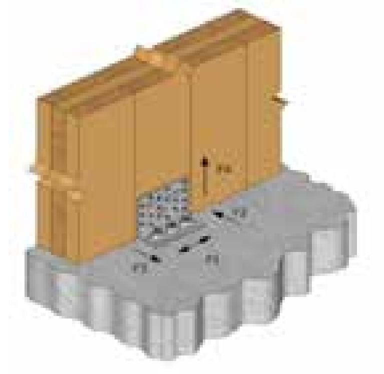
MASS TIMBER CONNECTIONS

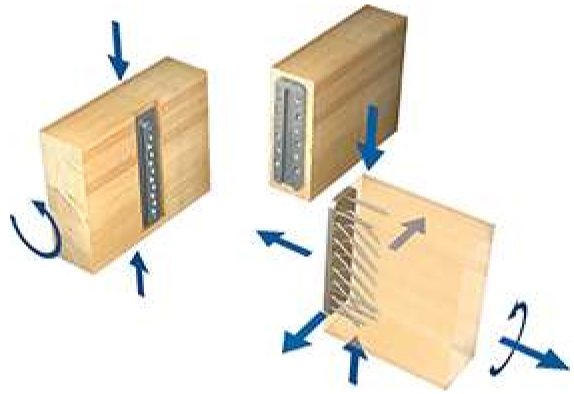
Photo: Eric Mortenson / Capital Press

Long self-tapping screws used extensively in mass timber construction

Connection “Classes”

