Mass Timber Structural Design: Engineering Modern Timber Structures

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Photo: Alex Schreyer

Bullitt Center

Seattle, WA

2x4 NLT roof deck

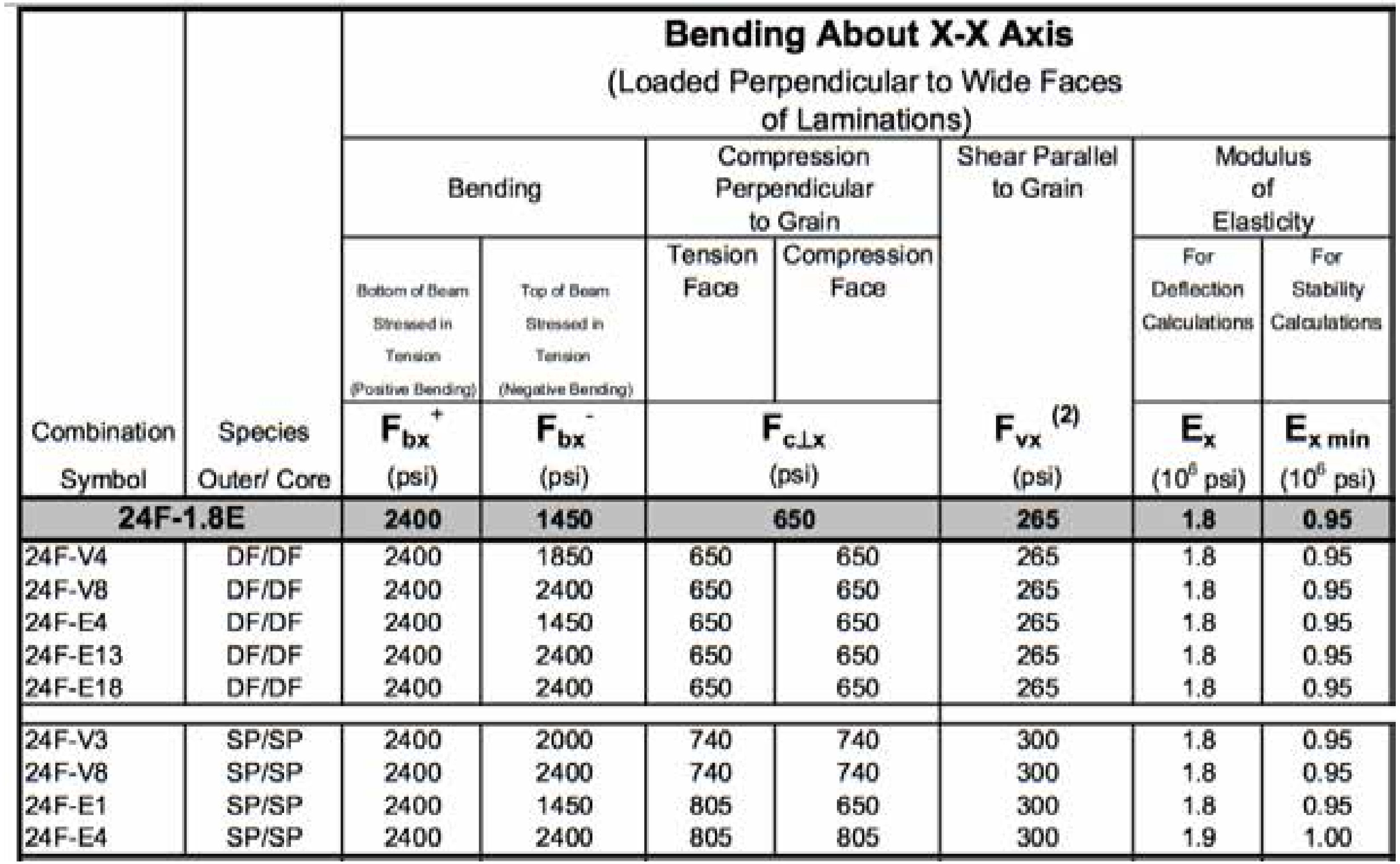
2x6 NLT floor deck

Floor assembly top to bottom:

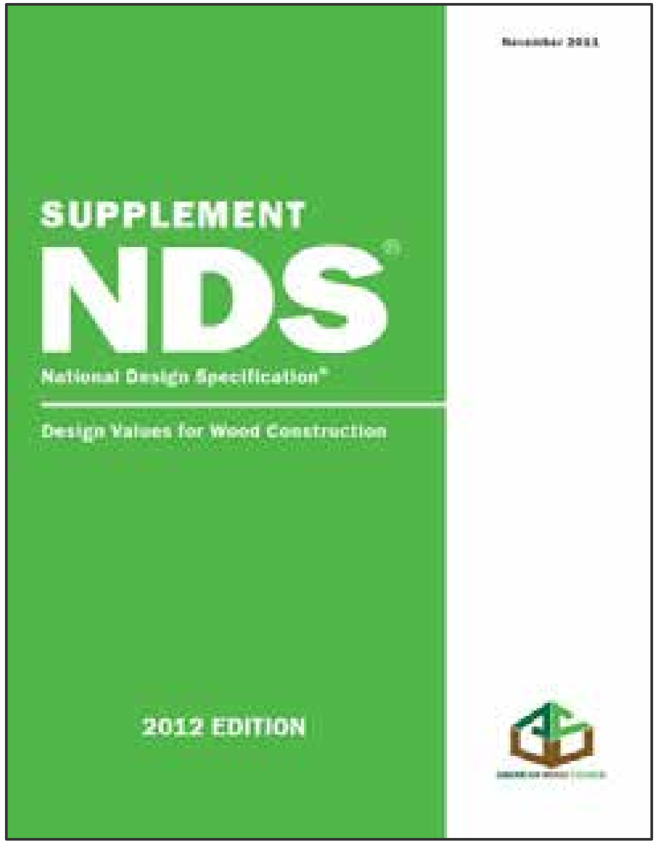
3” concrete topping, acoustical mat, WSP, 2x6 NLT

Photo Credit: John Stamets

Glulam Design Values



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



November 2011

SUPPLEMENT

NDS®

National Design Specification®

Design Values for Wood Construction

2012 EDITION

Source: NDS supplement Table 5A

Mass timber design

Fire resistance

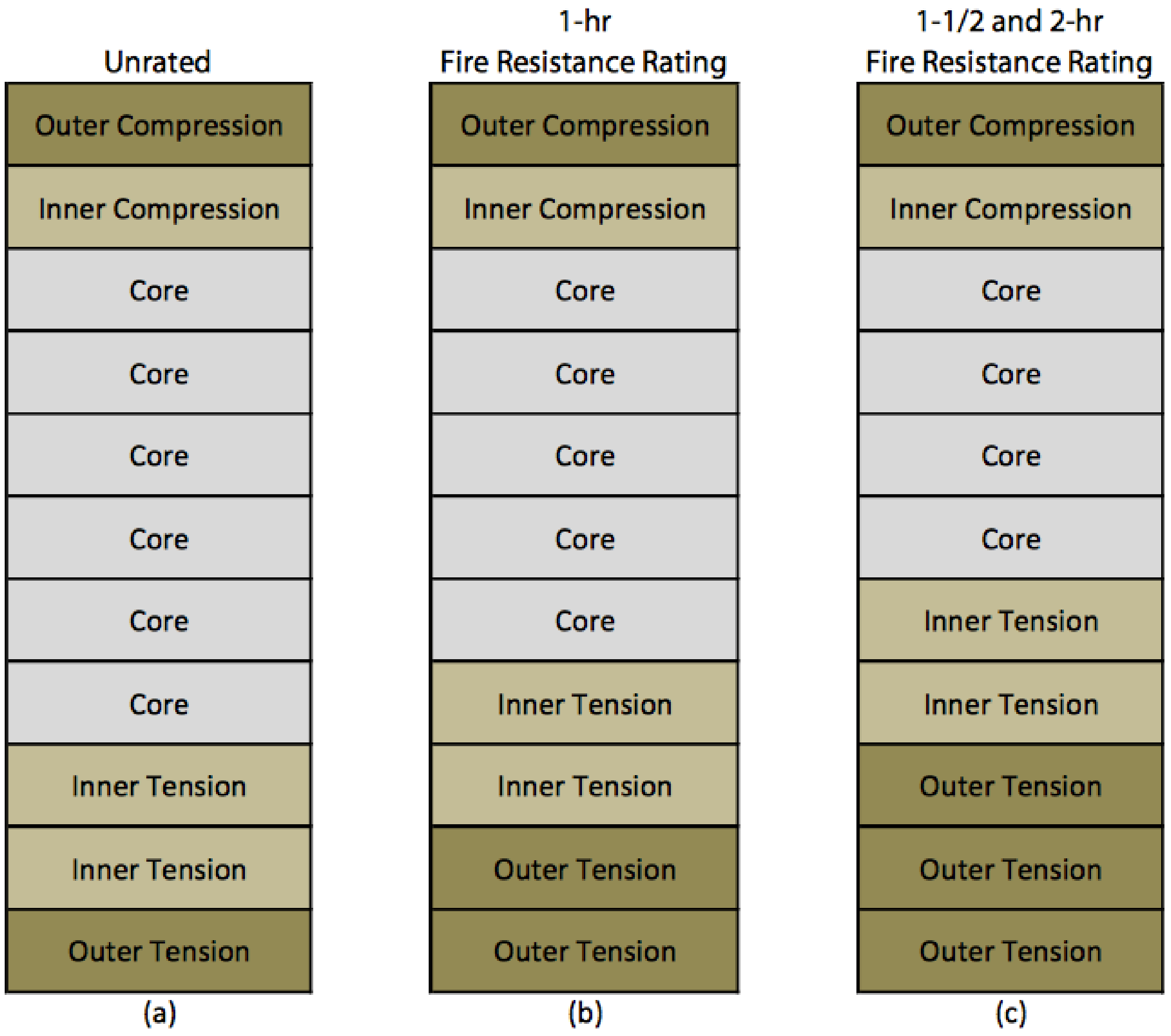


Figure 3-1 Typical glulam unbalanced beam layups

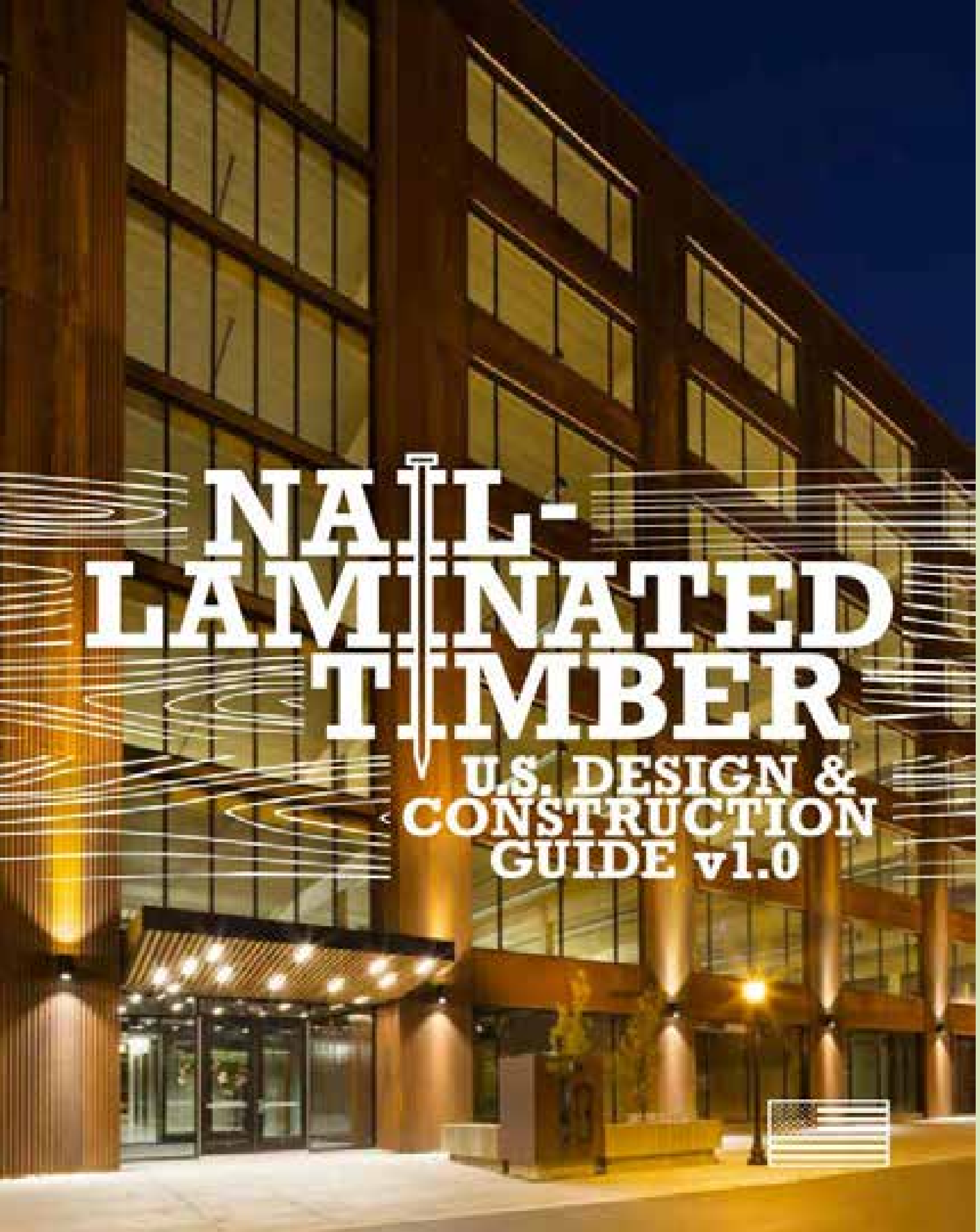
Glulam beam fire design:

- For unbalanced beams, Substitute 1 core lam for 1 tension lam for 1 hour rating, 2 core lams for 2 tension lams for 1.5 & 2 hour rating
- For balanced beams, match on compression side

NLT Structural Design

NLT shrinkage/expansion design:

Rule of thumb: leave gap between ½” and one ply wide per 8’-10’ wide panel



NLT Structural Design

NLT Design Guide includes:

- Architecture
- Fire
- Structure
- Enclosure
- Supply and Fabrication
- Construction and Installation
- Erection engineering

Free download from www.thinkwood.com

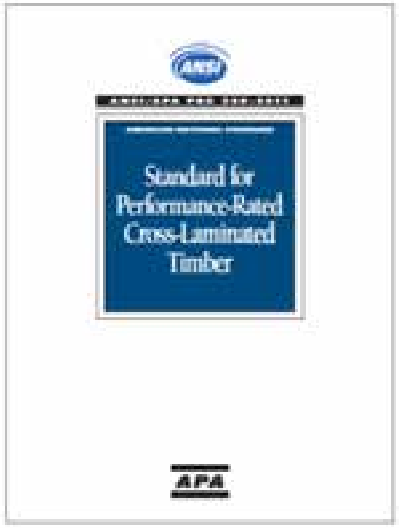
Cross Laminated Timber

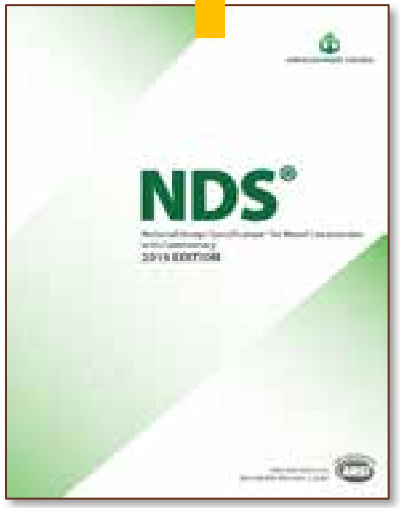
Considerations:

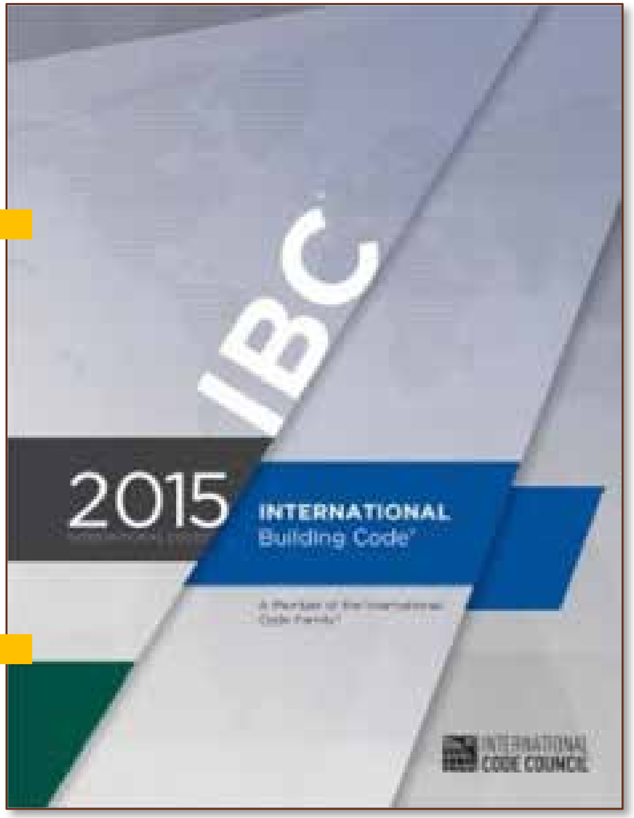
- Large light-weight panels
- Dimensionally stable
- Precise CNC machining available
- Recognized by IBC
- Dual Directional span capabilities
- Often architecturally exposed
- Fast on-site construction

Graphic Credit: StructureCraft

Building Code Acceptance of CLT





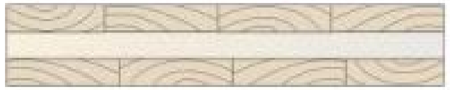


2015 International Building Code

Common CLT Layups

Most Designs
Least $/sf

3-ply 3-layer

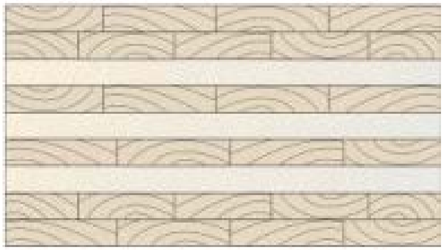


5-ply 5-layer

7-ply 7-layer

7-ply 5-layer

9-ply 9-layer



9-ply 7-layer

PRG 320 Defined Layups

CLT Grade (basic)

Layup

Panel Properties

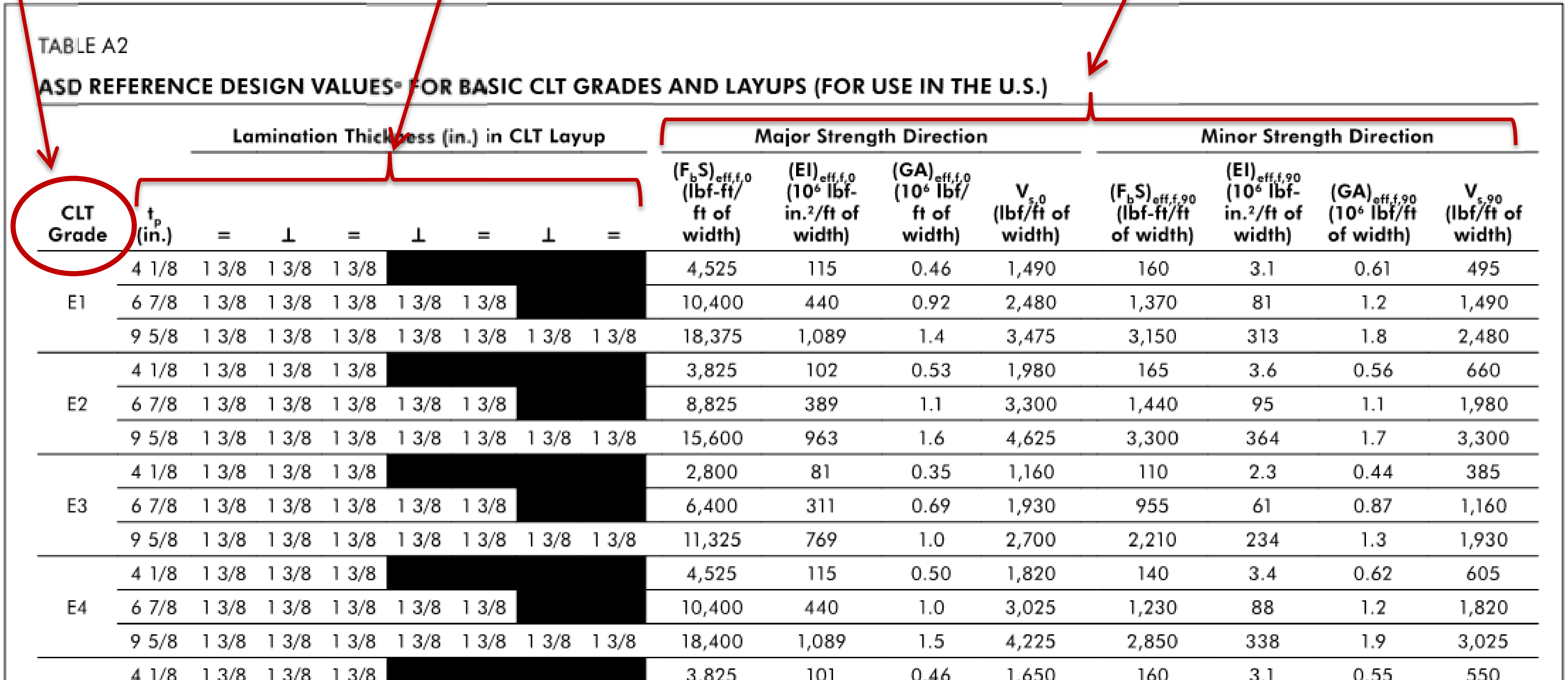


TABLE A2

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

CLT Grade	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	1,490	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	2,480	1,370	81	1.2	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	18,375	1,089	1.4	3,475	3,150	313	1.8	2,480
E2	4 1/8	1 3/8	1 3/8	1 3/8					3,825	102	0.53	1,980	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	3,300	1,440	95	1.1	1,980
	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	4,625	3,300	364	1.7	3,300
E3	4 1/8	1 3/8	1 3/8	1 3/8					2,800	81	0.35	1,160	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	1,930	955	61	0.87	1,160
	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	2,700	2,210	234	1.3	1,930
E4	4 1/8	1 3/8	1 3/8	1 3/8					4,525	115	0.50	1,820	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	3,025	1,230	88	1.2	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	18,400	1,089	1.5	4,225	2,850	338	1.9	3,025
	4 1/8	1 3/8	1 3/8	1 3/8					3,825	101	0.46	1,650	160	3.1	0.55	550

3rd Party Product Qualification of CLT

APA PRODUCT REPORT

DRJ Cross-Laminated Timber
Riddle Laminators, Inc.

