KPFF

40104179

CLT Presentation

KPFFCLT0118

Eric McDonnell, PE

January 18, 2018

Credit(s) earned on completion of this course will be reported to AIA CES for AIA members. Certificates of Completion for both AIA members and non-AIA members are available upon request.

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

This course is registered with AIA CES

Course Description

This presentation will provide an overview of Cross Laminated Timber (CLT) including applicability, design, construction, and lessons learned. KPFF will share our current experience with this material and its use in a variety of building designs

Learning Objectives

At the end of the this course, participants will be able to:

1. Explain the benefits and limitations of CLT as a structural material in addition to provide information avail-able for designers

2. Summarize regulatory challenges and current code requirements for the use of CLT particularly in seismic applications

3. Classify typical gravity and lateral force resisting systems using CLT

4. Describe the design of the Framework project (12-story CLT) including the resilient/low damage CLT core design

Mass Timber Design

18th January, 2018

ZGF

Eric McDonnell

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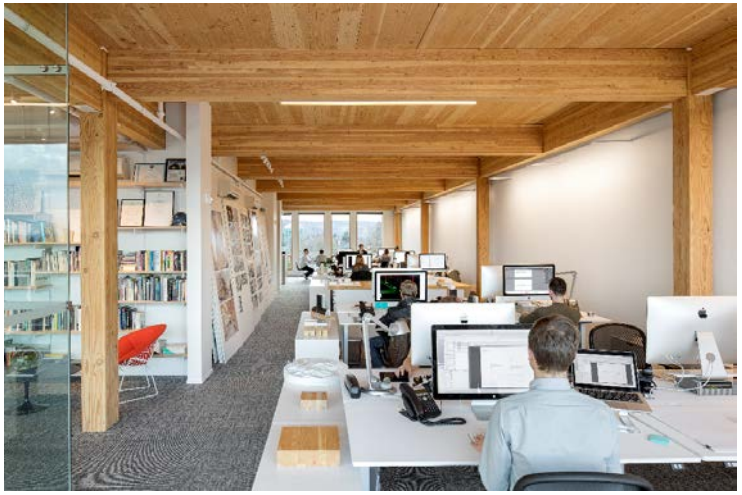
WHAT IS MASS TIMBER ?

Mass Timber Suite






Mass Timber Suite

Cross Laminated Timber (CLT)

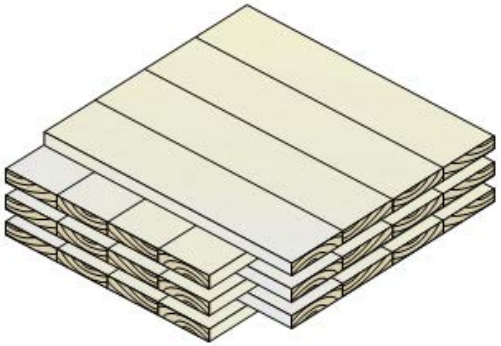


Figure 1
CLT panel configuration

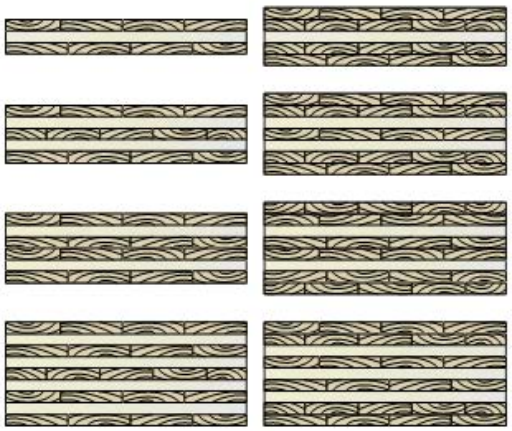
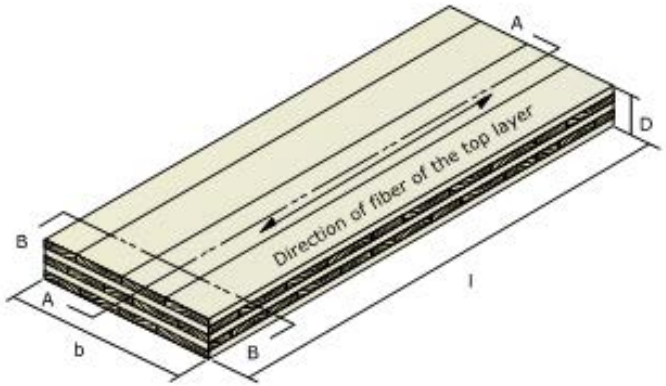


Figure 2
Examples of CLT panel cross-sections



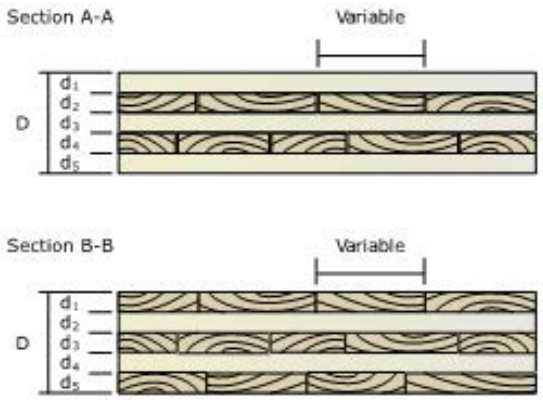
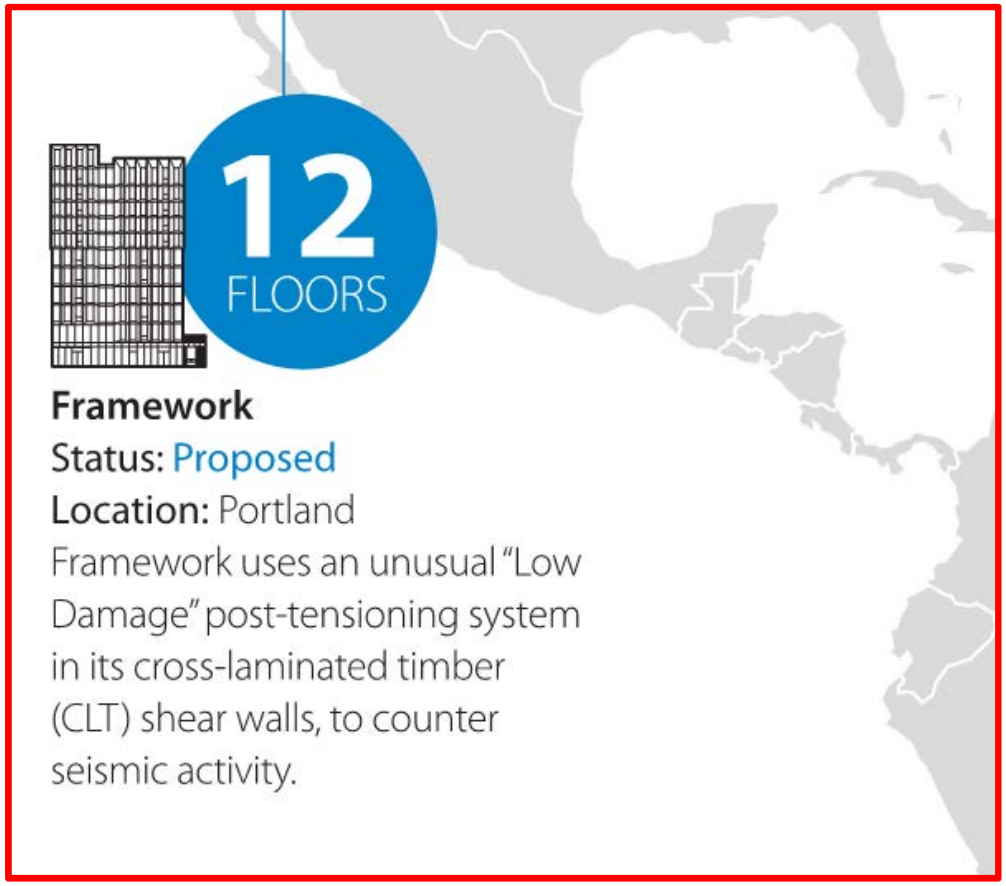
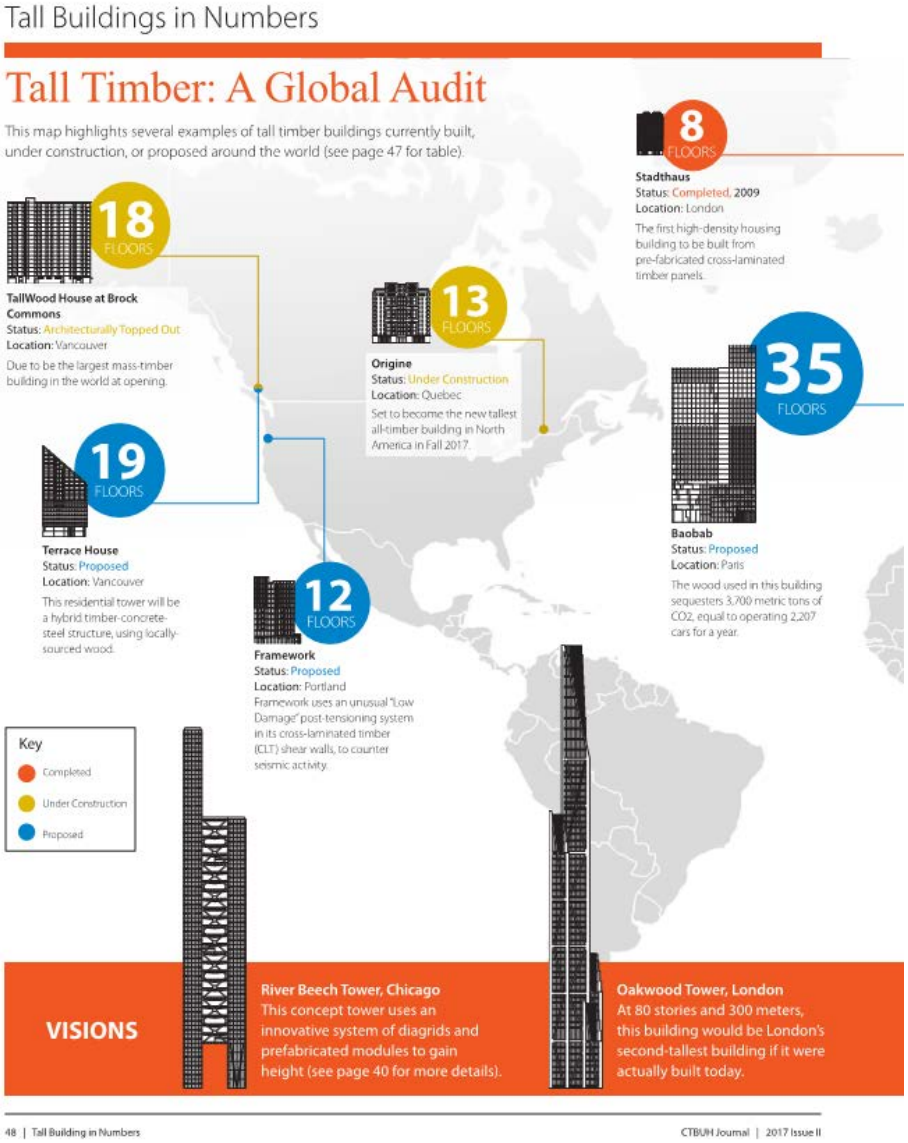


Figure 3
Example of CLT panel cross-sections and direction of fibers of the top layers

