Structural Solutions: Cross-Laminated Timber for Lateral Resistance

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Photo Ema Peter Photography

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Course Description

The 2015 International Building Code prescriptively recognizes cross-laminated timber (CLT) as an acceptable building material in construction types III, IV and V. However, its use as part of a seismic force-resisting system—either as a diaphragm or shear wall—is not yet codified. This panel session will cover three topics key to the structural design, review and approval of CLT buildings. First, it will investigate the use of CLT in shear wall applications. Next, it will explore the use of CLT in horizontal diaphragm applications and the associated detailing requirements. Discussion will then turn to special inspections and structural detailing considerations for CLT, including challenges and solutions.

Learning Objectives

1. Develop an understanding of structural design challenges as it pertains to designing CLT while meeting the intent of the code.

2. Examine the use of CLT in shear wall applications and review design options and recommendations for seismic resistance.

3. Examine the use of CLT in diaphragm applications and review design options and recommendations for seismic resistance.

4. Describe some of the detailing challenges and solutions with regard to CLT and how special inspections play a role

CLT Shear Walls for Seismic Applications

Presented by Chris Duvall

COUGHLINPORTERLUNDEEN
STRUCTURAL CIVIL SEISMIC ENGINEERING

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CLT Shear Walls for Seismic Applications

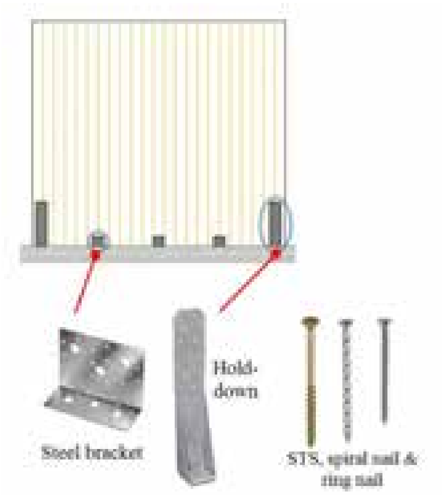
- Currently not in the US building code
- Lacks seismic parameters for design (Response Modification Factor)
- Current Research:
  - FEMA P695 process to develop Seismic Design Parameters for CLT Shear Walls
  - NEHRI Tall Wood Research Project to develop rocking CLT wall systems for tall buildings

Jefferson Elementary School CLT Portable Additions | Image credit: John Gilson & Paula Saurez, Walsh Construction Co.

CLT Shear Wall Construction

CLT Panel

- High-strength & stiffness values
- Tested strength & stiffness values from manufacturer

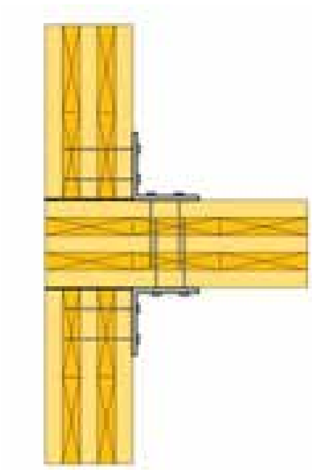


CLT Wall Components

Source: Shahnewaz, Building Journal, August 2018.

Angle Brackets

- Transfer shear
- Capacity from NDS dowel bearing equations

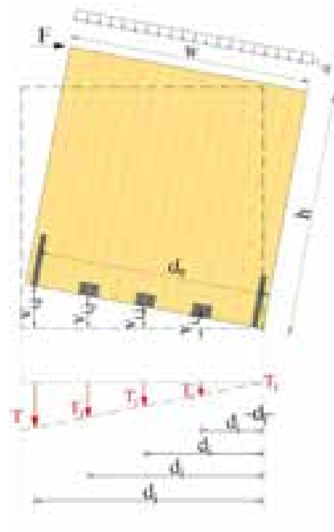


Diaphragm Connection Detail

Source: CLT Handbook

Holdowns

- Resist overturning
- CLT panel acts as a rigid body



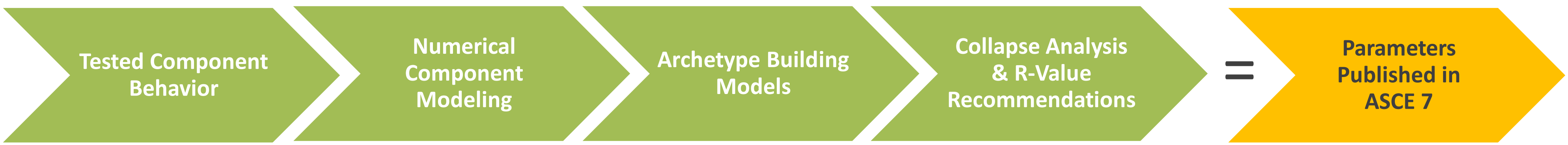
CLT Wall Overturning

Source: Lukacs, Science Direct, October 2018

Development of Seismic Design Parameters

Overview of the FEMA P695 Methodology

Project lead by John van de Lindt at Colorado State University with support from the United States Department of Agriculture Forest Product Lab.



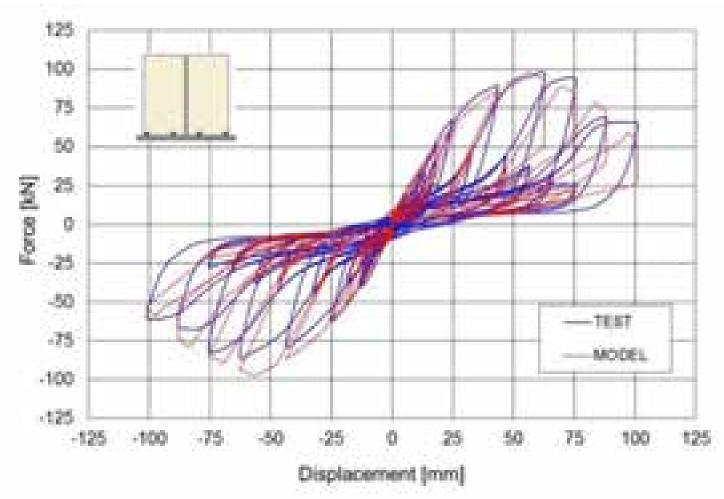
Tested Component Behavior

- CLT wall construction
  - CLT Panels
  - Generic angle bracket connections to the diaphragm
  - Generic shear connectors between panels for energy dissipation
- Performed experiments with various CLT Panel aspect ratios (height: width)

Source: Omar Amini, PhD Student, Colorado State University

Numerical Component Modeling

Developed numerical models to match experimental results CLT panels



Hysteresis of CLT shear wall

Source: Omar Amini, PhD Student, Colorado State University

***(a)** Before test*

***(b)** After test*

Wall-to-floor angle bracket shear and uplift tests

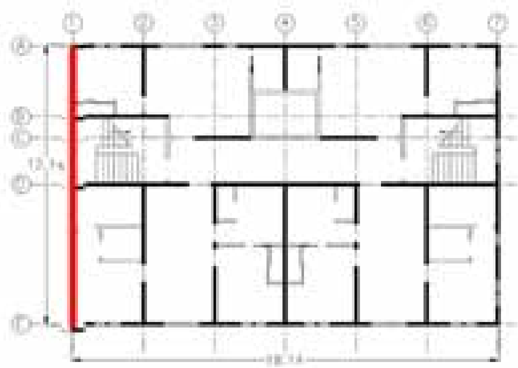
Source: Omar Amini, PhD Student, Colorado State University

Archetype Building Models

Index Buildings (Archetypes)

- Focused on single & multi-family
- 1 to 6 stories
- 10 ft story height
- Platform Construction

Index Bldg.	Type	Stories
1	Single Family (SF)	3
2	SF	2
3	SF	1
4	Multi-family (MF)	4, 6
5	MF	2
6	MF	2
7	MF	3
8	MF	4, 6
9	MF	6

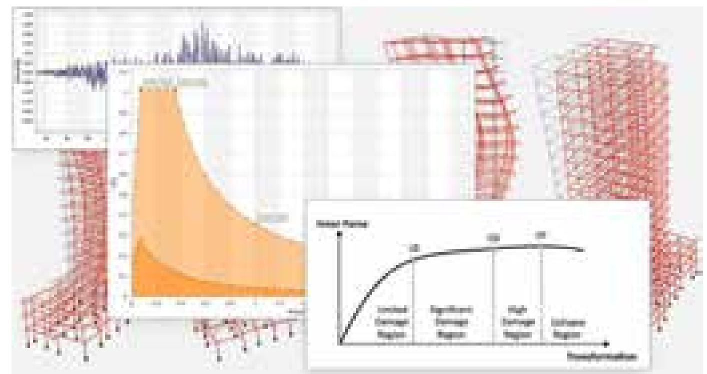


Index building 4 floor plan

Source: Omar Amini, PhD Student, Colorado State University

Collapse Analysis & R-Value Recommendations

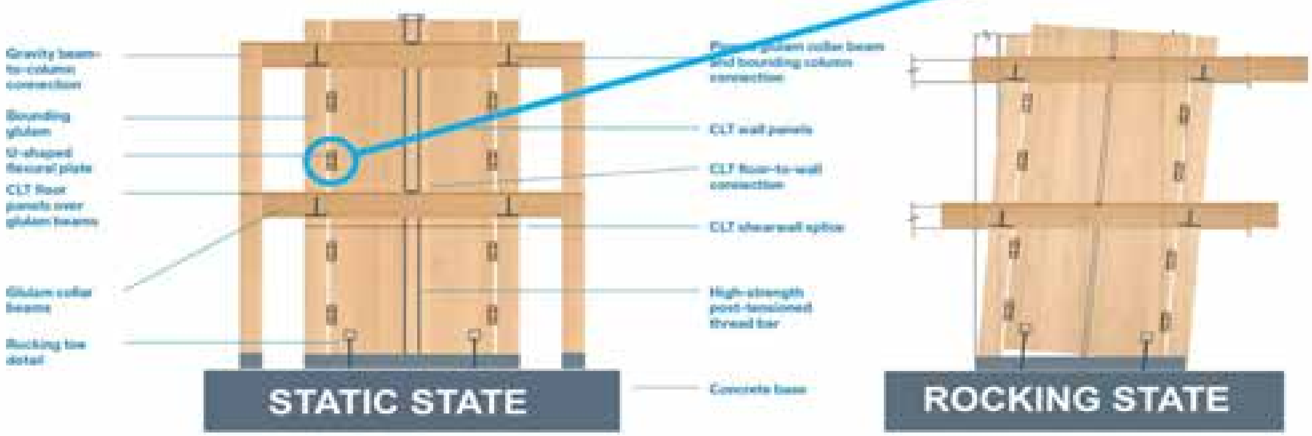
- Preliminary findings:
  - R = 3 for low aspect ratio (height: width) CLT panels (less vertical connectors for energy dissipation)
  - R= 4 for high aspect ratio (height: width) CLT panels (more vertical connectors for energy dissipation)
- Goal is to get parameters into ASCE 7-22, IBC 2024