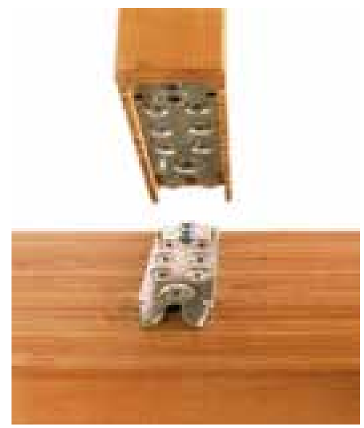
Simple Bearing





Custom Steel

Proprietary - Exposed

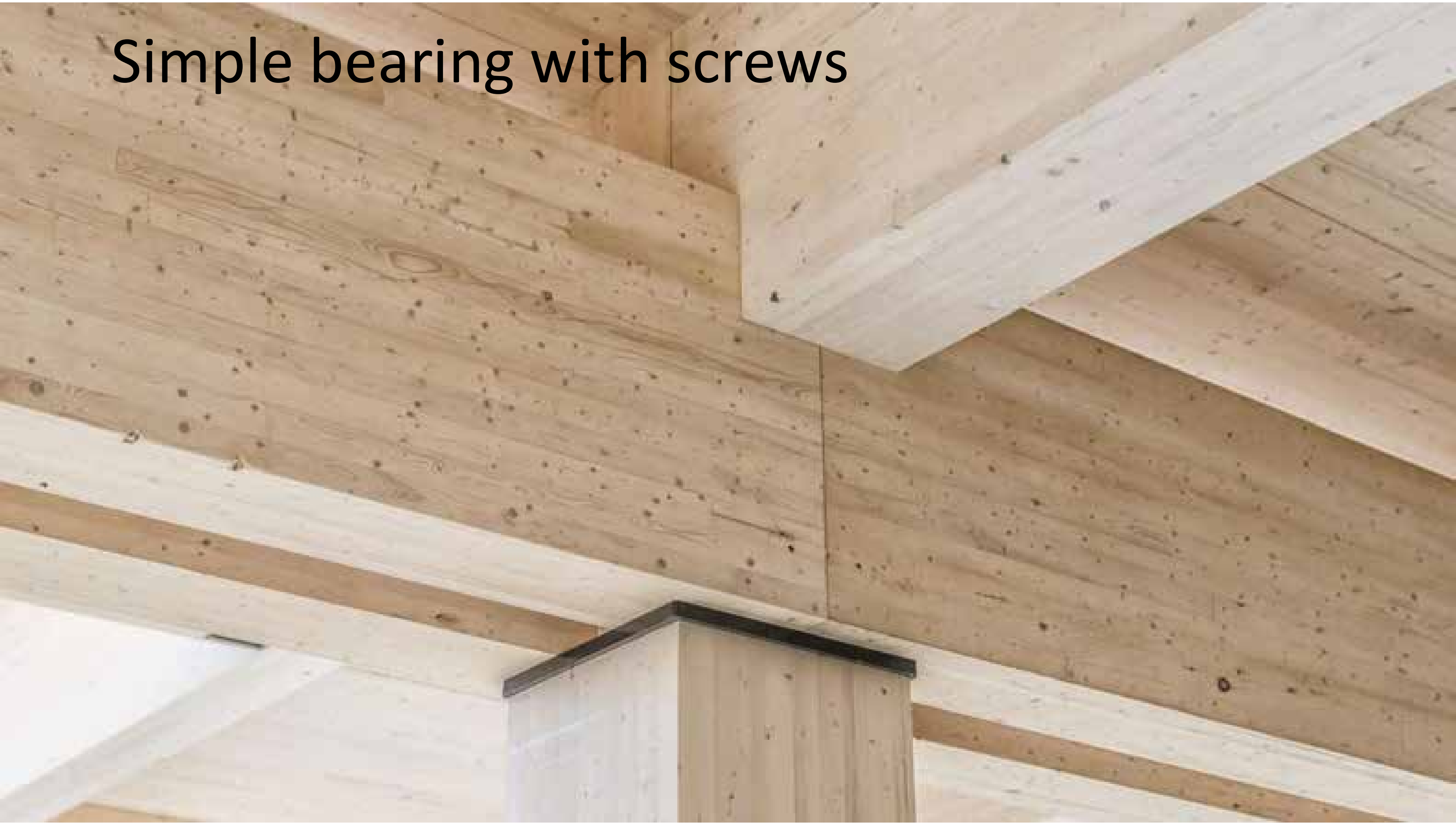


Proprietary - Concealed

Photo Credit: myticon

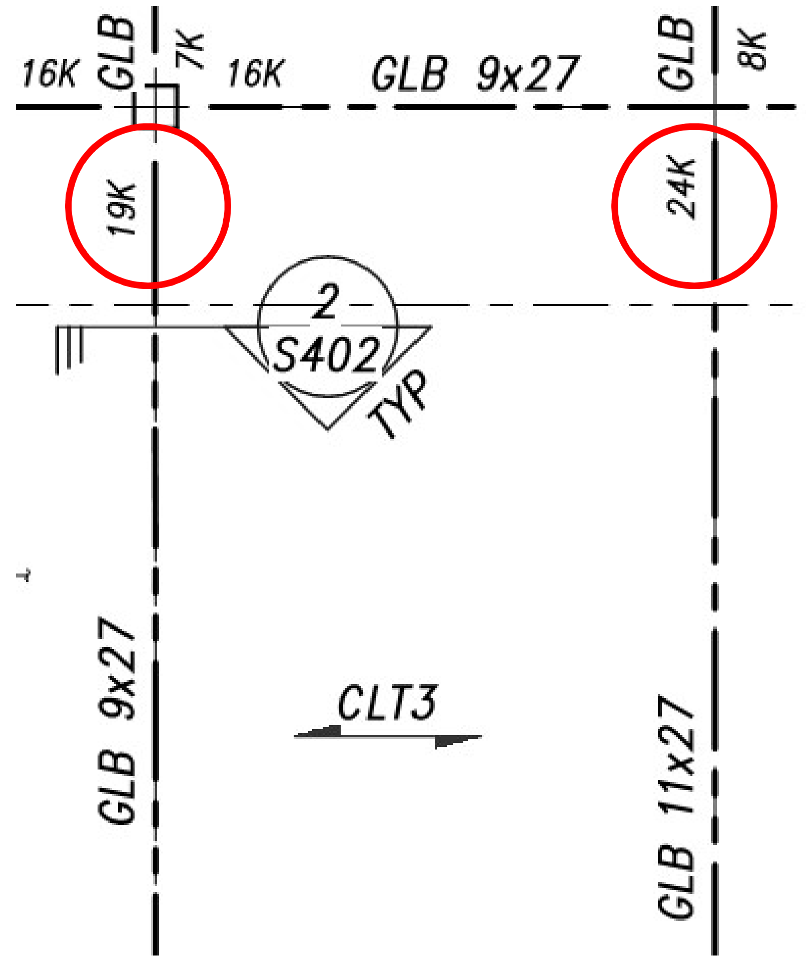
Panel to beam connections

Simple bearing with screws



Connection Considerations For Mass Timber

High Loads



Connection Considerations For Mass Timber