CLT & TALL WOOD BUILDINGS





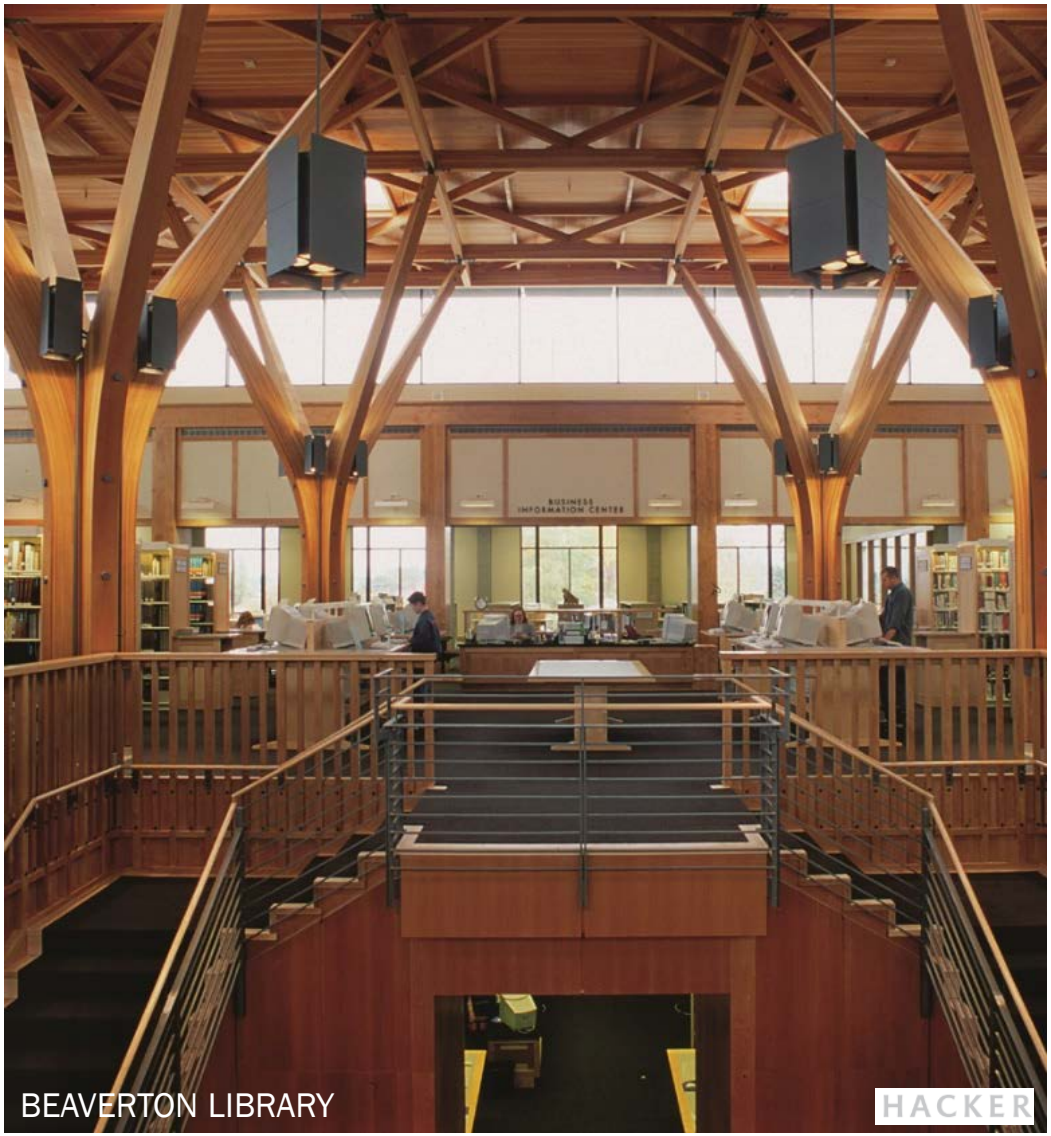
OUR JOURNEY

Background & Experience

Mass Timber Experience

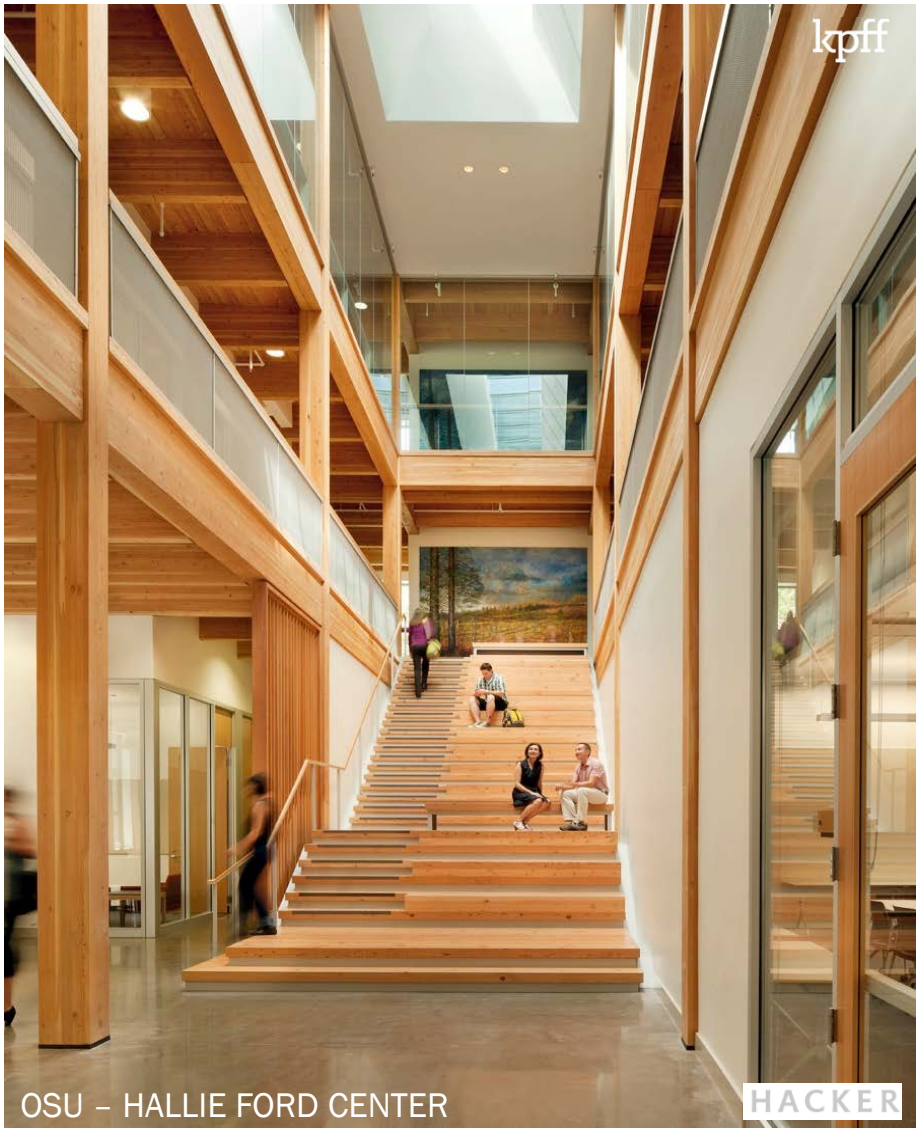
- 50+ years of design experience
- 9 CLT Projects Completed (in 5 States)
- 15+ CLT Projects in Design


WASHINGTON
PORTLAND
OREGON



BEAVERTON LIBRARY

HACKER



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OSU – HALLIE FORD CENTER

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COMPLETED / PERMITTED CLT PROJECTS

1 COOLEY LANDING EDUCATIONAL FACILITY, PALO ALTO, CA

FOG Studio

2 SHORELINE INTERNATIONAL HEALTH SERVICES CLINIC, SHORELINE, WA

Miller Hayashi Architects

3 WASHINGTON STATE UNIVERSITY VISITOR CENTER, PULLMAN, WA

Olson Kundig Architects

4 ROCKY MOUNTAIN INSTITUTE INNOVATION CENTER, BASALT, CO

ZGF Architects

5 ALBINA YARD, PORTLAND, OR

LEVER Architecture

6 FRAMEWORK, PORTLAND, OR

LEVER Architecture

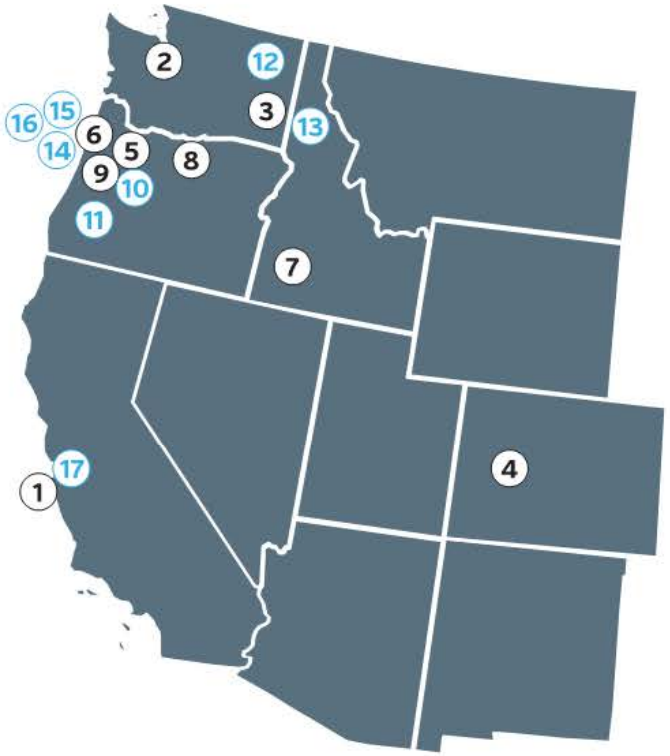
WINNER OF THE U.S. TALL WOOD COMPETITION

7 LIBRARY! AT BOWN CROSSING, BOISE, ID

FFA Architecture and Interiors

8 WY'EAST CANOPY, HOOD RIVER, OR
Opsis Architecture

9 OREGONIAN BUILDING MEZZANINE PORTLAND, OR
SRG



Notable Projects in Design:

10 EASTSIDE OFFICE, PORTLAND, OR

Hacker Architects

11 GLENWOOD PARKING GARAGE, SPRINGFIELD, OR

SRG

12 South Landing Office, Spokane, WA - Katerra

13 Idaho Basketball Arena, Moscow, ID - Opsis Architecture

14 Office Building, Portland, OR - ZGF Architects

15 PDXNext, Portland, OR - ZGF Architects

16 Three K-12 Projects, Portland Metro, OR

17 Dublin Station, Dublin, CA - BAR Architects / Katerra

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RESEARCH -> DEVELOPMENT -> IMPLEMENTATION -> DISSEMINATION

- LITERATURE REVIEWS
- PHYSICAL SITE VISITS
- GLOBAL MANUFACTURING CAPABILITIES
- COLLABORATION WITH ACADEMIA
- DESIGN GUIDES / CODE DEVELOPMENT

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UNITED STATES
THE ~~NORTH AMERICAN~~ CONTEXT

Code Limitations

- Fire Ratings
- Seismic Considerations

Manufacture Capabilities

Contractor Experience

Aesthetic Preference

WHY MASS TIMBER ?

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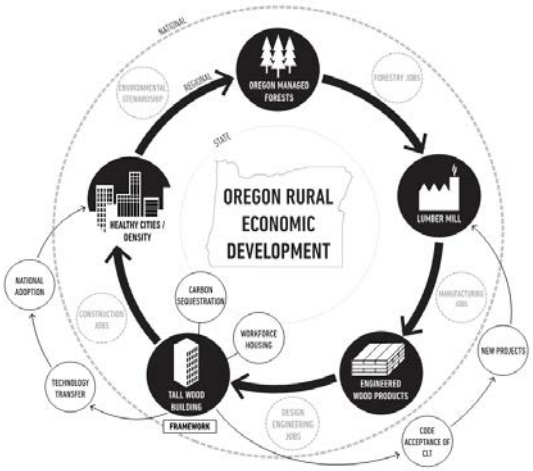
Why Mass Timber ?

Architectural / Societal Benefits

- Sustainability
  - Renewable Resource
  - Carbon Sink
- Architectural Warmth / Biophilia
- Rural Economic Development



Graphic courtesy of Lever Architecture

Why CLT ?

Structural Benefits

- High Strength – Low Mass
- Dimensionally Stable
- Spans 2-Directions
- Fire Ratings

Construction Benefits

- Panelized / Prefabrication
- Speed of Construction
- Reduced Workforce
- Quiet Construction

Why CLT ?

Prefabrication / Speed of Erection

CHALLENGES & LIMITATIONS

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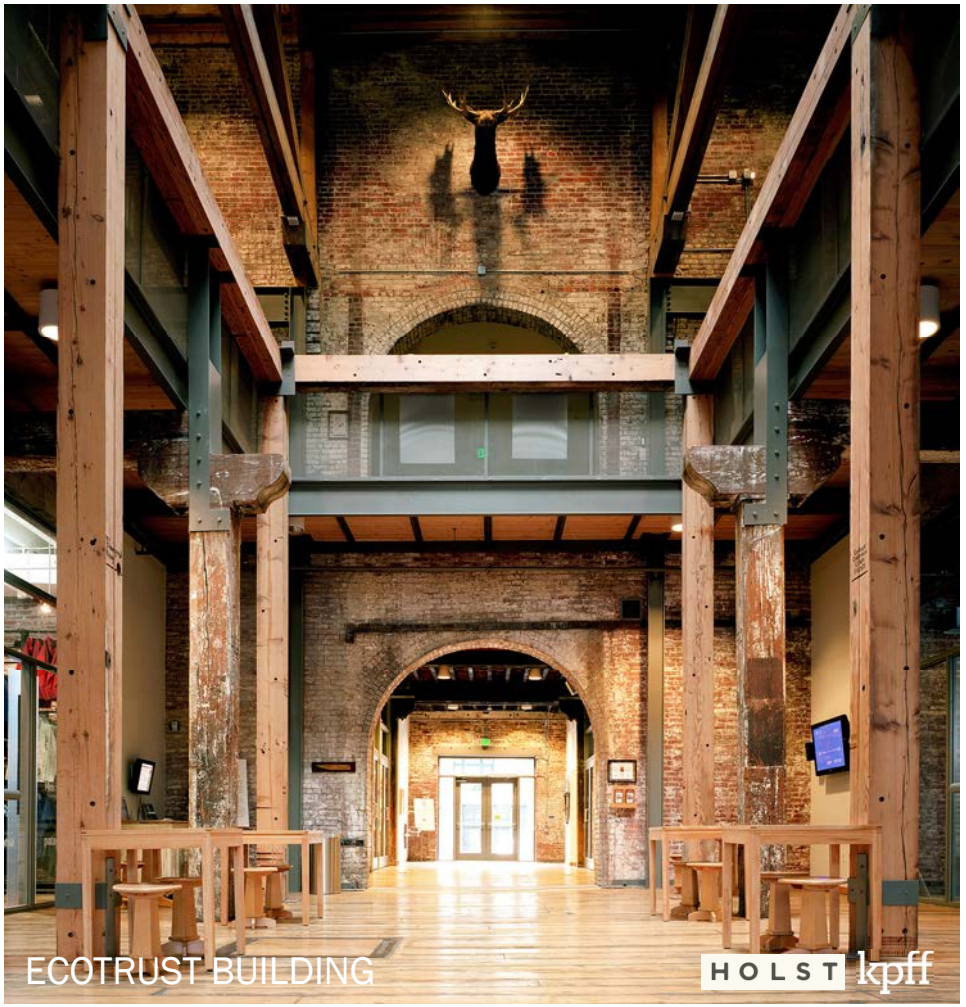
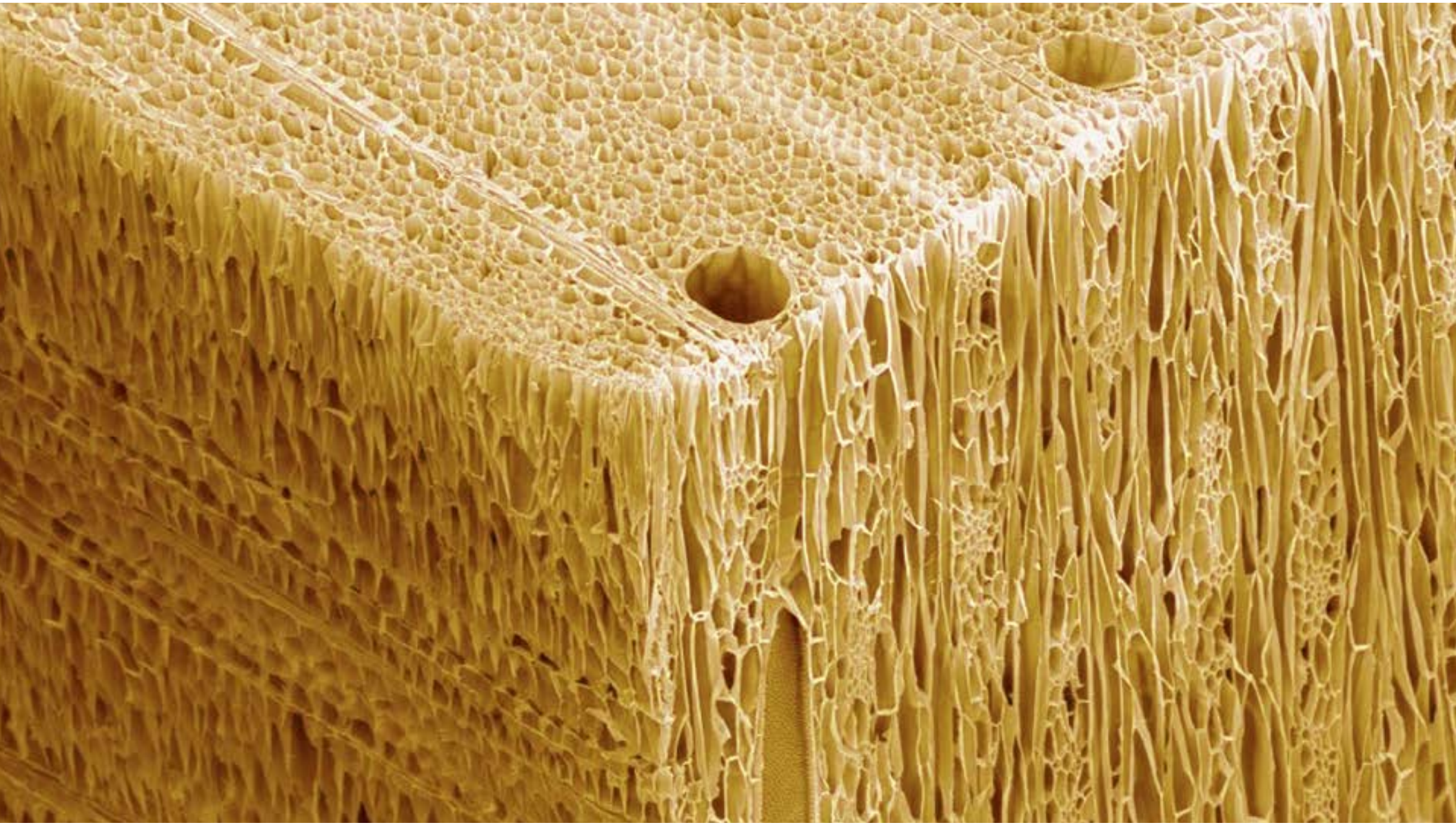
HISTORIC PRECEDENCE