Tested Component Behavior → Numerical Component Modeling → Archetype Building Models → Collapse Analysis & R-Value Recommendations = Parameters Published in ASCE 7

Rocking CLT Wall Implementation

Deformed shape of u-shaped flexural plates "fuse" to dissipate energy



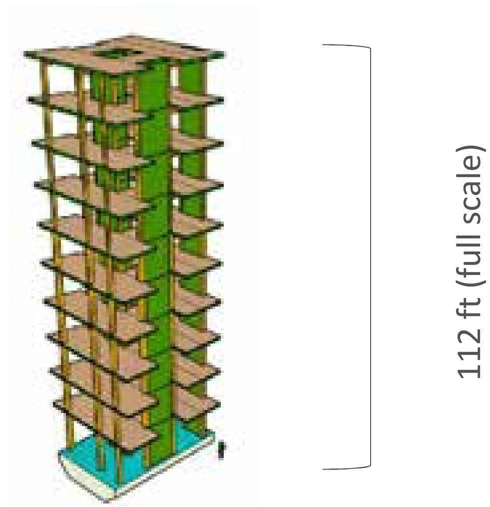
NHERI Tall Wood Research Project

Goal: Design Method for seismically-resilient tall wood buildings

Validation: Shake table tests at University of San Diego California

Intercollegiate project with industry involvement lead by Shiling Pei at Colorado School of Mines

Shake Table Test on a 2-story Rocking Wall Building (2017)



Shake Table Test on a 10-story Rocking Wall Building (2021)

CLT Diaphragms for Seismic Applications

Presented by Scott Breneman

WoodWorks

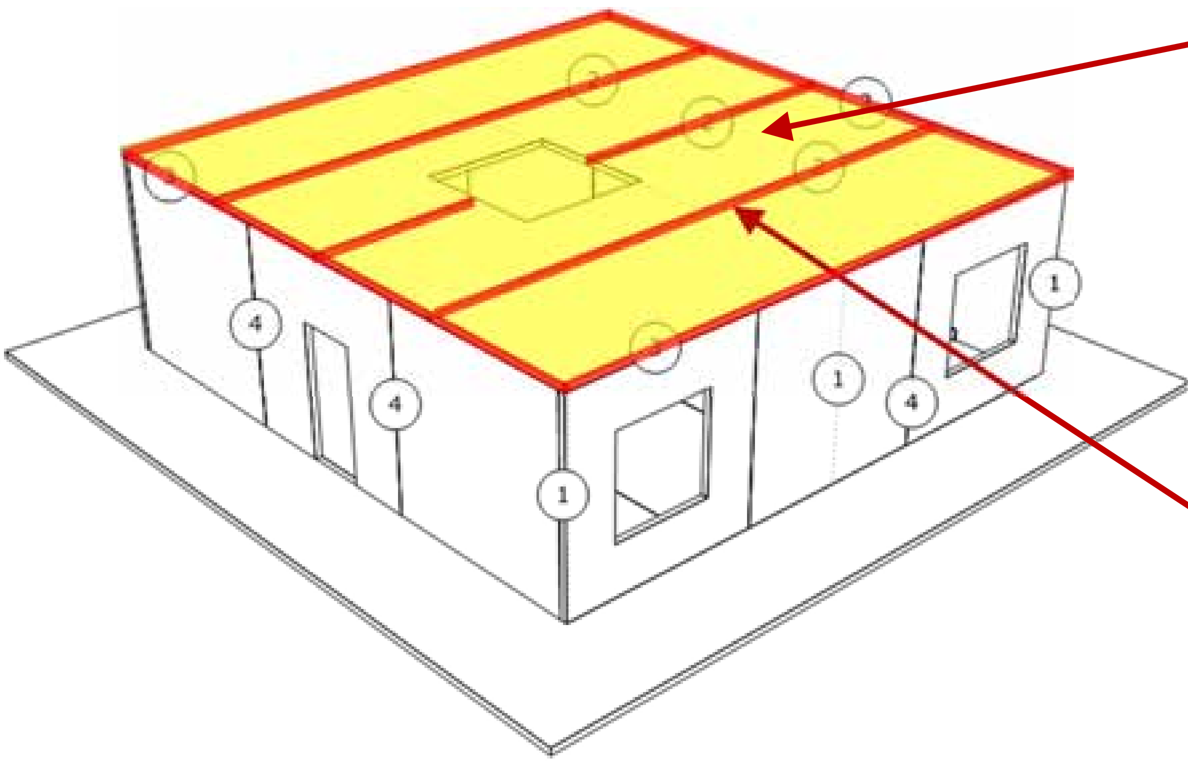
CLT Seismic Design

CLT Seismic Force Resisting Systems **Not** addressed In

ASCE/SEI 7-10 or 7/16

SDPWS 2015

CLT Diaphragms



Strength of CLT rarely (never?) governs. Capacity provided by manufactures via ASTM standard testing referenced in PRG 320.

Strength of Connections covered by NDS 2015 and Proprietary Fastener Evaluation Reports

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

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

145 to 290 PSI Allowable Edgewise Shear
= 1.7 to 3.5 kips/ft/in
Cd = 1.6 for short term loading

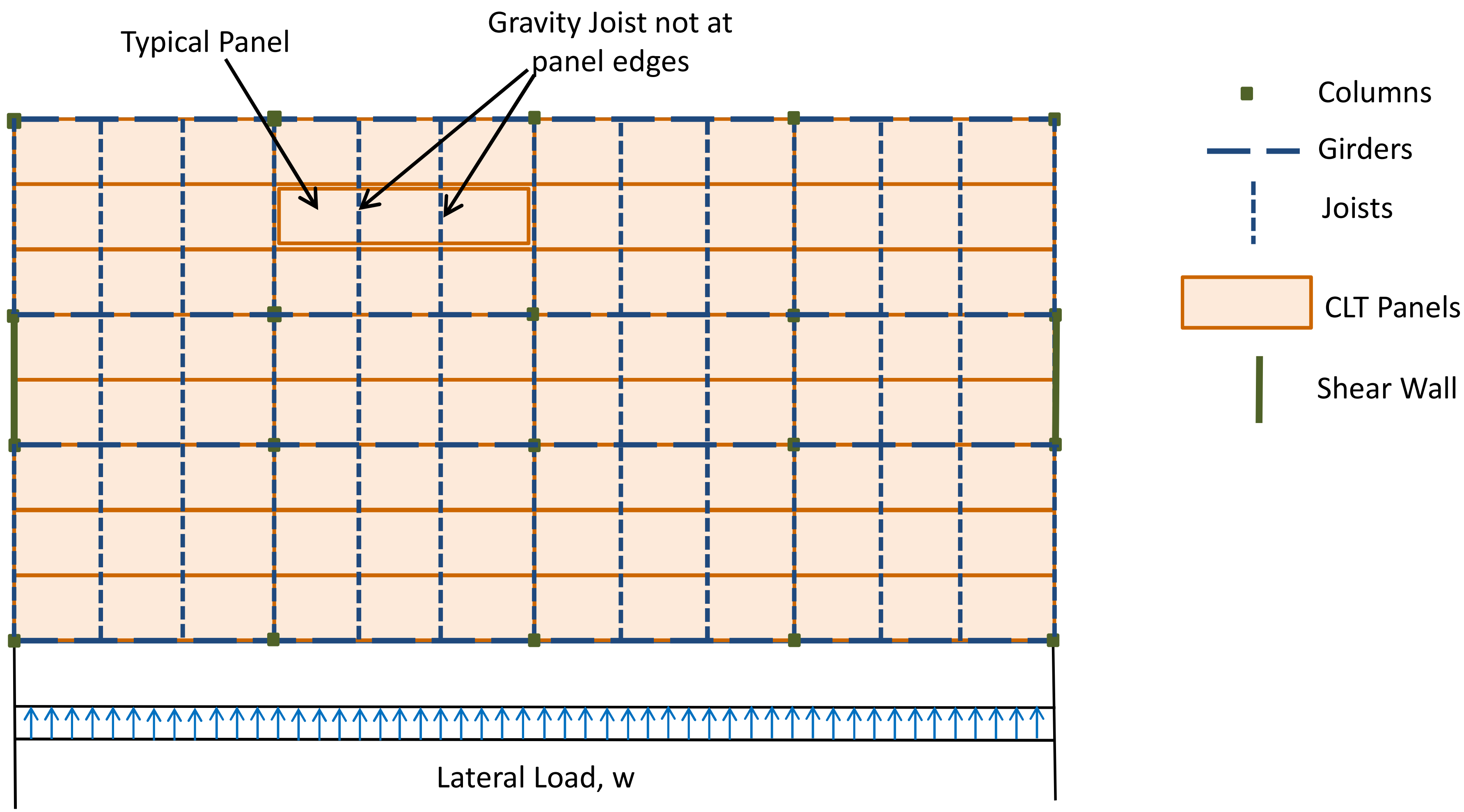
= 2.8 to 5.6 kips/ft length (ASD)
per Inch of Thickness.

ane Shear Stress for Nordic X-Lam[(a)] (For Use in the U.S.)