PR-L320
Issued January 25, 2017

Products: DRJ Cross-Laminated Timber

APA PRODUCT REPORT

Structurlam CrossLam
Structurlam Products LP

PR-L314
Revised May 9, 2016

Products: Structurlam CrossLam Cross-Laminated Timber
Structurlam Products LP
2176 Government Street

ICC EVALUATION SERVICE

Most Widely Accepted and Trusted

ICC-ES Report

ESR-3631

DIVISION: 06 00 00—WOOD, PLASTICS AND COMPOSITES
SECTION: 06 17 19—CROSS-LAMINATED TIMBER

REPORT HOLDER:

STRUCTURLAM PRODUCTS LP

2176 GOVERNMENT STREET
PENTICTON, BRITISH COLUMBIA V2A 8B5
CANADA

EVALUATION SUBJECT:

STRUCTURLAM CROSSLAM® CLT

APA PRODUCT REPORT

SmartLam Cross-Laminated Timber
SmartLam, LLC

PR-L319
Revised August 15, 2017

Products: SmartLam Cross-Laminated Timber

APA PRODUCT REPORT

Nordic X-Lam
Nordic Structures

PR-L306
Revised March 26, 2016

Products: Nordic X-Lam
Nordic Structures
1100 Avenue des Canadiens-de-Montréal, Suite 504

Intertek

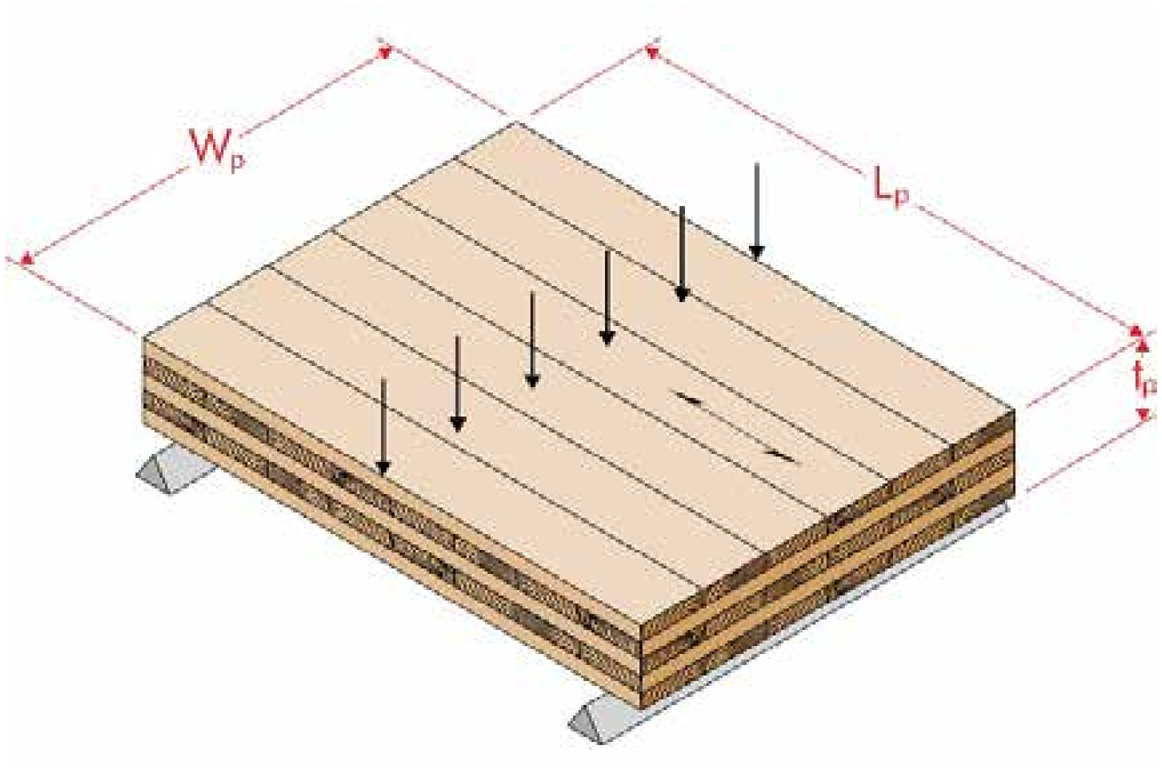
LISTING INFORMATION OF KLH Massivholz GmbH – Massivholzplatten (solid wood slabs) CLT

SPEC ID: 36204

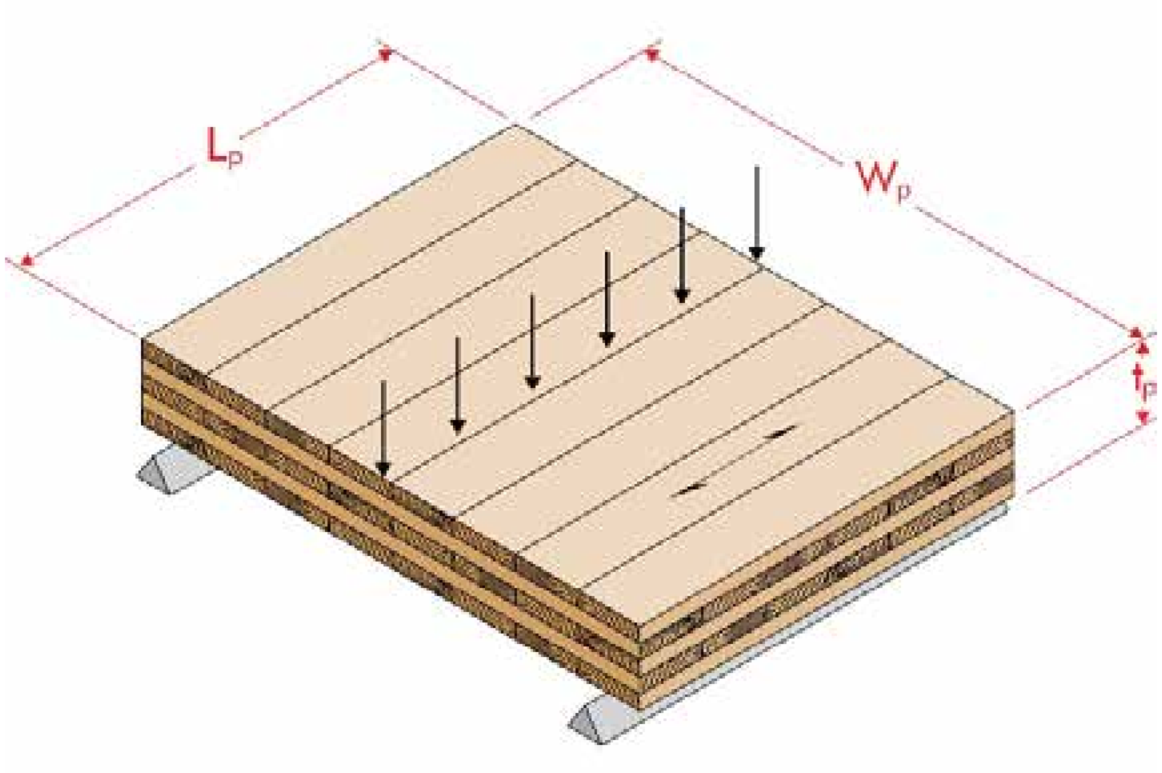
KLH Massivholz GmbH
Katsch an der Mur 202

Teufenbach-Katsch, A-8842
Austria

FLATWISE Panel Loading



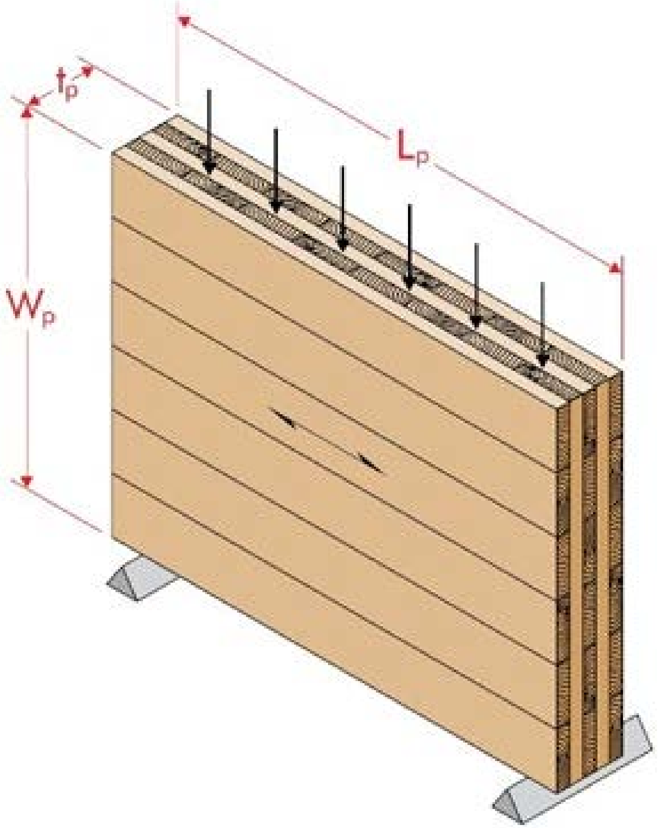
Span in MAJOR Strength Direction
"Parallel" Direction
Use subscript '0' in Notation



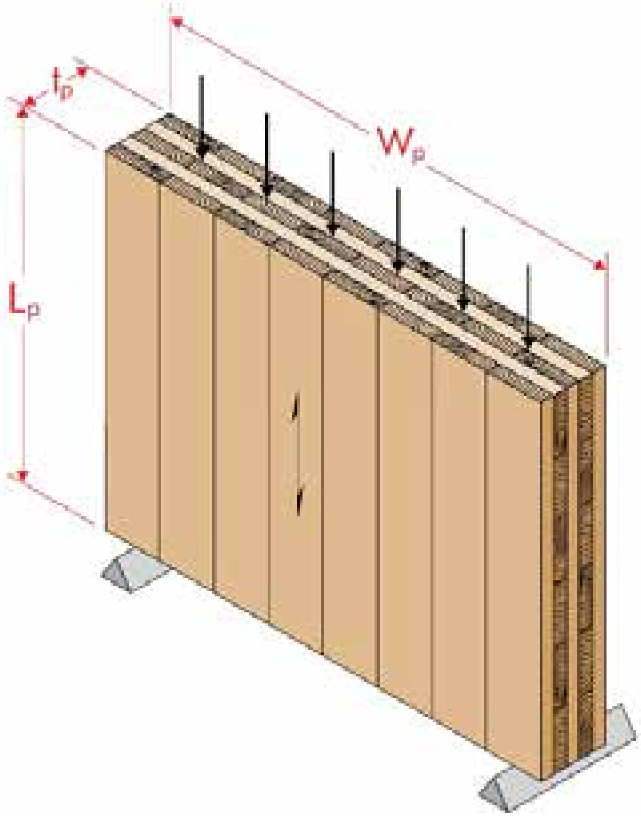
Span in MINOR Strength Direction
"Perpendicular" Direction
Use subscript '90' in Notation

Reference & Source: ANSI/APA PRG 320

EDGEWISE Panel Loading



Span in MAJOR Strength Direction

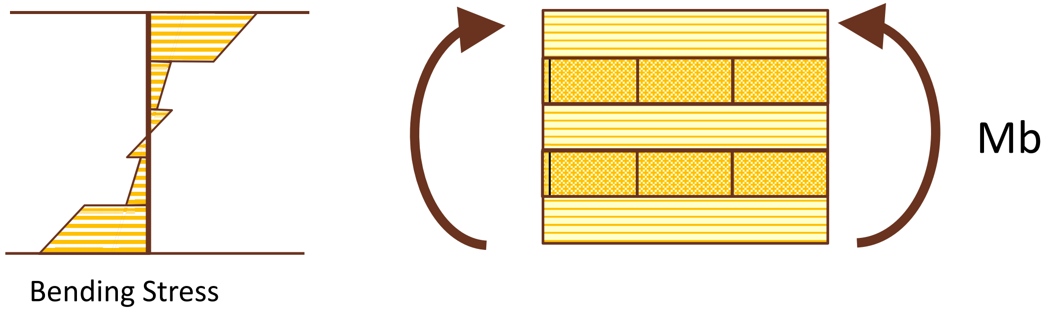


Span in MINOR Strength Direction

Reference & Source: ANSI/APA PRG 320

Flatwise Flexural Strength

Flexural Capacity Check (**ASD**)



$$(F_bS_{eff})' = \underset{\text{per NDS}}{C_D}\ \underbrace{C_M\ C_t\ C_L}_{\text{Commonly 1.0}}\ \underbrace{(F_bS_{eff})}_{\text{Provided as combined value}}$$

$$M_b \leq C_D\ (1.0)\ (F_bS_{eff})$$

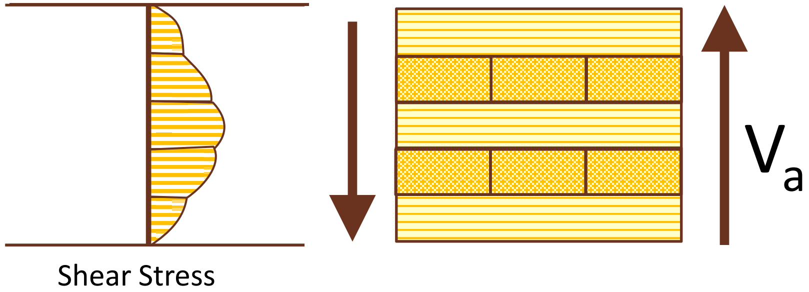
Here and in the following, items in RED are provided CLT properties

Reference: NDS

Flatwise Shear Strength

Design Properties based on Extreme Fiber Model:

Shear Capacity Check (ASD):



$$F_s(IbQ)_{eff}' = \underbrace{C_M\, C_t}_{\text{Commonly } 1.0}\ \underbrace{(F_s(IbQ)_{eff})}_{\text{From Manufacturer}} = C_M\, C_t\, \underbrace{V_s}$$

$$V_a \leq (1.0)\ V_s$$

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

Reference: NDS & Product Reports

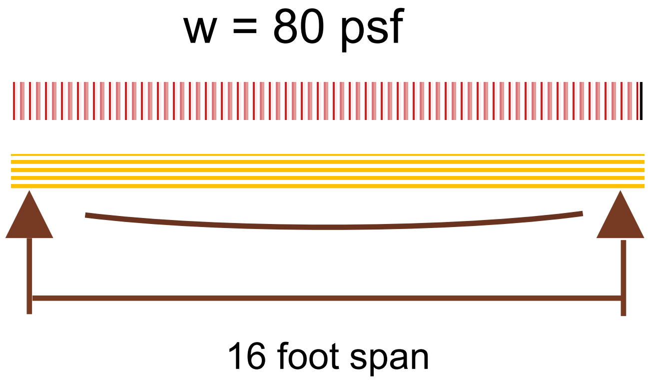
Flatwise Deflection Example

Uniform loading on one way slab:

Beam Analysis using

- Flexural Stiffness: $EI_{eff,0}$
- Shear Stiffness: $GA_{eff,0}$

Maximum Deflection @ Mid-Span

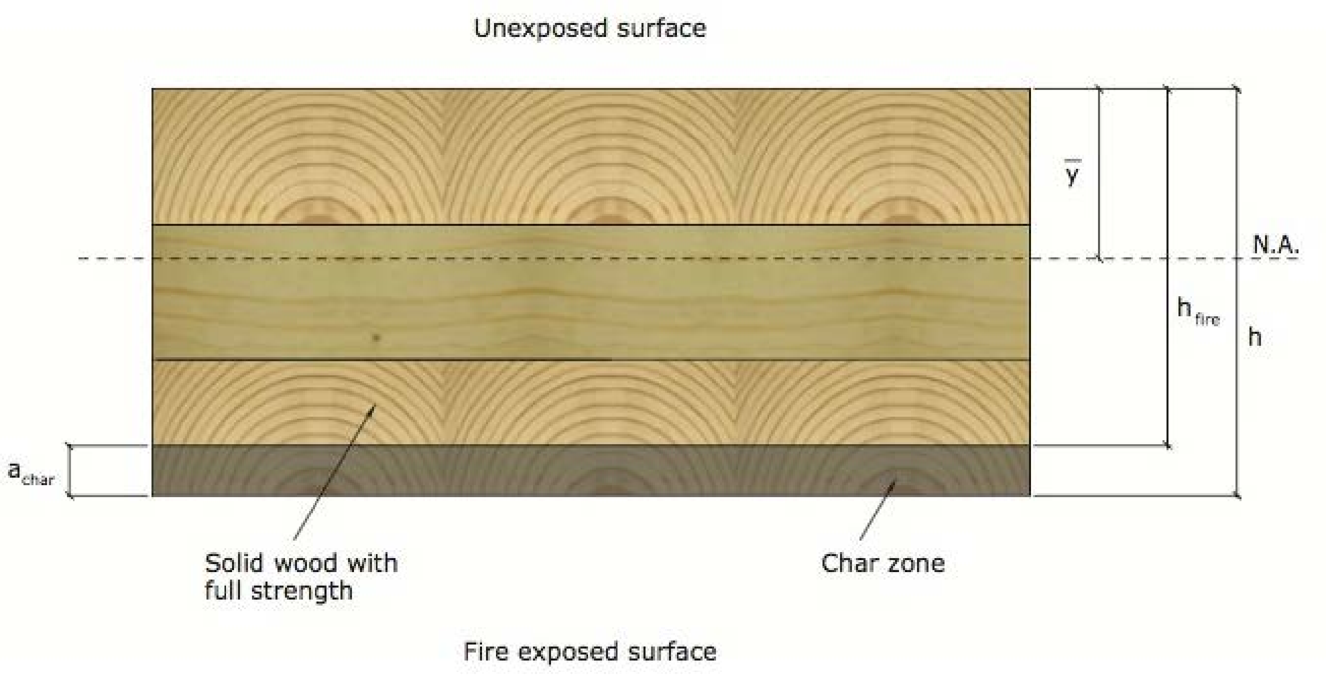


$$\Delta_{max} = \frac{5}{384} * \frac{wL^4}{EI_{eff}} + \frac{1}{8} * \frac{wL^2}{5/6\ GA_{eff}}$$

Note: 5/6 is shear deformation form factor for rectangular section from mechanics of materials. See NDS C10.4.1, FPL “Wood Handbook”, etc.

Mass timber design

Fire resistance



CLT fire design:

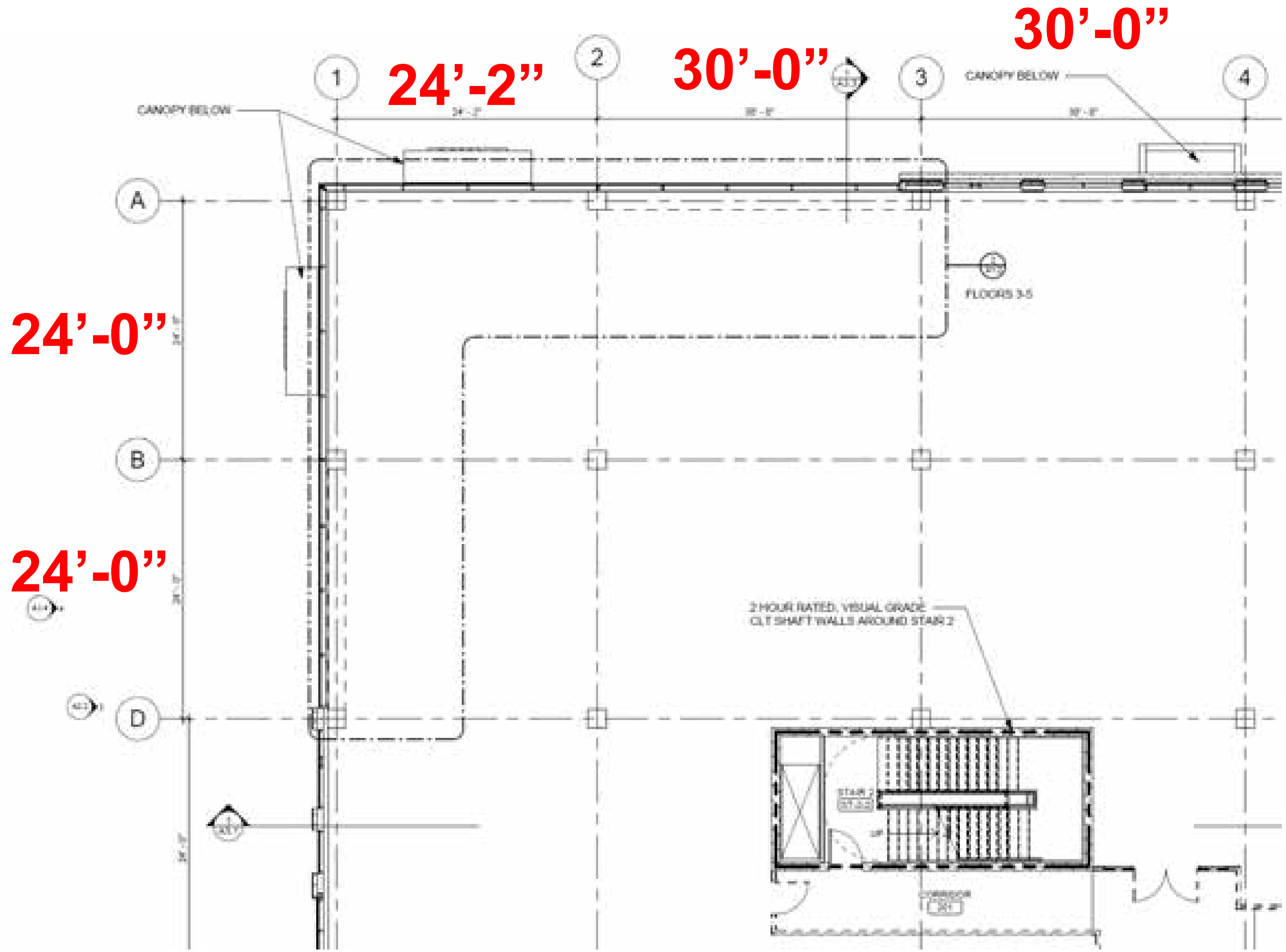
- Lam thickness affects char depth
- Partially charred cross layers are typically neglected for structural checks

Structural Grid

Structural Grid

Grids & Spans

- Consider Efficient Layouts
- Repetition & Scale
- Manufacturer Panel Sizing
- Transportation



Structural Grid

Member Sizes
- Impact of FRR on Sizing
- **Impact of Sizing on Efficient Spans**
- Consider connections – can drive member sizing

0 HR FRR: Consider 3-ply Panel
- Efficient Spans of 10-12 ft
- Grids of 20x20 (1 purlin) to 30x30 (2 purlins) may be efficient

Albina Yard, Portland, OR
20x20 Grid, 1 purlin per bay
3-ply CLT
Image: Lever Architecture

Structural Grid

Member Sizes

- Impact of FRR on Sizing
- **Impact of Sizing on Efficient Spans**
- Consider connections – can drive member sizing

0 HR FRR: Consider 3-ply Panel

- Efficient Spans of 10-12 ft
- Grids of 20x20 (1 purlin) to 30x30 (2 purlins) may be efficient

Platte Fifteen, Denver, CO
30x30 Grid, 2 purlins per bay
3-ply CLT
Image: JC Buck

Structural Grid

Member Sizes

- Impact of FRR on Sizing
- **Impact of Sizing on Efficient Spans**
- Consider connections – can drive member sizing

1 or 2 HR FRR: Likely 5-ply Panel

- Efficient spans of 14-17 ft
- Grids of 15x30 (no purlins) to 30x30 (1 purlin) may be efficient

First Tech Credit Union, Hillsboro, OR
12x32 Grid, One-Way Beams
5-ply (5.5”) CLT
Image: Swinerton

Structural Grid

Member Sizes

- Impact of FRR on Sizing
- **Impact of Sizing on Efficient Spans**
- Consider connections – can drive member sizing

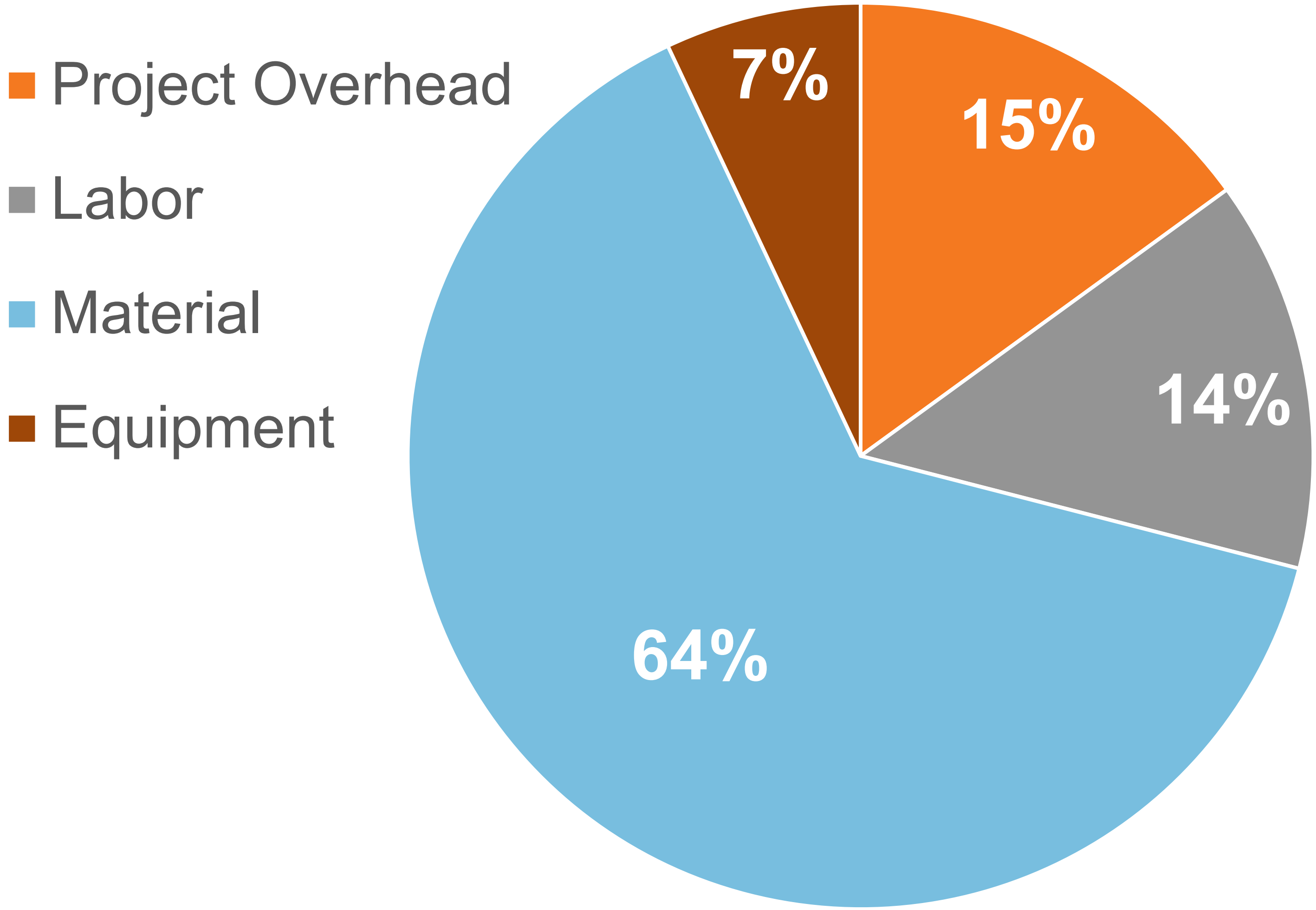
1 or 2 HR FRR: Likely 5-ply Panel

- Efficient spans of 14-17 ft
- Grids of 15x30 (no purlins) to 30x30 (1 purlin) may be efficient

Clay Creative, Portland, OR
30x30 Grid, 1 purlin per bay
2x6 NLT
Image: Mackenzie