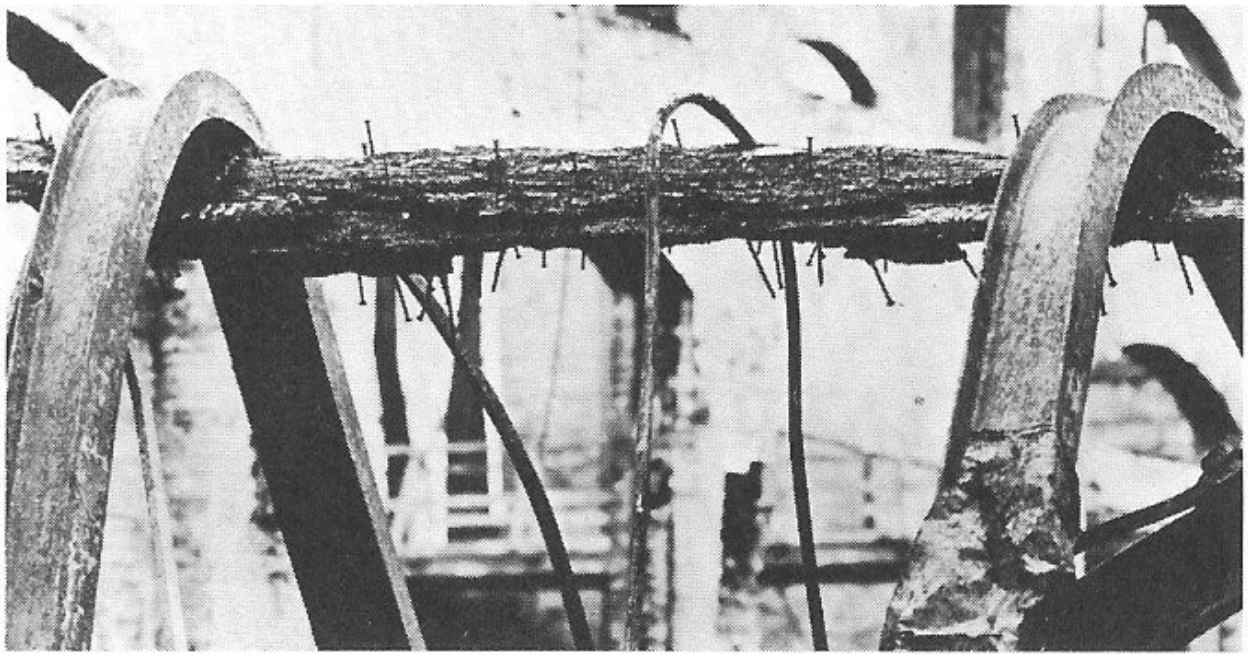
Challenges & Limitations

Crushing Perp to Grain / Shrinkage




Challenges & Limitations

Fire – Predictable Char Rates



After fire scene. Shows a wood beam supporting twisted steel I-beams.
(Forest Products Laboratory)

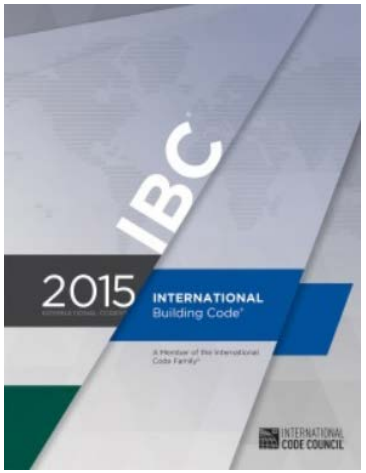
Challenges & Limitations

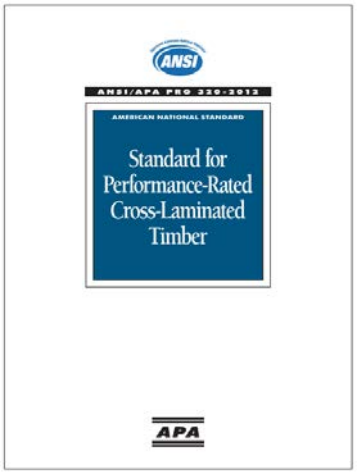
Structural & Architectural Limitations:

- Allowable Spans (versus concrete and steel)
- Crushing Perpendicular to Grain
- Shrinkage / Creep
- Vibrations / Acoustics
- Limited Local Supply Chain / Install Capabilities

Regulatory Challenges:

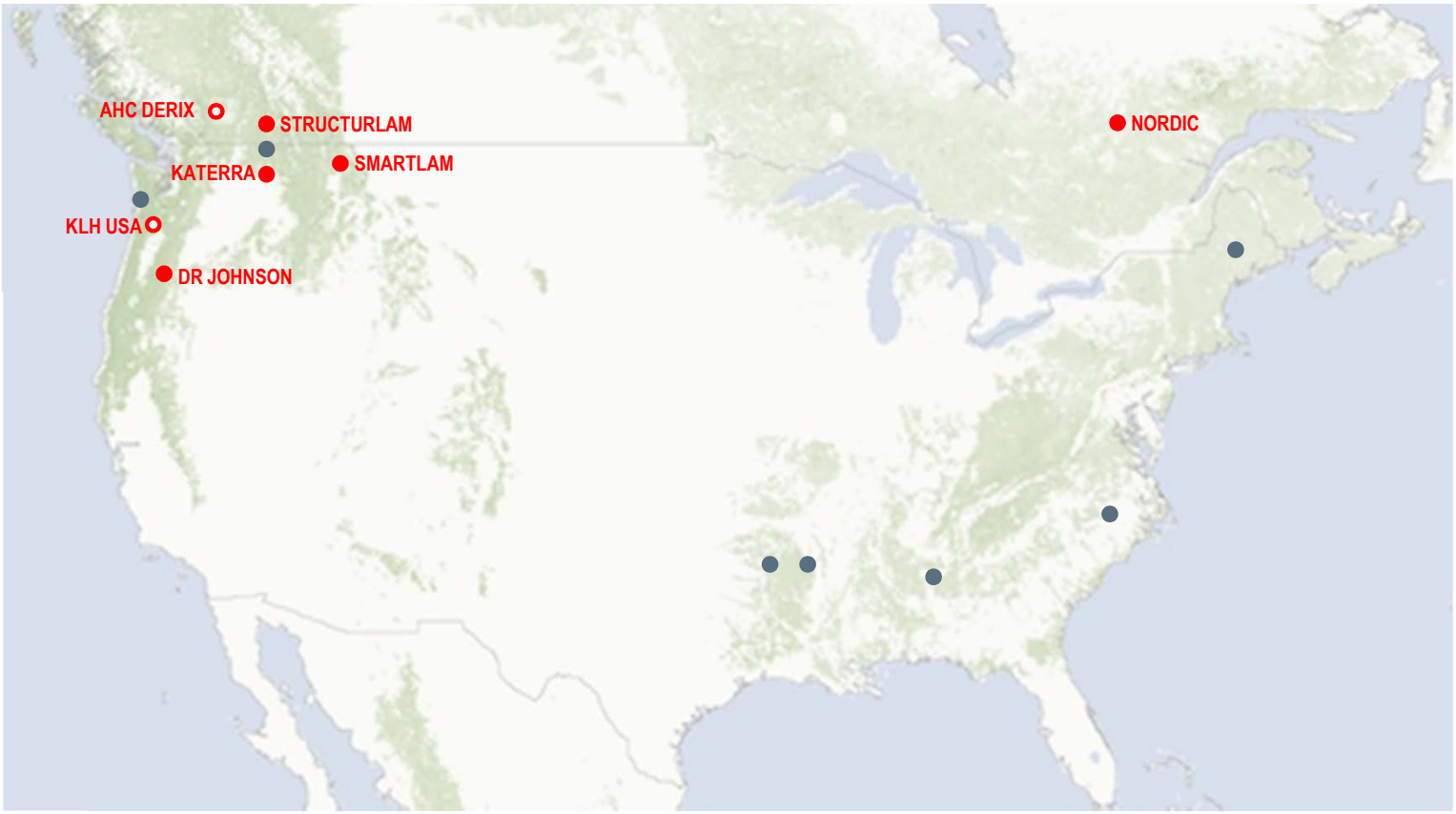
- Gravity: Limited obstacles
- Seismic => Performance Based Design
  - No prescriptive code path
  - Limited technical data available
  - Deformation compatibility of connections
- Fire: Exceed existing heights & areas => Performance Based Design





FRAMING OPTIONS

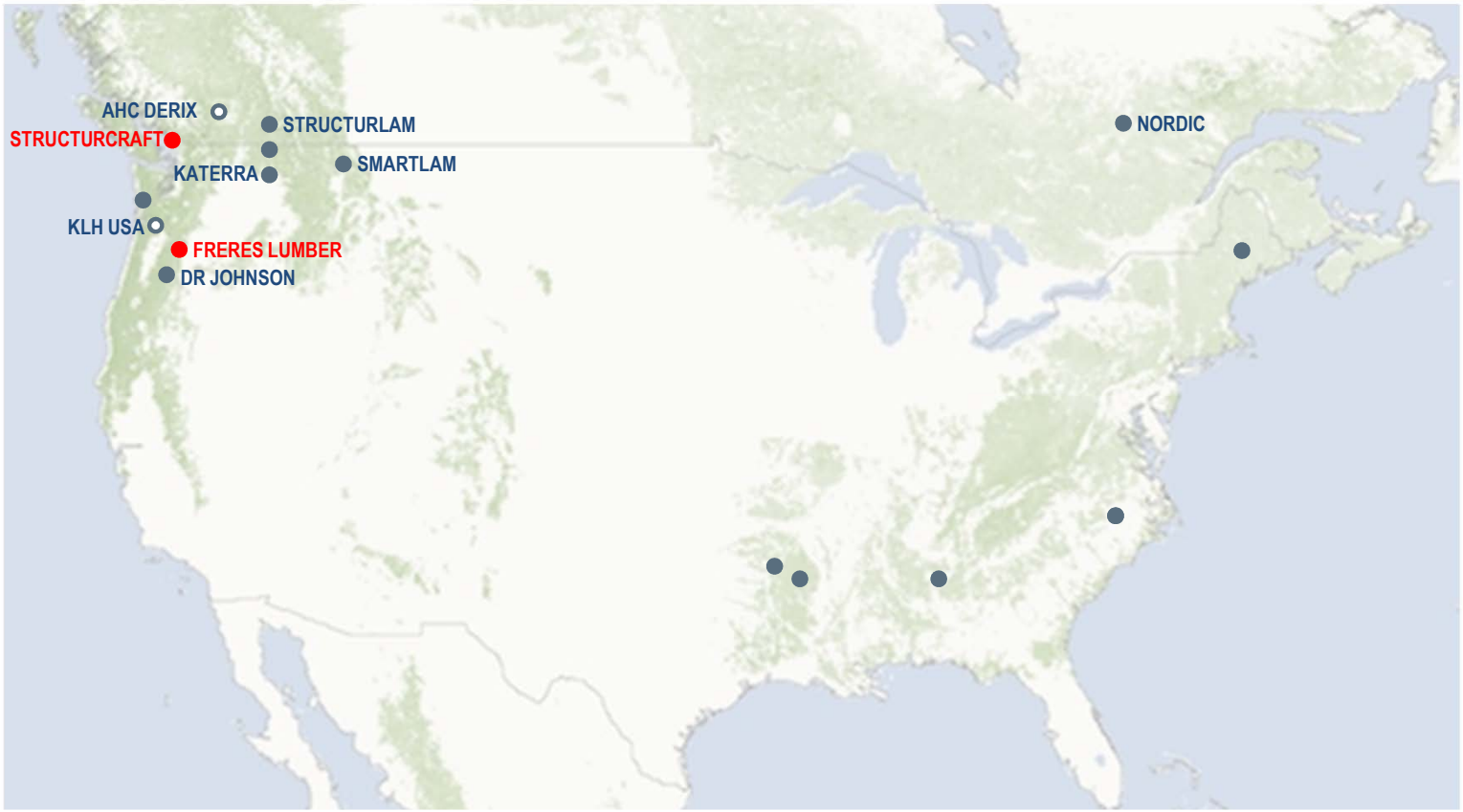
CLT Manufacturers



DR Johnson | Riddle, OR
Smartlam | Columbia Falls, MT
Structurlam | Penticton, BC
Nordic | Chibougamau, QB
Katerra I Spokane, WA
European

Panel Sizes: DF CLT3-7, 10’ x 37’ (-> 43’-6”)
Panel Sizes: SPF-S CLT3-9 10’ x 40’
Panel Sizes: SPF CLT3-9, 10’ x 40’
Panel Sizes: Black Spruce (SPF) CLT3-9, 8’ x 64’
Panel Sizes: Species? CLT3-9, 12’ x 60’
Panel Sizes: Spruce CLT3-9, 7’-6” x 39’-6”

CLT Manufacturers
& DLT / MMP



Structurcraft| Vancouver, BC
Freres Lumber | Lyons, OR

DLT Panel Sizes: 12’ x 60’ x 14”
MMP Panel Sizes: 12’ x 48’ x 12”

Gravity Framing Options

Allowable CLT Floor Spans

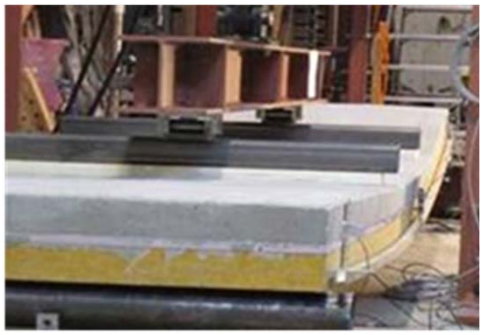
Floor

CrossLam® Floor Panel Load Table

	MAX. SPAN (ft)		FLOOR LIVE LOAD (psf)									
	PANEL TYPE	SIZE (in)	40 Residential		50 Office/ Classroom		75 Mechanical Room		100 Assembly/ Storage		150 Library	
			L/300* (4)	L/240 (5)	L/300* (4)	L/240 (5)	L/300* (4)	L/240 (5)	L/300* (4)	L/240 (5)	L/300* (4)	L/240 (5)
single span	SLT3	3.90	**11.50**	13.60	11.43	12.94	10.43	11.70	9.70	10.71	8.64	9.06
	SLT5	6.66	**16.22**	21.07	**16.22**	20.14	16.12	17.88	15.10	16.10	13.60	13.71
	SLT7	9.42	**20.42**	27.75	**20.42**	26.16	**20.42**	23.14	19.95	20.98	18.10	18.01
	SLT9	12.18	**24.35**	33.32	**24.35**	31.56	**24.35**	28.14	**24.35**	25.63	22.14	22.14
double span	SLT3	3.90	**11.50**	14.83	**11.50**	13.81	**11.50**	11.97	10.71	10.71	9.06	9.06
	SLT5	6.66	**16.22**	20.00**	**16.22**	20.00**	**16.22**	17.88	16.10	16.10	13.71	13.71
	SLT7	9.42	**US CLT Handbook recommends L/300 for preliminary design.*								18.01	18.01
	SLT9	12.18	***Span is governed by maximum panel length of 40ft - design as simple span using table values above.*									

Timber Concrete Composite (TCC)

- HSK System
- Screwed Systems



Gravity Framing Options

Support Structure

- **Steel Framing:**
  30’x30’ Bays with Purlins
- **Glulam Framing:**
  20’x20’ Bays with Purlins
  16’x30’ Bays with CLT
  20’-22’x30’ Bays with TCC, NLT, DLT, MMP
  30’x30’ Bays with pre-fabricated rib panels
- **Two-Way CLT Slabs:**
  10’x16’ Bays
  20’x20’ Bays w/CLT Drop Caps

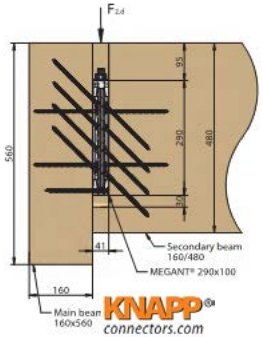
Framing Connections

Special Considerations

- Exposed Versus Concealed Connections
- Fire Rating Requirements
- Drift Demand & Capacity
- Proprietary Versus Custom
- Tolerances / CNC & Shop Fit-up
- Constructability

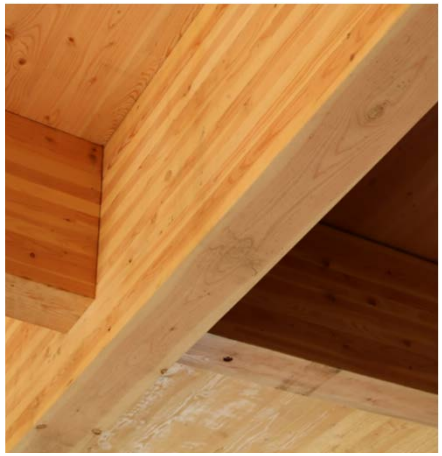
Proprietary Connections

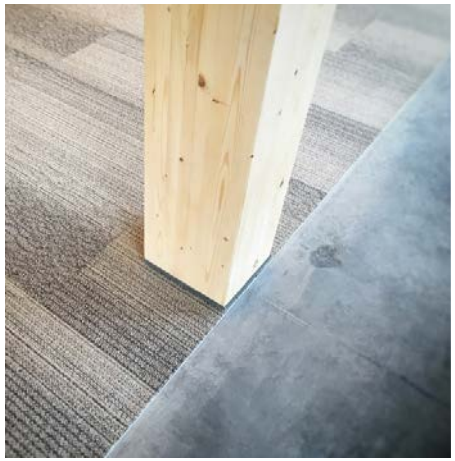
- Exposed Options:
  - Simpson Strong Tie
- Concealed Options:
  - Sherpa
  - Knapp – Ricon, Gigant, Megant