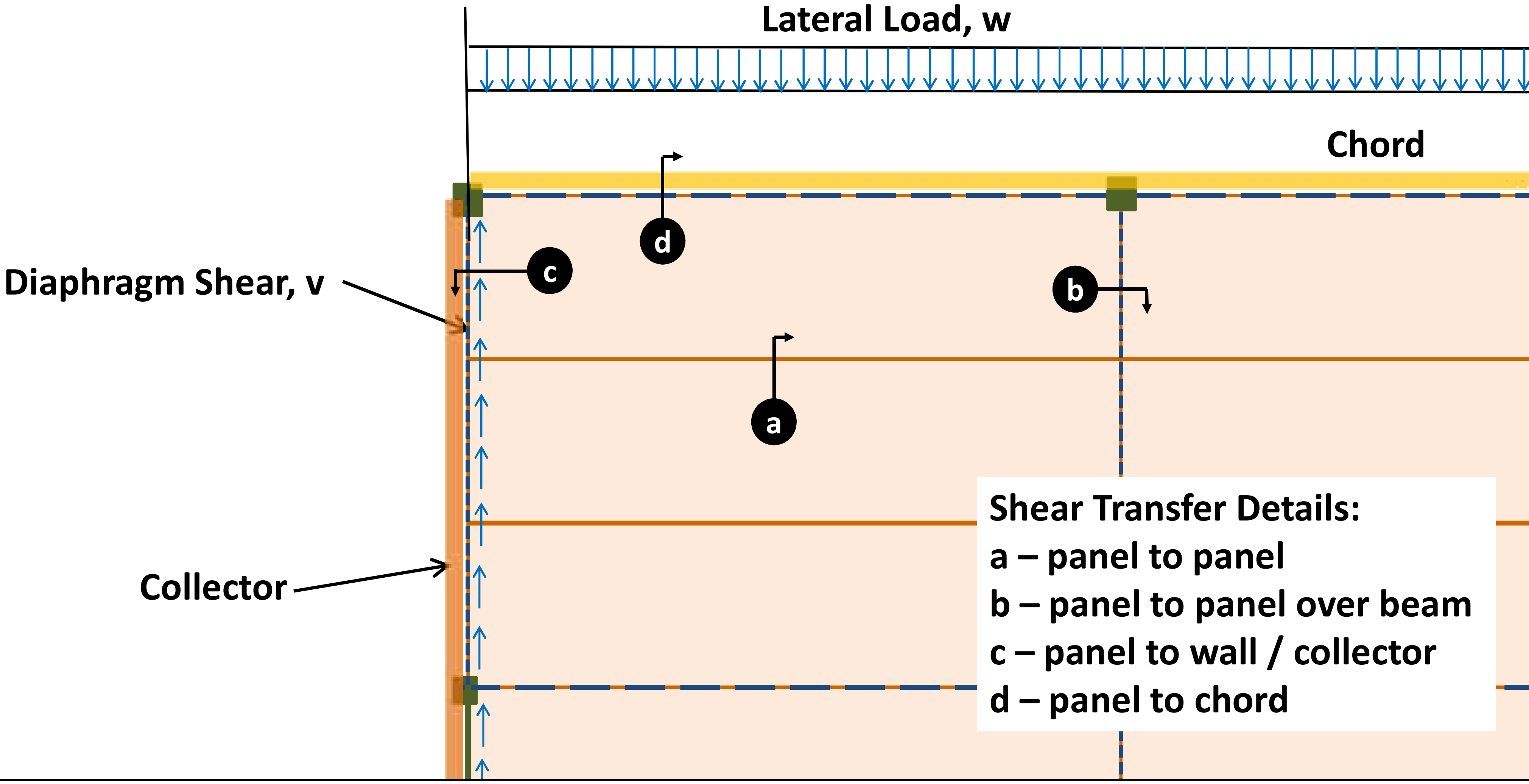
	ID	Thickness, t_p (in.)	Allowable In-Plane Shear Stress	
			$F_{v,e,0}$ (psi)	$F_{v,e,90}$ (psi)
	s	3 1/8	155[(b)]	190[(b)]
	s	3 1/2	155	190[(b)]
	ls	4 1/8	155	190
E1	...5s	5 1/8	185[(c)]	215[(c)]
	140-4s	5 1/2	145	190[(b)]
	143-5s	5 5/8	185[(c)]	215[(c)]
	175-5s	6 7/8	185	215
	197-7s	7 3/4	155[(b)]	215[(c)]
	213-7l	8 3/8	185[(c)]	215[(c)]
	220-7s	8 5/8	185[(c)]	215[(c)]
	244-7s	9 5/8	185[(c)]	215[(c)]
	244-7l	9 5/8	185[(c)]	215[(c)]
	267-9l	10 1/2	155[(b)]	215[(c)]
	314-9l	12 3/8	185[(c)]	215[(c)]

Source: *APA Product Report PR-L306*

Example CLT Diaphragm Design



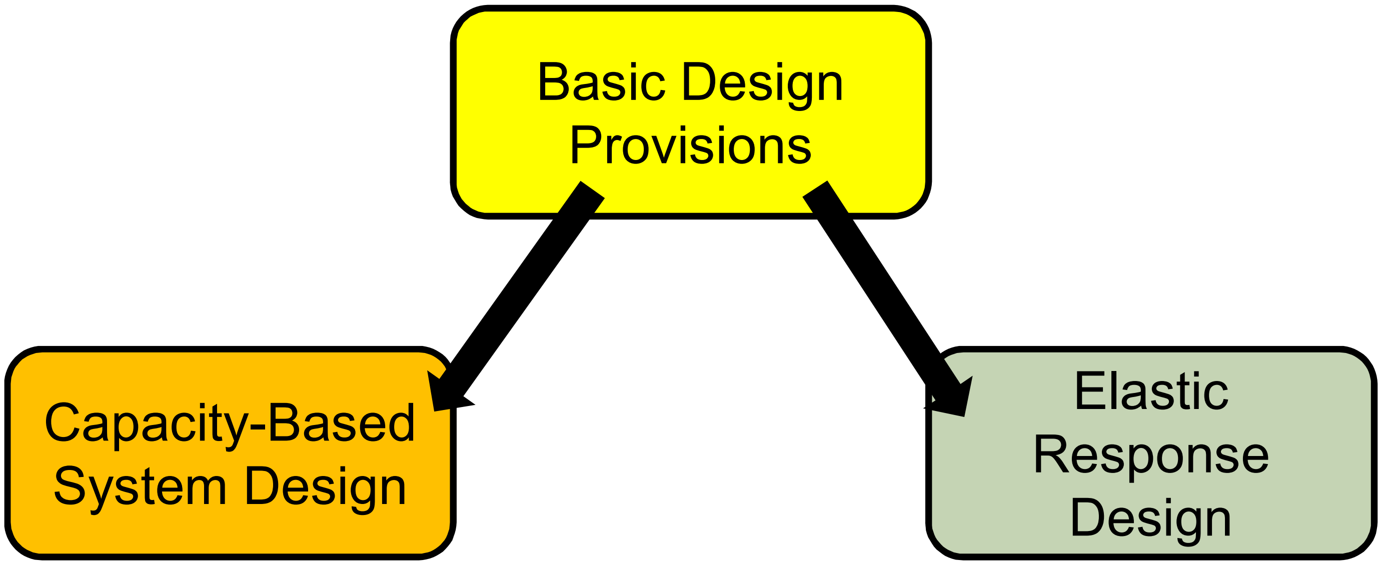
Example CLT Diaphragm Design



Suggestions for CLT Diaphragm Design

Until CLT diaphragms are formally defined through a consensus standardization, following are suggestions when considering diaphragms with CLT through an alternative means and methods process

CLT Diaphragm Design



CLT Diaphragm Design

Basic Design Provisions

- CLT diaphragms shall be designed in accordance with the principles of mechanics using fastener and member strength in accordance with the provisions of the NDS.

  (or proprietary connectors using 3rd party verified equivalence)

Calculations per NDS, not capacity tables in SDPWS

CLT Diaphragm Design

Basic Design Provisions

- Diaphragm shear connections at CLT panel edges and diaphragm boundary connections shall be designed to ensure that the connection capacity is limited by fastener yielding in accordance with Mode III or Mode IV per NDS 12.3.1.

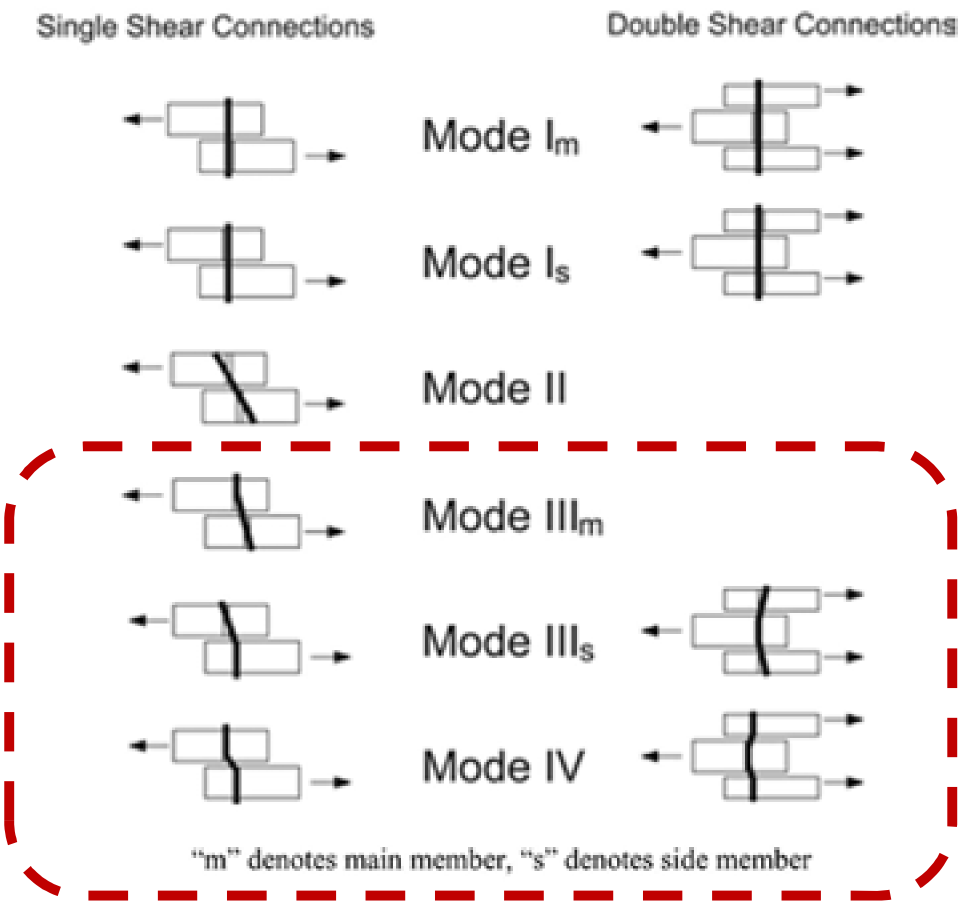
Design capacity of connection (ductile mode governing)