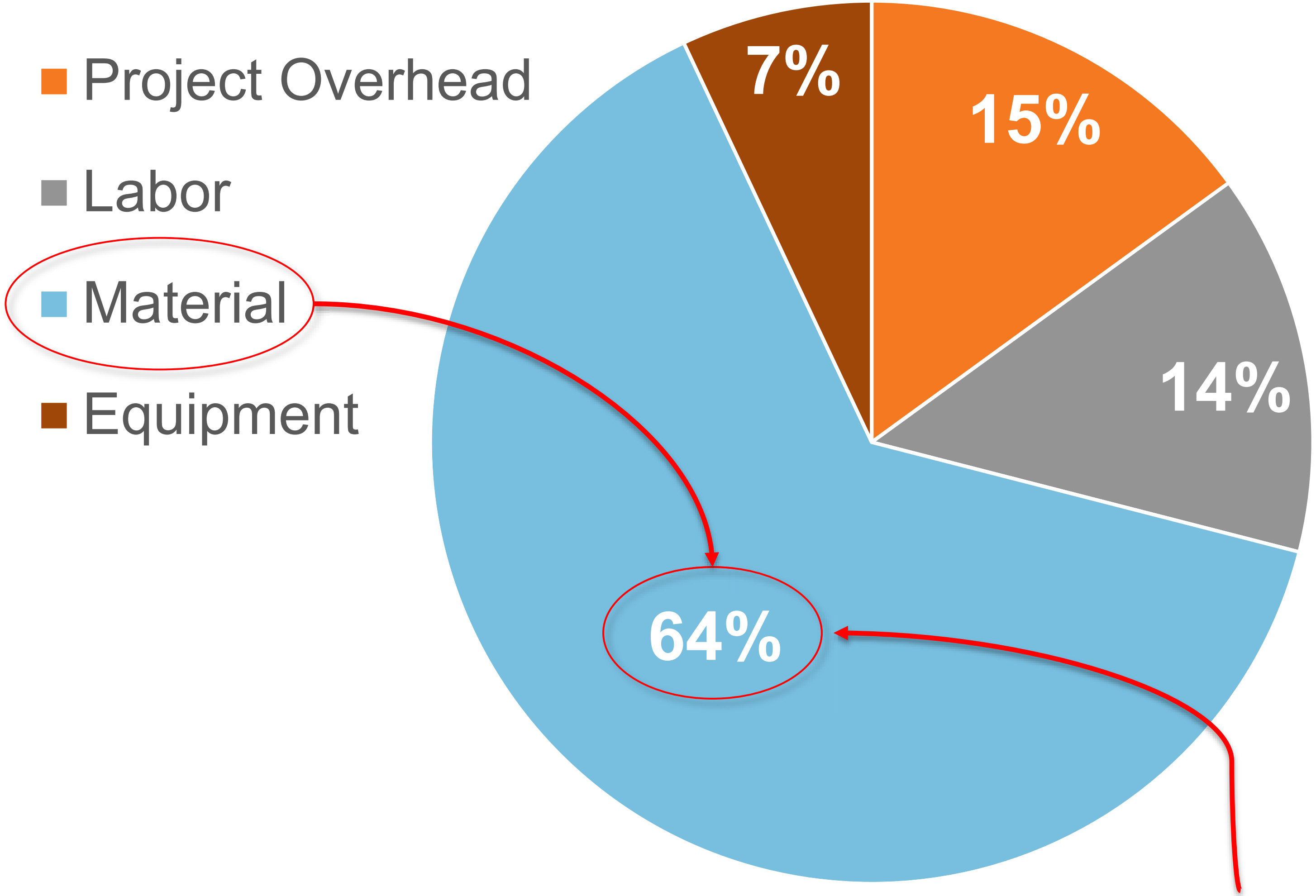
Key Early Design Decisions

Typical MT Package Costs



Source: Swinerton

Key Early Design Decisions

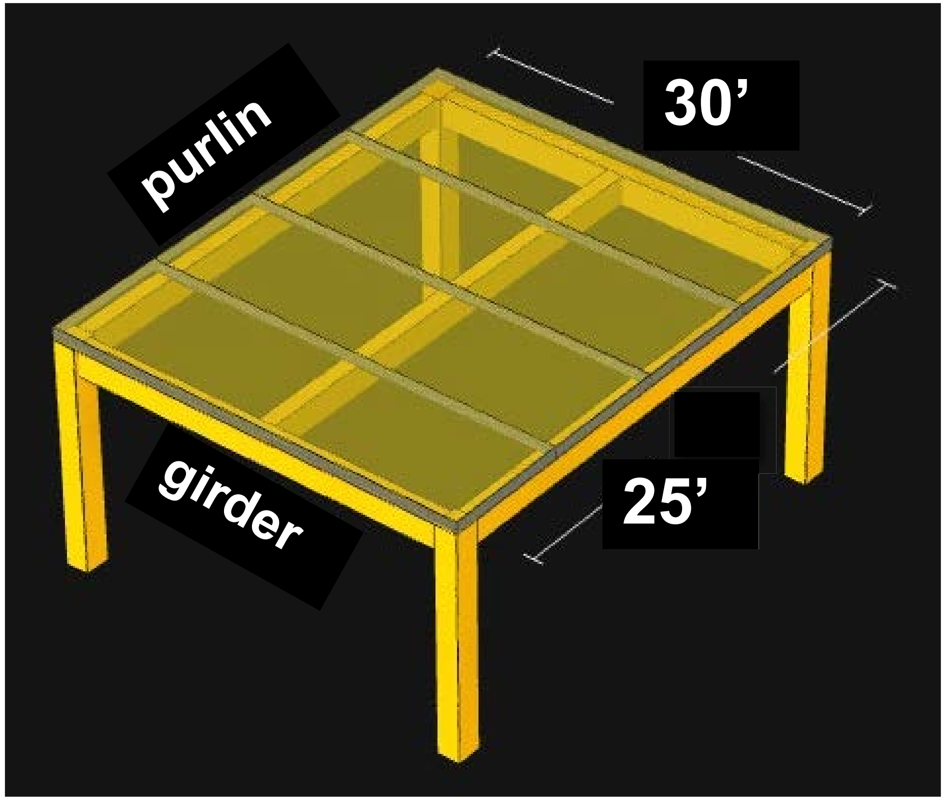


Panels are the biggest part of the biggest piece of the cost pie

Source: Swinerton

Key Early Design Decisions

Panel volume usually 65-80% of MT package volume



Source: Fast + Epp, Timber Bay Design Tool

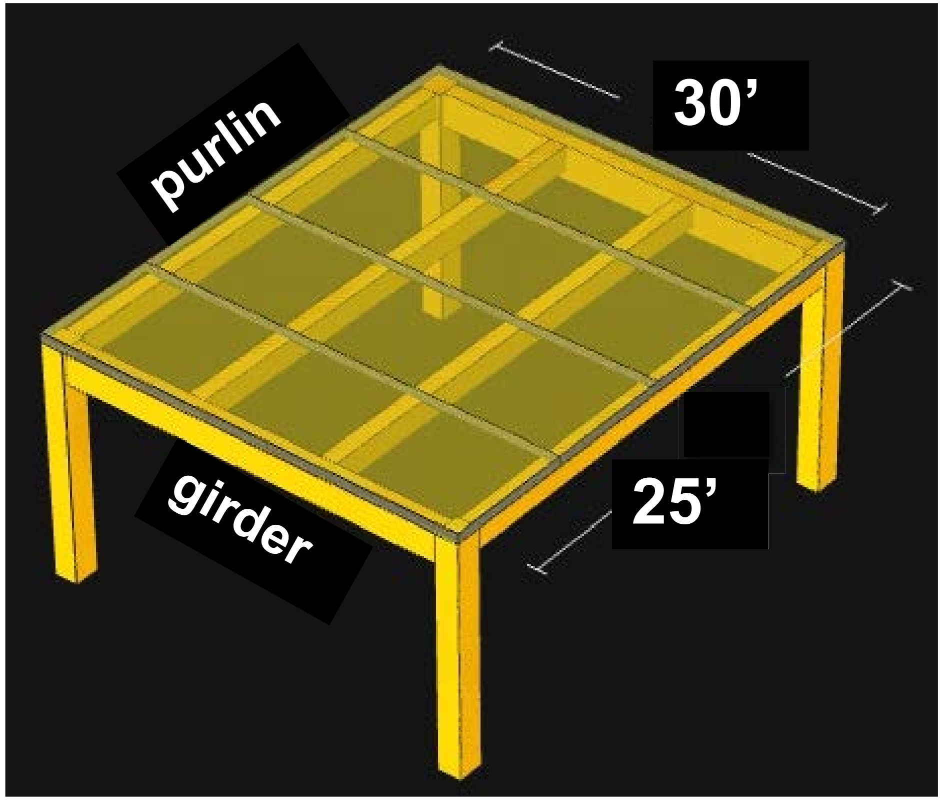
Type IIIA option 1

1-hr FRR
Purlin: 5.5”x28.5”
Girder: 8.75”x33”
Column: 10.5”x10.75”
Floor panel: 5-ply

Glulam volume = 118 CF (22% of MT)
CLT volume = 430 CF (78% of MT)
Total volume = 0.73 CF / SF

Key Early Design Decisions

Panel volume usually 65-80% of MT package volume



Source: Fast + Epp, Timber Bay Design Tool

Type IIIA option 2

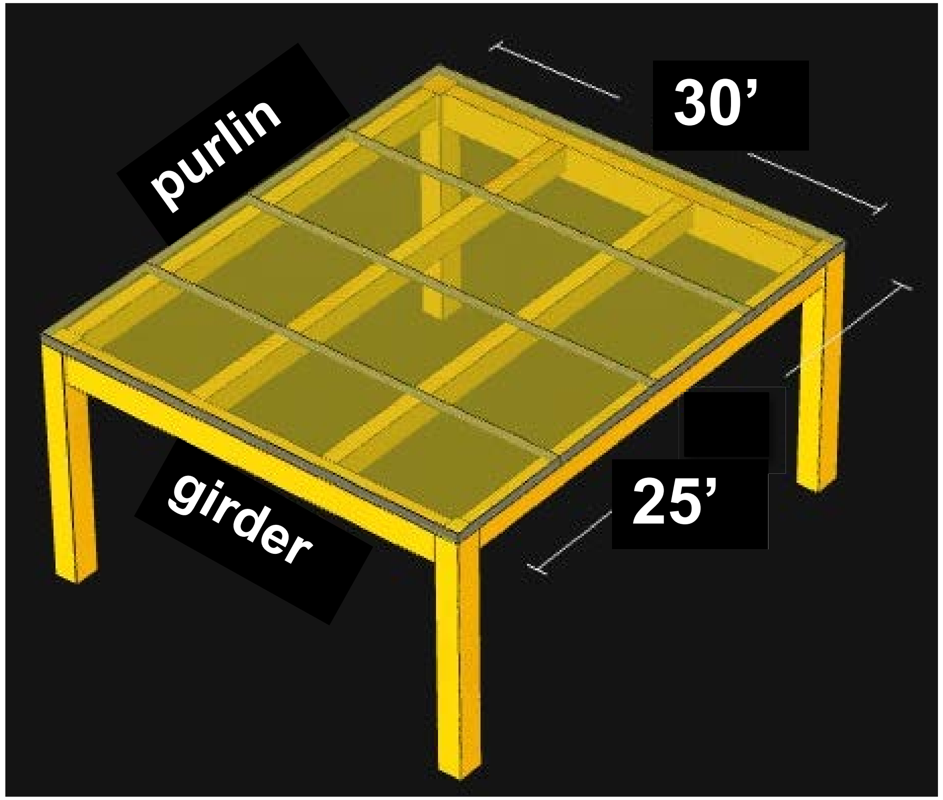
1-hr FRR
Purlin: 5.5”x24”
Girder: 8.75”x33”
Column: 10.5”x10.75”
Floor panel: 5-ply

Glulam volume = 123 CF (22% of MT)
CLT volume = 430 CF (78% of MT)
Total volume = 0.74 CF / SF

Cost considerations: One additional beam (one additional erection pick), 2 more connections

Key Early Design Decisions

Panel volume usually 65-80% of MT package volume



Source: Fast + Epp, Timber Bay Design Tool

Type IV-HT

0-hr FRR (min sizes per IBC)
Purlin: 5.5”x24” (IBC min = 5”x10.5”)
Girder: 8.75”x33” (IBC min = 5”x10.5”)
Column: 10.5”x10.75” (IBC min = 6.75”x8.25”)
Floor panel: 3-ply (IBC min = 4” CLT)

Glulam volume = 120 CF (32% of MT)
CLT volume = 258 CF (68% of MT)
Total volume = 0.51 CF / SF

Connections

Credit: Structurlam

Key Early Design Decisions

Many ways to demonstrate connection fire protection:
calculations, prescriptive NC, test results, others as approved by AHJ


Photo: John Stamets

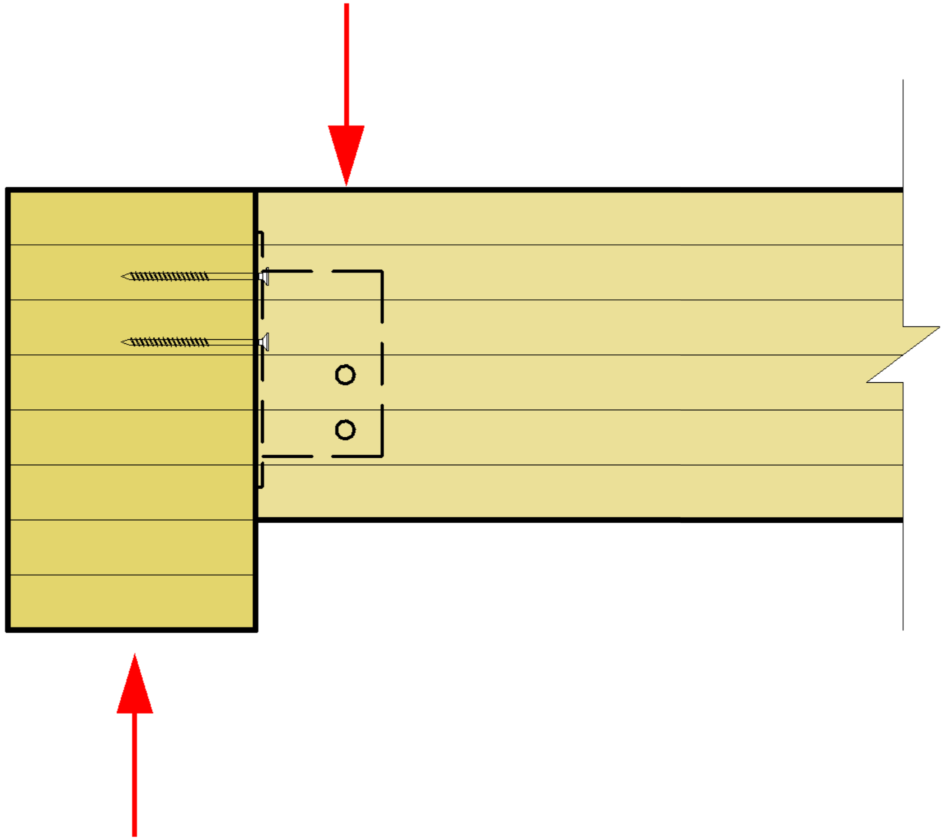

Photo: Josh Partee


Photo: Christian Columbres


Photo: Blaine Brownell

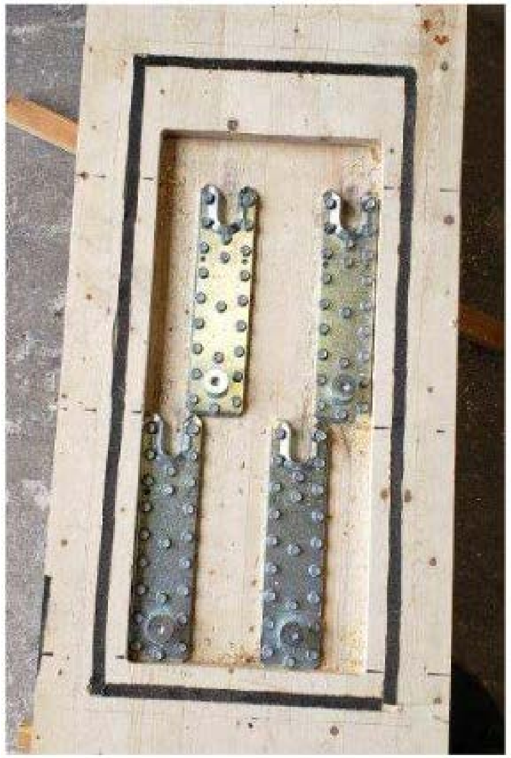
Key Early Design Decisions

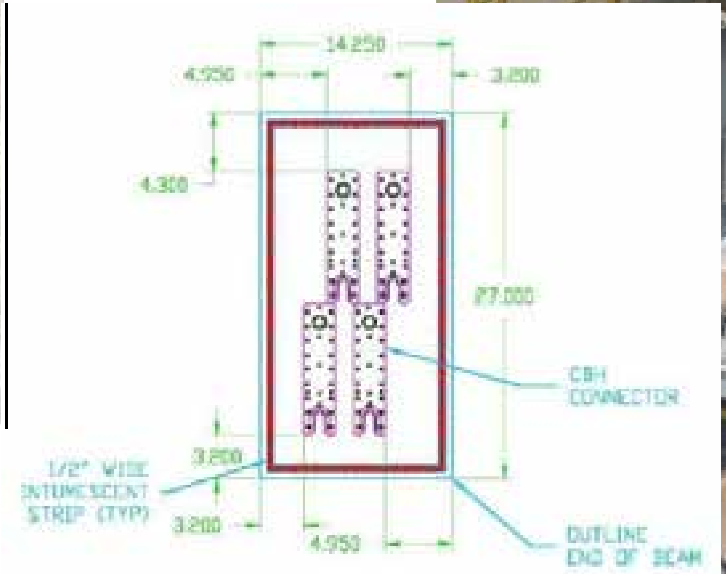
Steel hangers/hardware fully concealed within a timber-to-timber connection is a common method of fire protection



Key Early Design Decisions

Connection FRR and beam reactions could impact required beam/column sizes





Photos: Simpson Strong-Tie

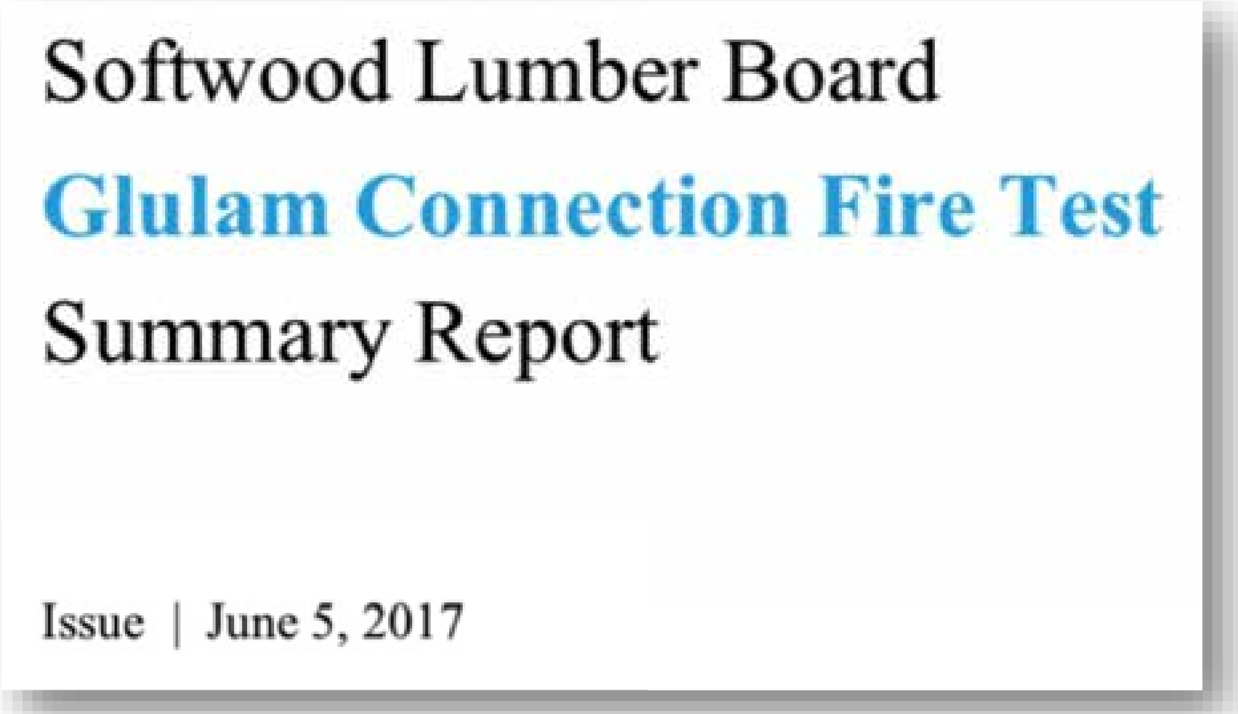
Photo: LEVER Architecture

Key Early Design Decisions

2017 Glulam Beam to Column Connection Fire Tests under standard ASTM E119 time-temperature exposure

Photo: ARUP/SLB

Key Early Design Decisions



Softwood Lumber Board

Glulam Connection Fire Test

Summary Report

Issue | June 5, 2017

SOUTHWEST RESEARCH INSTITUTE

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CHEMISTRY AND CHEMICAL ENGINEERING DIVISION

FIRE TECHNOLOGY DEPARTMENT
WWW.FIRE.SWRI.ORG
FAX (210) 522-3377

FIRE PERFORMANCE EVALUATION OF A LOAD BEARING GLULAM BEAM TO COLUMN CONNECTION, INCLUDING A CLT PANEL, TESTED IN GENERAL ACCORDANCE WITH ASTM E119-16a, *STANDARD TEST METHODS FOR FIRE TESTS OF BUILDING CONSTRUCTION AND MATERIALS*

FINAL REPORT
Consisting of 32 Pages

Full Report Available at:

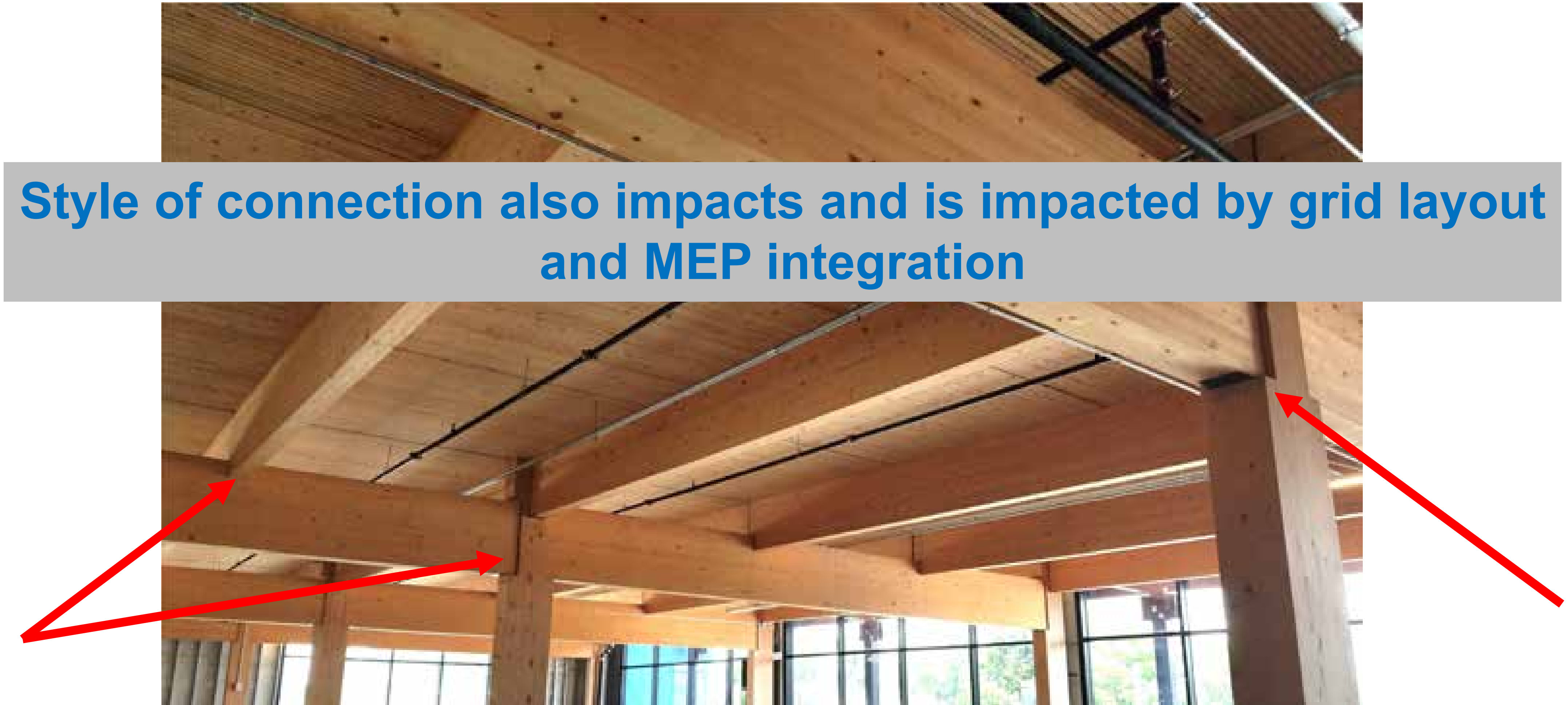
https://www.thinkwood.com/wp-content/uploads/2018/01/reThink-Wood-Arup-SLB-Connection-Fire-Testing-Summary-web.pdf

Key Early Design Decisions

Member to member bearing also commonly used, can avoid some/all steel hardware at connection

Key Early Design Decisions

Member to member bearing also commonly used, can avoid some/all steel hardware at connection



Style of connection also impacts and is impacted by grid layout and MEP integration

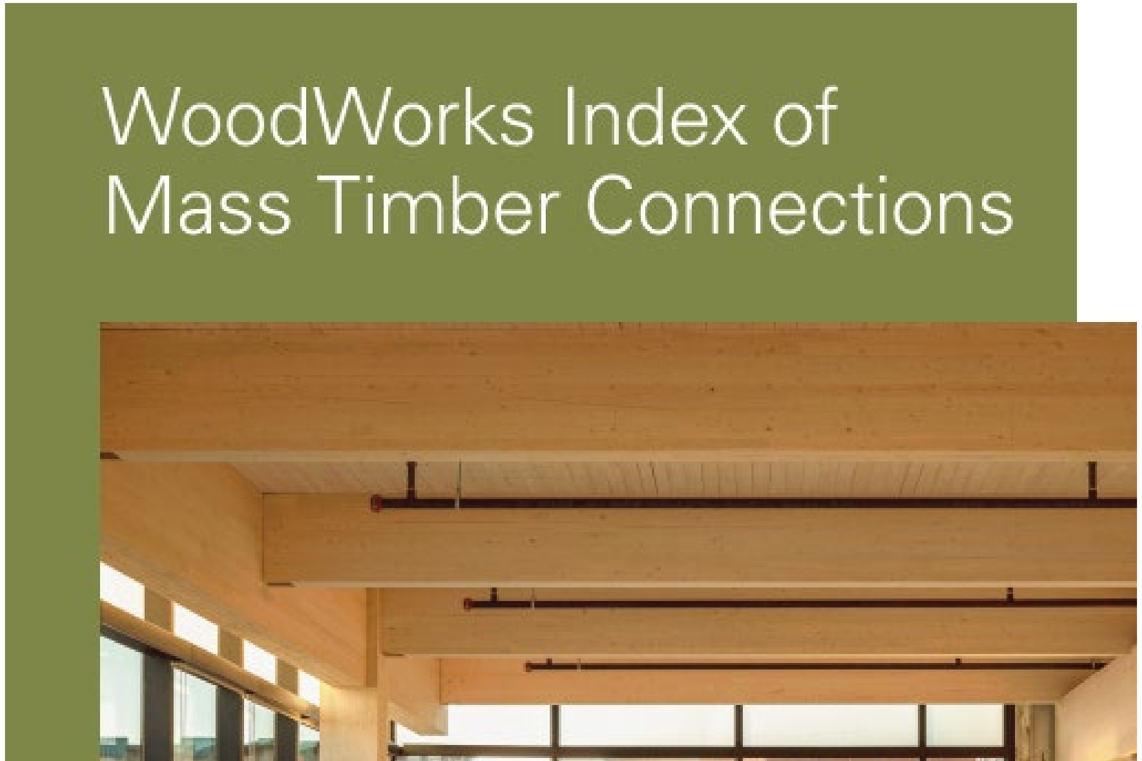
Key Early Design Decisions

WOODWORKS

KL&A
Engineers & Builders

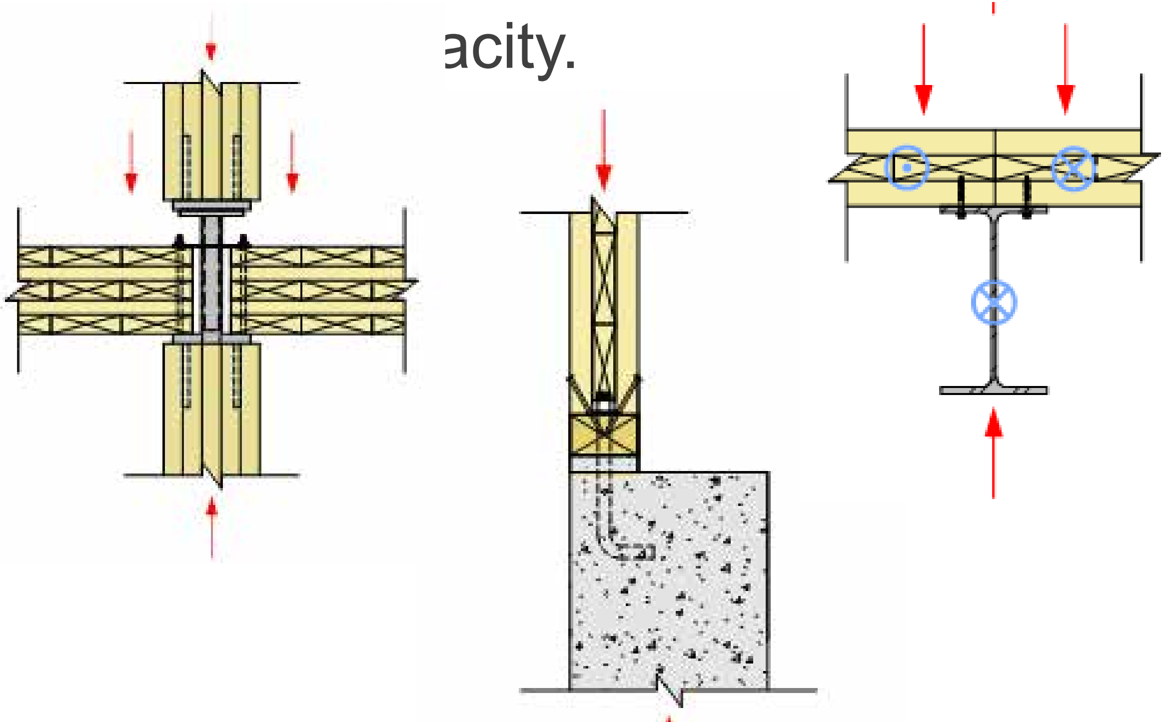
OZ
ARCHITECTURE
URBAN DESIGN
INTERIOR DESIGN

SWINERTON
MASS TIMBER


WoodWorks Index of Mass Timber Connections

MASS TIMBER CONNECTIONS INDEX

A library of commonly used mass timber connections with designer notes and information on fire resistance, relative cost and load-
acity.