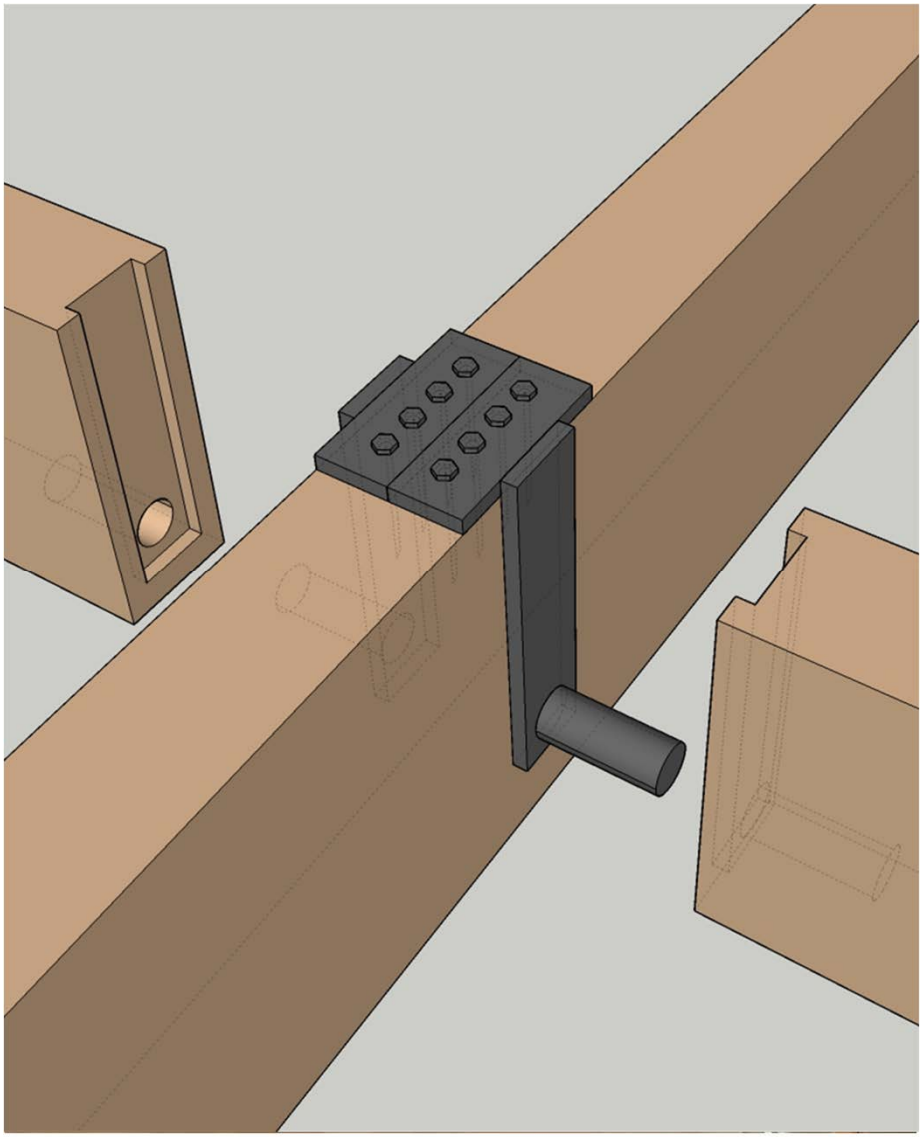


Framing Connections

Custom Connections



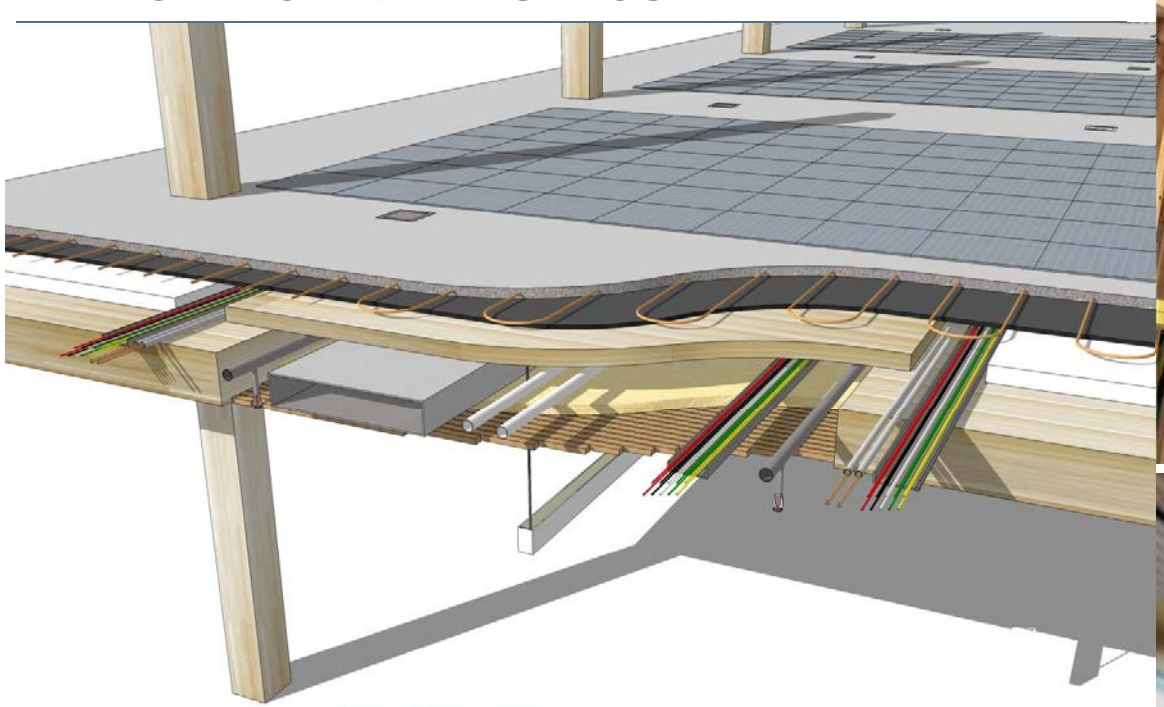


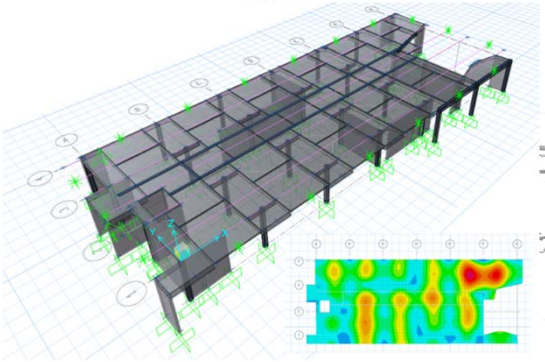


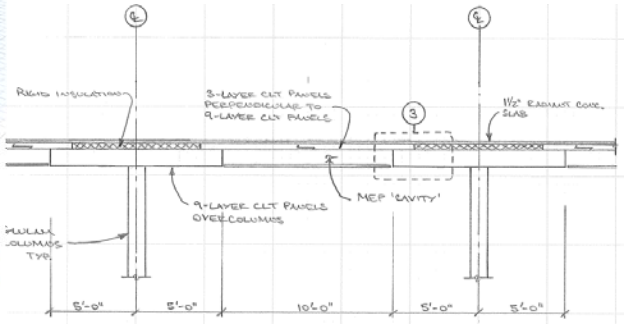
PROJECT EXAMPLES


ROCKY MOUNTAIN INSTITUTE – INNOVATION CENTER
ZGF | kpff

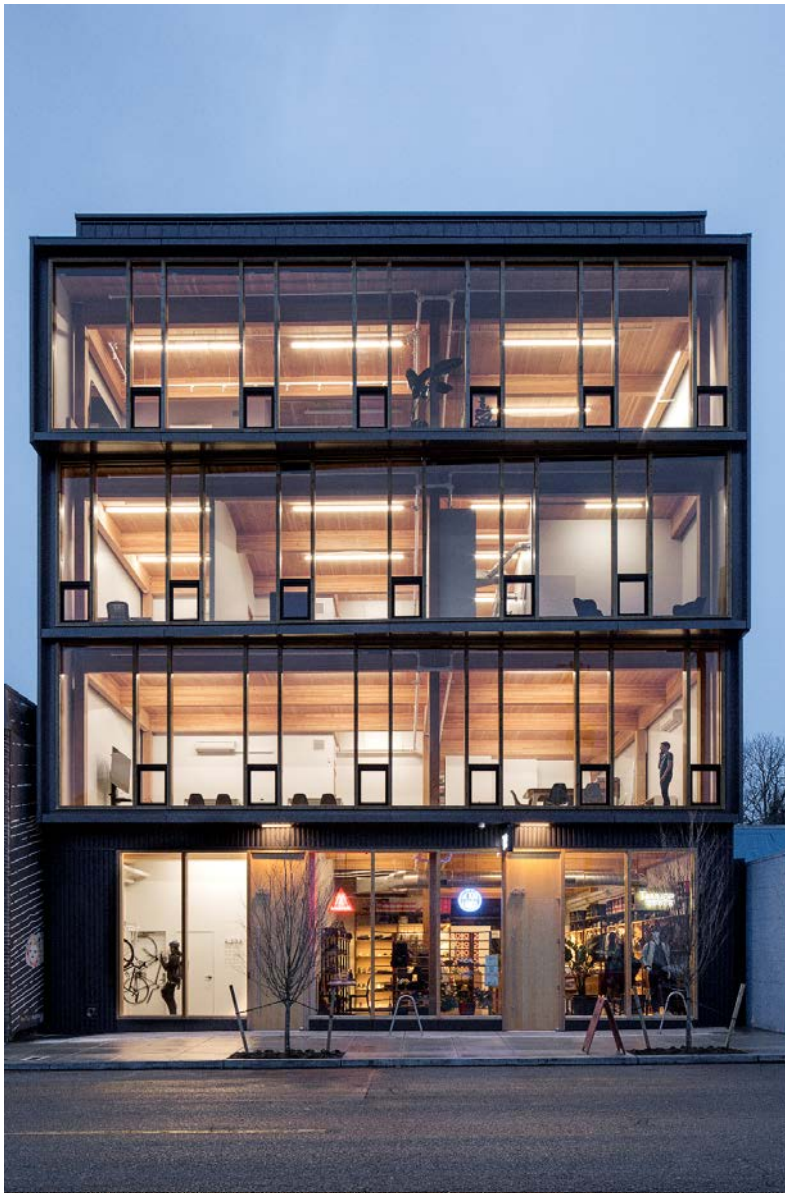
INNOVATION WITH PURPOSE

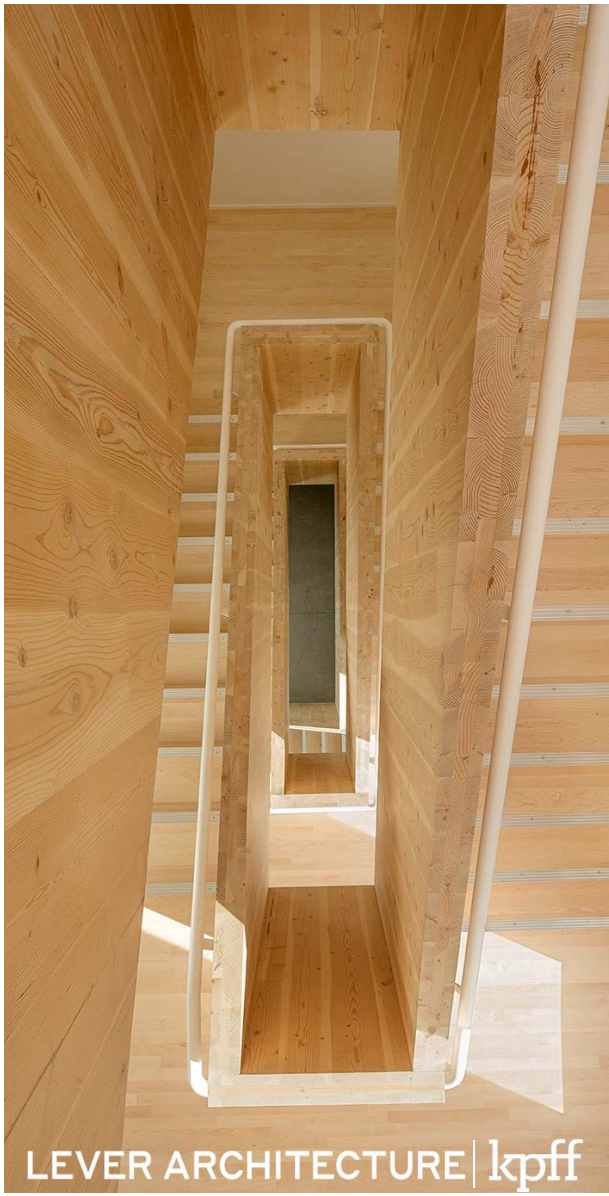






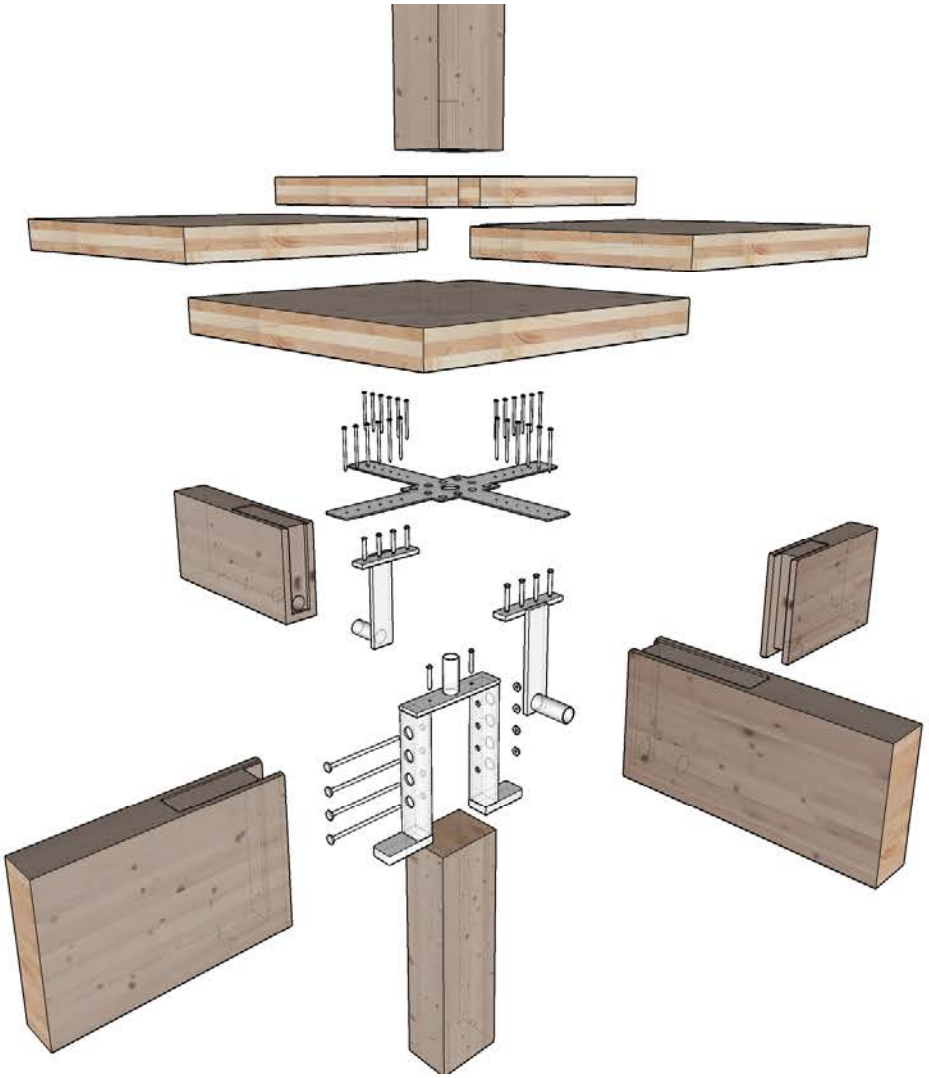

ALBINA YARD




LEVER ARCHITECTURE | kpff


MASS TIMBER RISING
WE SUPPORT OREGON'S FOREST ECONOMY AND LOCAL JOBS
reworks
project
ALBINA YARD
LEVER
ARCHITECTURE


DR Johnson
Lumber Co.
Riddle OR



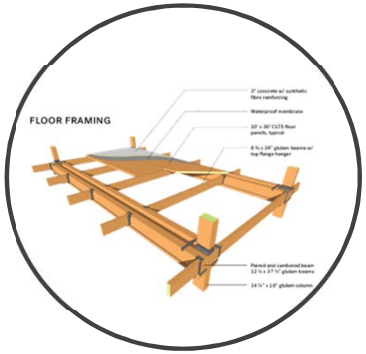

LEVER ARCHITECTURE | kpff

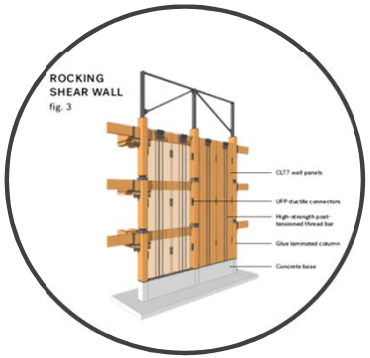
EASTSIDE OFFICE

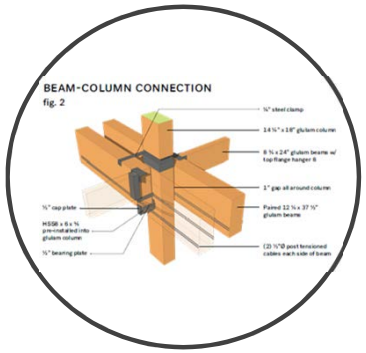
GLENWOOD CLT PARKING GARAGE

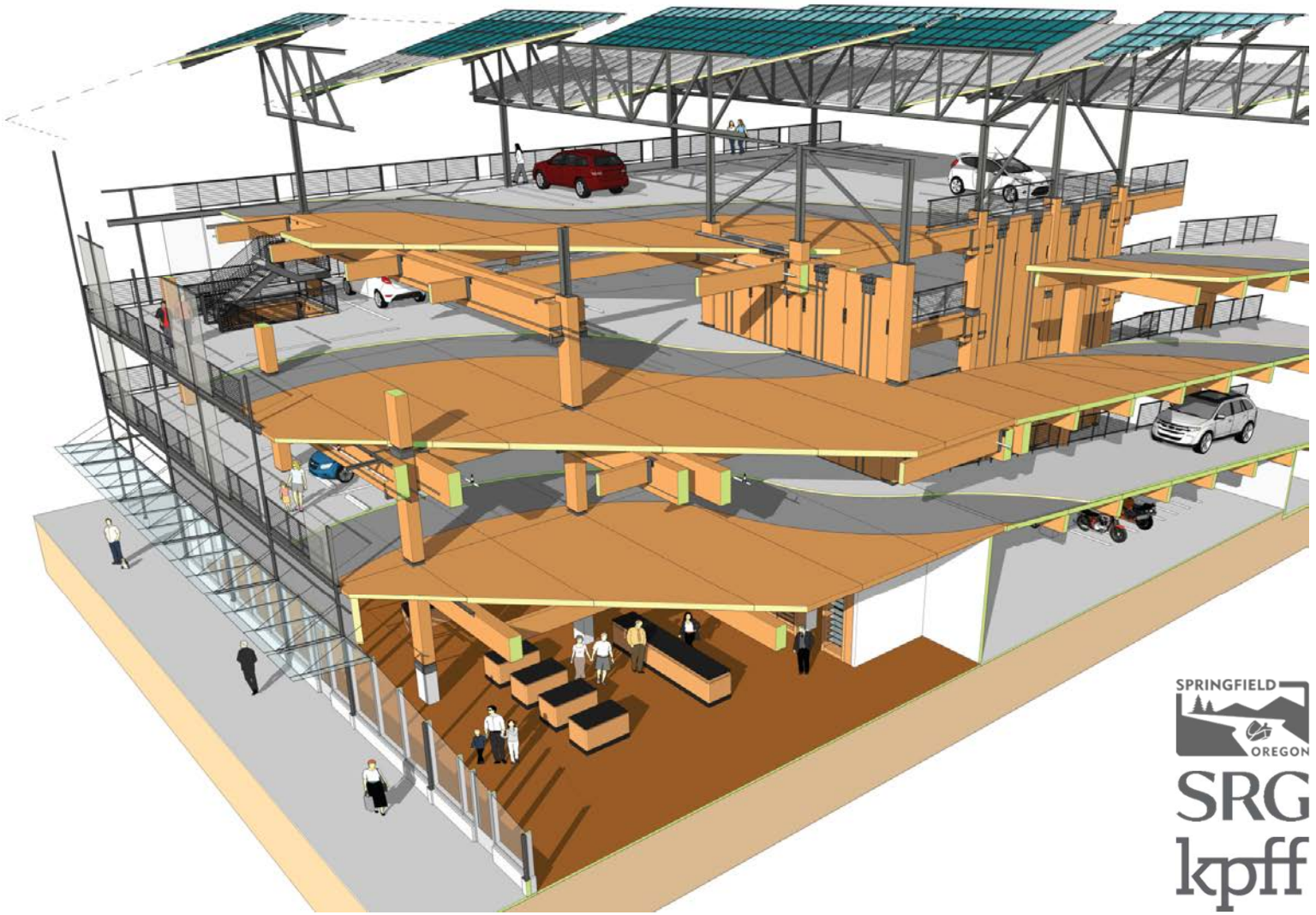