High Loads Parallel to Grain

Connection Considerations For Mass Timber

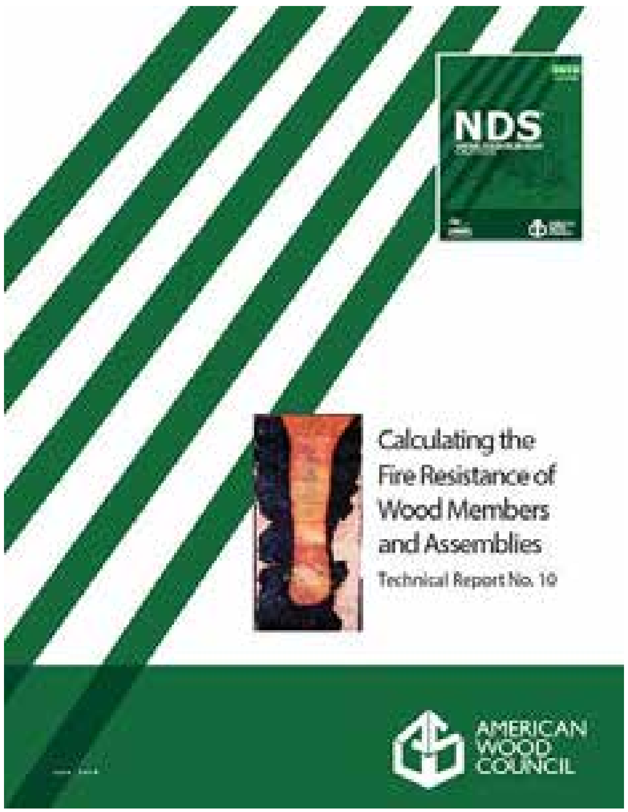
Aesthetics

Connection Considerations For Mass Timber

Shrinkage

Connection Considerations For Mass Timber

Fire Ratings

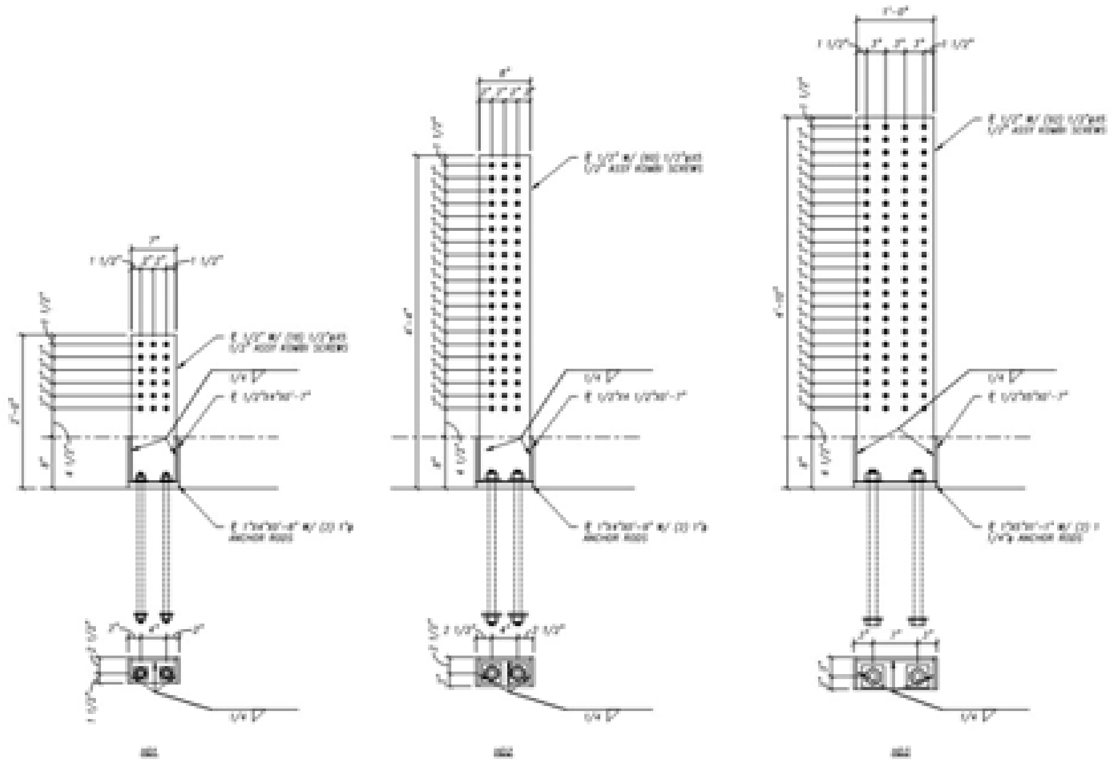


CLT SHEAR WALLS

3-Story, small building maxed out potential of rigid CLT shear walls.