Connections

Other connection design considerations:

- Structural capacity
- Shrinkage
- Constructability
- Aesthetics
- Cost

Credit: Alex Schreyer

Floor Vibration Design

"One might almost say that **strength is essential** and **otherwise unimportant**"

- Hardy Cross

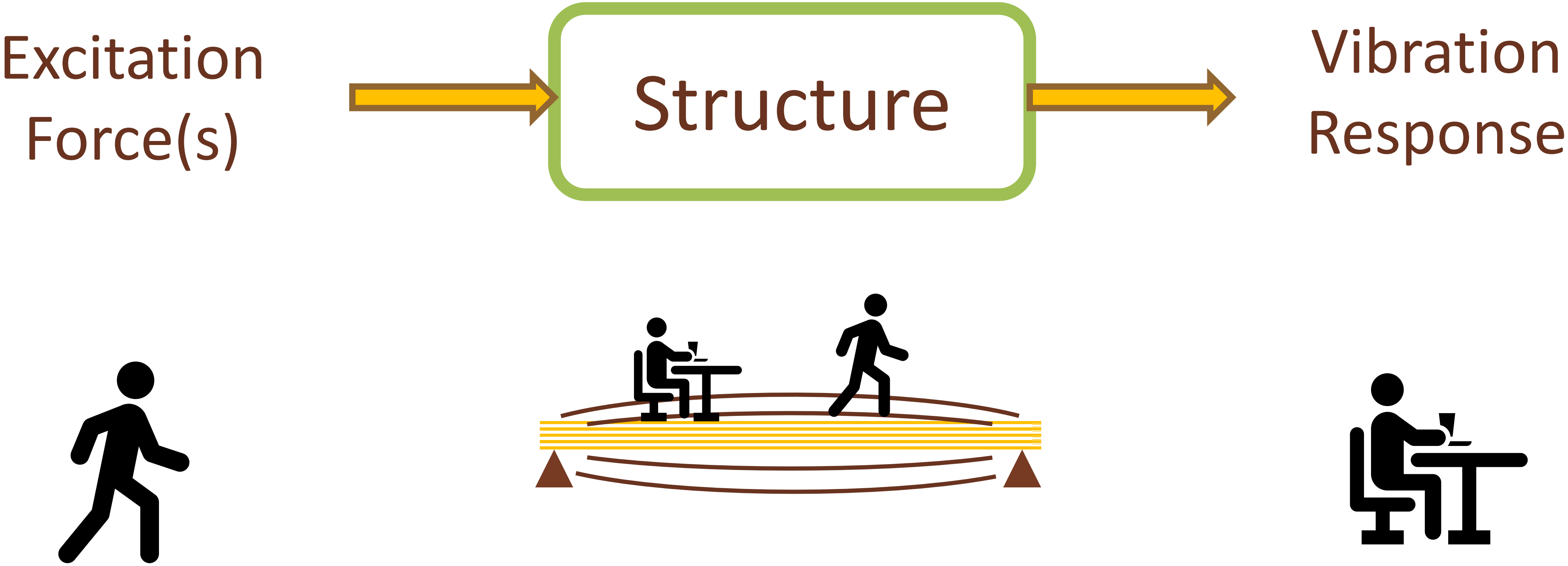
US Building Code Requirements for Vibration

None

Barely discussed in IBC, NDS, etc.

ASCE 7 Commentary Appendix C has some discussion, no requirements

Systems View of Vibration



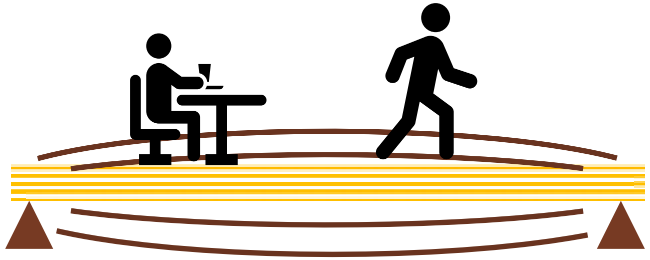
Excitation Force(s)

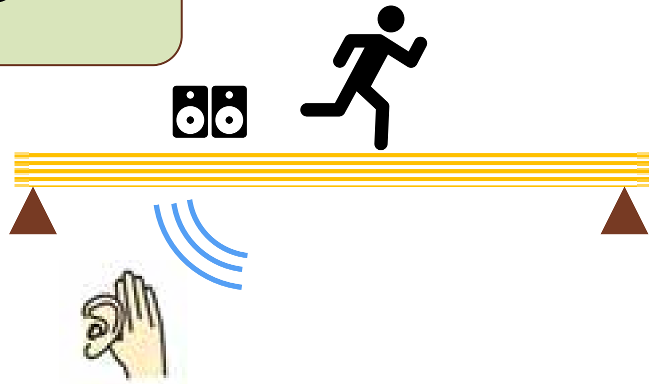
Structure

Vibration Response

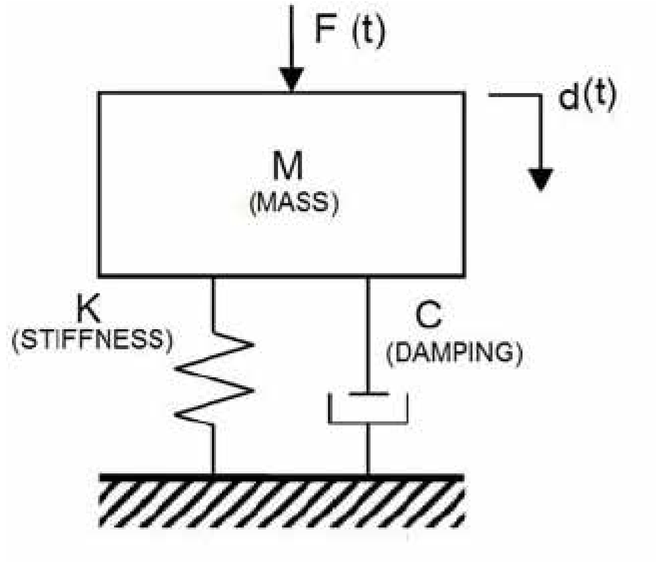
Vibrations vs Acoustics

Structural Vibrations	Acoustic Vibrations
1 Hz – 100 Hz	20 Hz – 15,000 Hz
Transmitted through structure or through ground	Transmitted through air, walls, floors, windows
Physical effects	Audible effects





Floor Vibration Dynamics

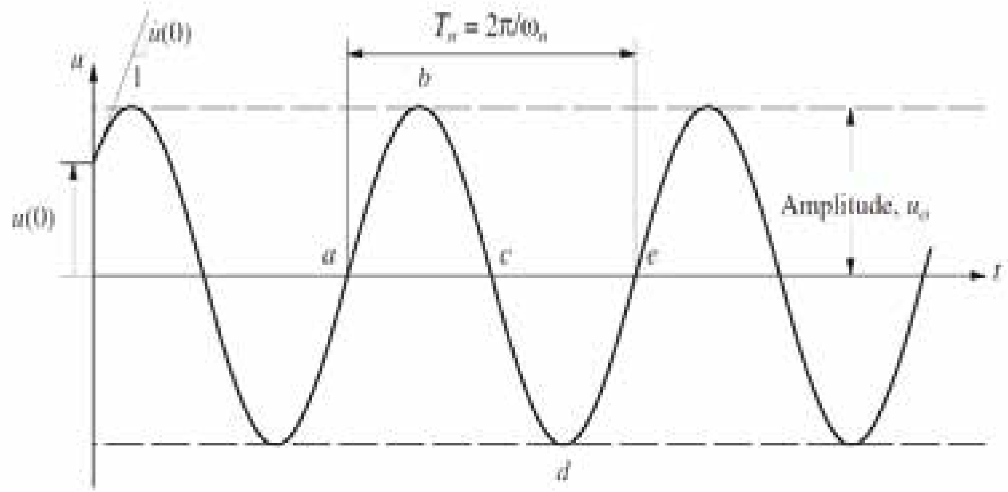


Natural Frequency

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

Undamped Free Response

Period T = 1 / f_n Frequency

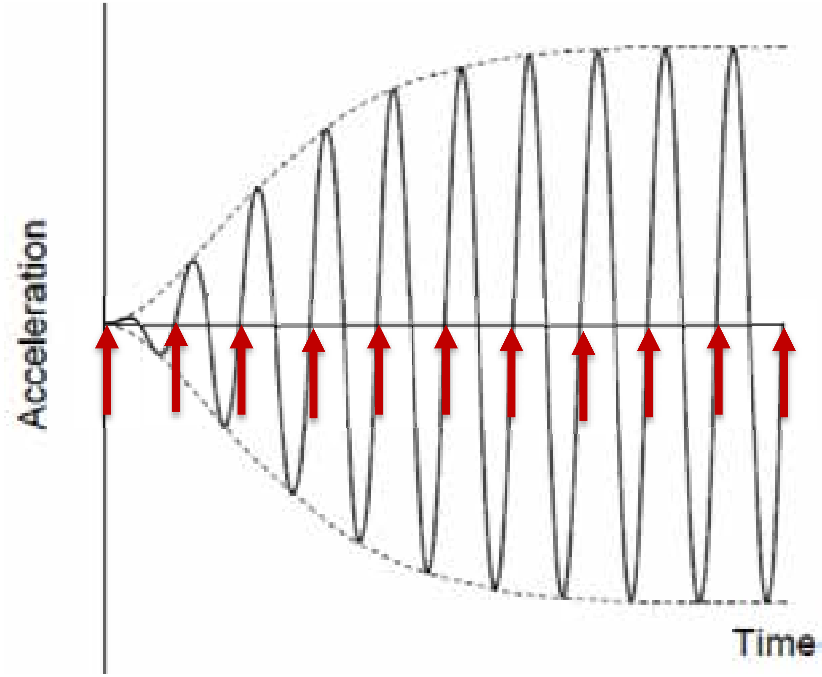


Walking Frequency f_w

Walking Speed	Walking Frequency	Steps Per Minute
Very Slow	1.25 Hz	75 SPM
Slow	1.6 Hz	95 SPM
Moderate	1.85 Hz	110 SPM
Fast	2.1 Hz	126 SPM
Running	Up to 4.0 Hz	240 SPM
Practical Tip - walk to a metronome too understand the range		

The range of walking frequencies considered is an important consideration of vibration analysis

Resonant vs Impulsive Response



Excitation Frequency not >> Natural Frequency
Excitation Creates Resonant Build-up of Vibration

Resonant Response

Resonance occurs when
walking frequency = natural frequency

$$f_w = f_n$$

Also occurs when a harmonic of the walking frequency ~= natural frequency

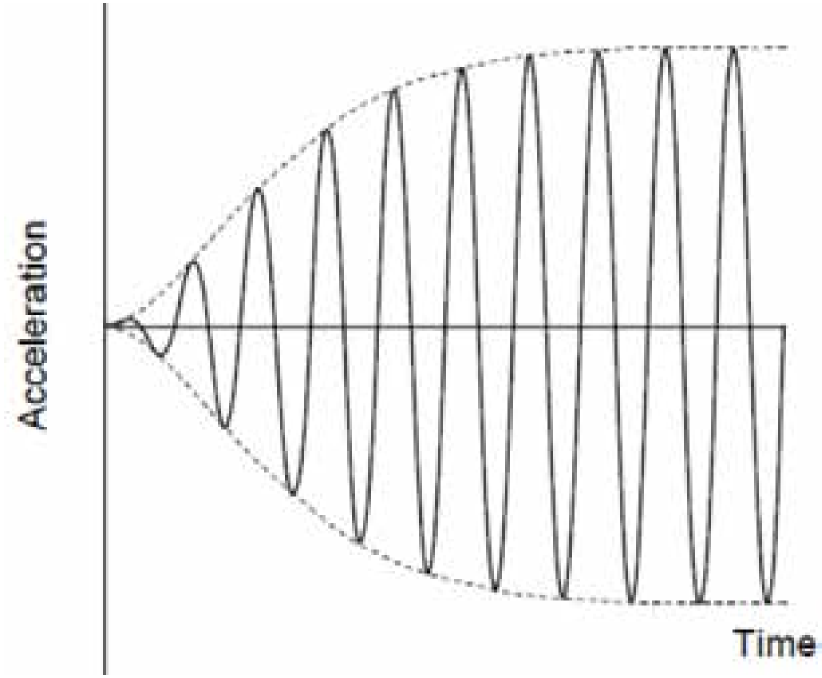
$$n\ f_w = f_n$$

For ‘n’ up to around 4

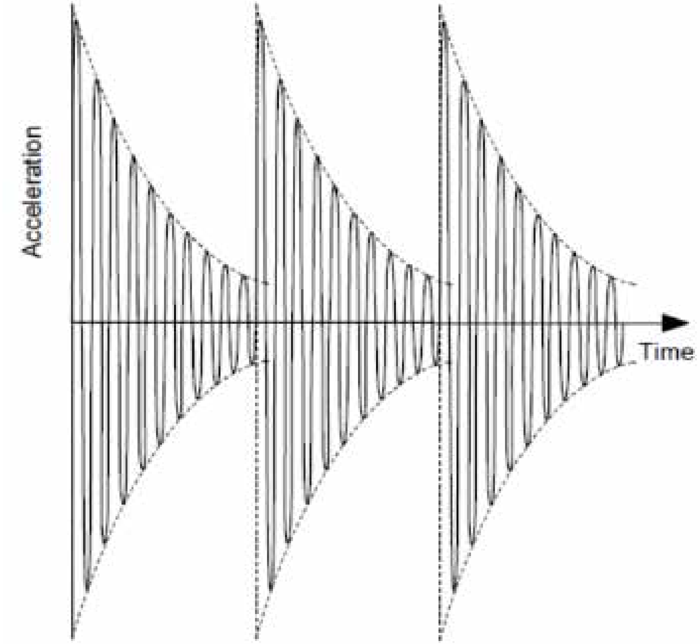
Walking at f_w =2 Hz creates resonance in floor with natural frequency, f_n, at

2Hz, 4 Hz, 6 Hz, and 8Hz

Resonant vs Impulsive Response



Excitation creates <u>Resonant</u> build-up of vibration



Response decays out between load impulses

<u>Resonant Response</u>

<u>Impulsive/Transient Response</u>

For walking excitations

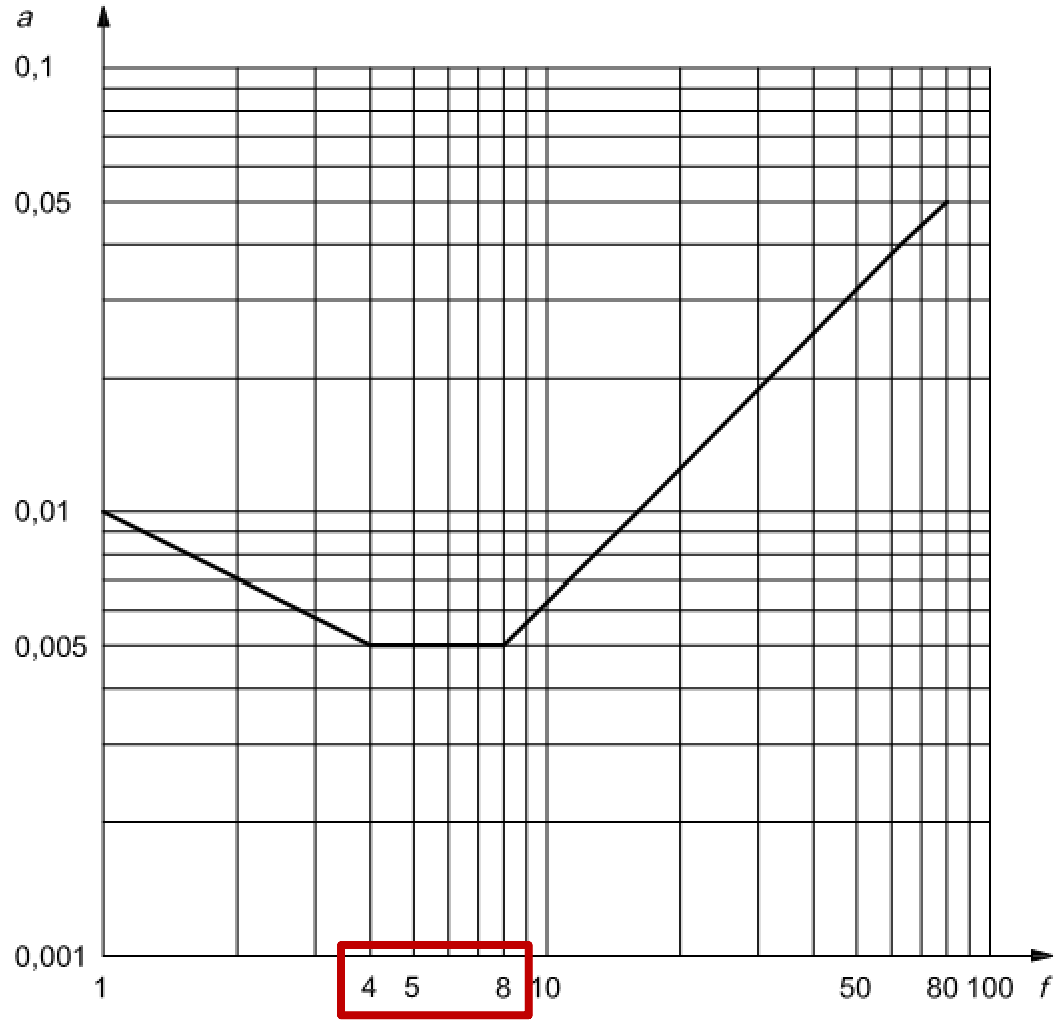
f_n ~< 8-10 Hz

f_n ~> 8-10 Hz

Limits of Human Perception of Vertical Acceleration

Acceleration

0.05% g



Frequency

ISO 10137:2007

Most sensitive to Acceleration around 4-8 Hz

Human Body Dynamics

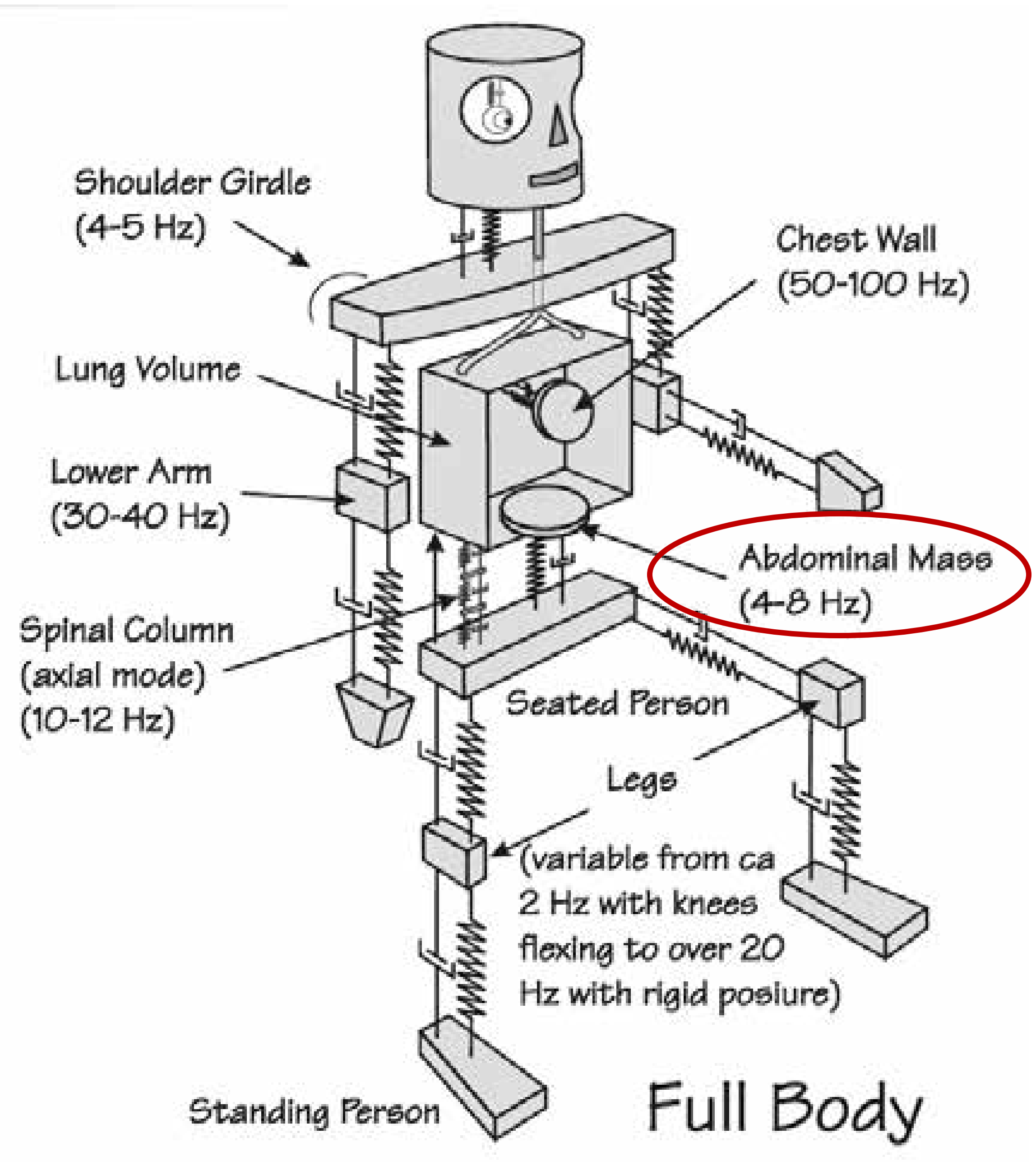
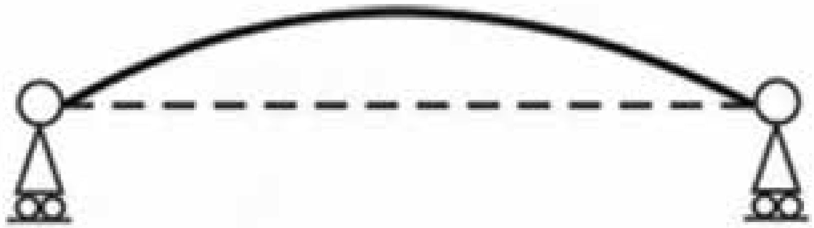


Illustration: “Sven Jr.” by Sven-Olof Emanuelsson

Natural Frequency of Uniform Beam



Uniform simple span beam

- Span, L
- Flexural stiffness, EI
- Mass per length, m, or w/g

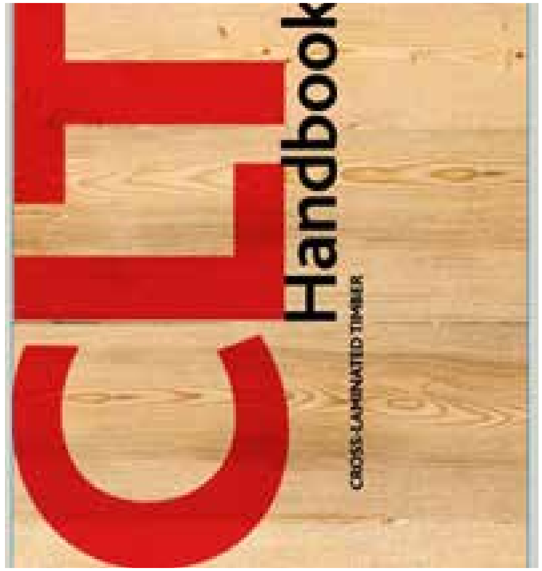
$$f_n = \frac{\pi}{2L^2}\sqrt{\frac{EI}{m}}$$