SRG | kpff


Oregon
230 BXE









SPRINGFIELD OREGON

SRG

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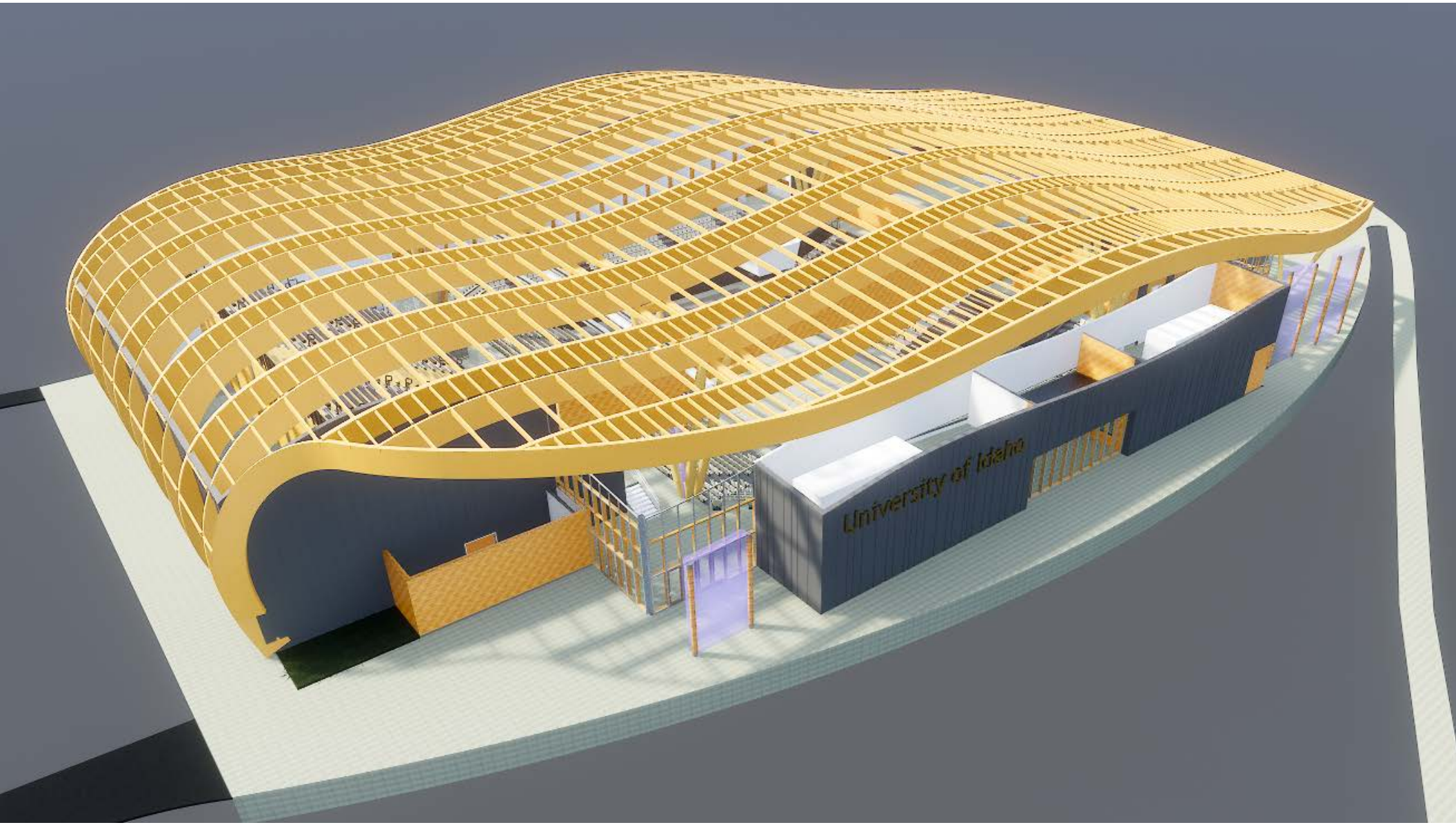
IDAHO BASKETBALL ARENA

opsis | kpff


University of Idaho


PLYWOOD PAVILLION
LEVER ARCHITECTURE | kpff

SUMMARY OF BUILDING TYPES

Mid- Rise (7-12 Stories)

- Office
- Residential / Hotels
- Mixed Use

Low Rise

- Class ‘A’ Office Space
- Residential / Hotels
- Civic
- Higher Ed / K-12

Parking Garages?

FRAMEWORK

U.S. TALL WOOD BUILDING PRIZE COMPETITION

SLB SOFTWOOD LUMBER BOARD USDA BSLC

FRAMEWORK

LEVER ARCHITECTURE | kpff

Owner:

- Home Forward
- Beneficial Bank

Project Team:

- project^
- LEVER ARCHITECTURE
- Walsh Construction / StructureCraft
- KPFF, ARUP, PAE

Project Facts:

- 12 Stories – 135 ft
- Mixed Use
- 90,000 Sq. ft.
- Type 1B Equivalent Construction