Next step: rocking walls

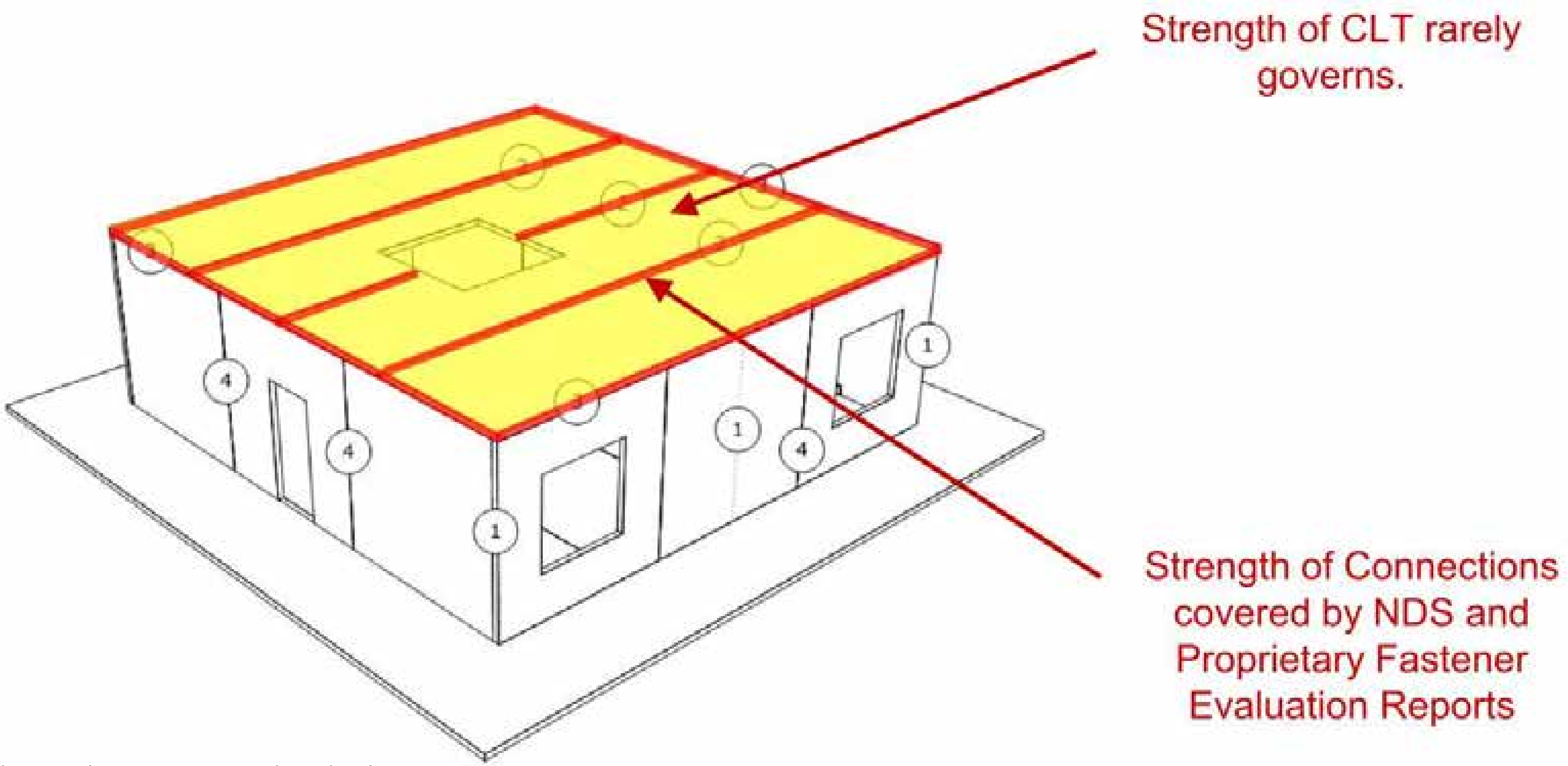
Significant Hold-down Forces



2 CLT SHEARWALL HOLD DOWNS
1" = 1'-0"

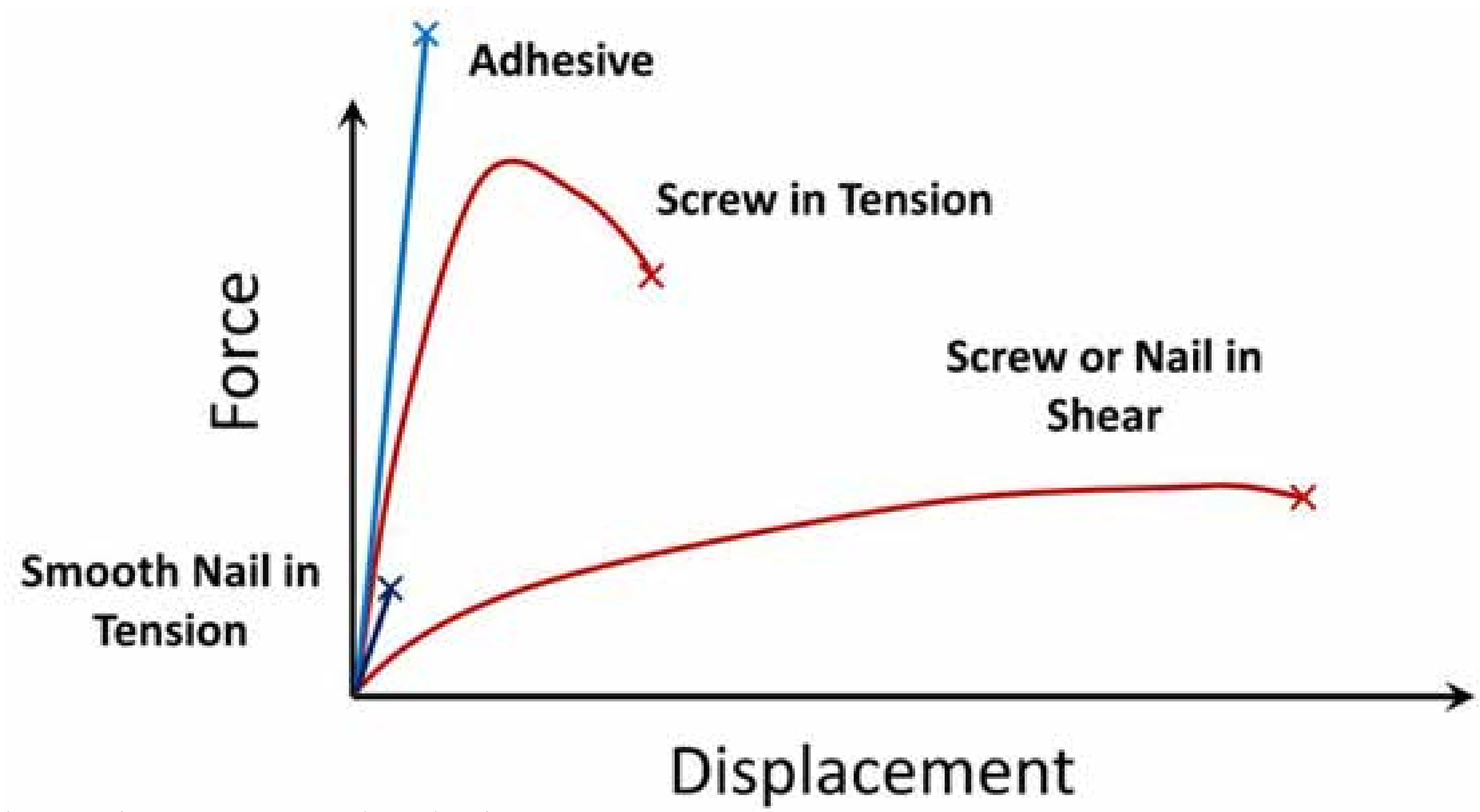

CLT DIAPHRAGMS

CLT Diaphragm design not yet codified

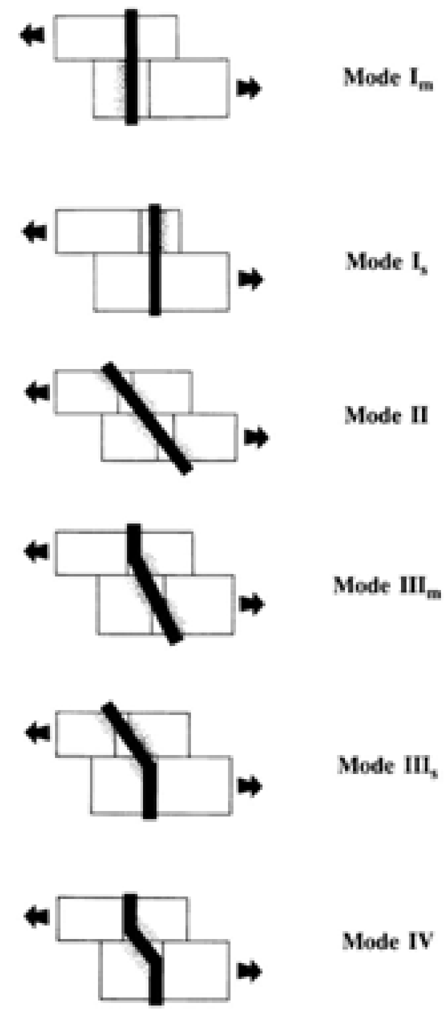


Slide content by Scott Breneman and WoodWorks

Suggestion: Diaphragm **shear connections** at CLT panel edges and diaphragm boundary connections should be designed to ensure that the connection capacity is limited by ductile fastener yielding in accordance with **Mode IIIs** or **Mode IV** per NDS 12.3.1