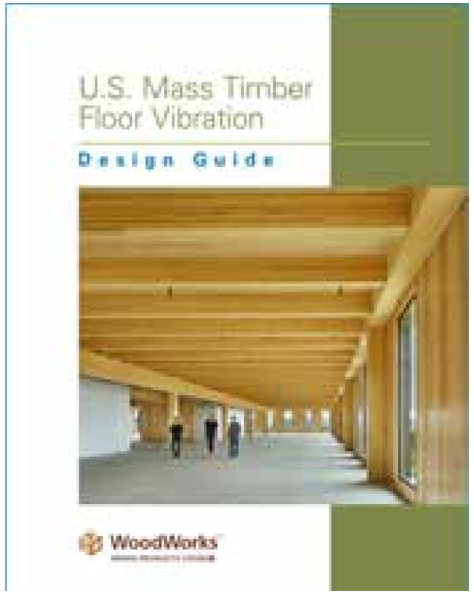
$$f_n = \frac{\pi}{2L^2}\sqrt{\frac{gEI}{w}}$$

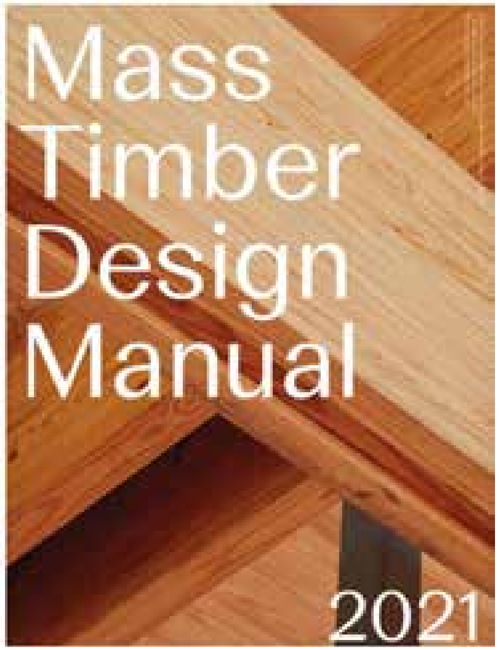
In floors, practical frequencies range from 5 Hz to 15+ Hz.
Generally, the higher the frequency the better

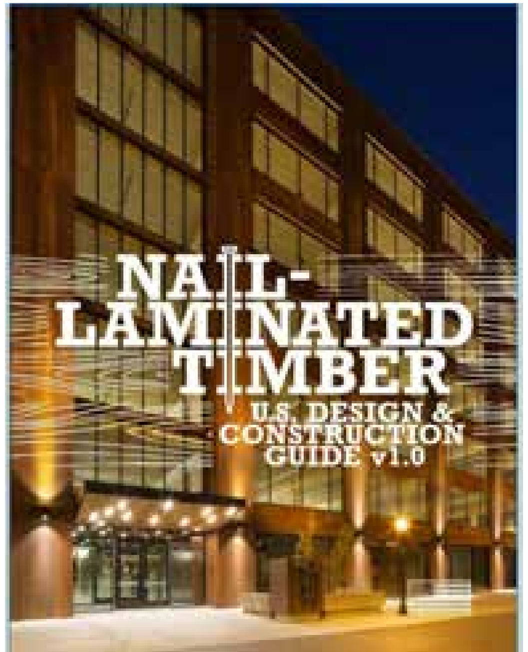
See Chopra "Dynamic of Structures", etc for more information

Important Concepts


CLT Handbook
CROSS-LAMINATED TIMBER


U.S. Mass Timber Floor Vibration
Design Guide
WoodWorks


Mass Timber Design Manual
2021


NAIL-LAMINATED TIMBER
U.S. DESIGN & CONSTRUCTION GUIDE v1.0

- No Code Requirements (good). No Precise Design Standard to Stand Behind (bad)
- Mass Effects – Increased mass decreases magnitude of response (good!) but decreases frequency of vibration (bad!)
- Resources: CLT Handbook, Mass Timber Floor Vibration, Mass Timber Design Manual, Nail-Laminated Timber Design Guide (all free download)

Vibration Design Methods

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

Less:

- ***Design Effort***
- ***Modelling and Analysis***
- ***Judgement***
- ***Flexibility***
- ***Room for Innovation***

More:

- ***Design Effort***
- ***Modelling and Analysis***
- ***Judgement***
- ***Flexibility***
- ***Room for Innovation***

Vibration Design Methods

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

Δ ≤ L/360 for floor live load

IBC code limit on floor deflection

Wood Frame

Floor Joists:
Δ ≤ L/360 for L < 15 ft
Δ < 0.5”   for L ≥ 15 ft
Floor Trusses:
Δ ≤ L/480 with strong-backs

Woeste and Dolan
Beyond Code: Preventing Floor Vibration.
1998, Journal of Light Construction

Vibration Design Methods

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

Wood Frame

$f_n \geq 14$ Hz for occupied (e.g. furnished) floors
$f_n \geq 15$ Hz for unoccupied floors

Dolan, Murray, et al.
Preventing Annoying Wood Floor Vibration
1999, Journal of Structural Engineering

Proprietary rating systems from Joist Manufacturers

Vibration Design Methods

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

Mass Timber

CLT Handbook Method

U.S. CLT Handbook, 2013
Canadian CLT Handbook 2nd Ed., 2019
FPInnovations

CLT Handbook Method

Recommended CLT Floor Span Limit (base value)

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

Where, for 12 in wide strip:

EI_{eff} = effective flexural stiffness (lbf-in^2)

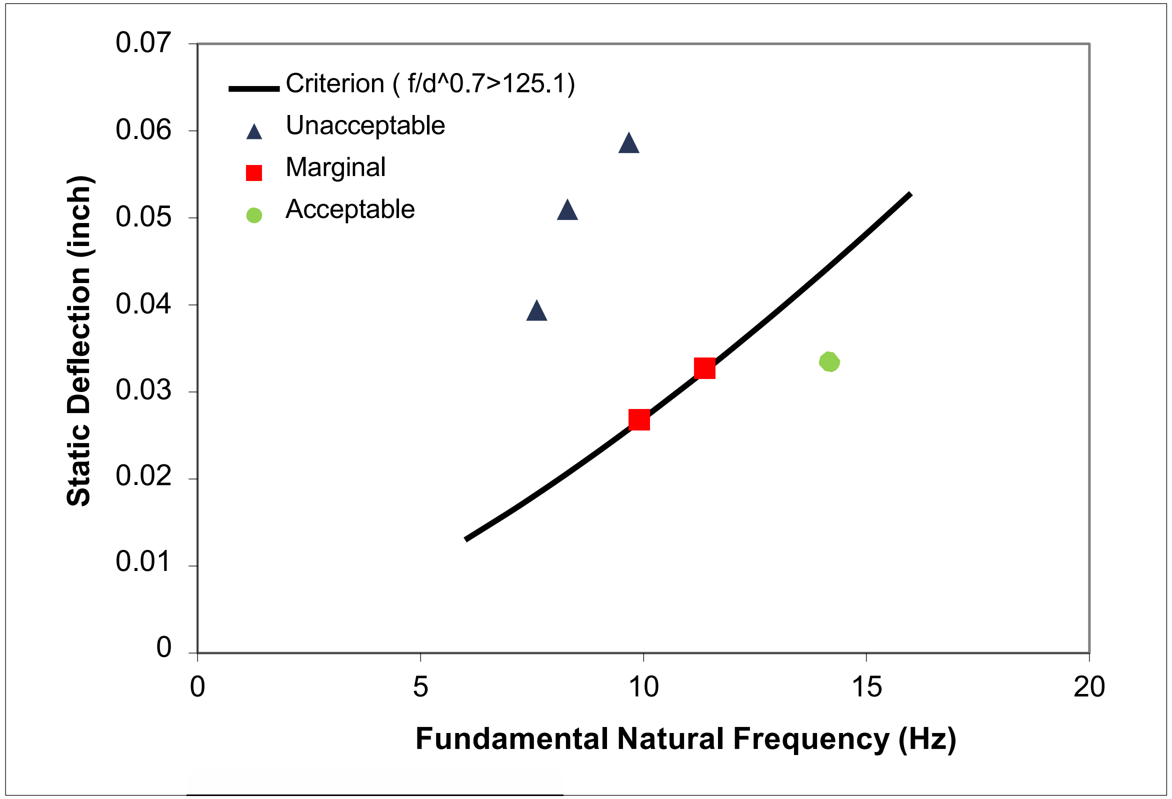
$\overline{\rho}$ = in-service specific gravity of the CLT, unitless
e.g. weight normalized by weight of water

A = the cross-section area (in^2) = thickness * 12 in

Reference: US & Canadian CLT Handbooks, Chapter 7

CLT Handbook Method

Experimentally Derived Relationship



Research by Lin Hu, et al. at FPInnovations

CLT Handbook Method

Recommended CLT Floor Span Limit (base value)

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

2013 US CLT Handbook uses EI_{app}
2019 Canadian CLT Handbook uses EI_{eff}

Recommend using EI_{eff}

Easier to implement.
Less conservative.

Reference: Canadian CLT Handbook, Chapter 7

CLT Handbook Method

Excitation Force

Structure

Vibration Response

Normal Walking

Normal Human Sensitivities

Method NOT applicable to other Excitations or Sensitivities

CLT Handbook Base Span Limit

For PRG 320-2019 Basic CLT Grades and Layups from Solid Sawn Lumber

Grade	Layup	Thickness	Base Span Limit
E1	3ply	4 1/8”	13.1
	5ply	6 7/8”	18.2
	7ply	9 5/8”	22.7
E2	3ply	4 1/8”	12.4
	5ply	6 7/8”	17.2
	7ply	9 5/8”	21.6
E3	3ply	4 1/8”	12.0
	5ply	6 7/8”	16.7
	7ply	9 5/8”	20.9
E4	3ply	4 1/8”	12.7
	5ply	6 7/8”	17.6
	7ply	9 5/8”	22.1
E5	3ply	4 1/8”	12.6
	5ply	6 7/8”	17.5
	7ply	9 5/8”	21.9

Grade	Layup	Thickness	FPI Span Limit
V1	3ply	4 1/8”	12.6
	5ply	6 7/8”	17.6
	7ply	9 5/8”	22.0
V1(N)	3ply	4 1/8”	12.6
	5ply	6 7/8”	17.6
	7ply	9 5/8”	22.0
V2	3ply	4 1/8”	12.4
	5ply	6 7/8”	17.2
	7ply	9 5/8”	21.5
V3	3ply	4 1/8”	12.0
	5ply	6 7/8”	16.7
	7ply	9 5/8”	20.9
V4	3ply	4 1/8”	11.7
	5ply	6 7/8”	16.3
	7ply	9 5/8”	20.4
V5	3ply	4 1/8”	12.1
	5ply	6 7/8”	16.8
	7ply	9 5/8”	21.0

Reference: US Mass Timber Floor Vibration Design Guide, assuming 12% M.C.

CLT Handbook Base Span Limit

For PRG 320-2019 Basic CLT Grades and Layups from Solid Sawn Lumber

Grade	Layup	Thickness	Base Span Limit
E1	3ply	4 1/8”	13.1
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E2	3ply	4 1/8”	12.4
	5ply	6 7/8”	17.2
	7ply	9 5/8”	21.6
E3	3ply	4 1/8”	12.0
	5ply	6 7/8”	16.7
	7ply	9 5/8”	20.9
E4	3ply	4 1/8”	12.7
	5ply	6 7/8”	17.6
	7ply	9 5/8”	22.1
E5	3ply	4 1/8”	12.6
	5ply	6 7/8”	17.5
	7ply	9 5/8”	21.9

Approximate Base Span Limits:

4 $^{1}/_{8}$” 3-ply: ~12 to 13 ft

6 $^{7}/_{8}$” 5-ply: ~16 to 18 ft

9 $^{5}/_{8}$” 7-ply: ~20 to 22 ft

Grade	Layup	Thickness	FPI Span Limit
V1	3ply	4 1/8”	12.6
	5ply	6 7/8”	17.6
	7ply	9 5/8”	22.0
V1(N)	3ply	4 1/8”	12.6
	5ply	6 7/8”	17.6
	7ply	9 5/8”	22.0
V2	3ply	4 1/8”	12.4
	5ply	6 7/8”	17.2
	7ply	9 5/8”	21.5
V3	3ply	4 1/8”	12.0
	5ply	6 7/8”	16.7
	7ply	9 5/8”	20.9
V4	3ply	4 1/8”	11.7
	5ply	6 7/8”	16.3
	7ply	9 5/8”	20.4
V5	3ply	4 1/8”	12.1
	5ply	6 7/8”	16.8
	7ply	9 5/8”	21.0

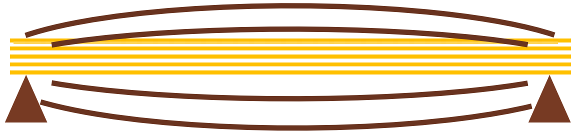
Limitations:

- **Does not account for strength or deflections**
- **Does not account for beam flexibility**
- **Does not account for project specifics**

Reference: US Mass Timber Floor Vibration Design Guide, assuming 12% M.C.

CLT Handbook Method

Structure

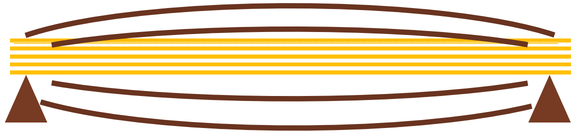


Base Recommended Span Limit assumes:

- Single simply span CLT panel
- No heavy topping layer
- Rigid, pin supports (bearing walls)

CLT Handbook Method

Structure



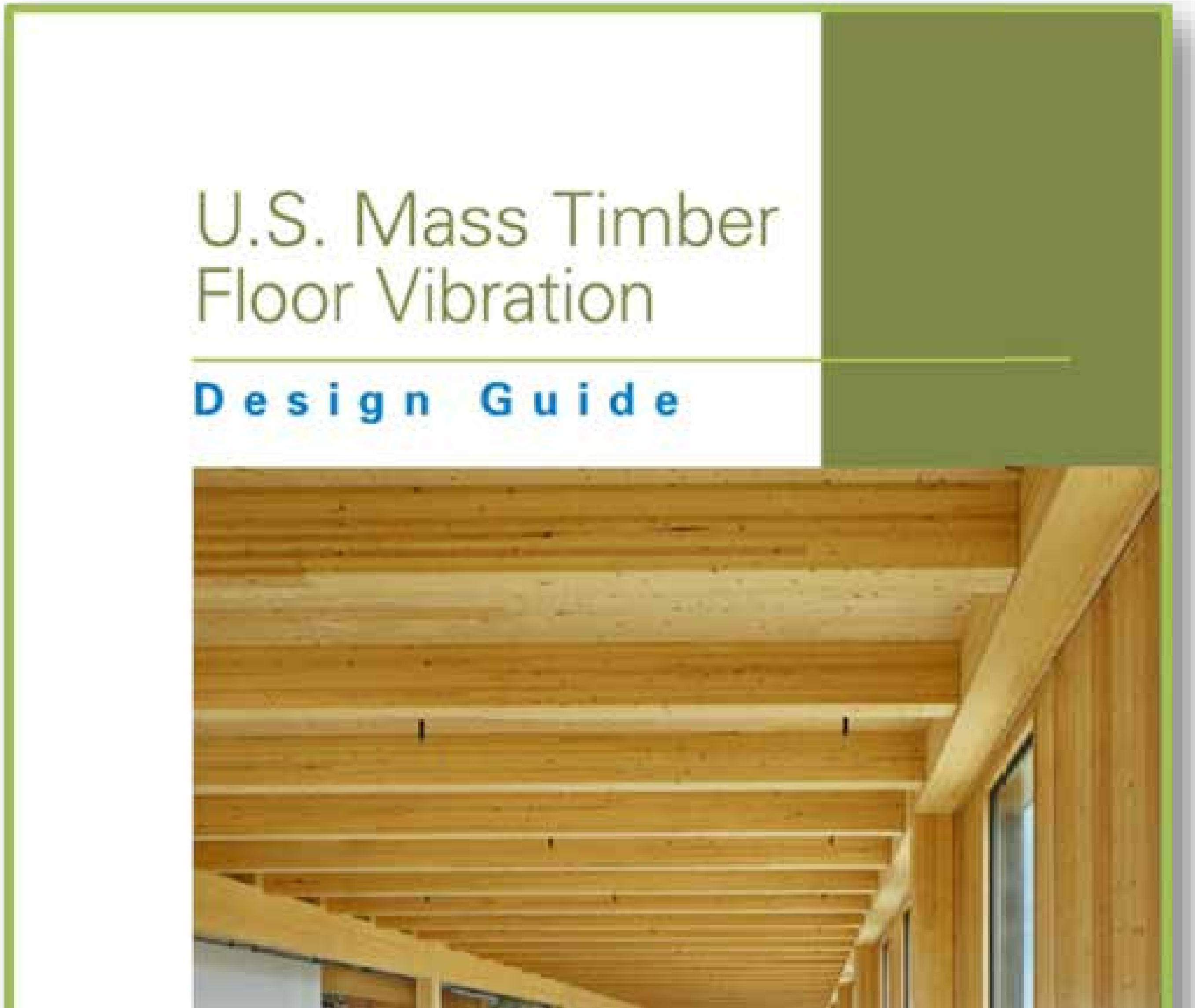
Multi-Span Conditions?

- Check the longest span

- Recommend a 20% increase in the Basic Span Limit when non-structural elements are present which provide enhanced stiffening effect*
  *Partition walls, finishes, ceilings

Reference: 2019 Canadian CLT Handbook, Chapter 7

US Mass Timber Vibration Design Guide



U.S. Mass Timber Floor Vibration

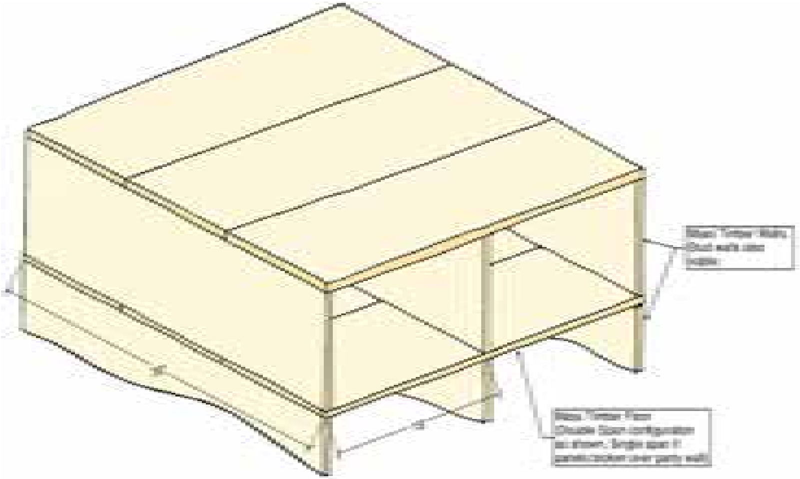
Design Guide

Guide available for free download from WoodWorks.org

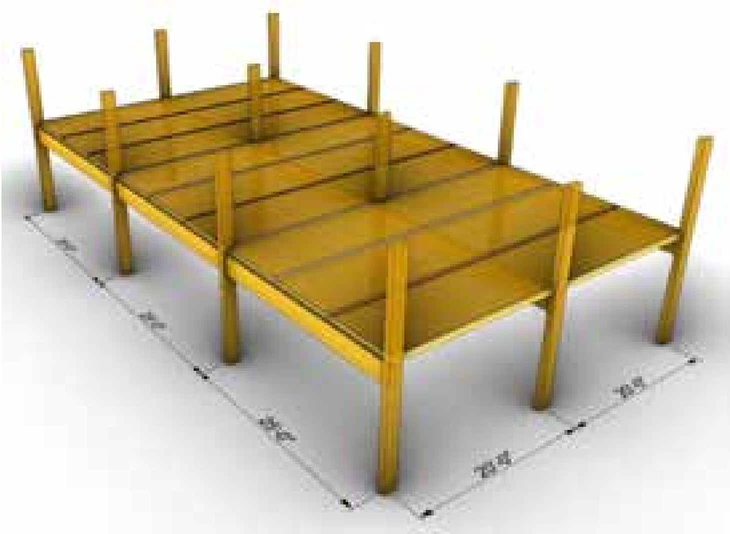
Project Team: WoodWorks, KPFF, Aspect, StructureCraft, & Fast+Epp

U.S. Mass Timber Floor Vibration Design Guide

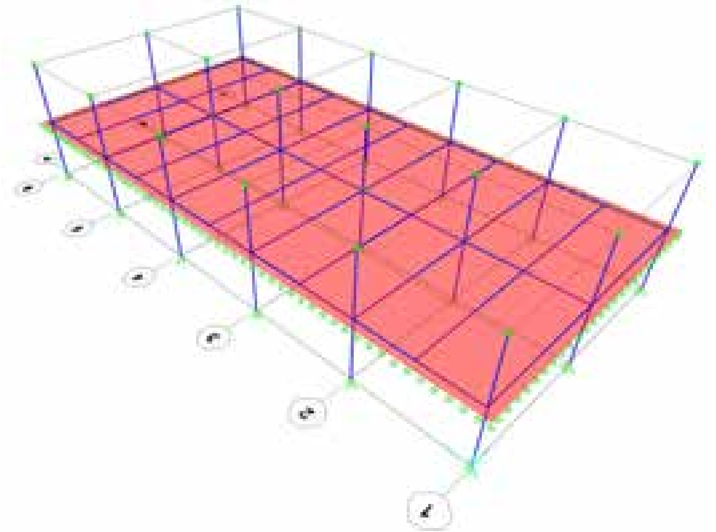
Vibration Design Examples



Residential Bearing Wall Building with CLT



Open Office with NLT on Glulam Frame

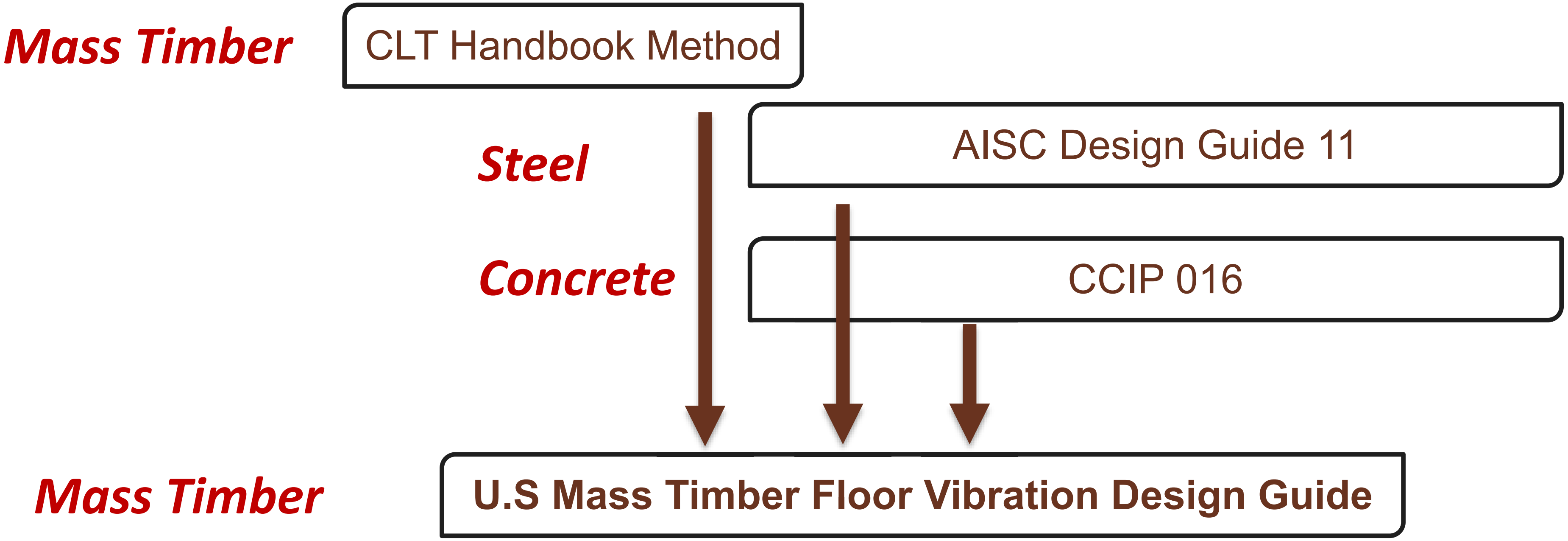


High Performance Lab Space with CLT on Glulam Frame

Available for free from www.woodworks.org

Vibration Design Methods

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



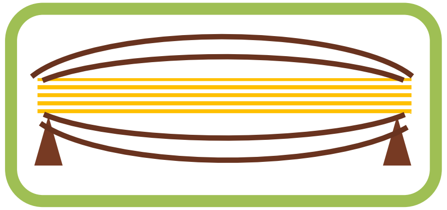
Mass Timber CLT Handbook Method

Steel AISC Design Guide 11

Concrete CCIP 016

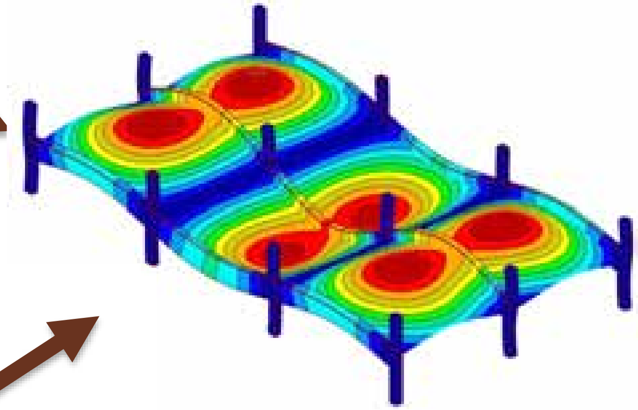
Mass Timber **U.S Mass Timber Floor Vibration Design Guide**

Modal Superposition Method



FEA Model

Walking frequency, f_w
Walker weight
Walking location(s)
Observation location(s)
Damping
etc.