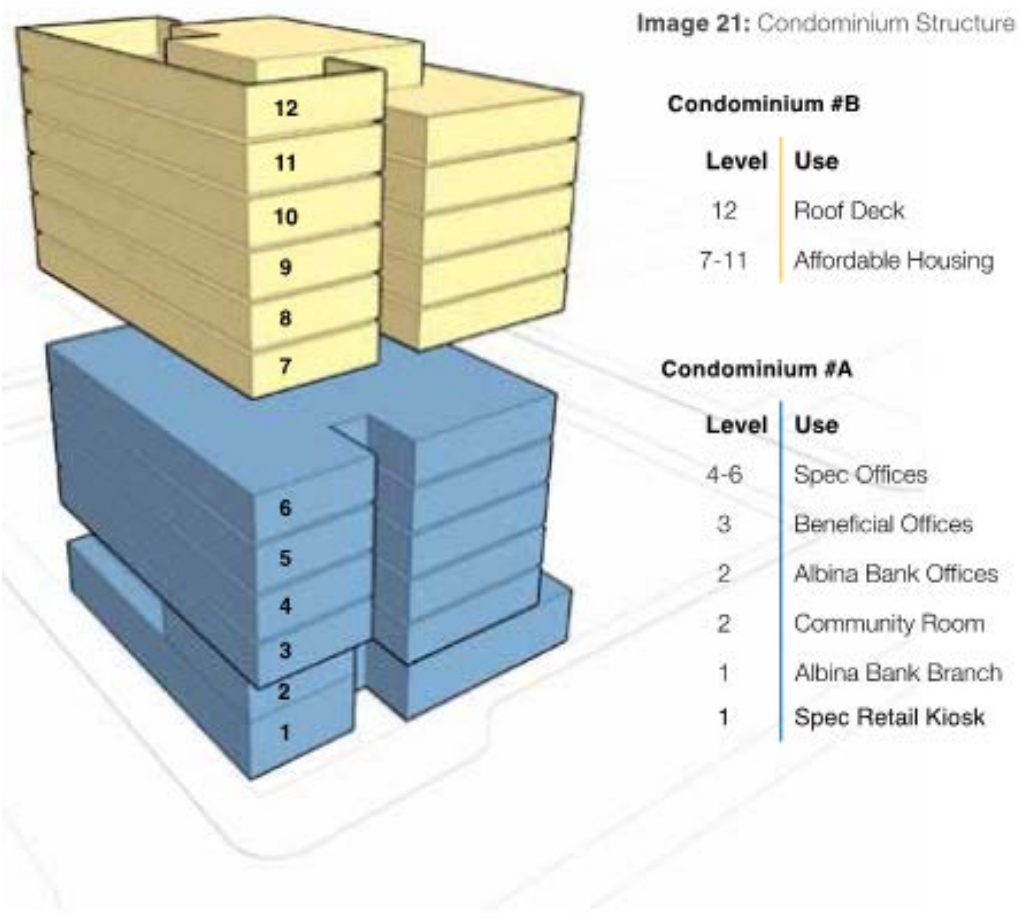


Image 21: Condominium Structure

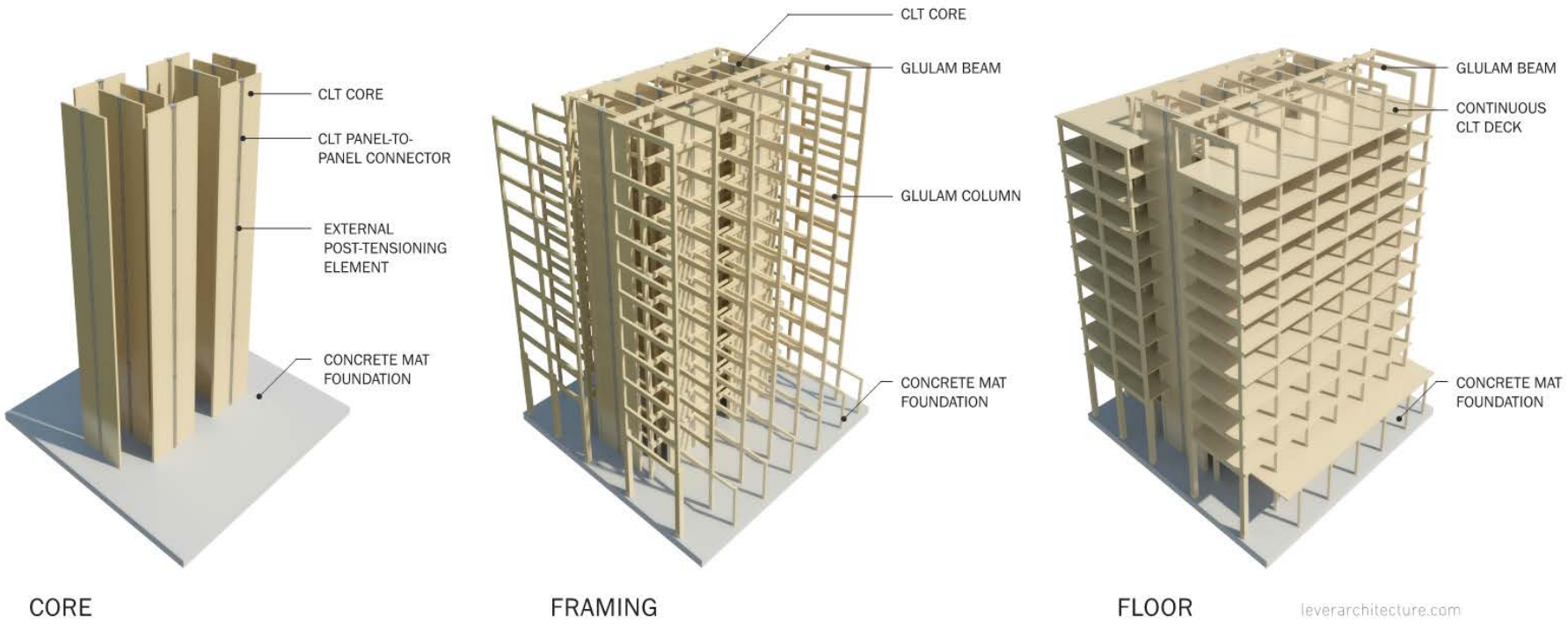
Condominium #B

Level	Use
12	Roof Deck
7-11	Affordable Housing

Condominium #A

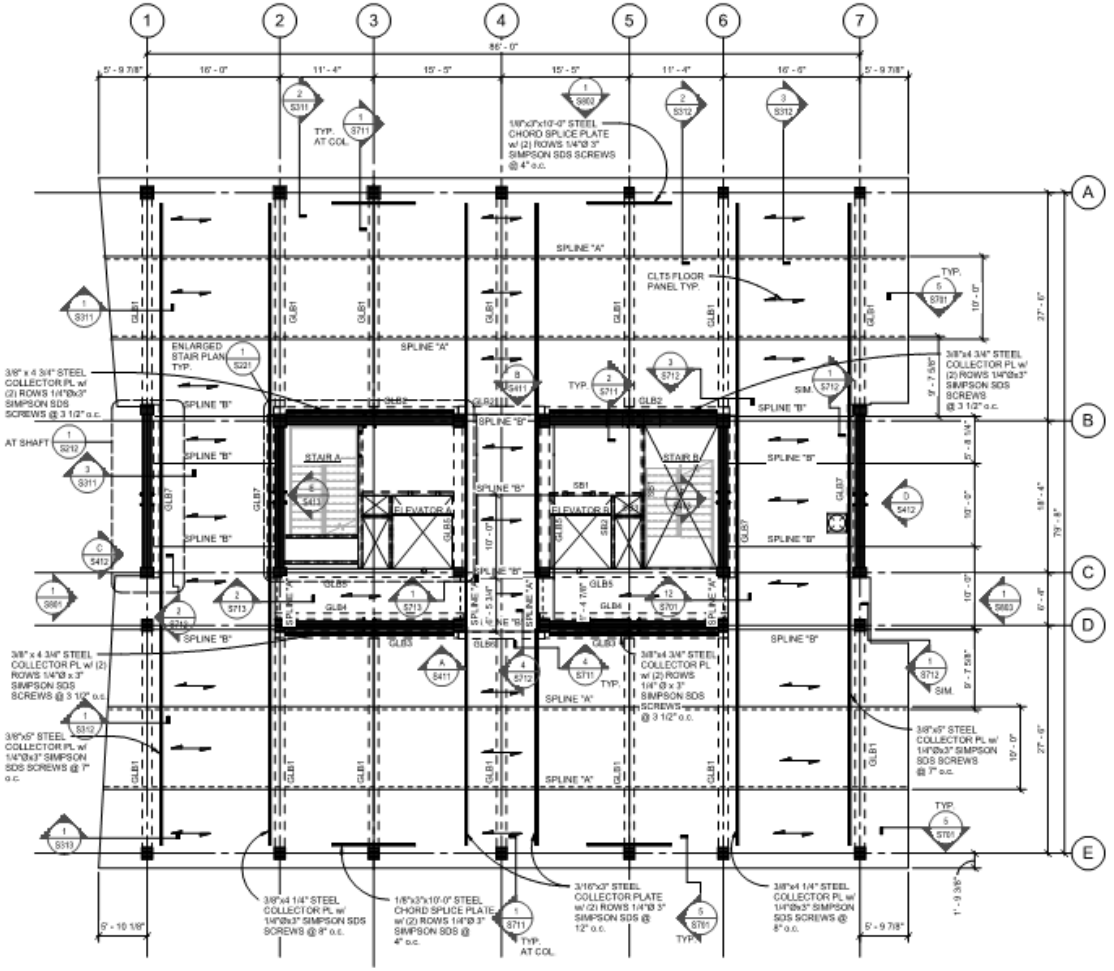
Level	Use
4-6	Spec Offices
3	Beneficial Offices
2	Albina Bank Offices
2	Community Room
1	Albina Bank Branch
1	Spec Retail Kiosk

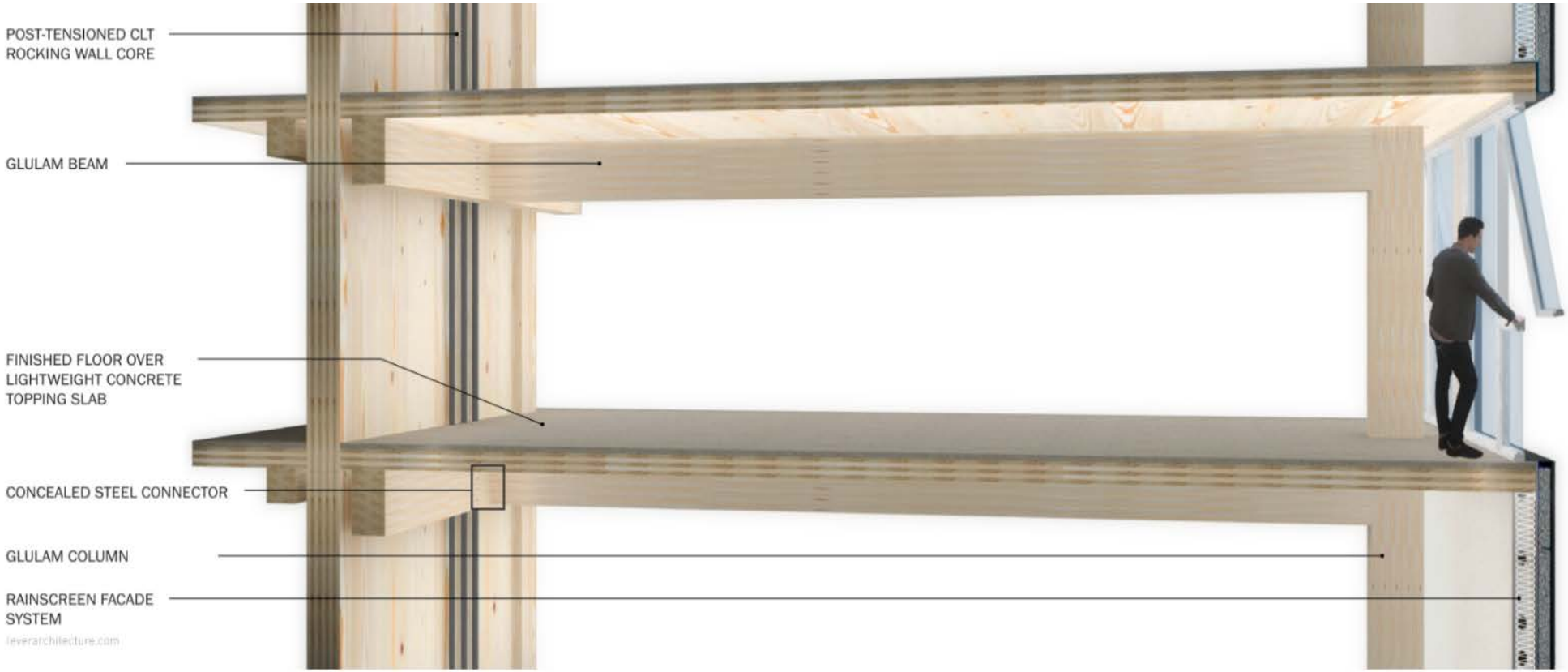
STRUCTURAL DESIGN



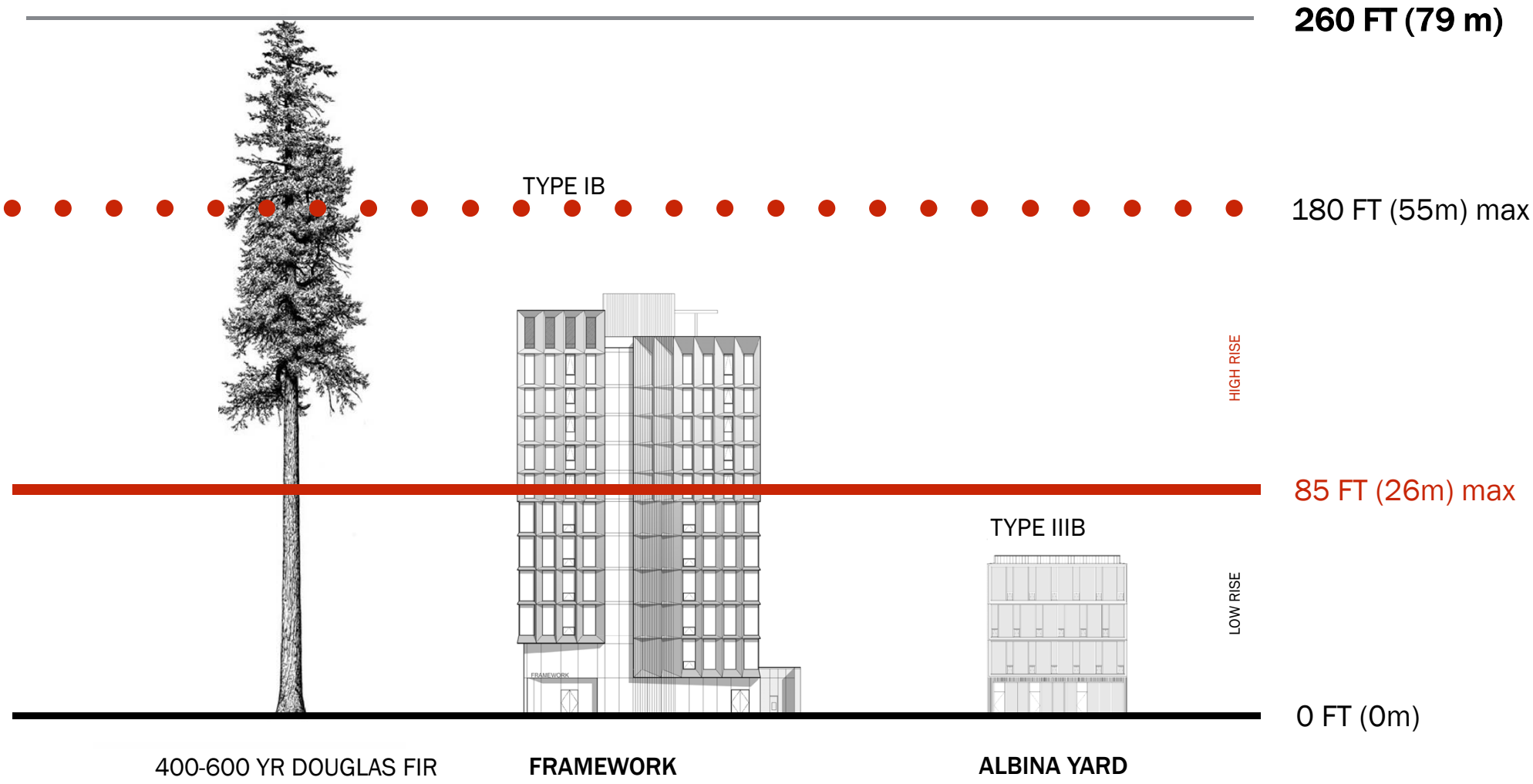
- Gravity System – Gypcrete & CLT5 Floor Panels spanning to Glulam Beams and Columns
- Lateral System – Resilient Post-tensioned Rocking CLT Walls
- Performance Based Design - Pursued for Fire Design and Seismic Design

TYPICAL FRAMING PLAN

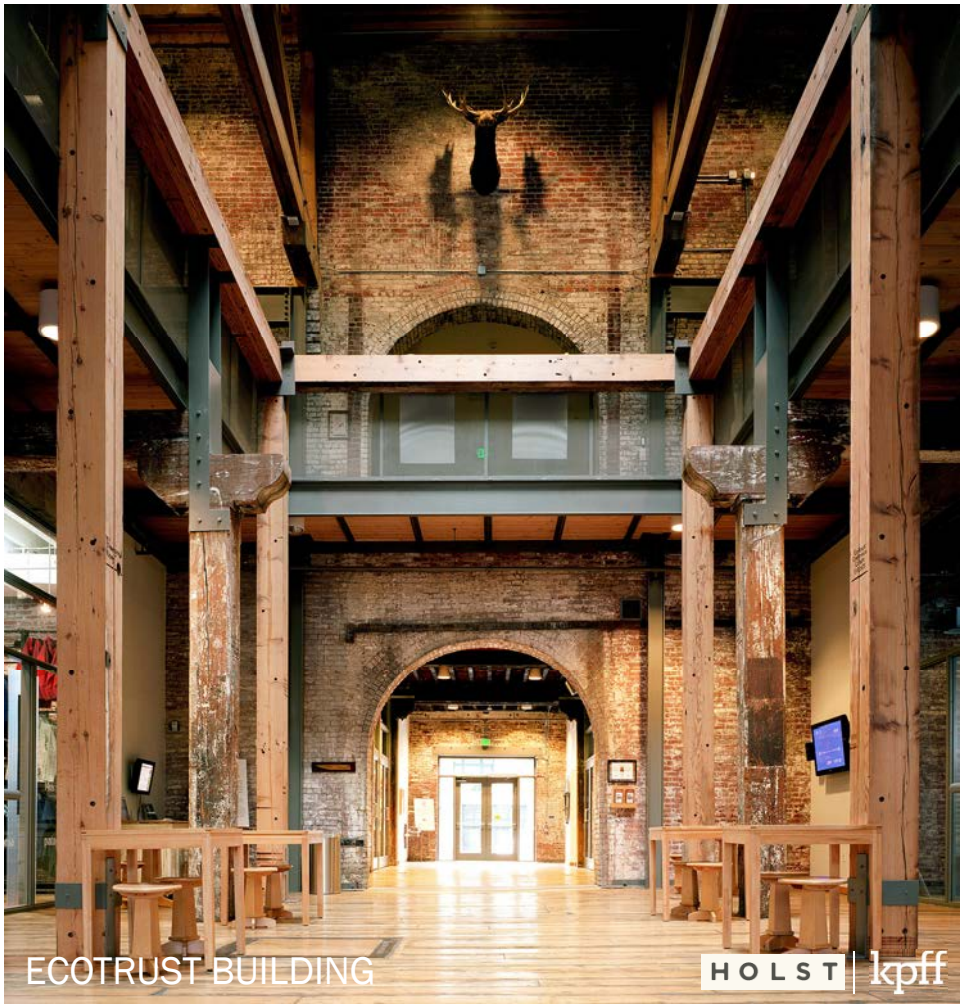



POST-TENSIONED CLT
ROCKING WALL CORE
GLULAM BEAM
FINISHED FLOOR OVER
LIGHTWEIGHT CONCRETE
TOPPING SLAB
CONCEALED STEEL CONNECTOR
GLULAM COLUMN
RAINSCREEN FACADE
SYSTEM
leverarchitecture.com