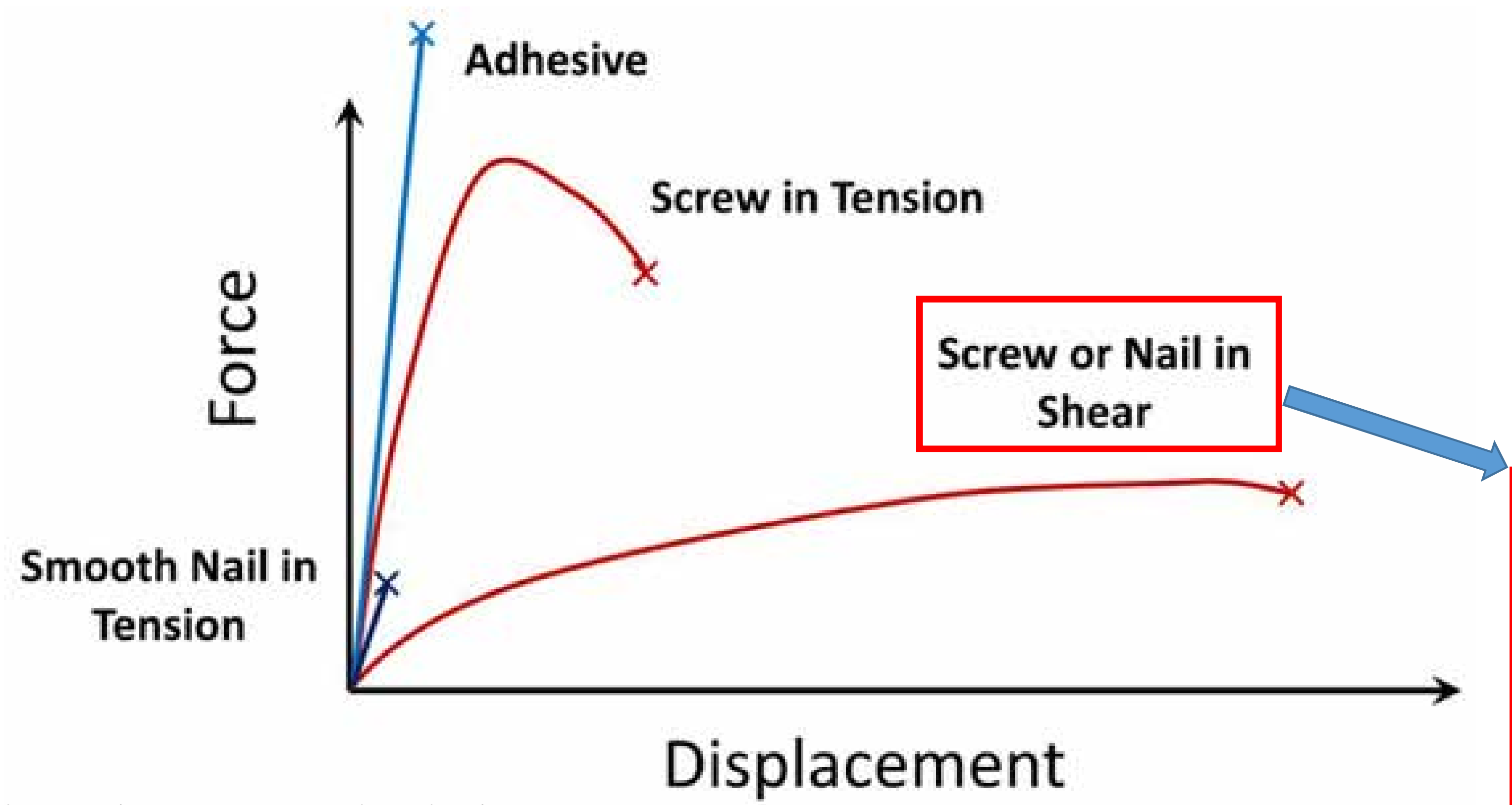
Single Shear Connections

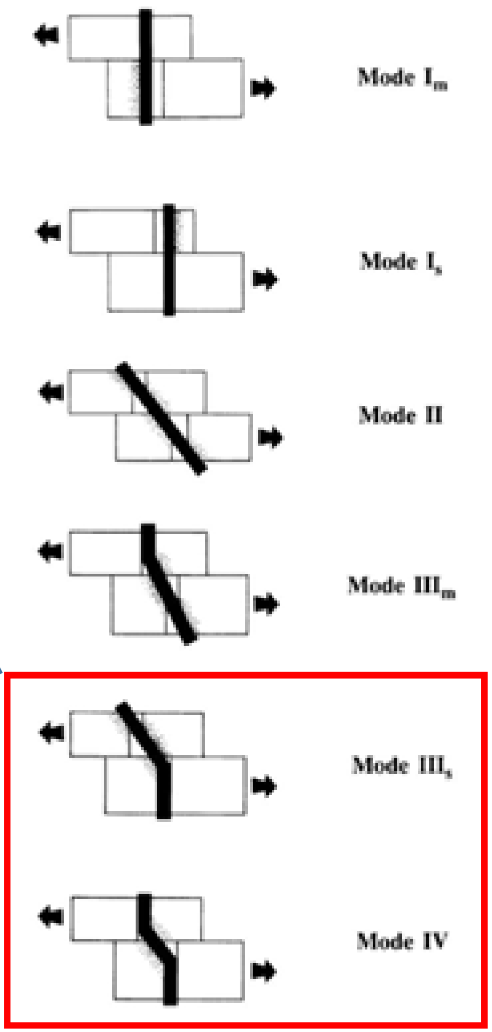


Slide content by Scott Breneman and WoodWorks

Suggestion: Diaphragm **shear connections** at CLT panel edges and diaphragm boundary connections should be designed to ensure that the connection capacity is limited by ductile fastener yielding in accordance with **Mode IIIs** or **Mode IV** per NDS 12.3.1

Single Shear Connections





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Half-lap Panel-Panel Connection