$$Z'_C \geq \mathrm{E}_h$$

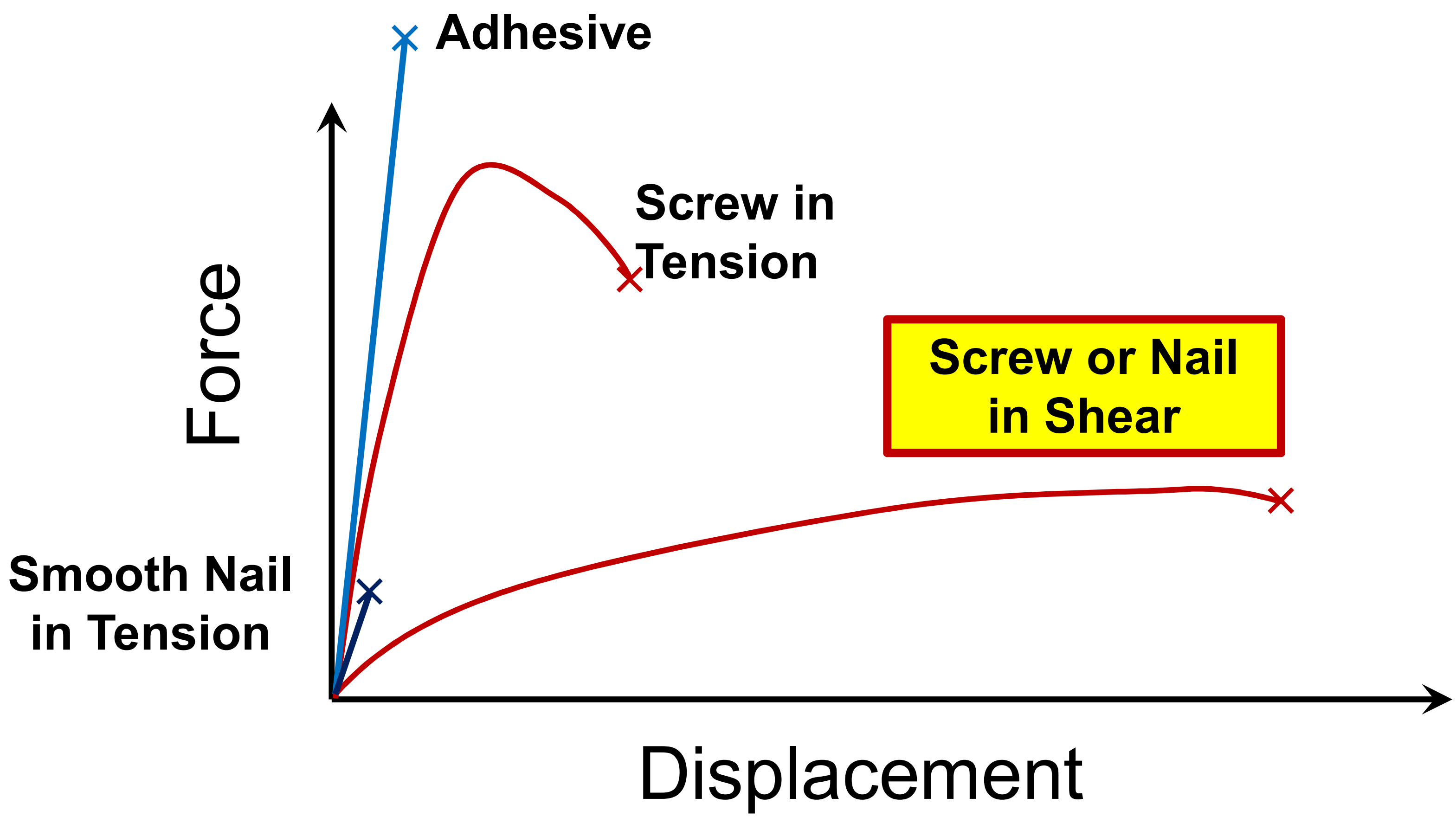
Applied Seismic Forces

Connection Yield Modes Per the NDS

Basic Design Provisions

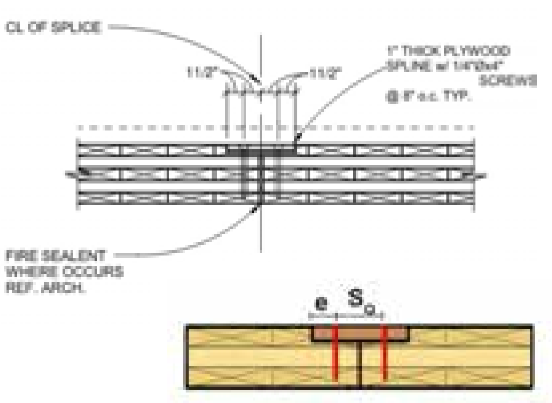


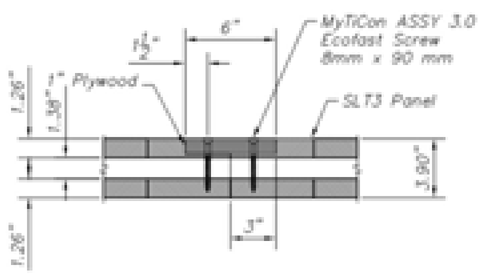
Conceptual Fastener Behavior



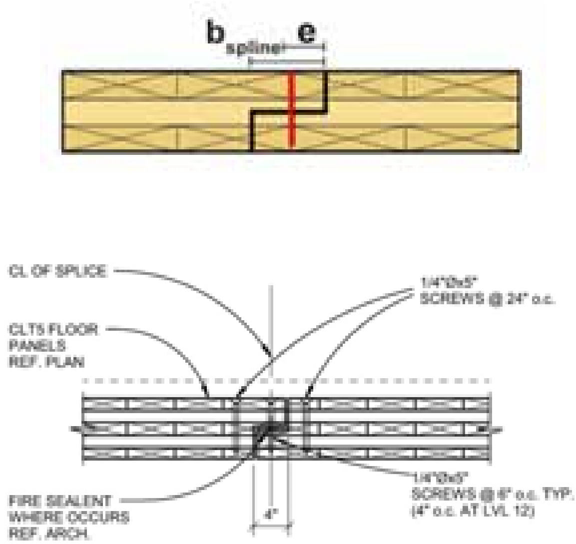
Panel to Panel Connection Styles

Surface Spline



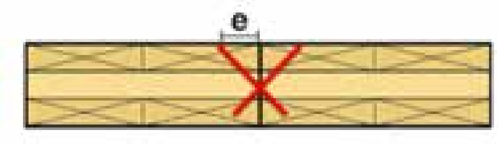


Half Lap

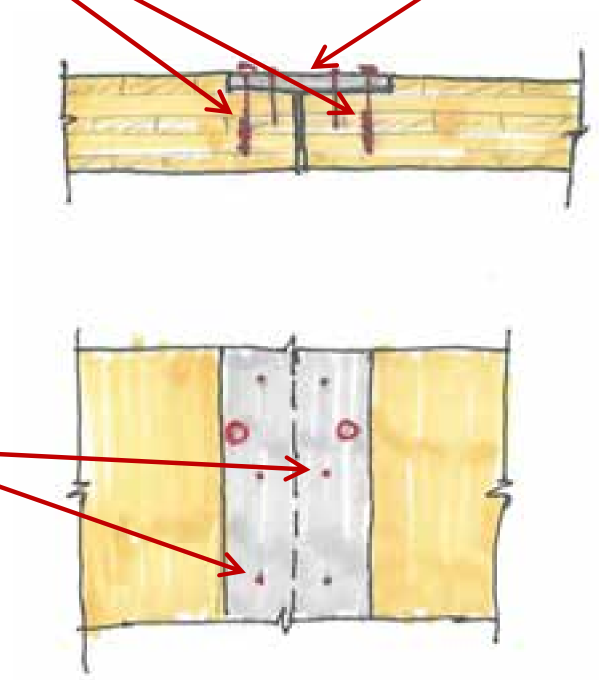


Load Sharing…
not load bearing

Butt Joint

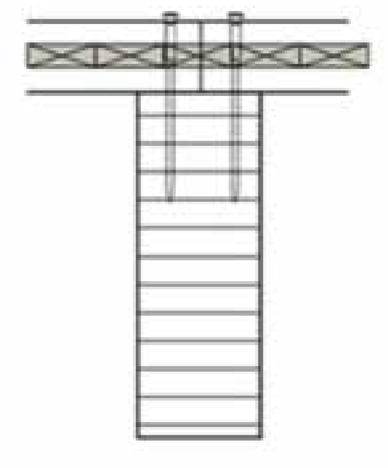


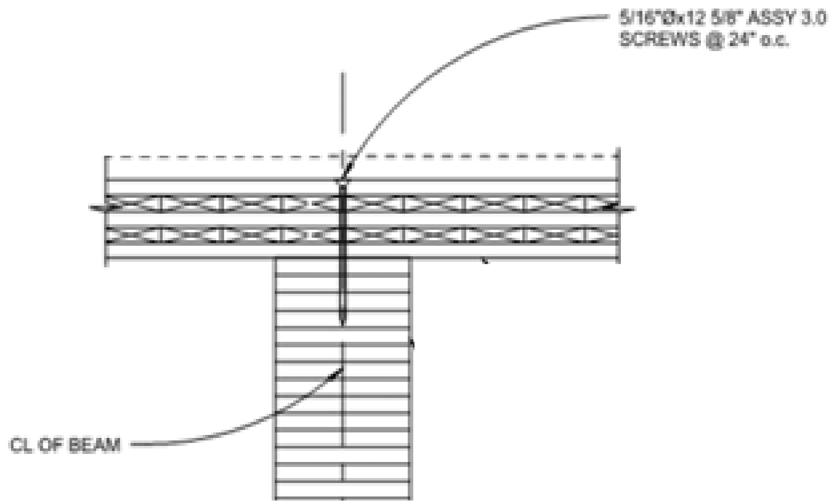
An Efficient Panel to Panel Connection

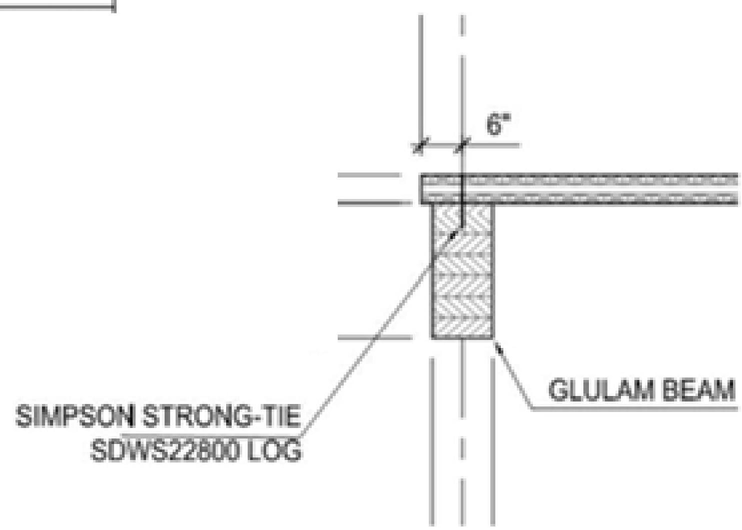


Graphics: ASPECT Structural Engineers

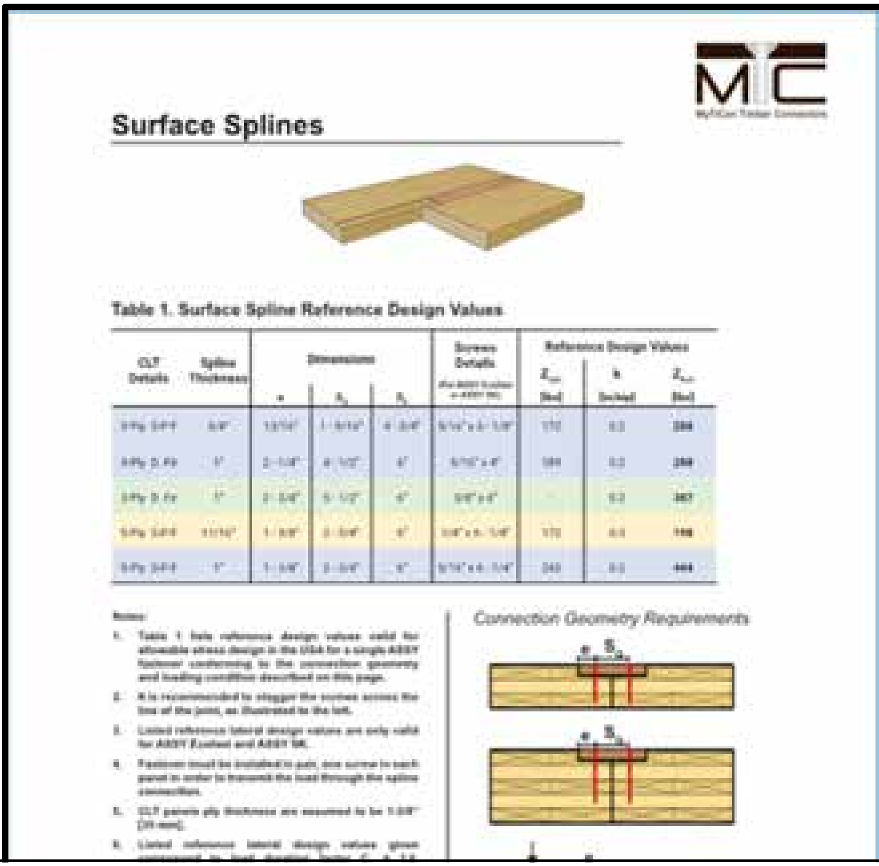
Panel to Beam Connection Styles







Fastener Vendor Design Support



Surface Splines

Table 1. Surface Spline Reference Design Values

CLT Details	Spline Thickness	Dimensions e	Dimensions S_1	Dimensions S_2	Screws Details	Reference Design Values Z [lbs]	k [in/lbs]	Z [lbs]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Notes:

Connection Geometry Requirements

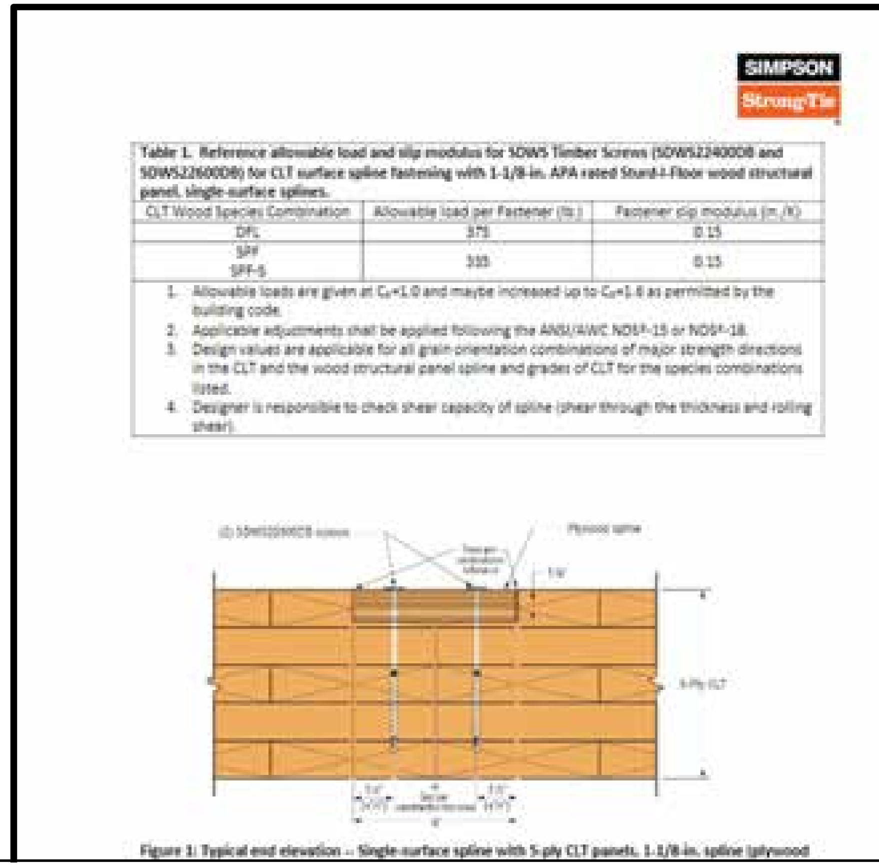