Modes of Vibration

Measures of Performance:

Accelerations for Resonant Low Frequency Floors

Velocities for Transient High Frequency Floors

Walking Frequency f_w

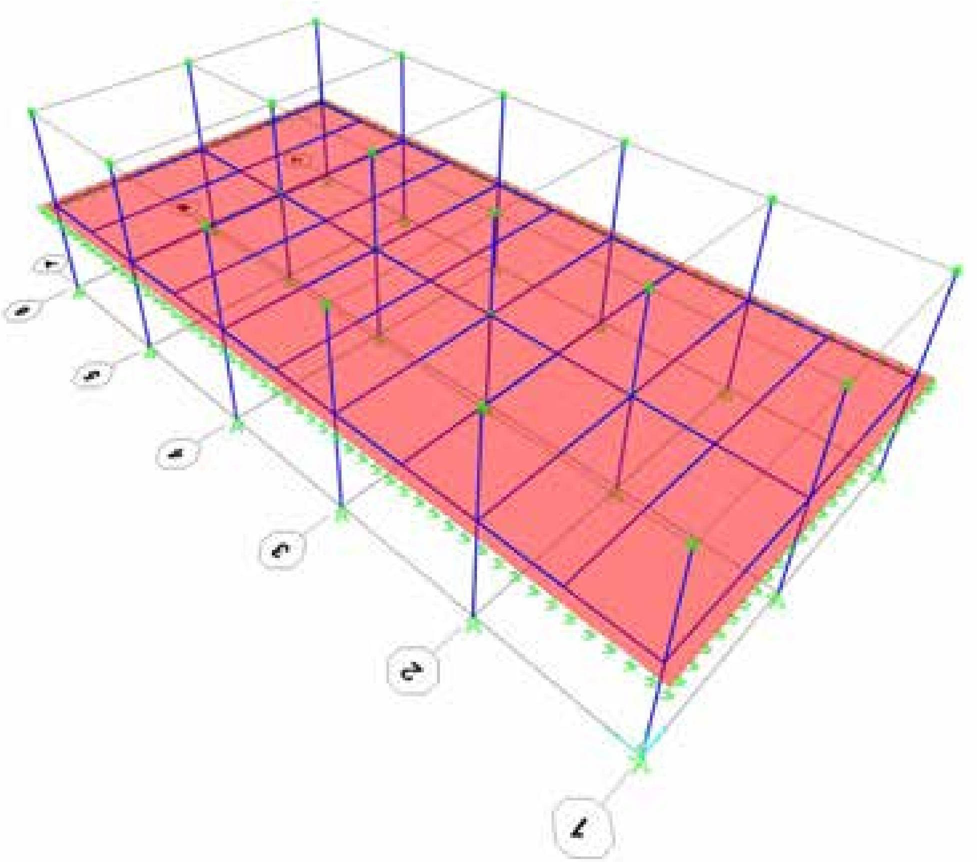
Walking Speed	Walking Frequency	Steps Per Minute
Very Slow	1.25 Hz	75 SPM
Slow	1.6 Hz	95 SPM
Moderate	1.85 Hz	110 SPM
Fast	2.1 Hz	126 SPM
Running	Up to 4.0 Hz	240 SPM
Practical Tip - walk to a metronome too understand the range		

The range of walking frequencies considered is
an important aspect of vibration analysis

Stiffness

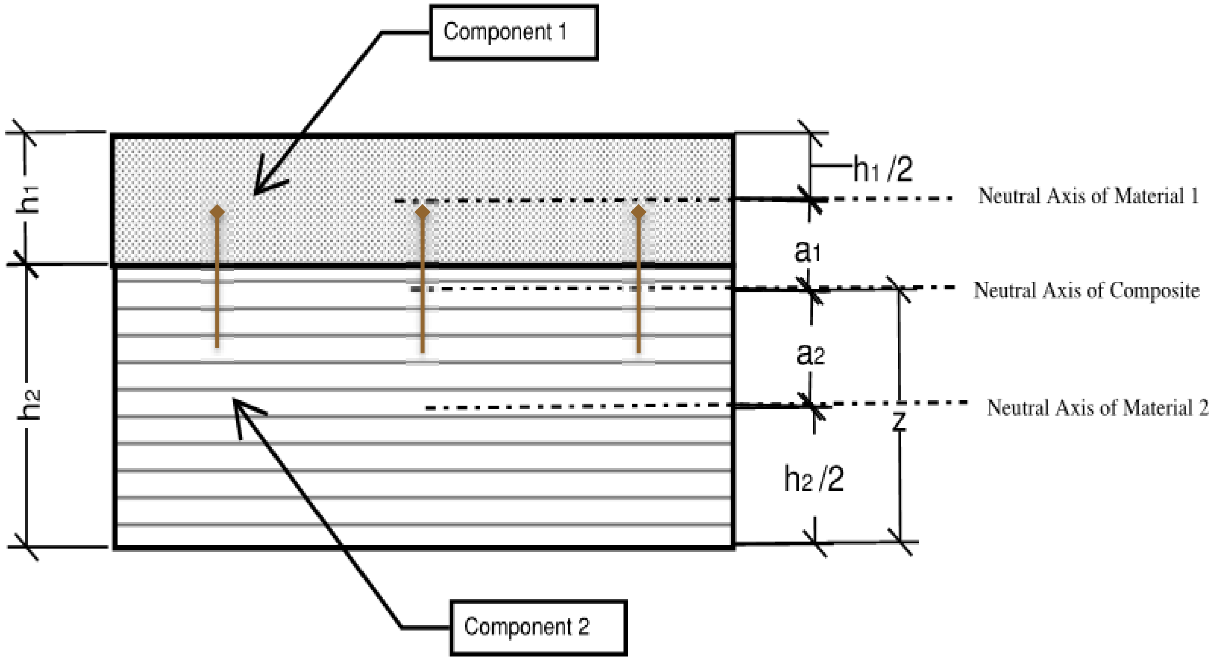
Beneficial to have a vibration specific structural analysis model.

When considering low amplitude deflection to walking excitation, following AISC Design Guide 11 et al:



- Perimeter non-load bearing walls provide vertical restraint or stiffness
- “Gravity” connections often behave as rigid connections
- Use dynamic stiffness values where different that static stiffness value (Concrete)
- “Non-composite” components can have some composite behavior

Composite Behavior



$$EI_{eff} > EI_1 + EI_2$$

$$GA_{eff} > GA_1 + GA_2$$

Even if NOT designed as a composite for code required strength and stiffness, real systems can show *partial composite action* for vibrations

Incidental Composite Behavior

	Consider Composite for:		
Composite Behavior	Strength	Deflection	Vibration
Explicit	Yes	Yes	Yes
Incidental	No	No	Yes

Reference: US Mass Timber Floor Vibration Design Guide

Lateral

“What **R Value** Can I use?”

- Everybody

Mass Timber Design

Lateral framing systems

Light-frame wood shearwalls

Photo Credit: woodworks

Mass Timber Design

Lateral framing systems

Central Core – concrete shearwalls

Photo Credit: structurecraft

Mass Timber Design

Lateral framing systems

Exterior steel moment frame

Photo Credit: woodworks

Mass Timber Design

Lateral framing systems

interior steel moment frame

Photo Credit: woodworks

Mass Timber Design

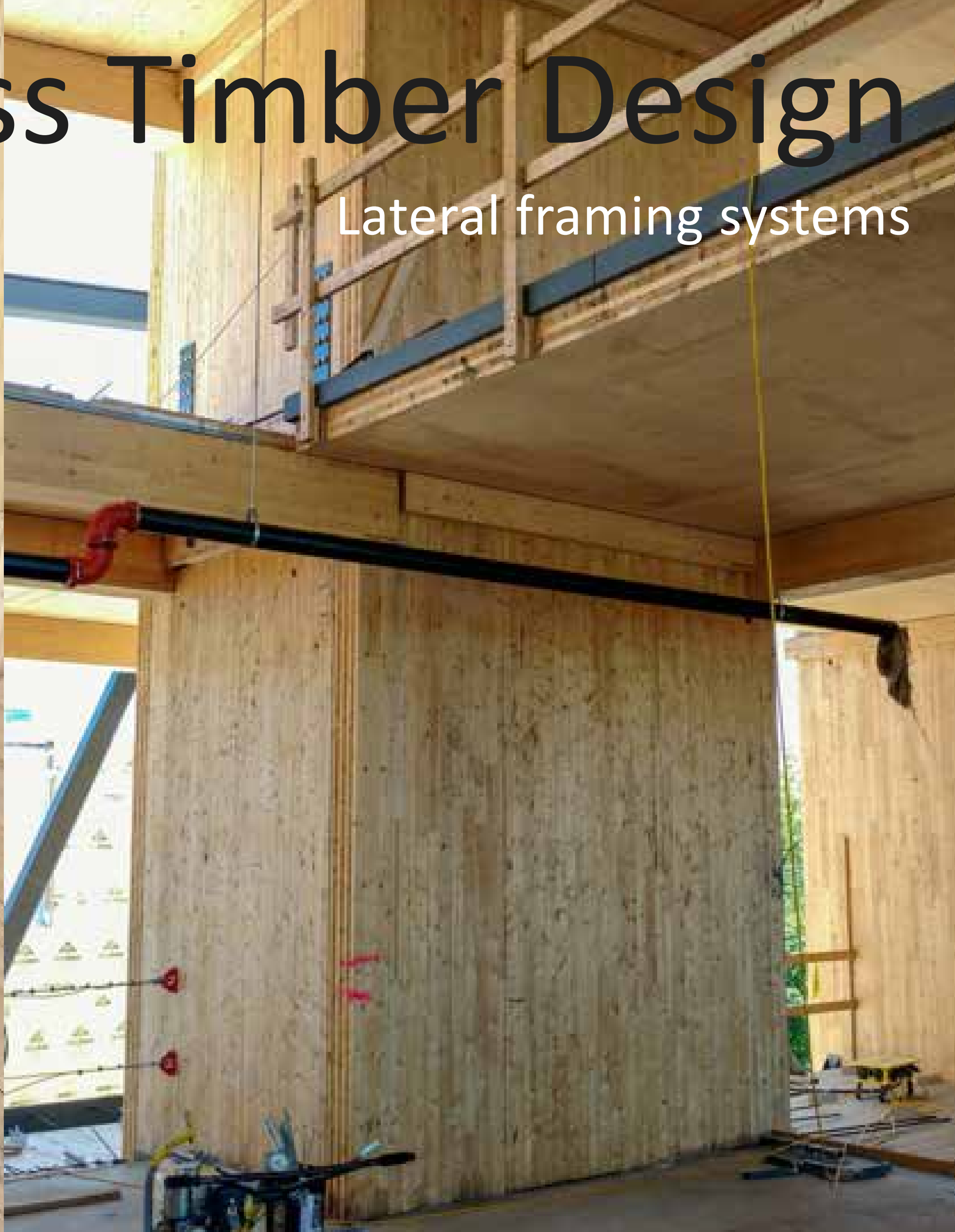
Lateral framing systems

Steel Braced Frame

Photo Credit: john stamets

Mass Timber Design

Lateral framing systems



Mass Timber Shearwalls

Photo Credit: alex schreyer

CLT in Lateral Force Resisting Systems

CLT Panels have a significant in-plane shear strength.

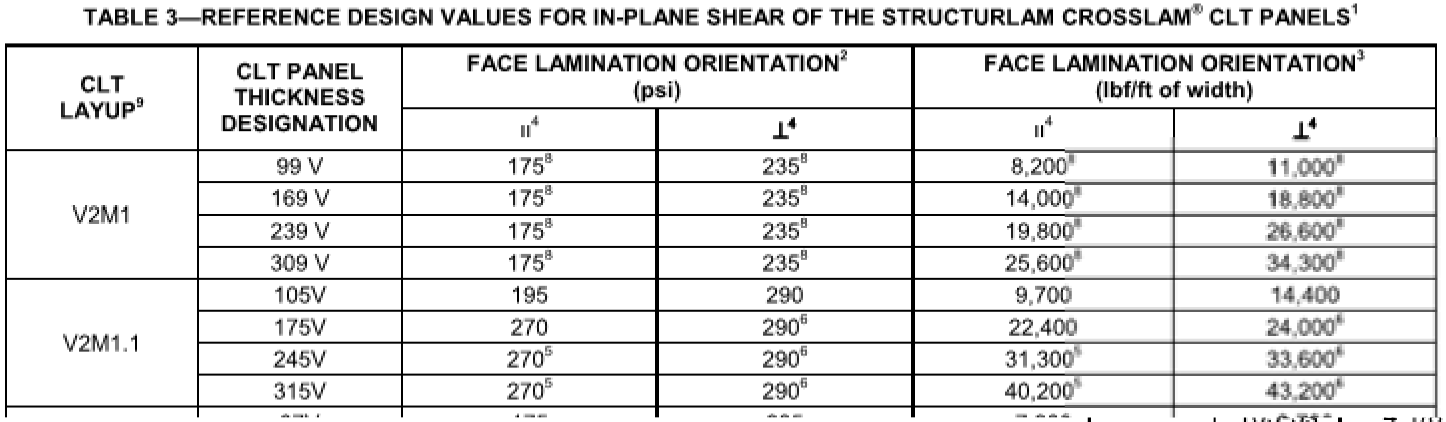
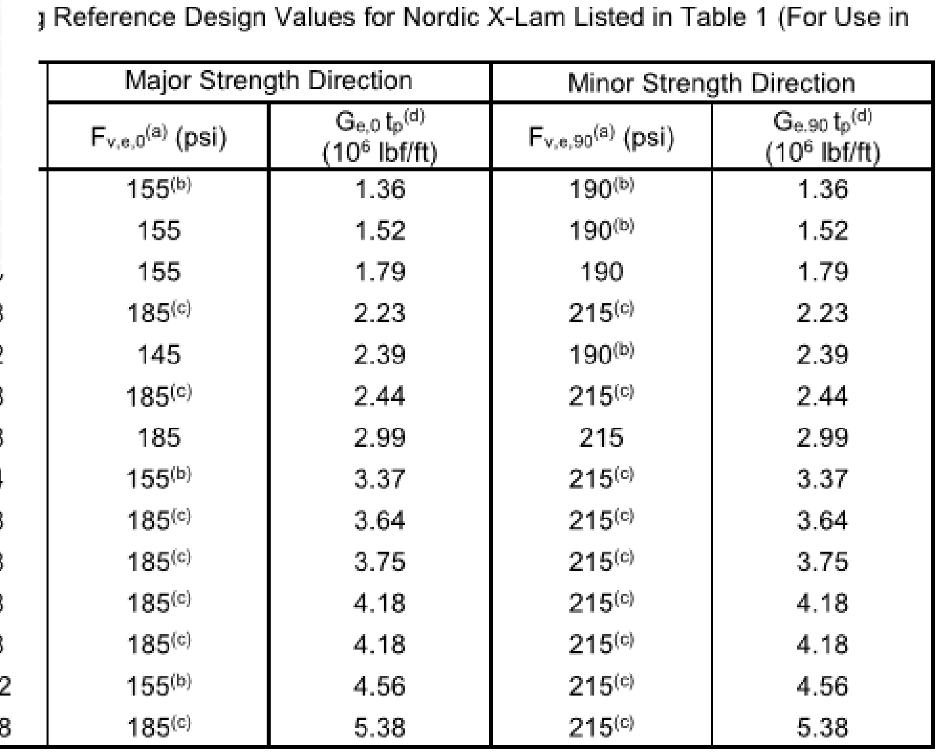


TABLE 3—REFERENCE DESIGN VALUES FOR IN-PLANE SHEAR OF THE STRUCTURLAM CROSSLAM® CLT PANELS[1]

CLT LAYUP[9]	CLT PANEL THICKNESS DESIGNATION	FACE LAMINATION ORIENTATION[2] (psi)		FACE LAMINATION ORIENTATION[3] (lbf/ft of width)	
		∥[4]	⊥[4]	∥[4]	⊥[4]
V2M1	99 V	175[8]	235[8]	8,200[8]	11,000[8]
	169 V	175[8]	235[8]	14,000[8]	18,800[8]
	239 V	175[8]	235[8]	19,800[8]	26,600[8]
	309 V	175[8]	235[8]	25,600[8]	34,300[8]
V2M1.1	105V	195	290	9,700	14,400
	175V	270	290[6]	22,400	24,000[6]
	245V	270[5]	290[6]	31,300[5]	33,600[6]
	315V	270[5]	290[6]	40,200[5]	43,200[6]

Source: ICC-ES/APA Joint Evaluation Report *ESR 3631*



Reference Design Values for Nordic X-Lam Listed in Table 1 (For Use in

			Major Strength Direction		Minor Strength Direction	
			$F_{v,e,0}$[(a)] (psi)	$G_{e,0}\,t_p$[(d)] (10^6 lbf/ft)	$F_{v,e,90}$[(a)] (psi)	$G_{e,90}\,t_p$[(d)] (10^6 lbf/ft)
E1			155[(b)]	1.36	190[(b)]	1.36
			155	1.52	190[(b)]	1.52
			155	1.79	190	1.79
	131-5s	5 1/8	185[(c)]	2.23	215[(c)]	2.23
	140-4s	5 1/2	145	2.39	190[(b)]	2.39
	143-5s	5 5/8	185[(c)]	2.44	215[(c)]	2.44
	175-5s	6 7/8	185	2.99	215	2.99
	197-7s	7 3/4	155[(b)]	3.37	215[(c)]	3.37
	213-7l	8 3/8	185[(c)]	3.64	215[(c)]	3.64
	220-7s	8 5/8	185[(c)]	3.75	215[(c)]	3.75
	244-7s	9 5/8	185[(c)]	4.18	215[(c)]	4.18
	244-7l	9 5/8	185[(c)]	4.18	215[(c)]	4.18
	267-9l	10 1/2	155[(b)]	4.56	215[(c)]	4.56
	314-9l	12 3/8	185[(c)]	5.38	215[(c)]	5.38

Source: *APA Product Report PR-L306*

145 to 290 PSI Allowable Edgewise Shear

= 1.7 to 3.5 kips/ft (ASD)
per inch of thickness!

Consult with the Manufacturers for Details

Multiply by ***Cd = 1.6*** *for short term loading*

CLT in the U.S. Building Code – IBC 2021 (Lateral)


2021
EDITION
SDPWS
SPECIAL DESIGN PROVISIONS
FOR WIND AND SEISMIC
ANSI
AMERICAN
WOOD
COUNCIL

Now with CLT shear wall and diaphragm requirements

AWC SDPWS 2021


7-16
Minimum Design
Loads for Buildings
and Other Structures
ASCE

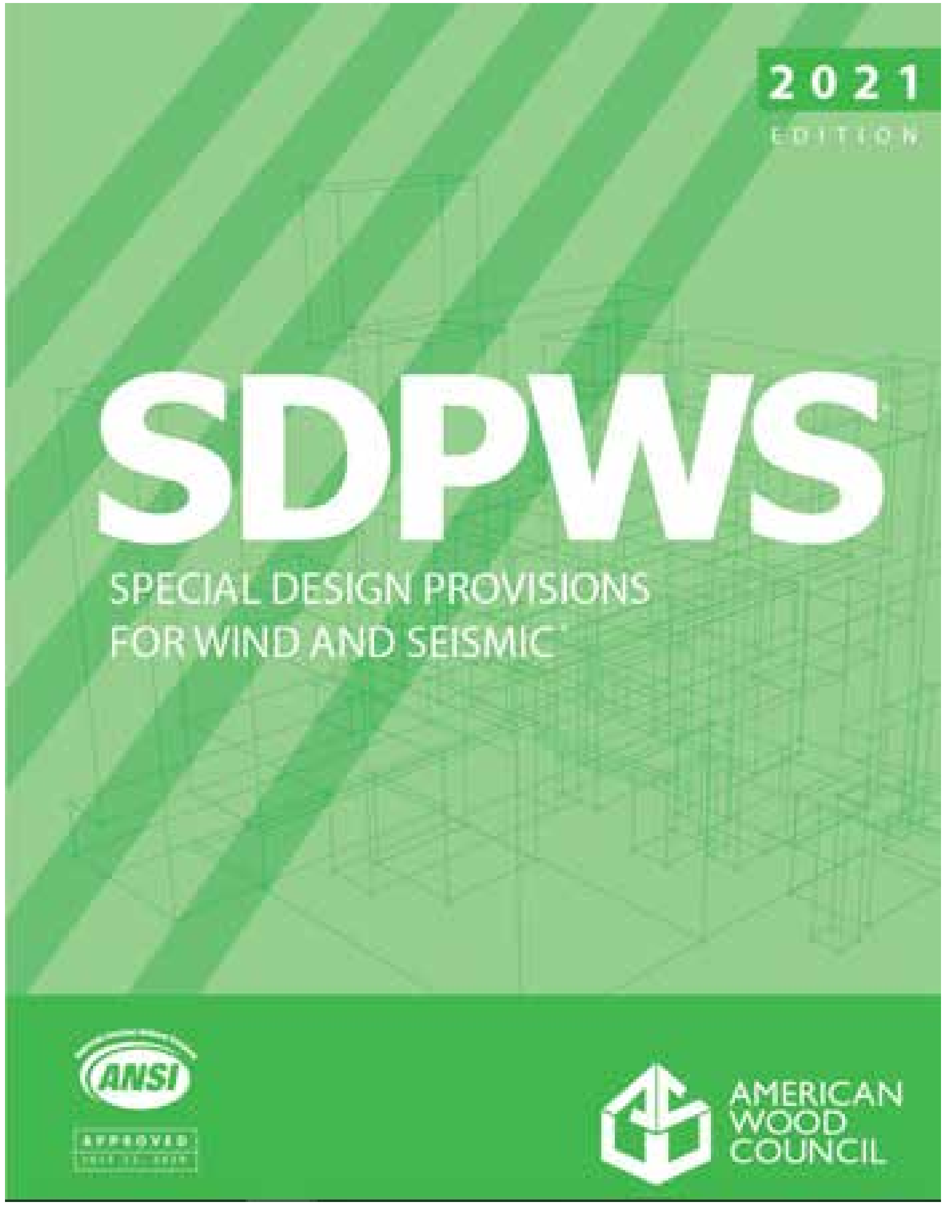
ASCE/SEI 7-16


IBC
INTERNATIONAL
BUILDING
CODE
2021

2021 International Building Code

New Requirements for CLT Lateral Systems in SDPWS 2021!
Referenced from IBC 2021

2021 Special Design Provisions for Wind and Seismic



2021
EDITION

SDPWS

SPECIAL DESIGN PROVISIONS
FOR WIND AND SEISMIC

ANSI
APPROVED

AMERICAN
WOOD
COUNCIL

Top Changes Relevant to CLT Lateral Systems:

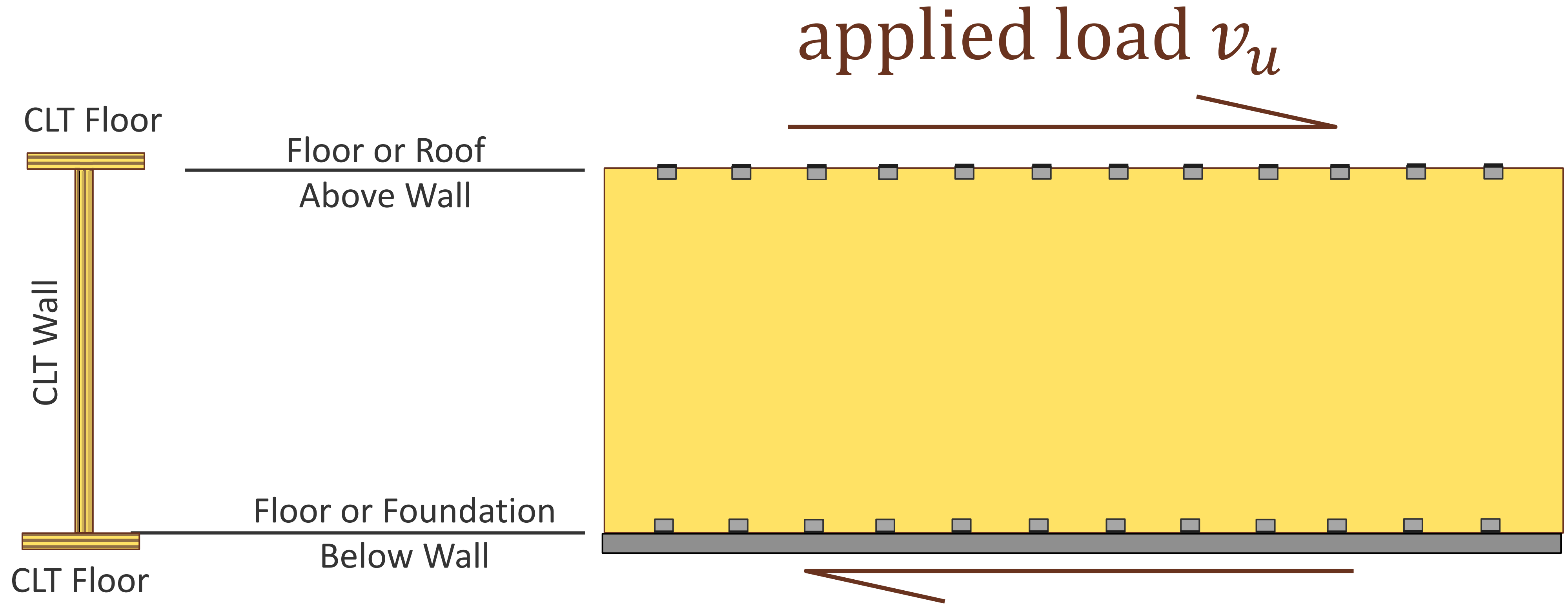
- New unified nominal shear capacity
- **New CLT Shear Wall requirements** (Appendix B)
- **New CLT Diaphragm requirements**

Available from awc.org

PowerPoint IS NOT the CODE!