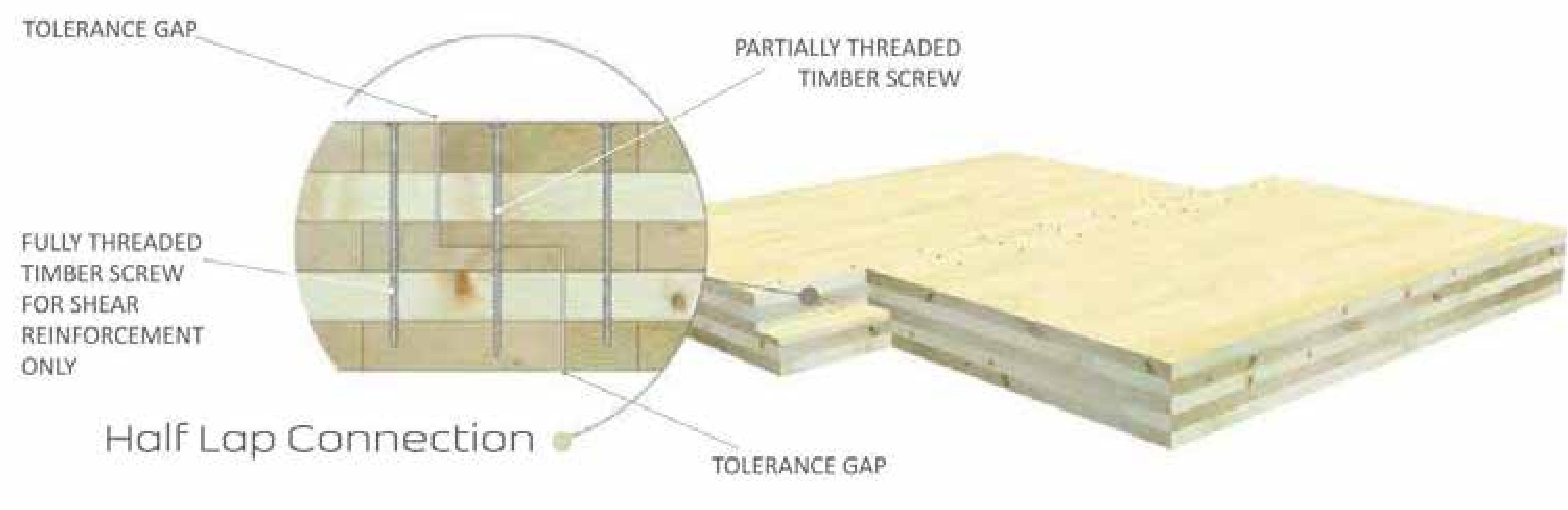


Image: Structurlam

Spline Panel-Panel Connection

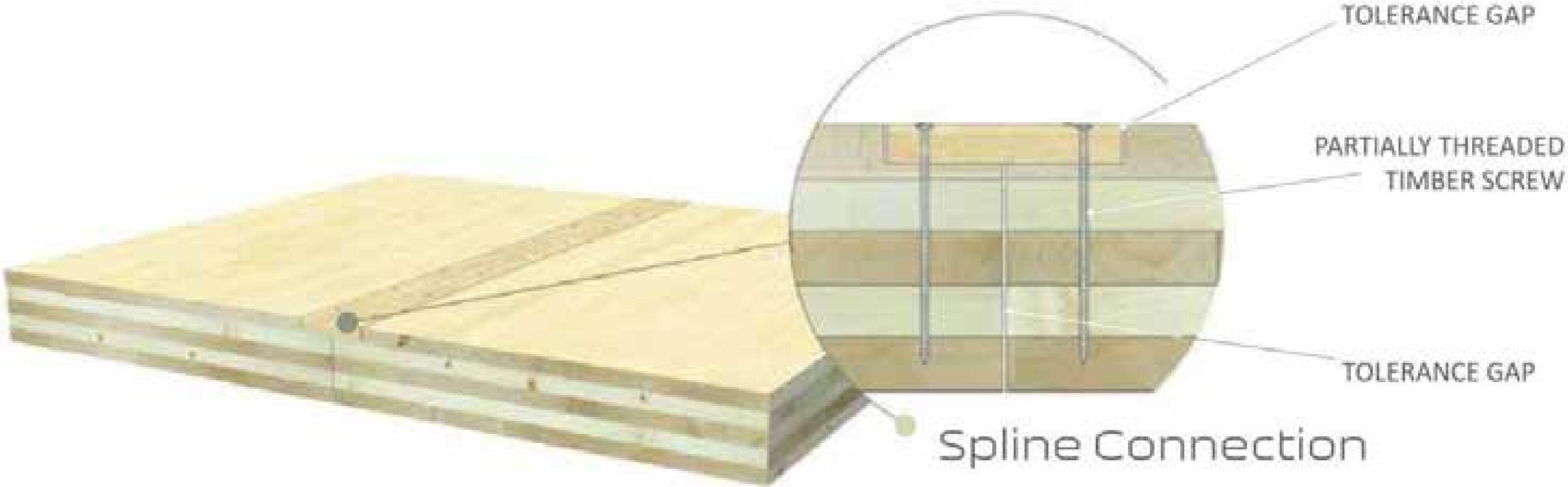
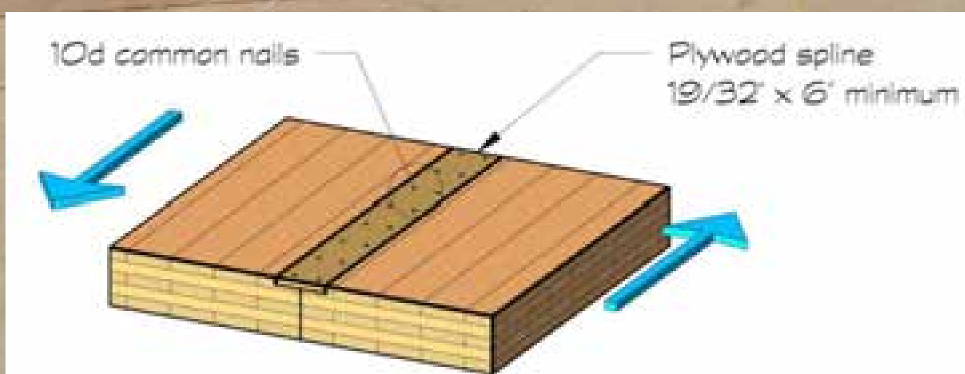