Table 1. Reference allowable load and slip modulus for SDWS Timber Screws (SDWS22400DB and SDWS22600DB) for CLT surface spline fastening with 1-1/8-in. APA rated Sturd-I-Floor wood structural panel, single-surface splines.

CLT Wood Species Combination	Allowable load per Fastener (lb.)	Fastener slip modulus (in./lb)
DFL	375	0.15
SPF SPF-S	335	0.15

1. Allowable loads are given at C_D=1.0 and maybe increased up to C_D=1.6 as permitted by the building code.
2. Applicable adjustments shall be applied following the ANSI/AWC NDS®-15 or NDS®-18.
3. Design values are applicable for all grain orientation combinations of major strength directions in the CLT and the wood structural panel spline and grades of CLT for the species combinations listed.
4. Designer is responsible to check shear capacity of spline (shear through the thickness and rolling shear).

Figure 1: Typical end elevation – Single-surface spline with 5-ply CLT panels, 1-1/8-in. spline (plywood

CLT Diaphragm Design Suggestion

Capacity-Based System Design

- Design CLT panels, diaphragm chord members and chord splices, to resist no less than 2.0 times the forces associated with development of the design strength of the diaphragm shear connections

Design capacity of other diaphragm components

$$Z'_D \geq 2.0\ Z'_C$$

Design capacity of connection (ductile mode governing)

Special Diaphragm Conditions?