CLT Shear Walls in SDPWS 2021

Platform Framed CLT Construction



applied load v_u

CLT Floor

Floor or Roof

Above Wall

CLT Wall

Floor or Foundation

Below Wall

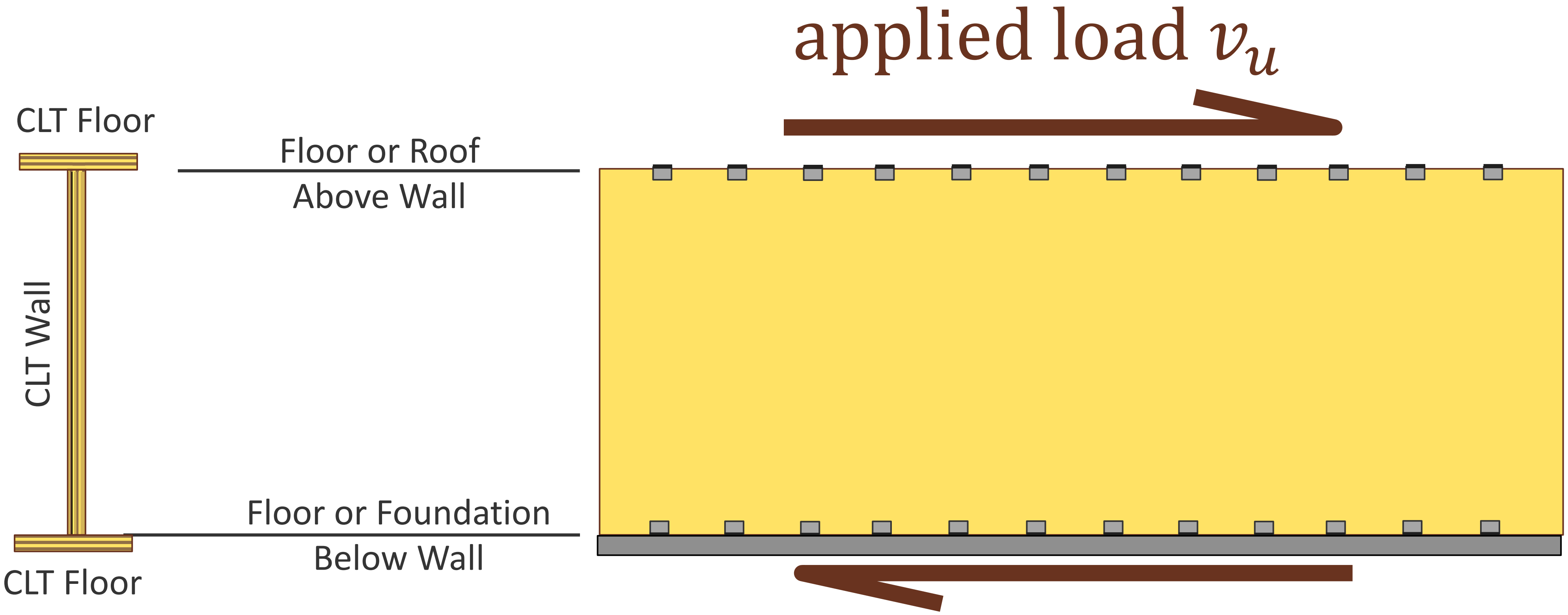
CLT Floor

Section View

Elevation View

CLT Shear Walls in SDPWS 2021

Platform Frame CLT Construction



applied load v_u

CLT Floor

Floor or Roof

Above Wall

CLT Wall

Floor or Foundation

Below Wall

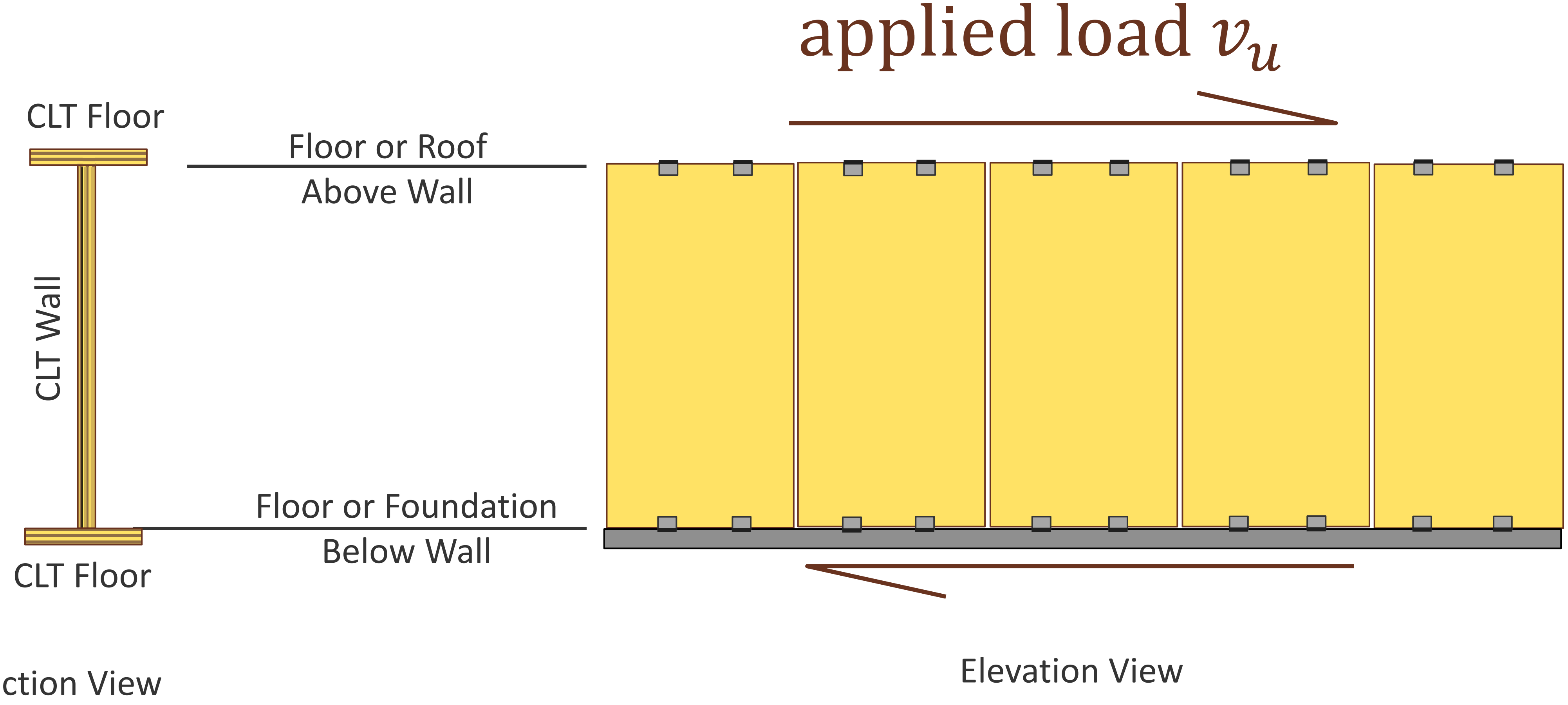
CLT Floor

Section View

Elevation View

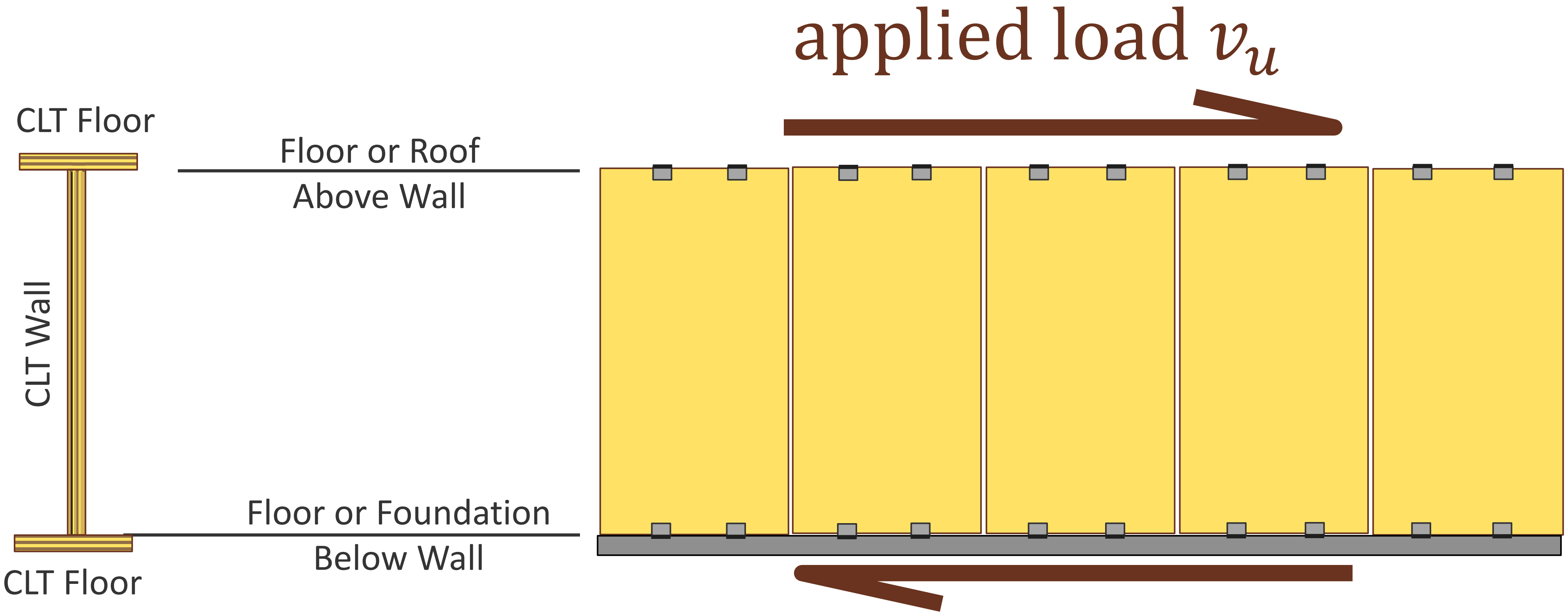
CLT Shear Walls in SDPWS 2021

Platform Frame CLT Construction



CLT Shear Walls in SDPWS 2021

Platform Frame CLT Construction

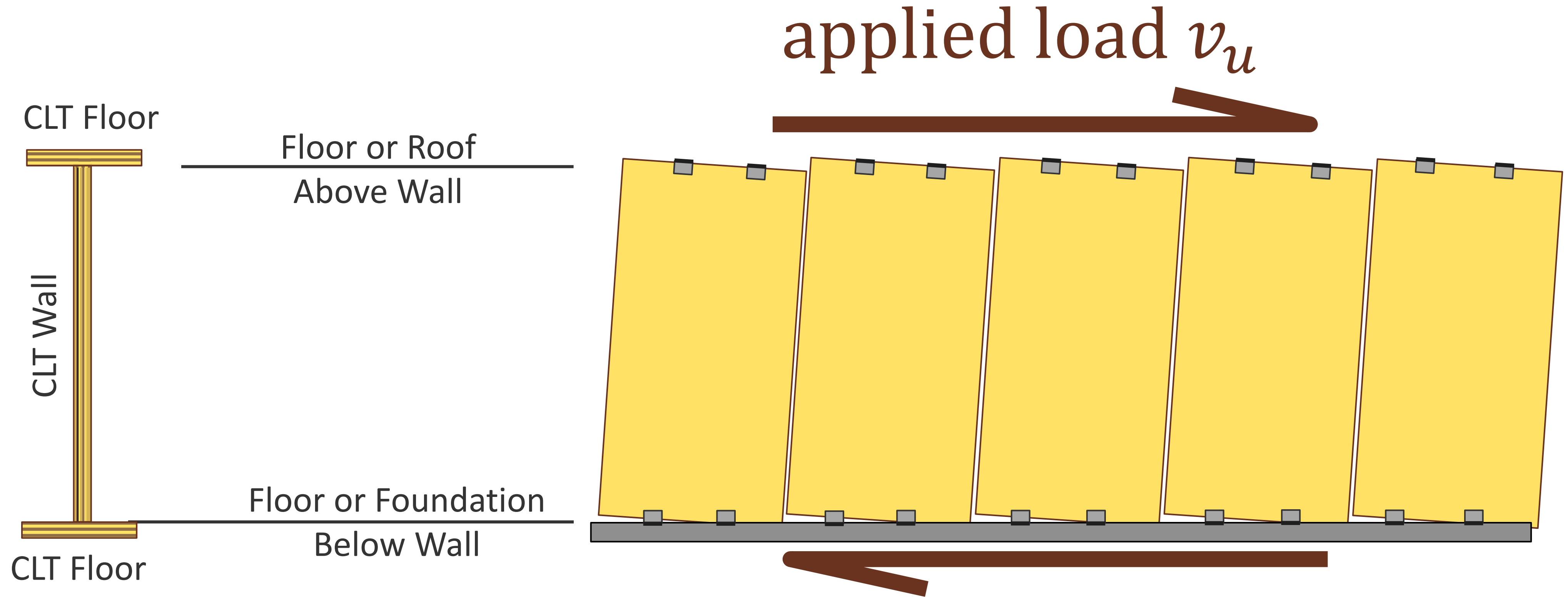


Section View

Elevation View

CLT Shear Walls in SDPWS 2021

Platform Frame CLT Construction

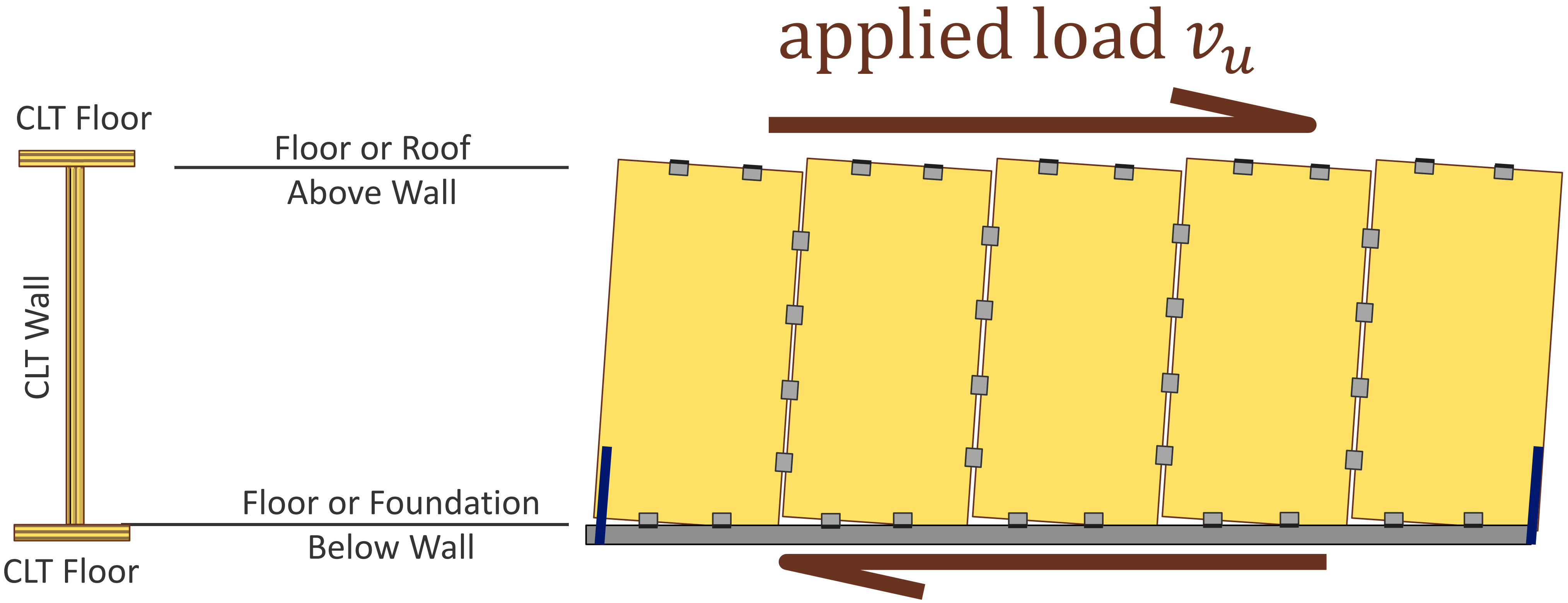


Section View

Elevation View

CLT Shear Walls in SDPWS 2021

Platform Frame CLT Construction

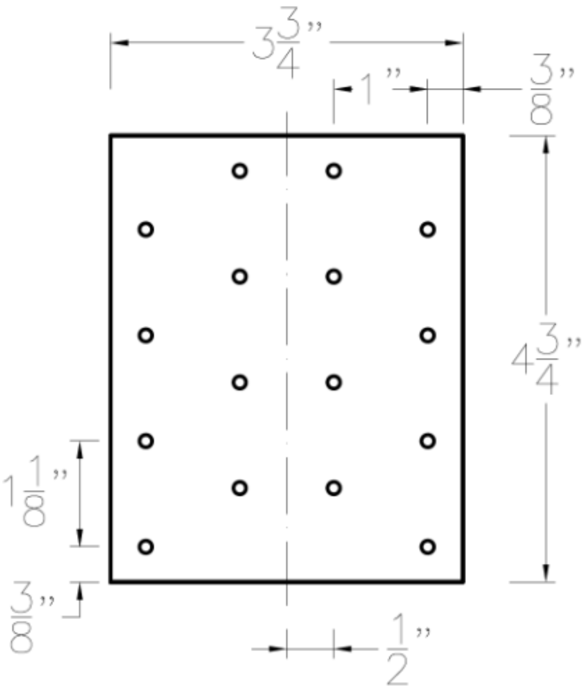


Section View

Elevation View

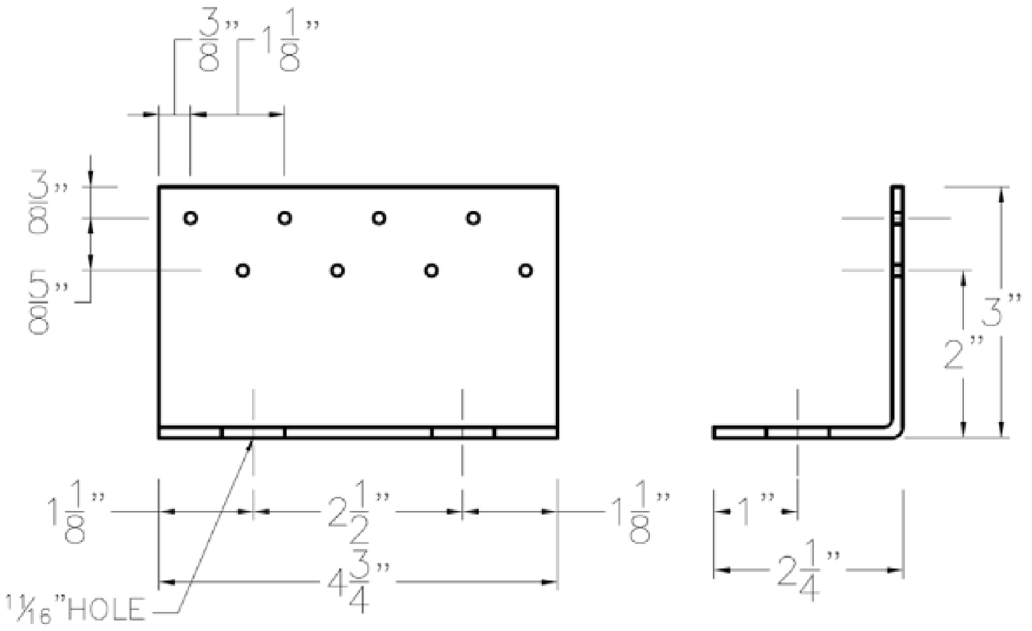
CLT Shear Walls in SDPWS 2021

Panel to Panel Connection



0.105” ASTM A653 Grade 33 Steel
(8) 16d box nails to each wall panel
3.5” long x 0.135”Ø shank with 0.344” Ø head

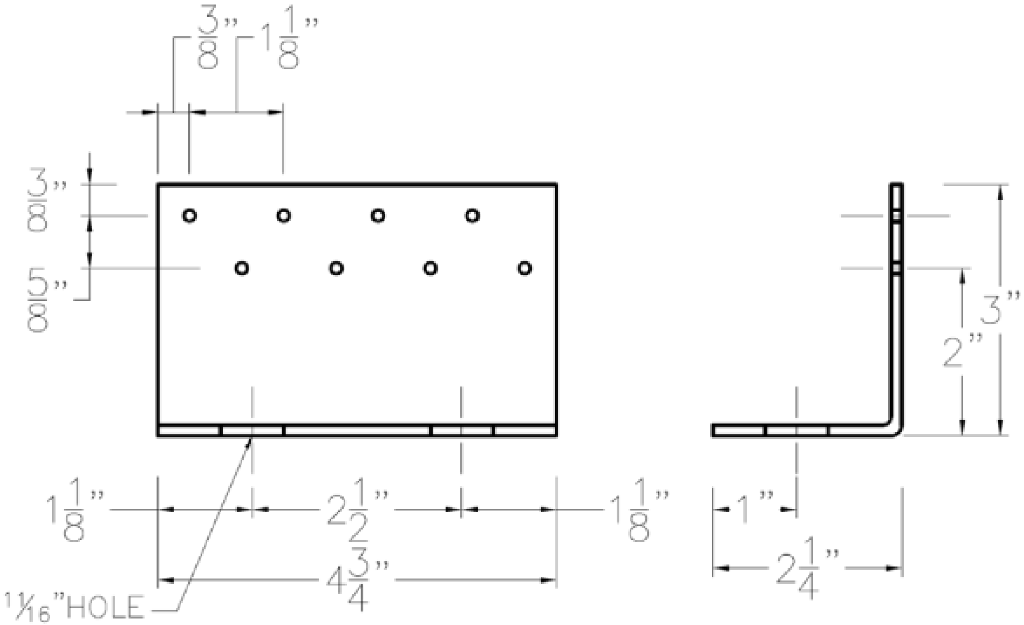
Panel to Platform Connection



Same steel plate and nails plus
5/8” Ø bolts or lag screws to roof, floor or foundation

CLT Shear Walls in SDPWS 2021

Panel to Platform Connection



Nominal shear capacity

v_n = 2605 C_G [lbs] per angle connector

C_G adjusts for specific gravity, G of CLT

C_G = 1.0	for $G \geq 0.42$
= 0.86	for G = 0.35
= 1.0 – 2 (0.42-G)	for $0.42 > G > 0.35$

Nominal unit shear capacity:

$v_n = n\ (2605 / b_s)\ C_G$ [lbs/ft]

CLT Shear Walls in SDPWS 2021

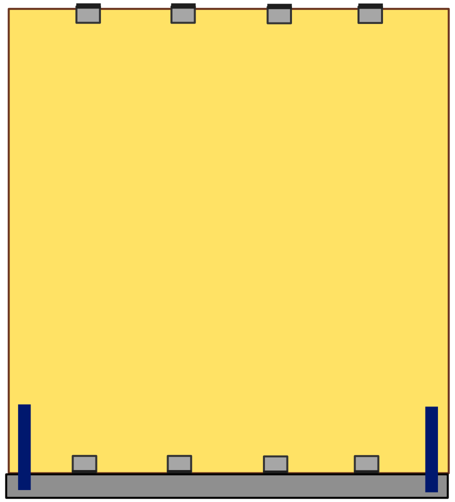
(other)

CLT Shear Walls

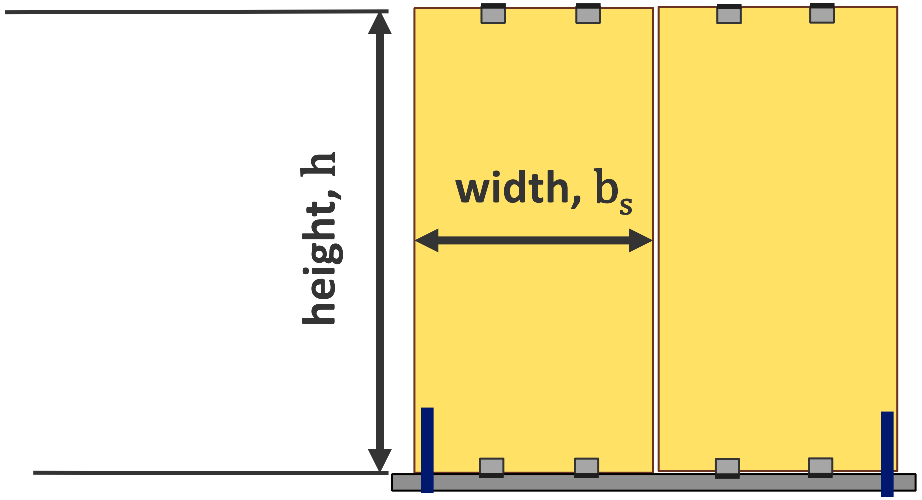
not meeting Appendix B

CLT Shear Walls

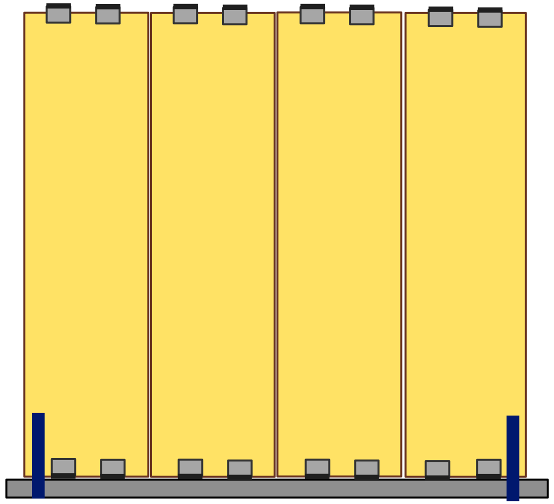
meeting SDPWS 2021 Appendix B



Seismic Design Category A
or SDC B and ≤ 65’ tall
in SDPWS 4.6.3 Exception



Panel aspect ratios
$2 \leq h/b_s \leq 4$



with shear resistance provided by high aspect ratio panels only (SDPWS B.3.7)

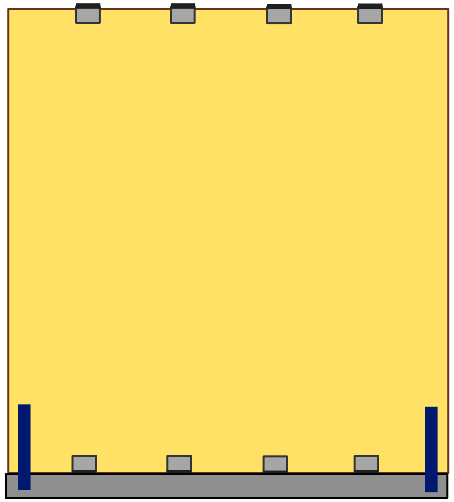
Panel aspect ratios
$h/b_s = 4$

R Values for CLT Shear Walls in SDPWS 2021

(other)

CLT Shear Walls

not meeting Appendix B



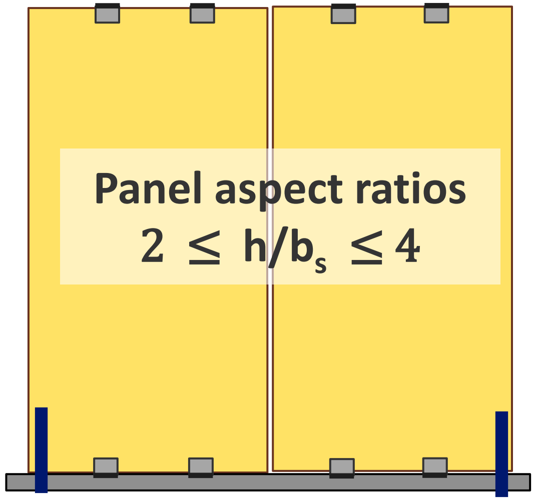
R = 1.5

$C_d = 1.5$ $\Omega_o = 2.5$

In SDPWS 2021 4.6.3

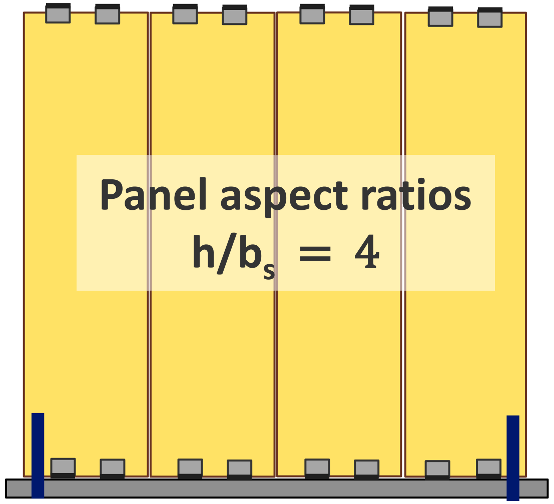
CLT Shear Walls

meeting SDPWS 2021 Appendix B



R = 3.0*

$C_d = 3.0$ $\Omega_o = 3.0$



R = 4.0*

$C_d = 4.0$ $\Omega_o = 3.0$

* ASCE 7-22

CLT in the U.S. Building Code – Lateral in IBC 2021

SDPWS 2015

Now with CLT shear wall and diaphragm requirements

AWC SDPWS 2021

Where Seismic (R values) and Wind Systems are Referenced. No CLT

ASCE/SEI 7-16

2021 International Building Code

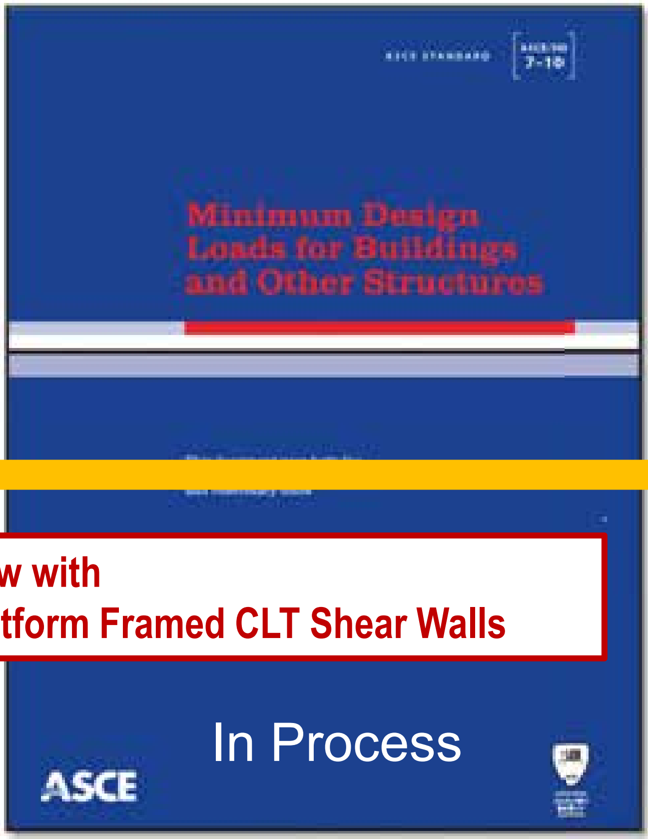
New Requirements for CLT Lateral Systems!