HI TECH TIMBER
TRADITIONAL VS.
MODERN FORESTRY

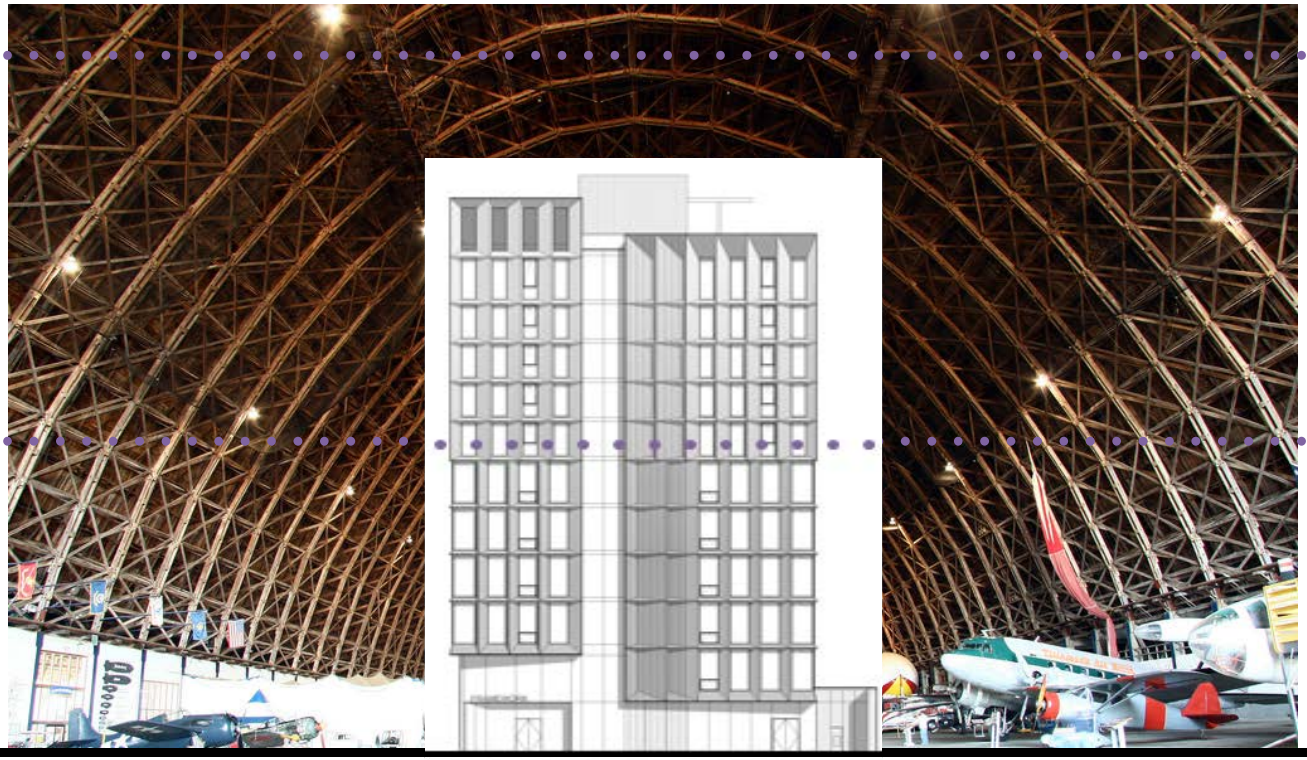

260 FT (79 m)
TYPE IB
180 FT (55m) max
HIGH RISE
85 FT (26m) max
TYPE IIIB
LOW RISE
0 FT (0m)
400-600 YR DOUGLAS FIR
FRAMEWORK
ALBINA YARD

HISTORIC PRECEDENCE



260 FT

185 FT (max)



85 FT (max)

0 FT

FIRE DESIGN

Fire Assemblies / Testing

- 2 hour floor & wall assembly – DR Johnson
- Connections – Project specific
- Penetrations – Existing manufacture data

Performance Based Fire Modeling

- Proving equivalence
- Determining how much wood can be exposed

Structural Fire Design

- Floor Assembly – Tested
- Glulam beams & columns – Apply char depths

SEISMIC RESILIENCE

SEISMIC LATERAL SYSTEM

Alternate Systems Considered

- Concrete Core
- Steel Braced Frames

Project Goals

- All Timber Solution
- Resilient Solution

System Chosen

- Post-Tension Rocking CLT Walls
  - Self-Centering
  - Resilient / Low Damage
  - Quickly / Easily Repairable

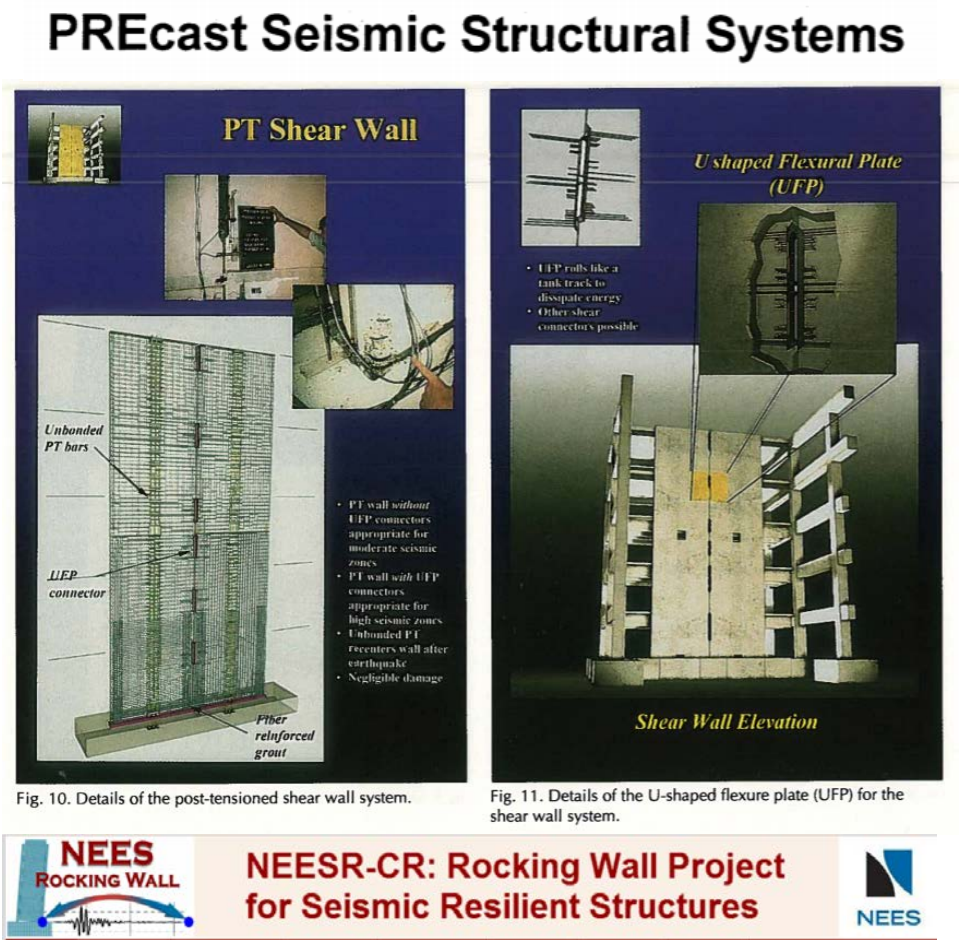
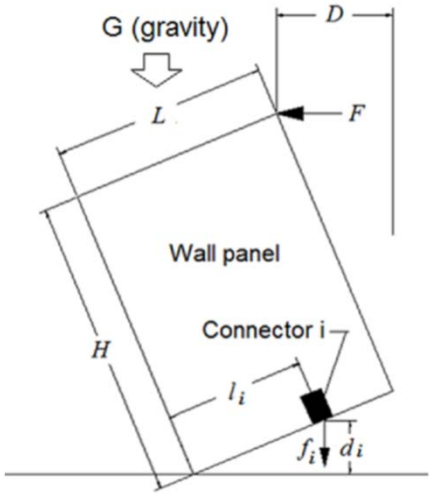
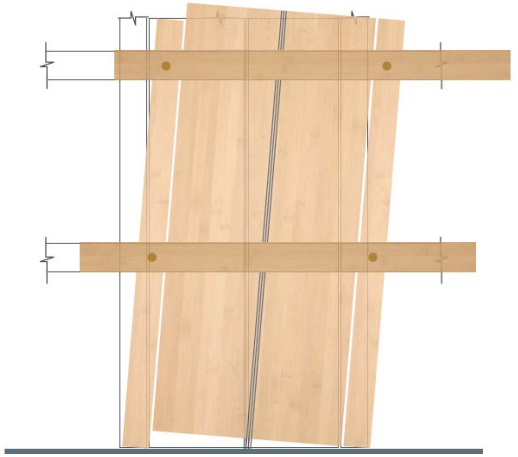


Fig. 10. Details of the post-tensioned shear wall system.

Fig. 11. Details of the U-shaped flexure plate (UFP) for the shear wall system.

RIGID PANEL ROCKING BEHAVIOR





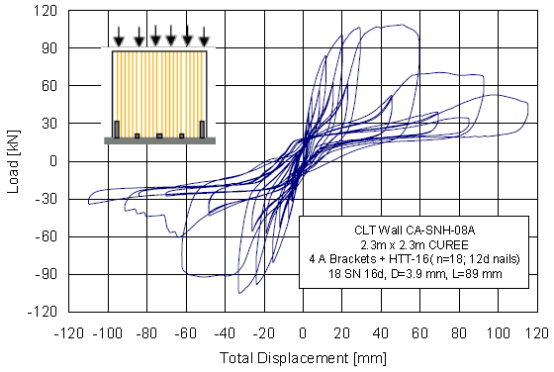


Figure taken from "Design and Performance of CLT Structures under Lateral Loads" by Marjan Popovski.

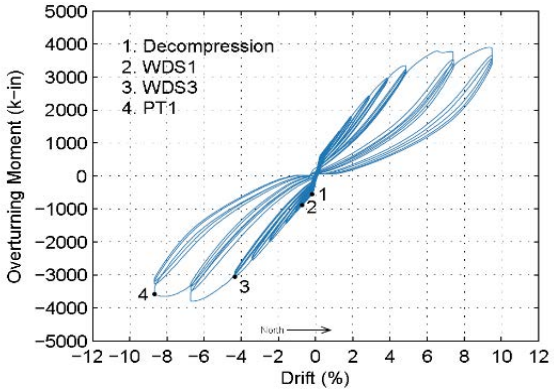
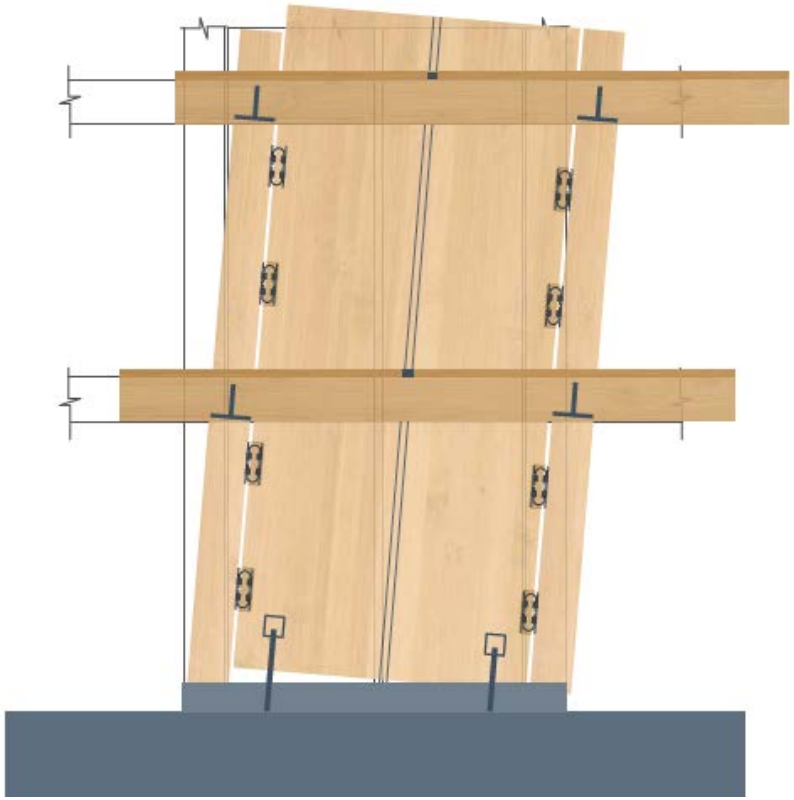
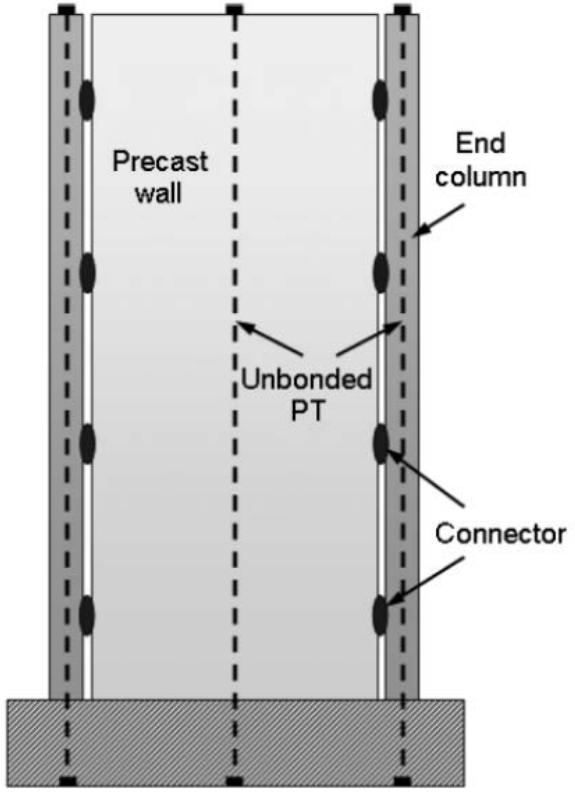


Figure taken from "Seismic Design and Testing of Rocking Cross Laminated Timber Walls" by Ryan Ganey.

SEISMIC FORCE-RESISTING SYSTEM



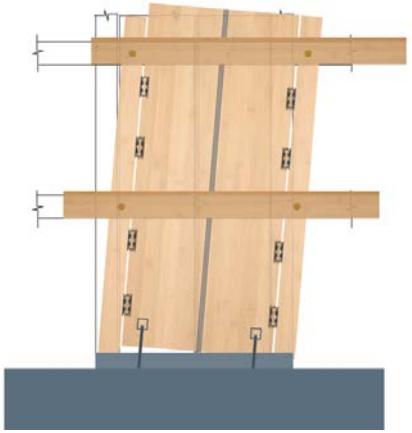
Resilient Rocking Mass Timber Wall

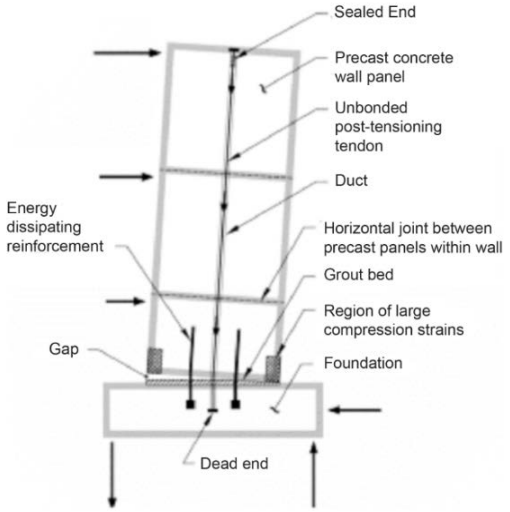


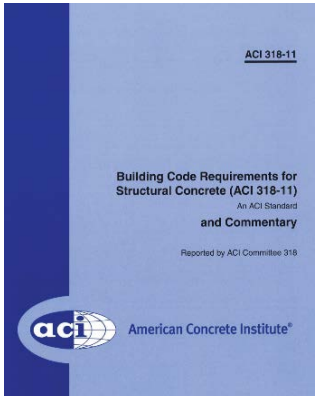
(c) PreWEC wall

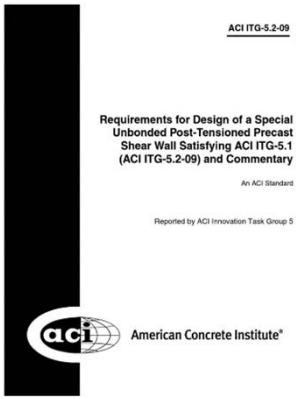
Figure taken from "Seismic Analysis of Low-Damage Precast Wall with End Columns (preWEC) Including Interaction with Floor Diaphragms" by Henry R.S., Aaleti, S. Sritharan, S and Ingham, J. M.