Elastic Response Design

- Cantilevers past 35' wood structural panel diaphragm limit
- Elevated seismic performance (low damage objective)

Suggest:

ASCE 7-16 Section 12.10.3 Alternative Diaphragm ***Loading***

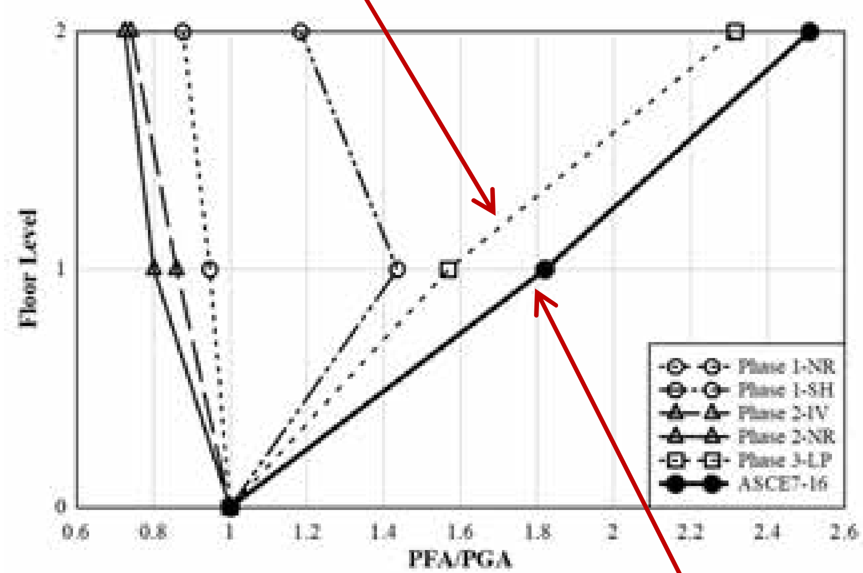
Rs = 1.0 ~essentially elastic response to DBE

Rs = 0.7 ~essentially elastic response to MCE

UCSD Two-Story Shake Table Test

Courtesy Shilling Pei

Maximum floor acceleration from MCE ground motions

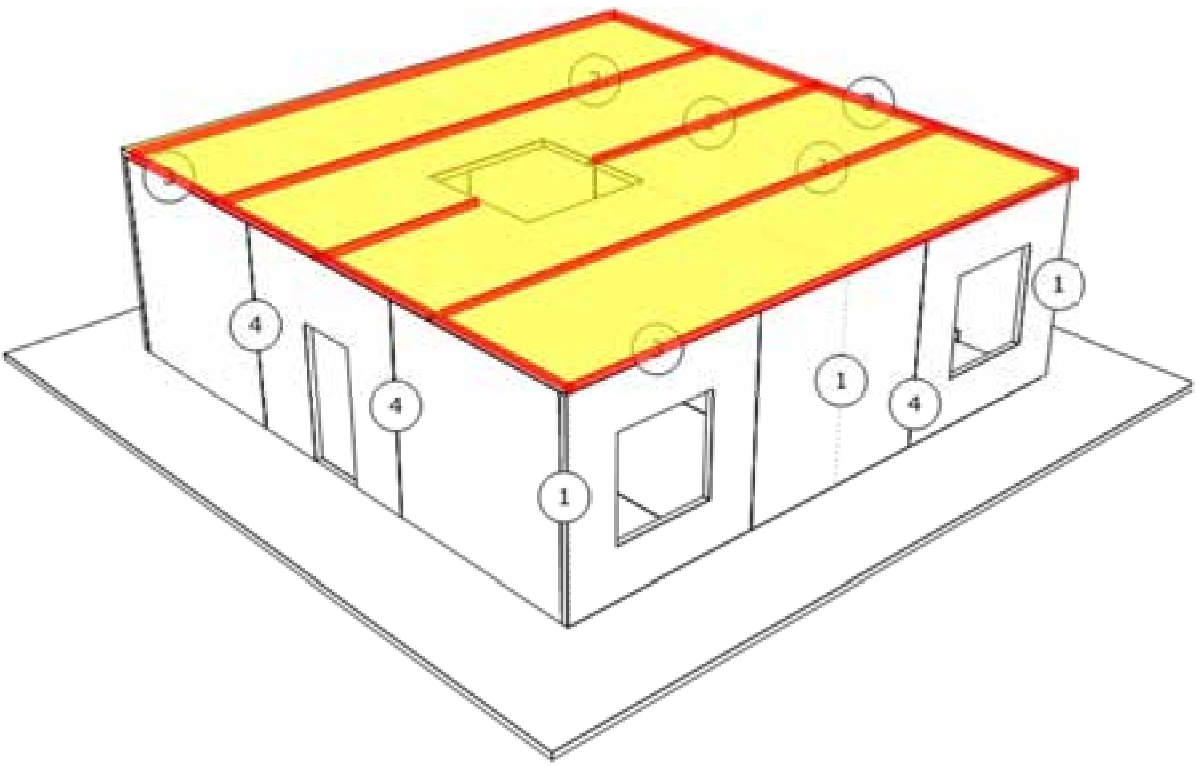


Courtesy Andre Barbosa

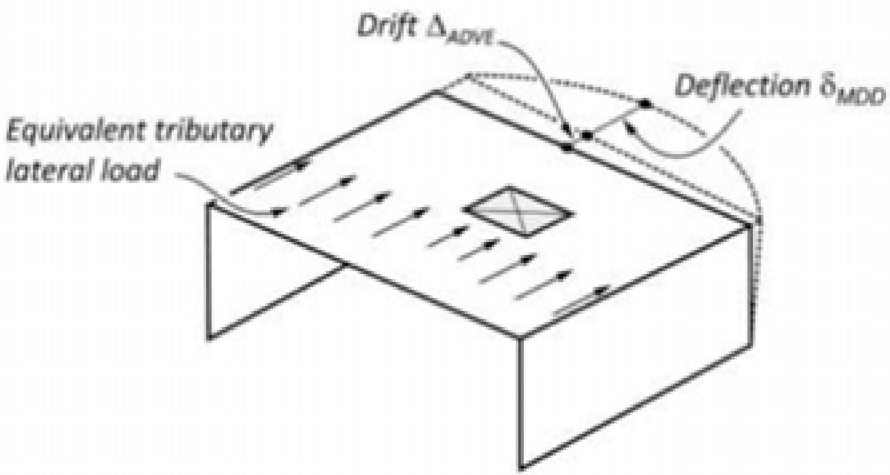
ASCE 7-16 Alt. Diaphragm Design R = 4, Rs = 1.0

Diaphragm went through 22 DBE or greater ground motions with no repairs!

CLT Diaphragms



Is the Diaphragm
Rigid or Flexible?



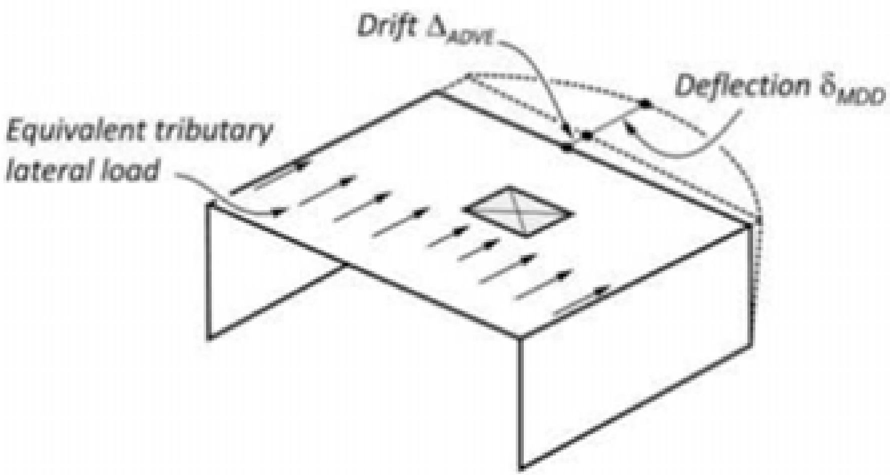
12.3.1.3 Calculated Flexible Diaphragm Condition. Diaphragms not satisfying the conditions of Sections 12.3.1.1 or 12.3.1.2 are permitted to be idealized as flexible provided:

$$\frac{\delta_{MDD}}{\Delta_{ADVE}} > 2 \qquad (12.3\text{-}1)$$

where δ_{MDD} and Δ_{ADVE} are as shown in Fig. 12.3-1. The loading used in this calculation shall be that prescribed in Section 12.8.

Flexible by Calculation

ASCE 7 12.3.1.3

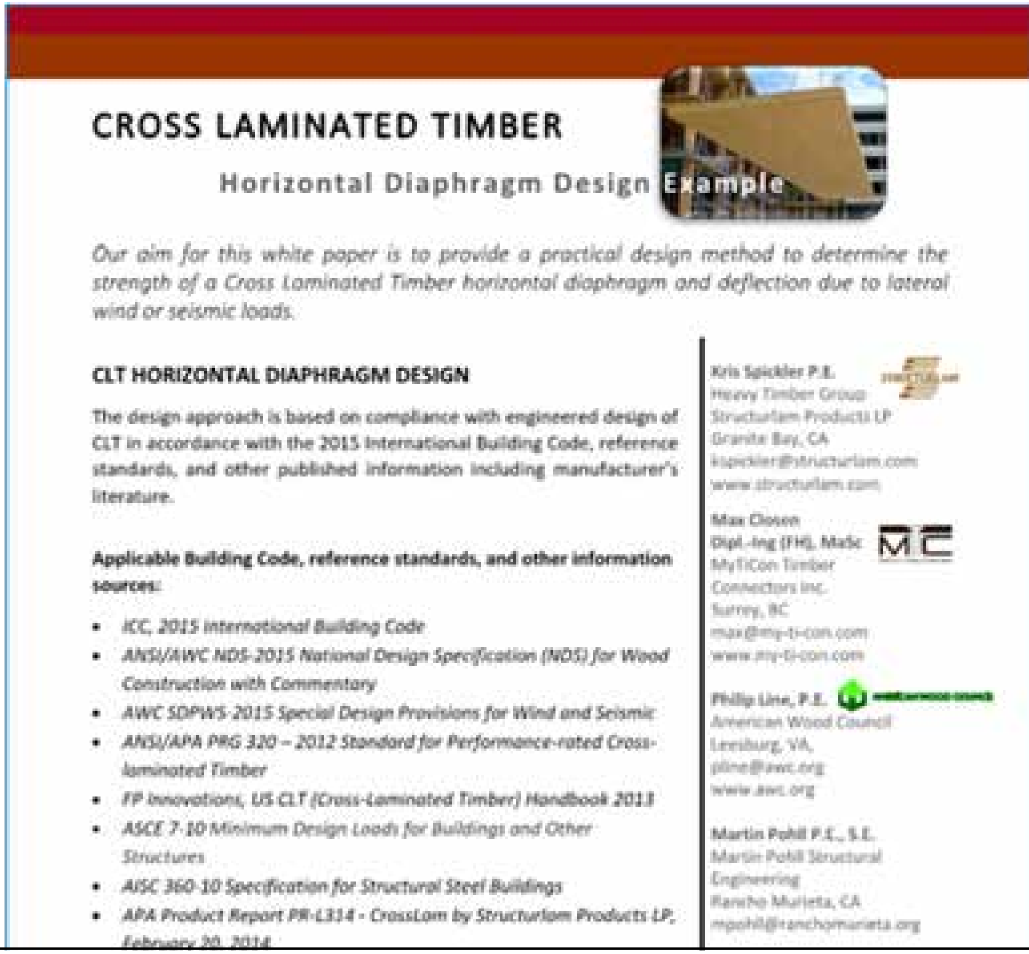


IBC1604.4: A diaphragm is rigid for the purpose of distribution of story shear and torsional moment when the lateral deformation of the diaphragm ***is less than*** or equal to two times the average story drift.