(but R values for CLT Shear Walls not in ASCE 7-16)

CLT in the U.S. Building Code – Lateral in the IBC 2024?

Now with CLT shear wall and diaphragm requirements

AWC SDPWS 2021



Now with
Platform Framed CLT Shear Walls

In Process

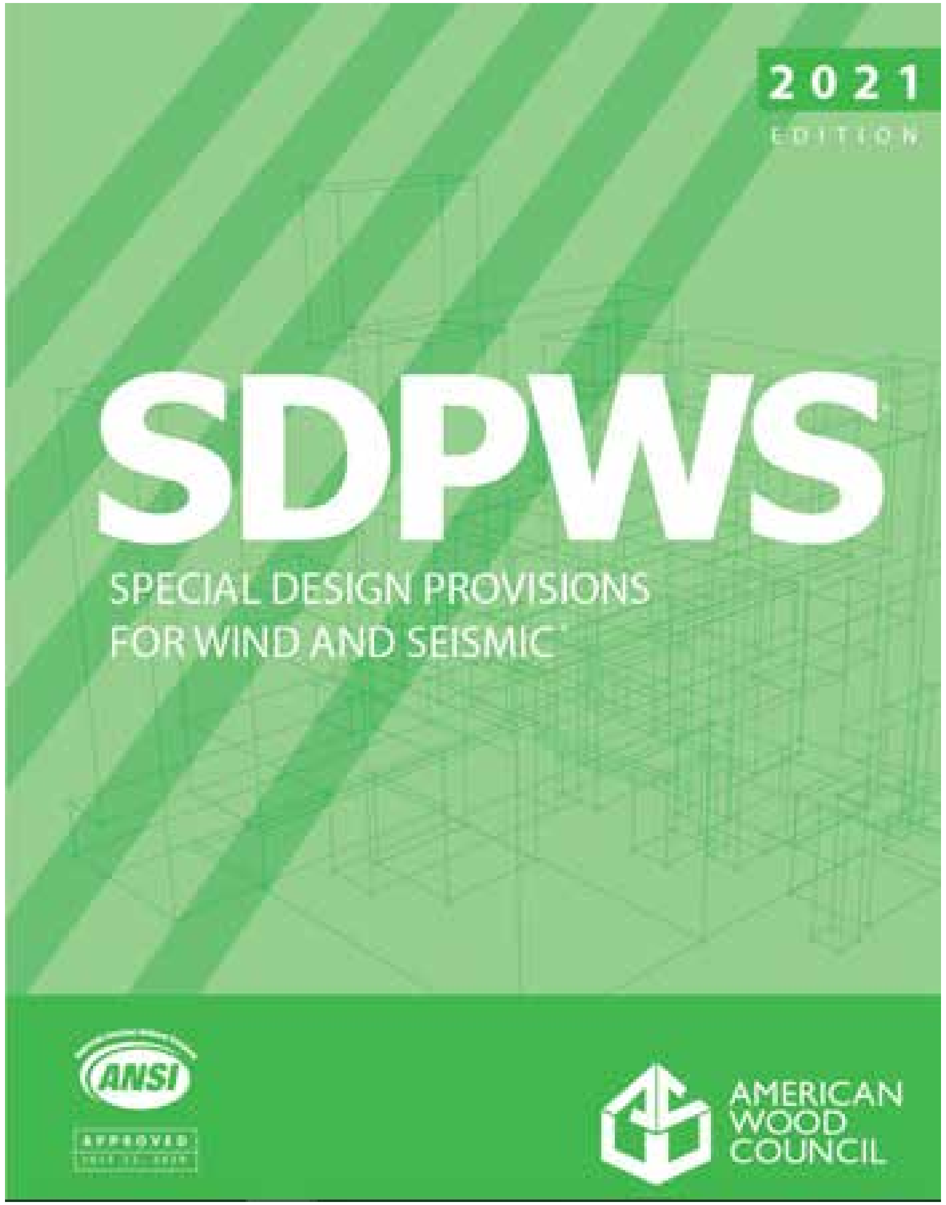
ASCE/SEI 7-22

To Be Made

2024 IBC
(in process)

Future Full Recognition of CLT Lateral Systems

2021 Special Design Provisions for Wind and Seismic



2021

EDITION

SDPWS

SPECIAL DESIGN PROVISIONS FOR WIND AND SEISMIC

ANSI

APPROVED

AMERICAN WOOD COUNCIL

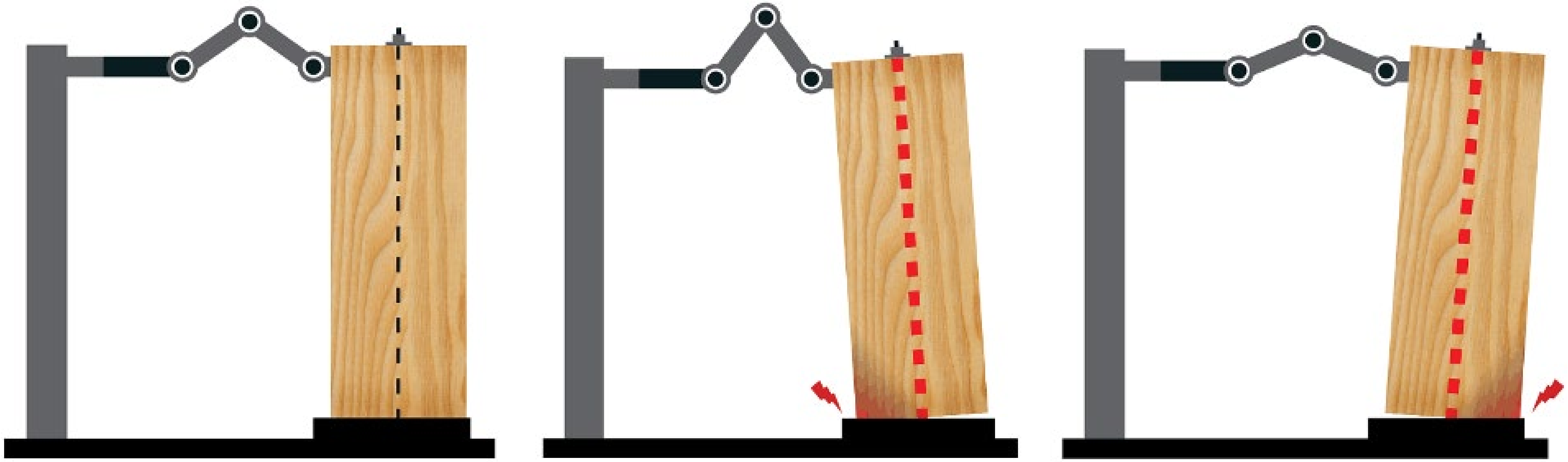
Top Changes Relevant to CLT Lateral Systems:

- New unified nominal shear capacity
- **New CLT Shear Wall requirements**
- **New CLT Diaphragm requirements**

Available from awc.org

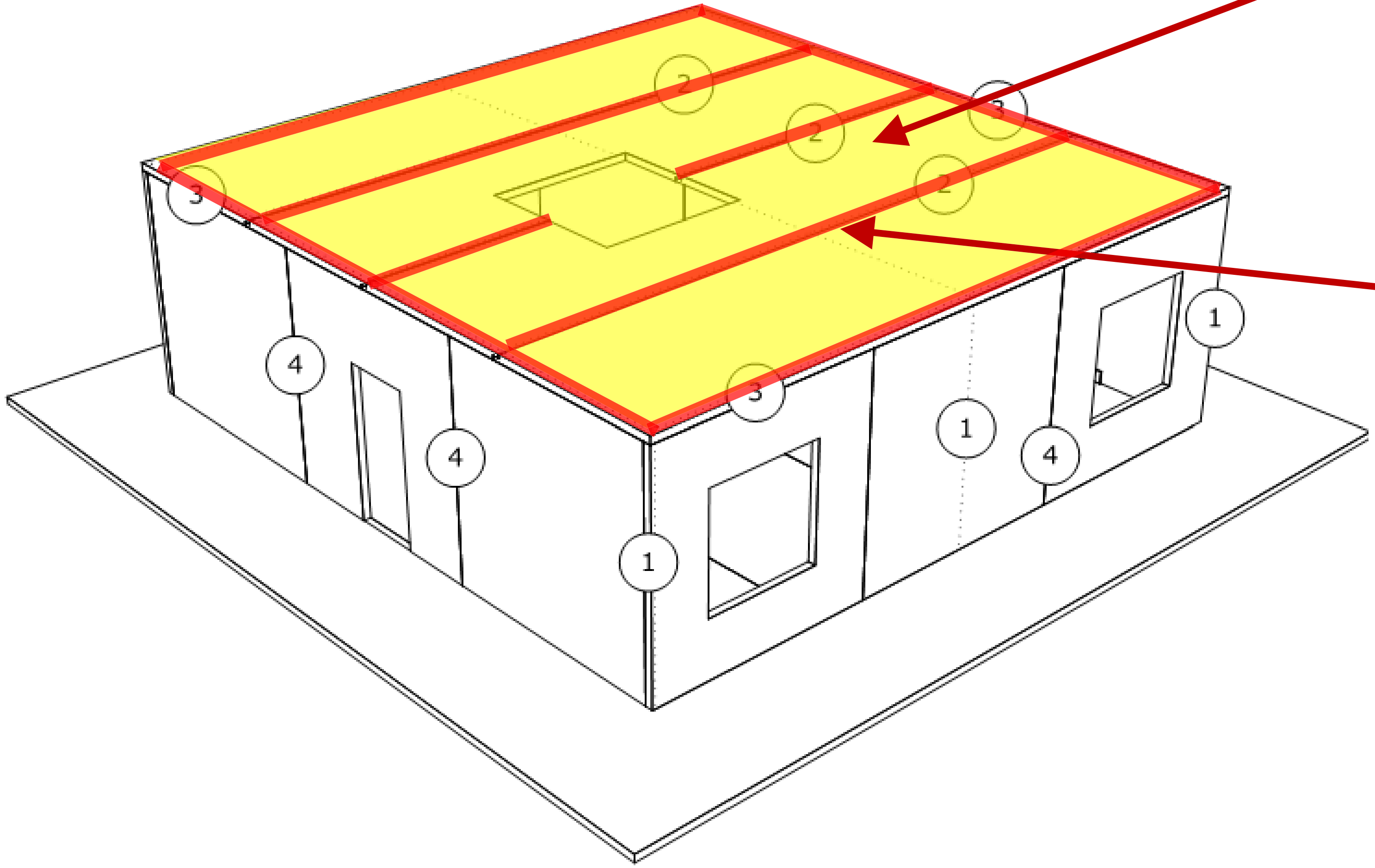
PowerPoint IS NOT the CODE!

Innovative Systems under continued research



Mass Timber Post-Tensioned Rocking Shear Walls
CLT Balloon Framed Shear Walls

CLT Diaphragms



Strength of CLT rarely governs.

Strength of Connections covered by NDS and Proprietary Fastener Evaluation Reports

More information

- Detailing for performance and constructability
- Determination of diaphragm flexibility
- Calculation of diaphragm deflections
- Precalculated connection capacities
- Combination SDPWS γ_D
  and ACSE 7 Ω_o and ρ

Available from woodworks.org

WOODWORKS

CLT Diaphragm Design for Wind and Seismic Resistance

Using SDPWS 2021 and ASCE 7-22

Cross-laminated timber (CLT) has become increasingly prominent in building construction and can be seen in buildings throughout the world. Specifically, the use of CLT floor and roof panels as a primary gravity force-resisting component has become relatively commonplace. Now, with availability of the 2021 *Special Design Provisions for Wind and Seismic* (SDPWS 2021) from the American Wood Council (AWC), U.S. designers have a standardized path to utilize CLT floor and roof panels as a structural diaphragm. Prior to publication of this document, projects typically had to receive approval to use CLT as a structural diaphragm on a case-by-case basis from the local Authority Having Jurisdiction (AHJ).

This paper highlights important provisions of SDPWS 2021 for CLT diaphragm design and recommendations developed by the authors in the more extensive *CLT Diaphragm Design Guide*, based on SDPWS 2021, published by WoodWorks – Wood Products Council.

AWC SDPWS 2021

SDPWS 2021 is the first edition to provide direct provisions for CLT to be used as an element in a diaphragm or shear wall. To differentiate between CLT and light-frame lateral force-resisting systems, it adopts the terminology sheathed wood-frame for light-frame diaphragms (SDPWS §4.2) and shear walls (SDPWS §4.3), and includes new sections for CLT diaphragms (SDPWS §4.5) and shear walls (SDPWS §4.6). SDPWS 2021 is referenced in the 2021 International Building Code (IBC).

Shear Capacity

SDPWS 2021 has a single nominal shear capacity for each set of construction details, v_n, defined in §4.1.4 for use with both wind and seismic design. From this nominal shear capacity, the Allowable Stress Design (ASD) and Load and Resistance Factor Design (LRFD) wind and seismic design capacities are determined by dividing by the ASD reduction factor, Ω_D, or multiplying by a resistance factor, ϕ_D, for LRFD design as summarized in Table 1. For sheathed wood-frame diaphragms, the SDPWS

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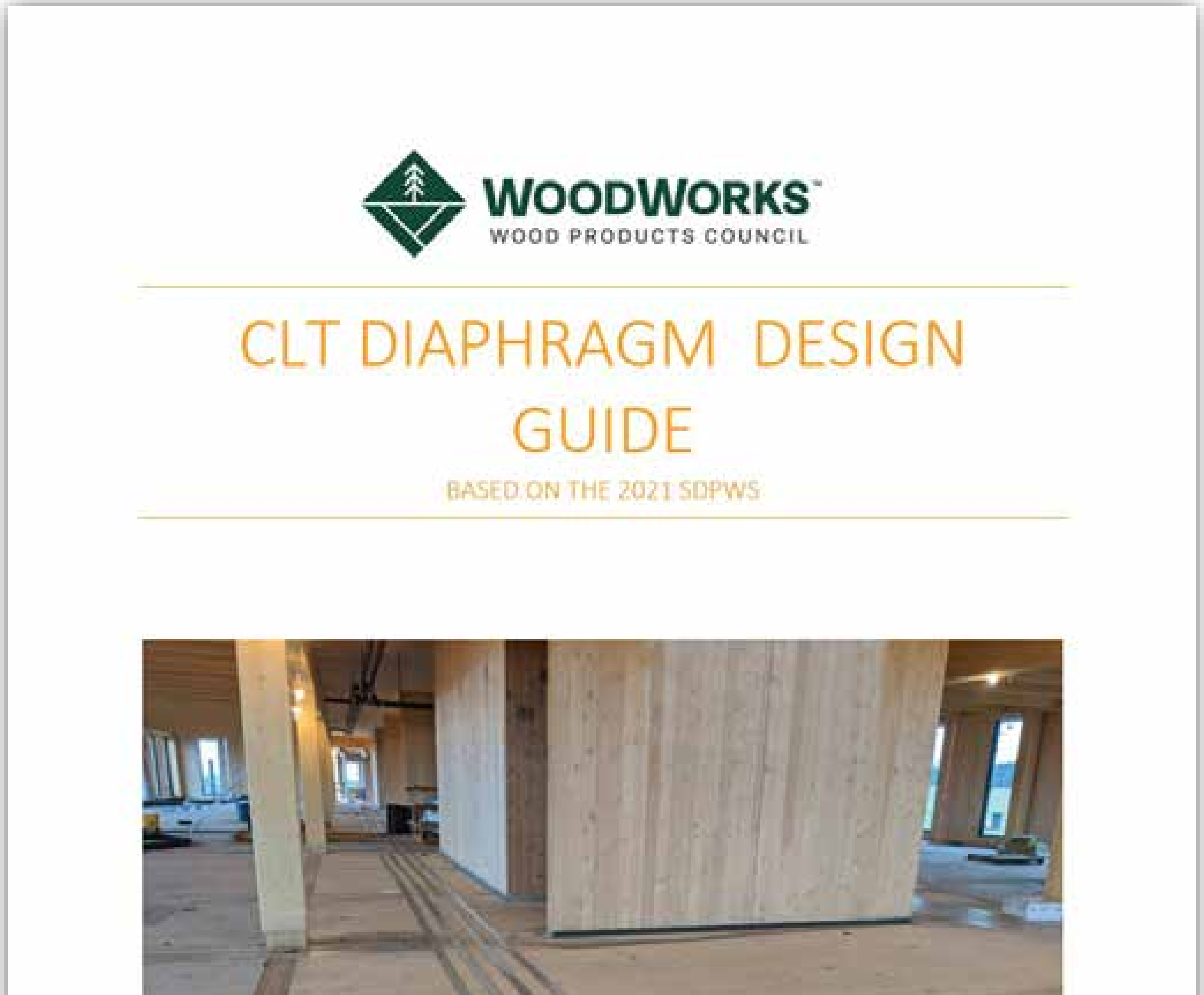
Donovan Llanes, PE
Jonas Houston, PE, SE
Mengzhe Gu, PhD, PE

WoodWorks CLT Diaphragm Design Guide



WOODWORKS
WOOD PRODUCTS COUNCIL

CLT DIAPHRAGM DESIGN GUIDE

BASED ON THE 2021 SDPWS

Under Development By:

WOODWORKS
WOOD PRODUCTS COUNCIL

Holmes

kpff

SWINERTON
MASS TIMBER

Funded By:

U.S. Endowment
for Forestry and Communities

USDA

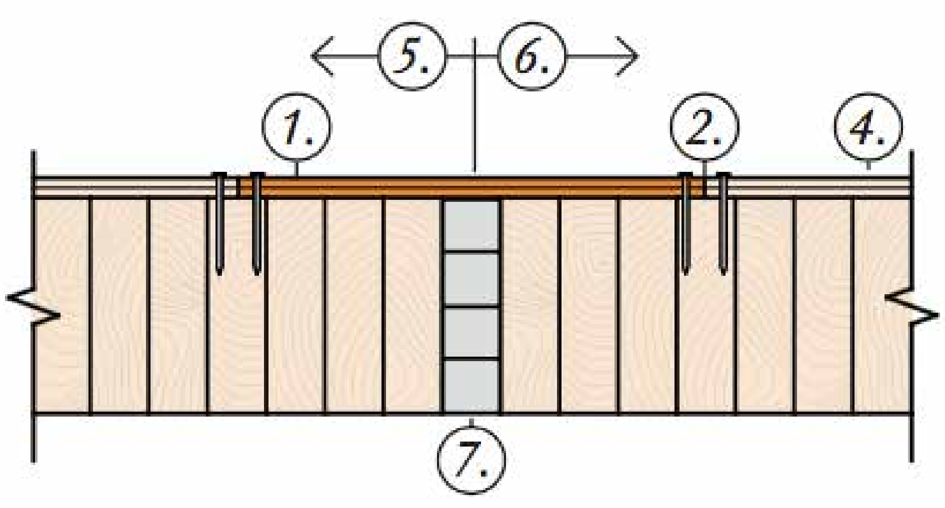
Photo Credit: structurecraft

NLT Diaphragm Design

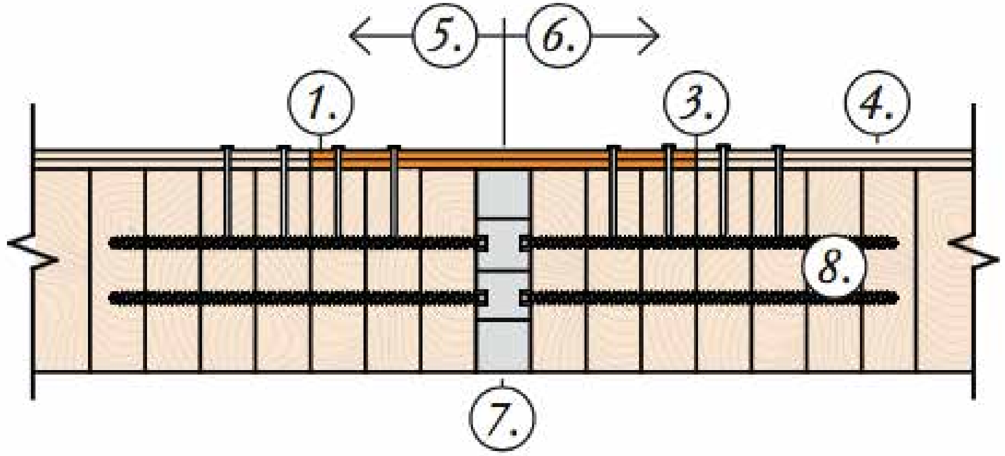
Pre-fabricated panels often pre-sheathed

Once installed, add splice strips, tape joint if applicable

NLT Diaphragm Design



Typical Diaphragm



High Load Diaphragm

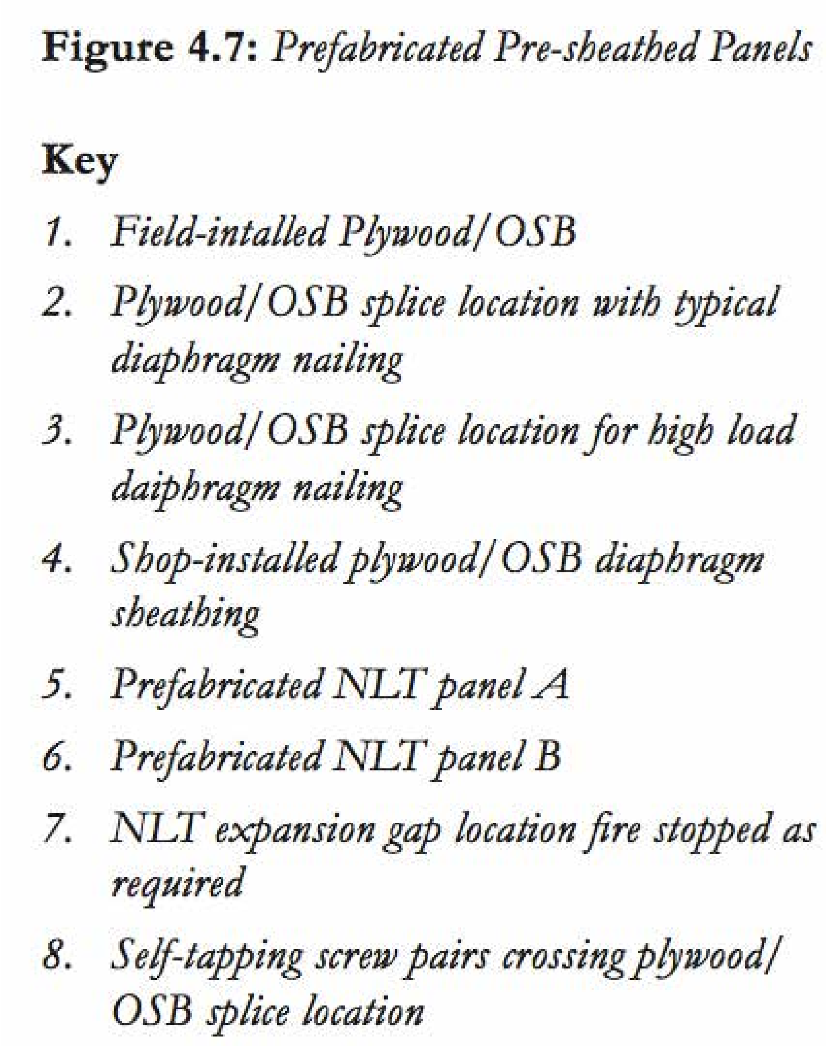


Figure 4.7: *Prefabricated Pre-sheathed Panels*

Key

1. *Field-intalled Plywood/OSB*
2. *Plywood/OSB splice location with typical diaphragm nailing*
3. *Plywood/OSB splice location for high load daiphragm nailing*
4. *Shop-installed plywood/OSB diaphragm sheathing*
5. *Prefabricated NLT panel A*
6. *Prefabricated NLT panel B*
7. *NLT expansion gap location fire stopped as required*
8. *Self-tapping screw pairs crossing plywood/ OSB splice location*

Source: NLT Design & Construction Guide

Questions?

This concludes The American Institute of Architects Continuing Education Systems Course

WoodWorks – Wood Products Council

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