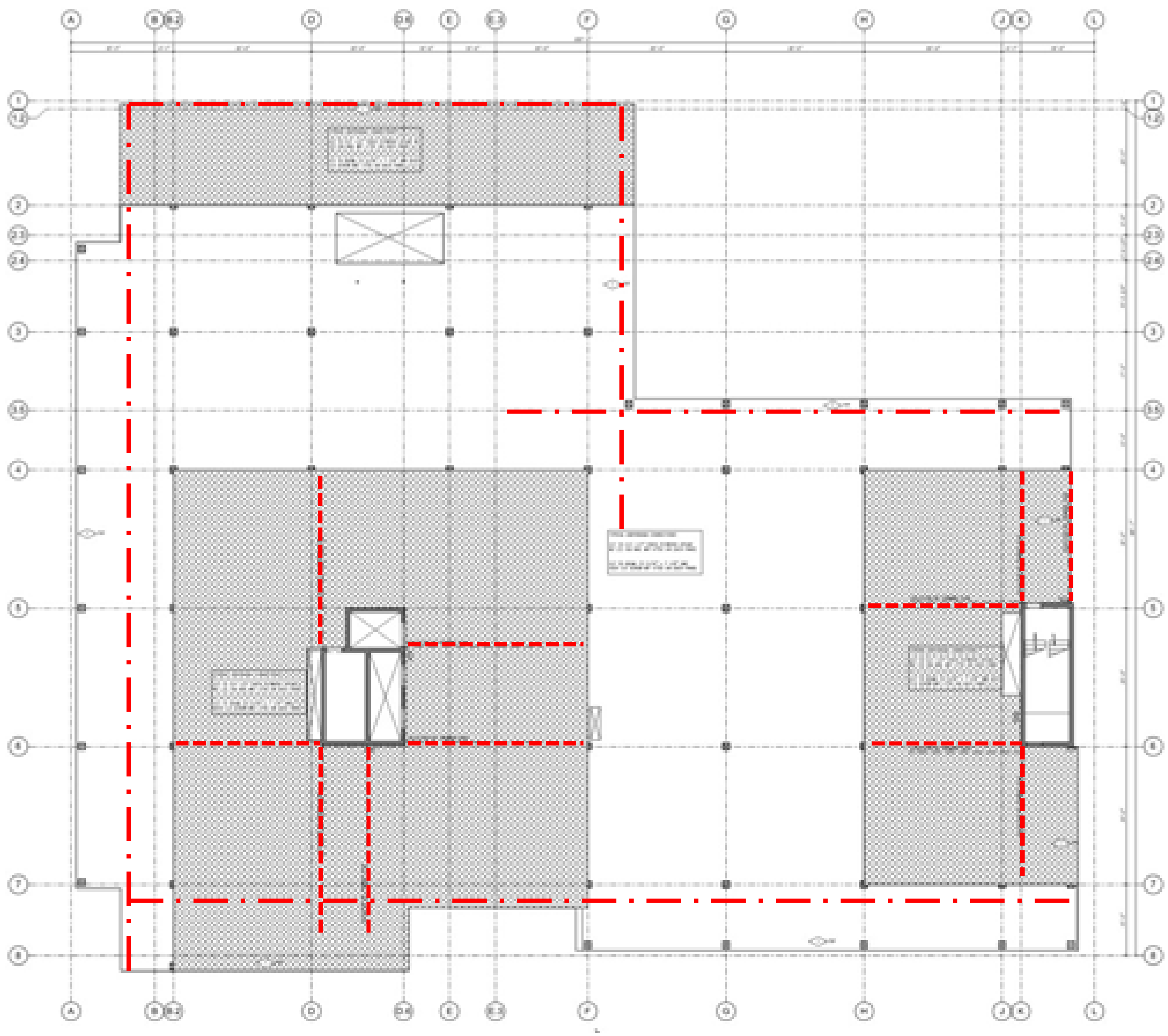
Image: Structurlam

NAILED SPLINE CONNECTION AT CLT DIAPHRAGM

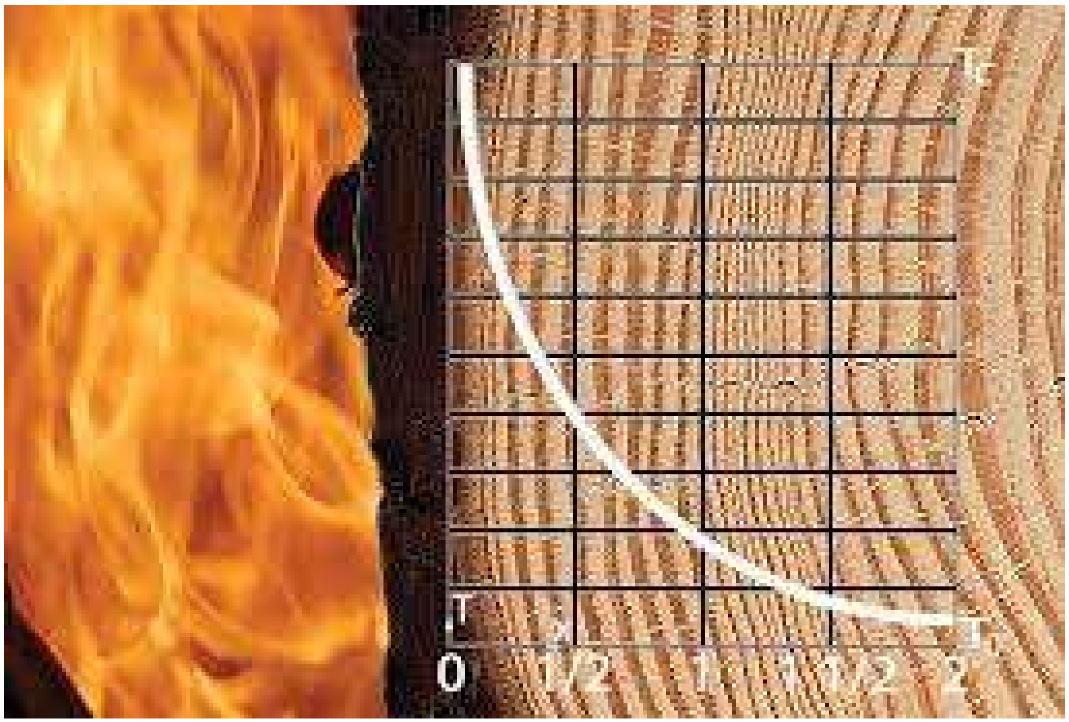


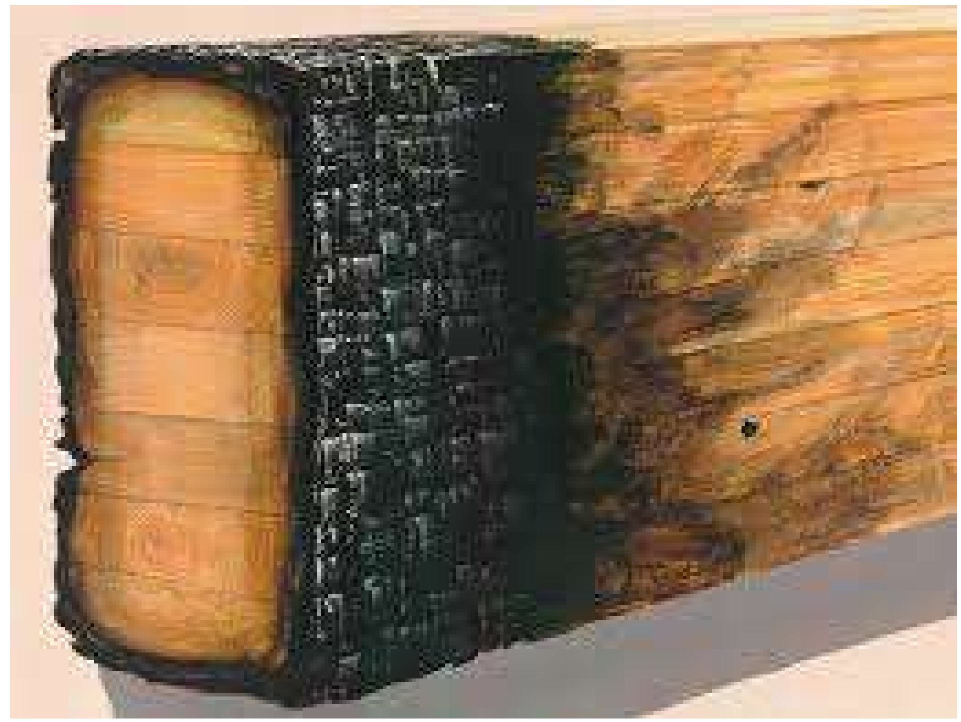
Spline Thickness	10d 6"o.c.	10d 4"o.c.	10d 2 ½"o.c.	2 rows 10d 4"o.c.	2 rows 10d 2 ½"o.c.
			Wind		
$^{19}/_{32}$"	505	672	1007		
$^{23}/_{32}$"				995	1427
			Seismic		
$^{19}/_{32}$"	360	480	720		
$^{23}/_{32}$"				710	1020

Diaphragm chords and collectors




FIRE RESISTANCE





Mass wood has inherent fire resistant rating

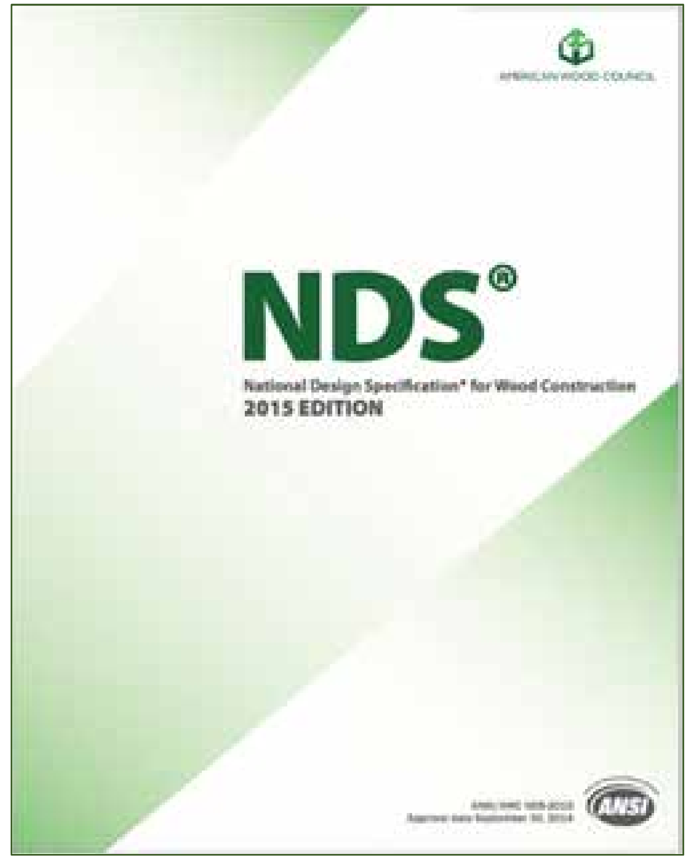
MT Fire Resistance Ratings (FRR)