Rigid by Calculation

IBC 1604.4

CLT Diaphragm Design Example Paper



CROSS LAMINATED TIMBER

Horizontal Diaphragm Design Example

Our aim for this white paper is to provide a practical design method to determine the strength of a Cross Laminated Timber horizontal diaphragm and deflection due to lateral wind or seismic loads.

CLT HORIZONTAL DIAPHRAGM DESIGN

The design approach is based on compliance with engineered design of CLT in accordance with the 2015 International Building Code, reference standards, and other published information including manufacturer's literature.

Applicable Building Code, reference standards, and other information sources:

- *ICC, 2015 International Building Code*
- *ANSI/AWC NDS-2015 National Design Specification (NDS) for Wood Construction with Commentary*
- *AWC SDPWS-2015 Special Design Provisions for Wind and Seismic*
- *ANSI/APA PRG 320 – 2012 Standard for Performance-rated Cross-laminated Timber*
- *FP Innovations, US CLT (Cross-Laminated Timber) Handbook 2013*
- *ASCE 7-10 Minimum Design Loads for Buildings and Other Structures*
- *AISC 360-10 Specification for Structural Steel Buildings*
- *APA Product Report PR-L314 - CrossLam by Structurlam Products LP, February 20, 2014*

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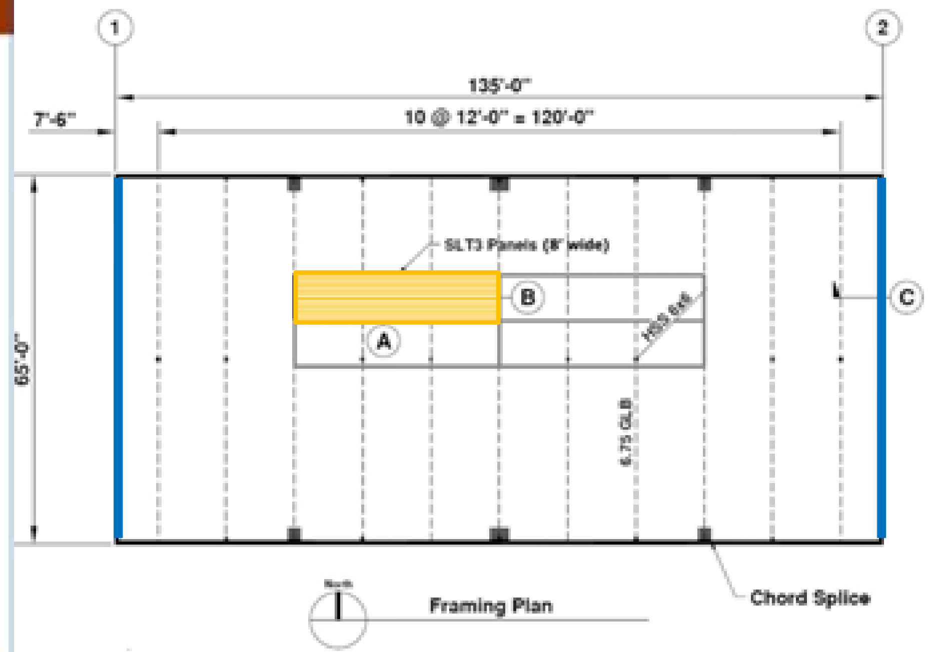


Available from structurlam.com

WoodWorks Solutions Paper on CLT Modeling

http://www.woodworks.org/wp-content/uploads/Approach-to-CLT-Diaphragm-Modeling-for-Seismic-WoodWorks-Jan-2017.pdf


WoodWorks
WOOD PRODUCTS COUNCIL

An Approach to CLT Diaphragm Modeling for Seismic Design with Application to a U.S. High-Rise Project

ABSTRACT:
A candidate cross-laminated timber (CLT) diaphragm analysis model approach is presented and evaluated as an engineering design tool motivated by the needs of seismic design in the United States. The modeling approach consists of explicitly modeling CLT panels as discrete orthotropic shell elements with connections between panels and connections from panels to structural framing modeled as two-point springs. The modeling approach has been compared to a developed CLT diaphragm design example based on U.S. standards showing the ability to obtain matching deflection results. The sensitivity of the deflection calculations to considering CLT panel-to-panel connection gap closure is investigated using a simple diaphragm example. The proposed modeling approach is also applied to the candidate floor diaphragm design for the Framework project, a winner of the U.S. Tall Wood Building Prize Competition, currently under design. Observations from this effort are that the proposed method, while a more refined model than typically used during building design, shows promise to meet the needs of innovative CLT seismic designs where appropriate simpler diaphragm models are not available.

Framework

CLT Detailing, Inspections, and Jurisdiction Approval

Presented by Alex Legé

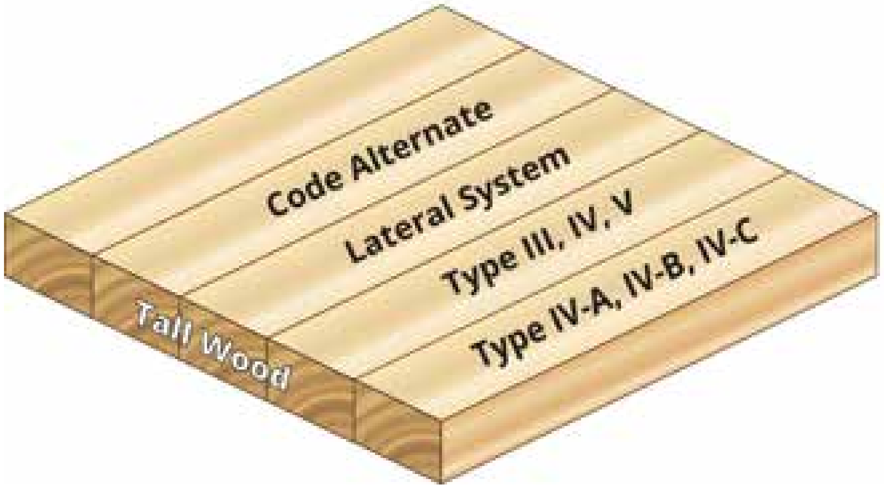
PCS Structural Solutions | Connected Teams. Bold Solutions.

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

CLT Detailing, Inspections, and Jurisdiction Approval

The "CLT Layer Cake"

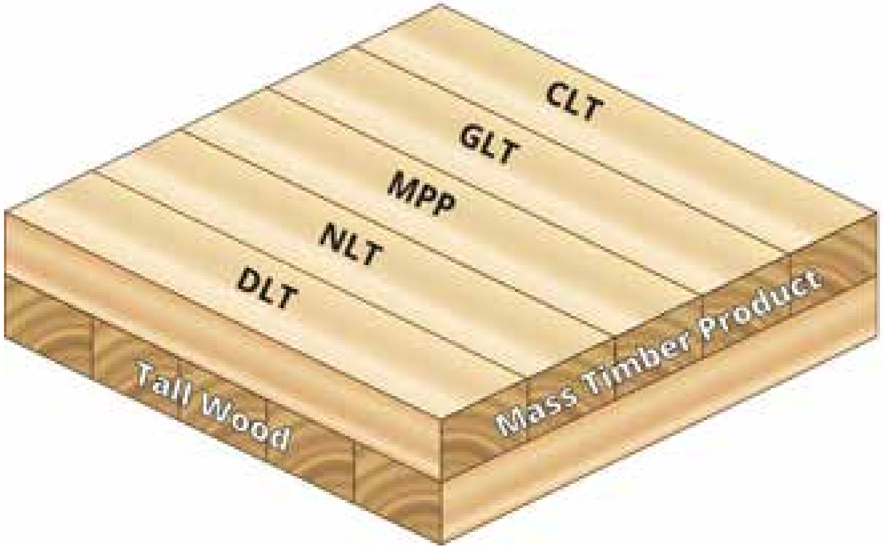
Carbon12, Portland, OR
Kaiser Group + Path Architecture
Photo credit: Kaiser+Path



CLT Detailing, Inspections, and Jurisdiction Approval

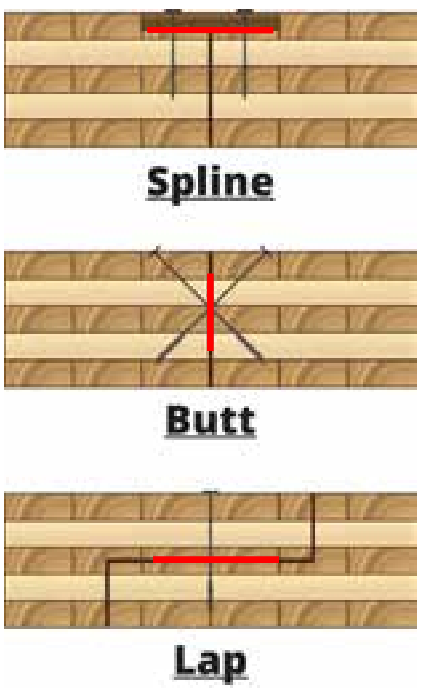
Product Selection

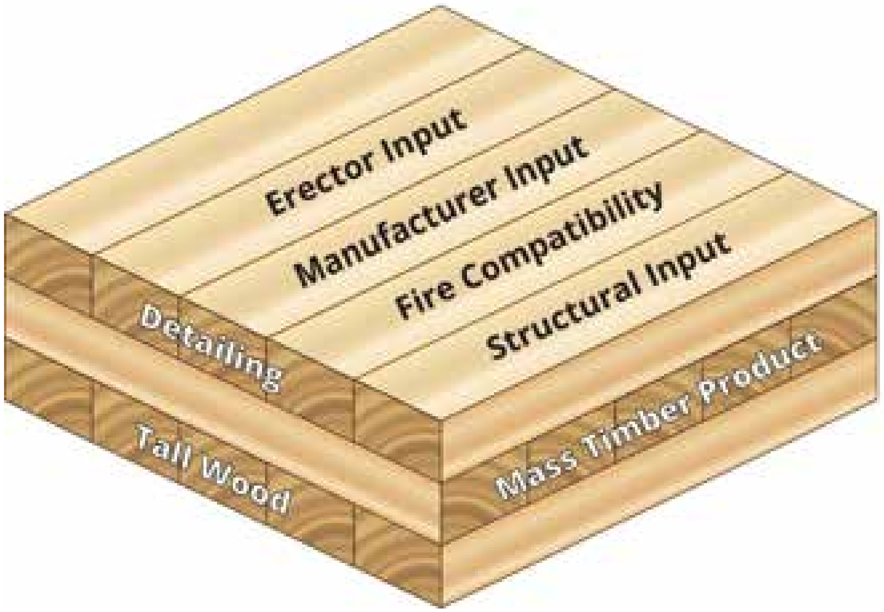
Eastside Community Center, Tacoma, WA
ARC Architects
Photo credit: Rick Keating



CLT Detailing, Inspections, and Jurisdiction Approval

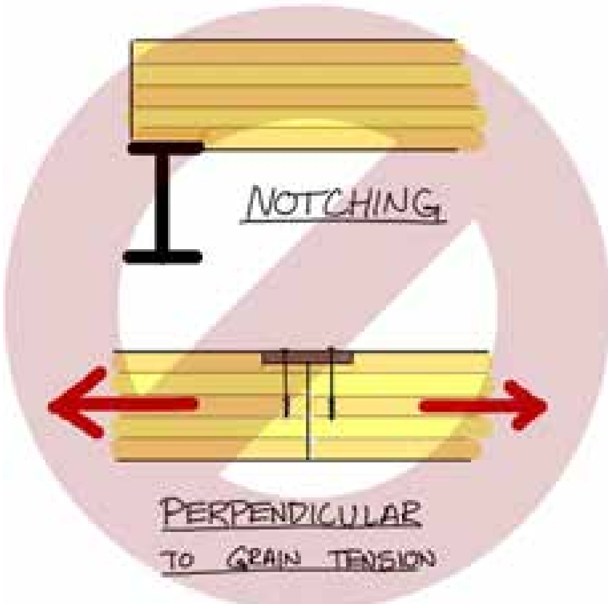
Detailing

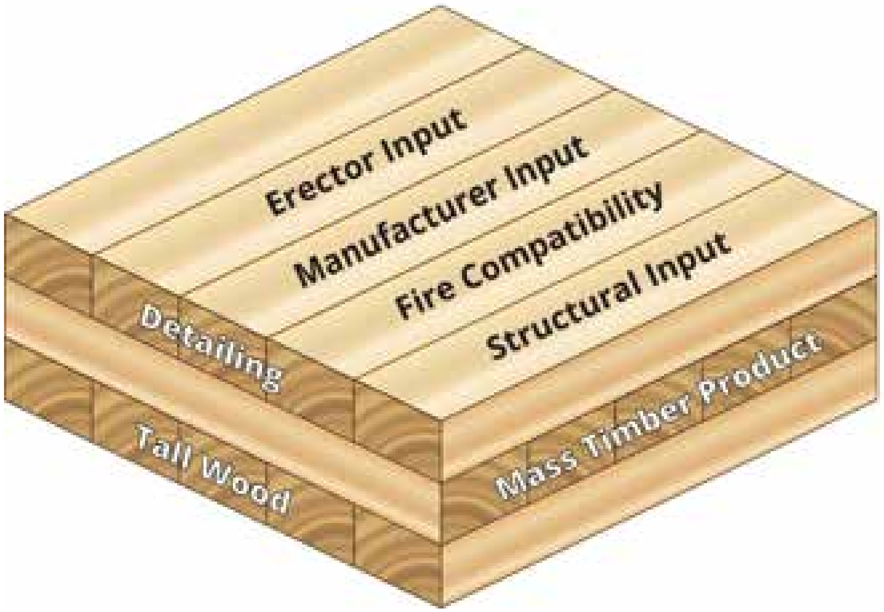




CLT Detailing, Inspections, and Jurisdiction Approval

Detailing





CLT Detailing, Inspections, and Jurisdiction Approval

Special Inspections

Ad Hoc Committee – Tall Wood Buildings
Structural Work Group
Draft Code Change Proposal
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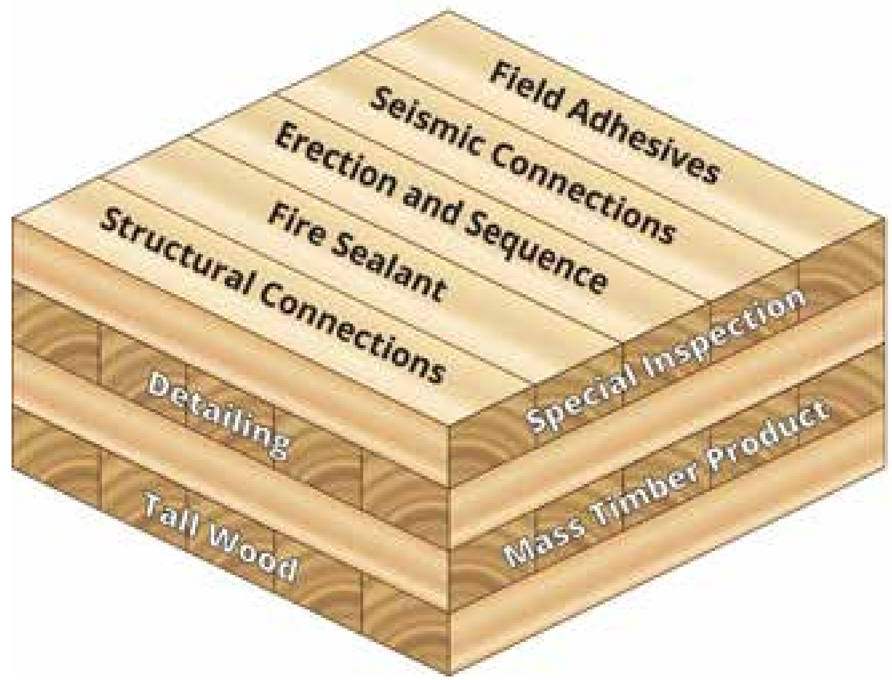
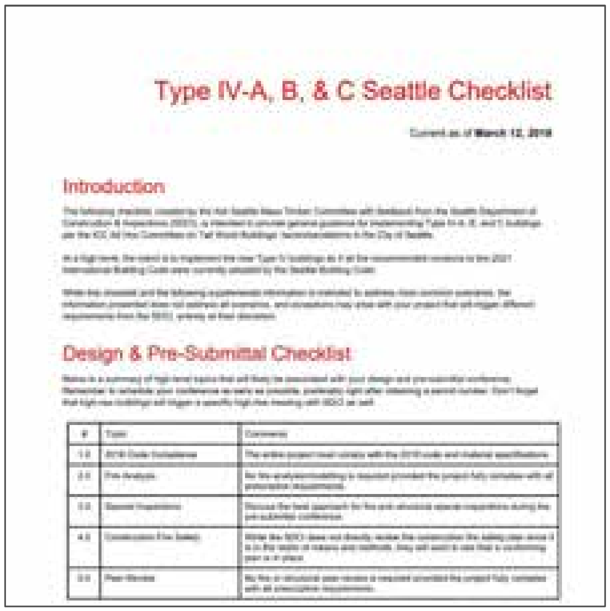
Source: International Code Council



CLT Detailing, Inspections, and Jurisdiction Approval

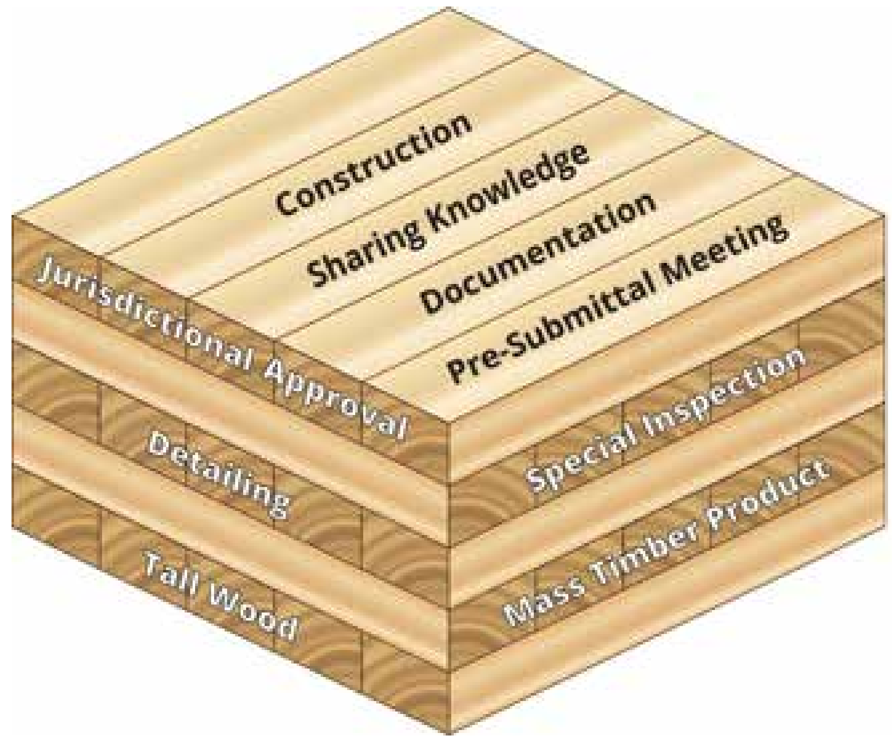
Jurisdiction Approval


Type IV-A, B, & C Seattle Checklist

Introduction

Design & Pre-Submittal Checklist

Available at: AIA Seattle Mass Timber Committee



QUESTIONS?

This concludes The American Institute of Architects Continuing Education Systems Course

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