NDS Chapter 16 addresses FRR of NLT, CLT, Glulam, Solid Sawn and SCL wood products

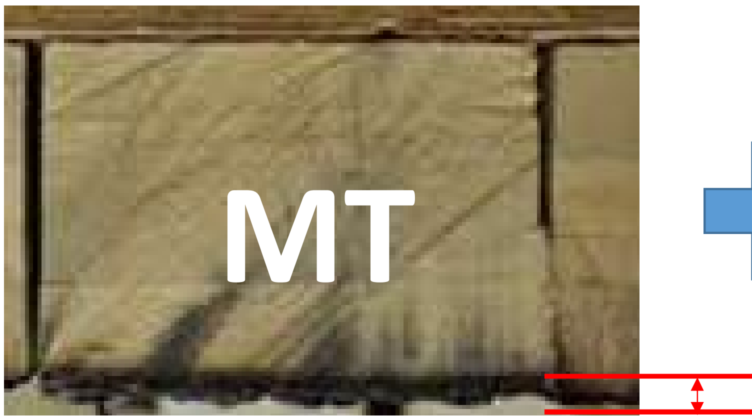
$$\beta_{eff} = \frac{1.2\beta_n}{t^{0.187}}$$

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

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



MT Fire Resistance Ratings (FRR)



+

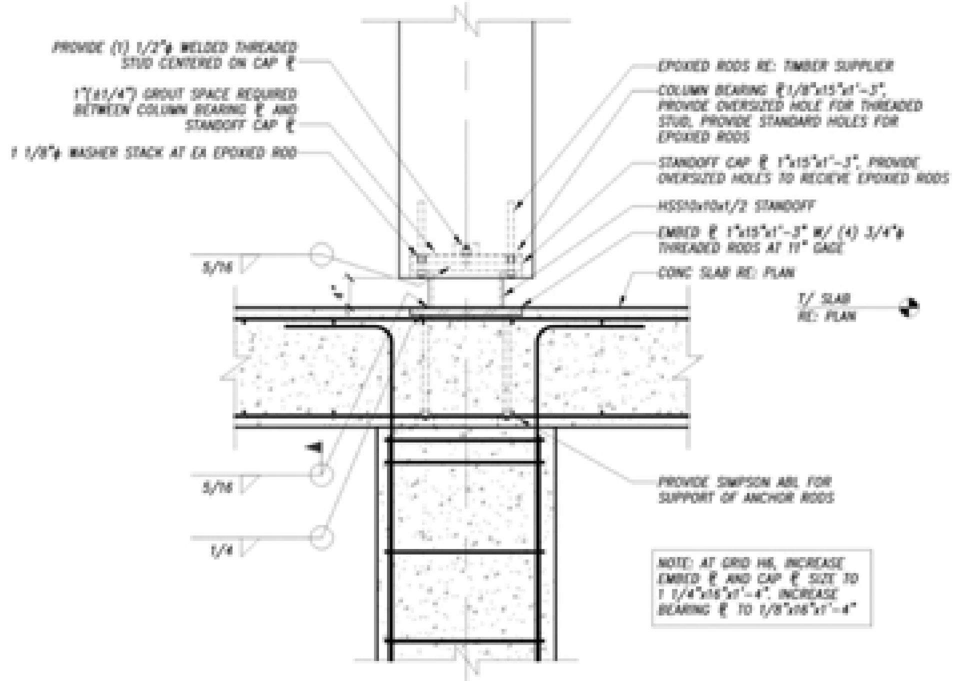
= FRR

IBC 722.7
The fire resistance rating of the mass timber elements shall consist of the fire resistance of the unprotected element (MT) added to the protection time of the noncombustible (NC) protection

DU Burwell Center for Career Achievement, Denver, Colorado

Photo Credit: Shears Adkins Rockmore Architects

CONSTRUCTABILITY
Photo Credit: KL&A


PROVIDE (1) 1/2"ɸ WELDED THREADED STUD CENTERED ON CAP ℄
1"(±1/4") GROUT SPACE REQUIRED BETWEEN COLUMN BEARING ℄ AND STANDOFF CAP ℄
1 1/8"ɸ WASHER STACK AT EA EPOXIED ROD
EPOXIED RODS RE: TIMBER SUPPLIER
COLUMN BEARING ℄1/8"x15"x1'-3", PROVIDE OVERSIZED HOLE FOR THREADED STUD, PROVIDE STANDARD HOLES FOR EPOXIED RODS
STANDOFF CAP ℄ 1"x15"x1'-3", PROVIDE OVERSIZED HOLES TO RECIEVE EPOXIED RODS
HSS10x10x1/2 STANDOFF
EMBED ℄ 1"x15"x1'-3" W/ (4) 3/4"ɸ THREADED RODS AT 11" GAGE
CONC SLAB RE: PLAN
T/ SLAB RE: PLAN
5/16
5/16
1/4
PROVIDE SIMPSON ABL FOR SUPPORT OF ANCHOR RODS
NOTE: AT GRID H6, INCREASE EMBED ℄ AND CAP ℄ SIZE TO 1 1/4"x16"x1'-4". INCREASE BEARING ℄ TO 1/8"x16"x1'-4"

CONCLUSIONS

Photo Credit: JC Buck

CONCLUSIONS

1. Materials – Are not commodities
2. Gravity Load Design – For strength rarely governs
3. Deflection and Vibration – Often govern floor design
4. Connections – Are cost drivers
5. Lateral Load Design – Is still evolving in the code
6. Fire Resistance – Is part of structural design
7. Constructability – Is key to economy

Photo Credit: JC Buck

QUESTIONS?

Photo Credit: JC Buck

Greg Kingsley
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