SEISMIC FORCE-RESISTING SYSTEM



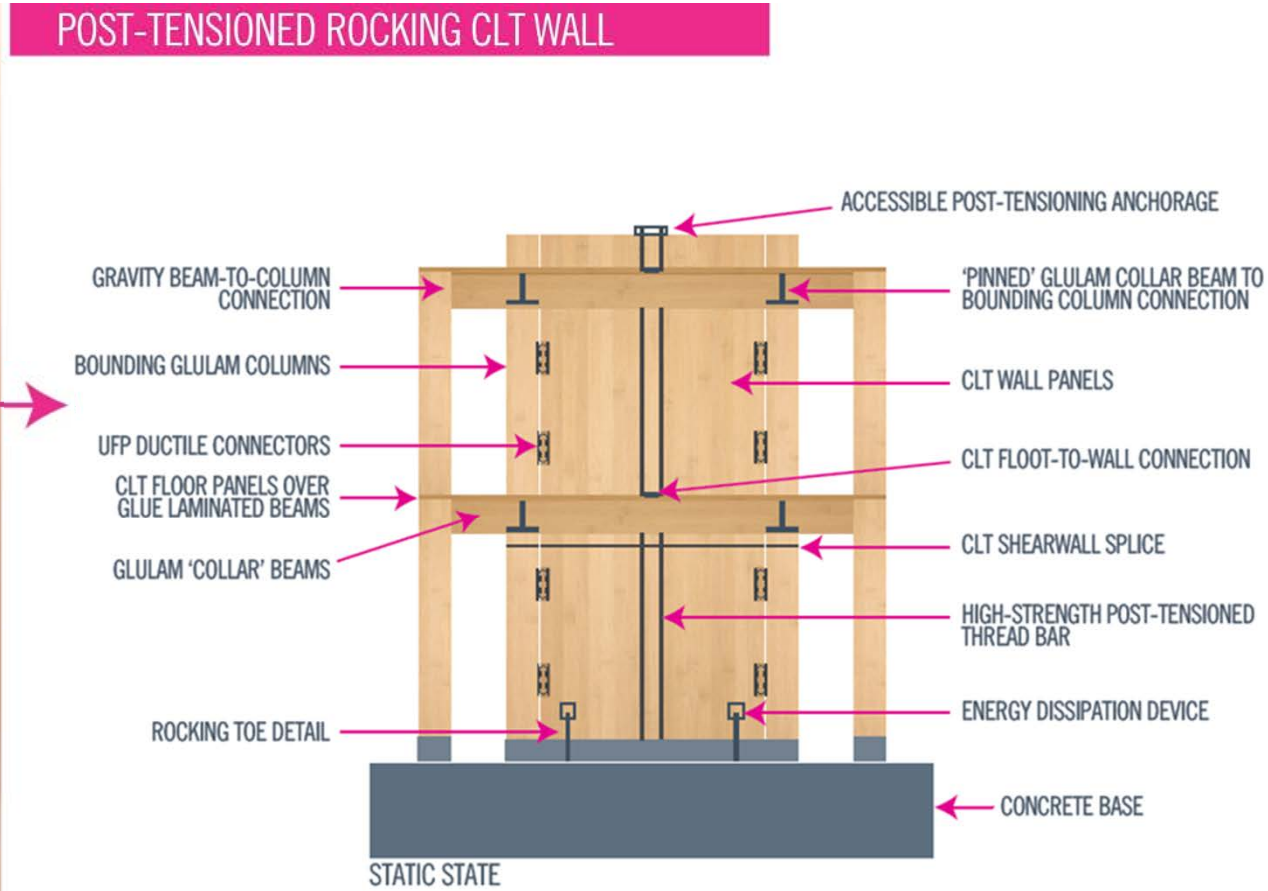




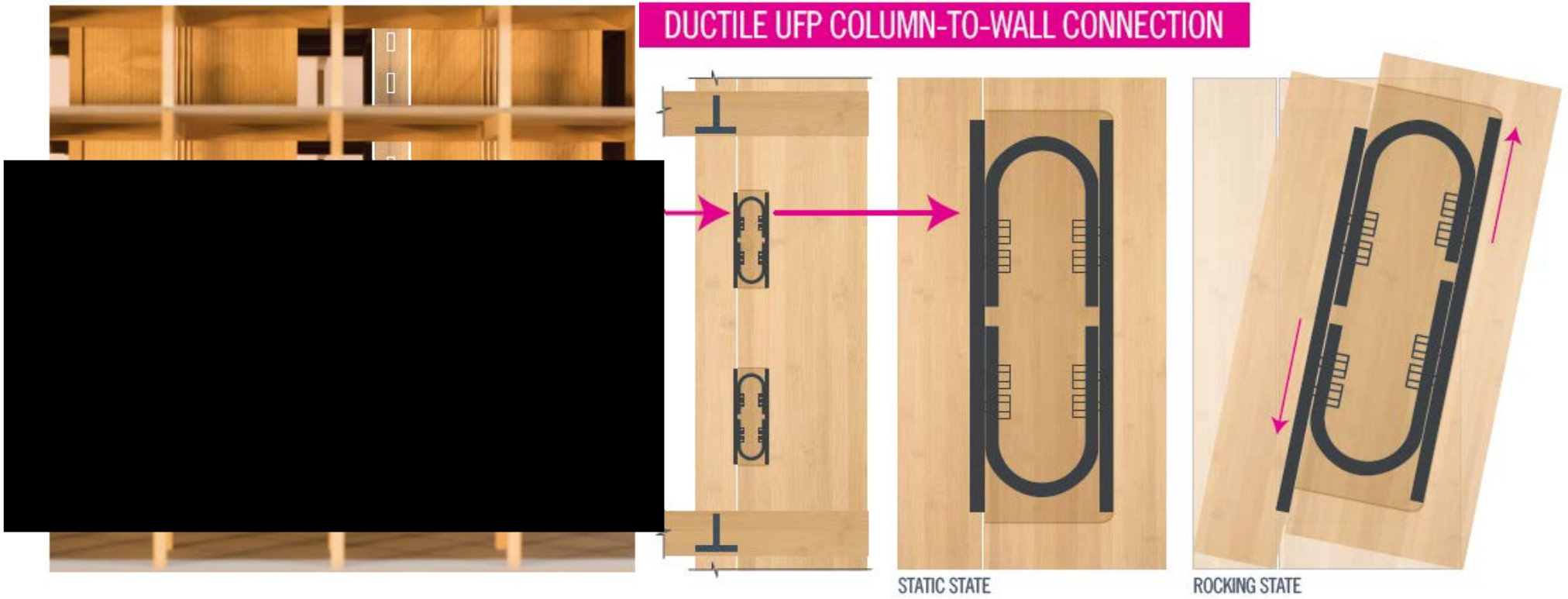


RESILIENT POST-TENSIONED ROCKING CLT WALLS

Resilient Self-Centering Solution



RESILIENT POST-TENSIONED ROCKING CLT WALLS



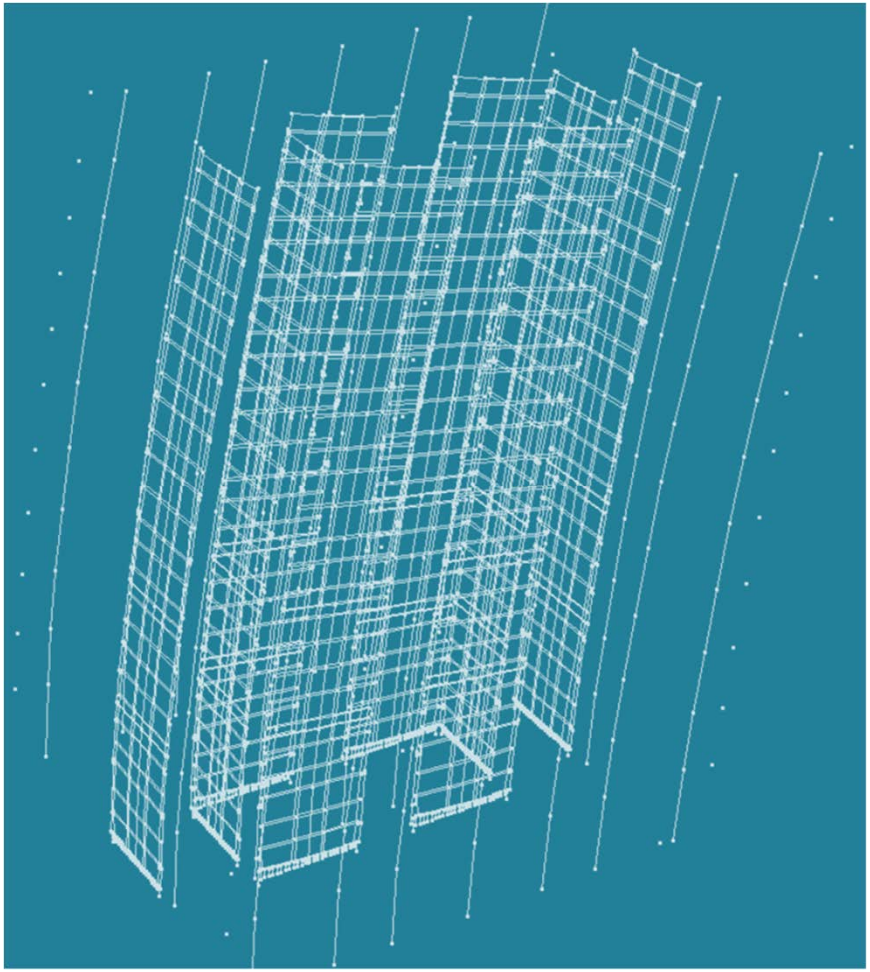
PERFORMANCE BASED DESIGN

Structural Design

- Post-Tensioned Rocking Walls
  - Extensive Review of Existing Research
  - Nonlinear Response History Analysis
  - Project-Specific Component Testing
- CLT Diaphragm
  - Analytical Modeling
- Connections – Drift Compatibility / Fire Rating
  - Project Specific Full-Scale Testing

Review

- Authority Having Jurisdiction
- Independent Peer Review Team
- Research Partners



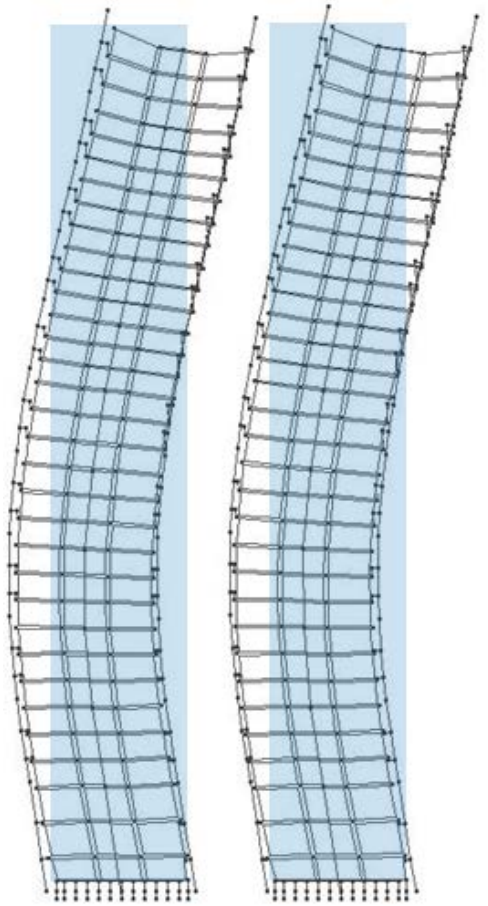
DESIGN CRITERIA

Demonstrating Code-Equivalent Performance

1. Strength-Level Wind
2. Establish Minimum Seismic Strength
3. Deformation- and Force-Controlled Actions and Drift Verification at MCE_R

Opportunities for Enhanced Performance

1. Reparability Earthquake
2. Serviceability Wind
3. Serviceability Earthquake



Framework

Performance-Based Seismic Design

UNIQUE CONSIDERATIONS FOR TALL MASS TIMBER

1. Effective Shear Modulus of CLT
2. Shear Capacity and Demand of CLT
3. Splicing Timber Panels for Earthquake Demands
4. Post-Peak Crushing Performance of CLT
5. Deformation Compatibility of the Gravity System
6. Beam Elongation in the Gravity System
7. CLT Diaphragms
8. LRFD and Expected Properties of Wood
9. Post-Tensioning Loss
10. Fire Rating and Char Depth

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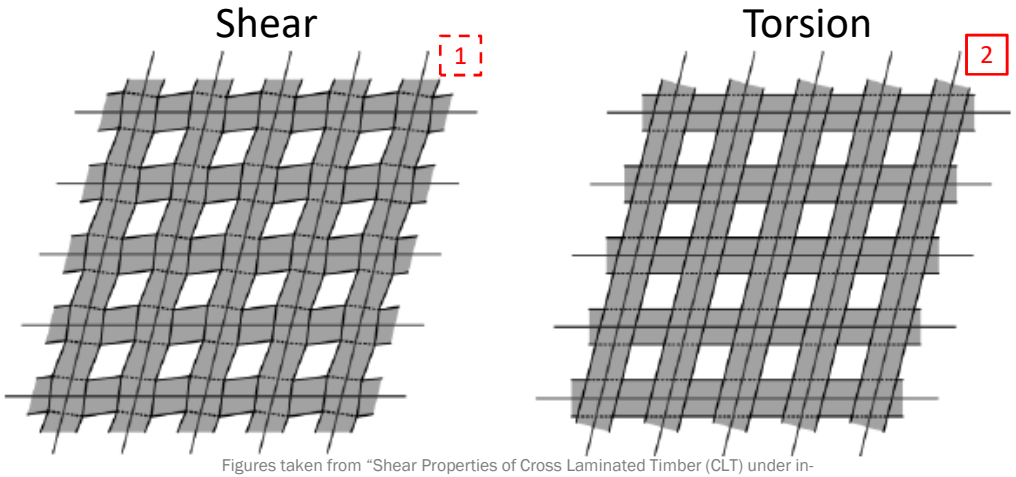
EFFECTIVE SHEAR MODULUS OF CLT

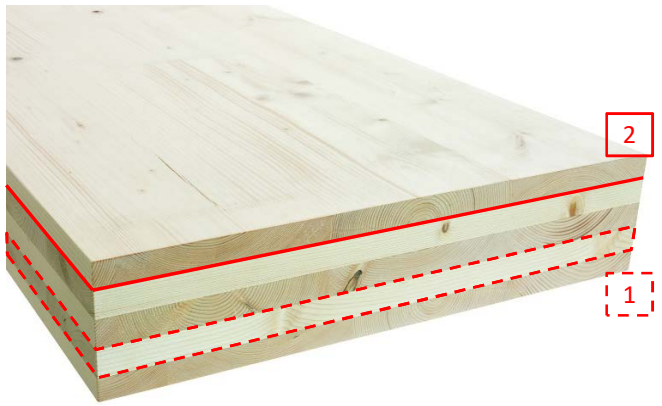
CLT to Concrete Comparison

	Concrete f'_c = 5000psi (34.5 MPa)	CLT DF No. 1	CLT / Concrete
EI_{eff}	2015ksi*I_g	1025ksi*I_g	50%
GA_{eff}	1610ksi*A_g	(35 to 75ksi)*I_g	2 to 5%

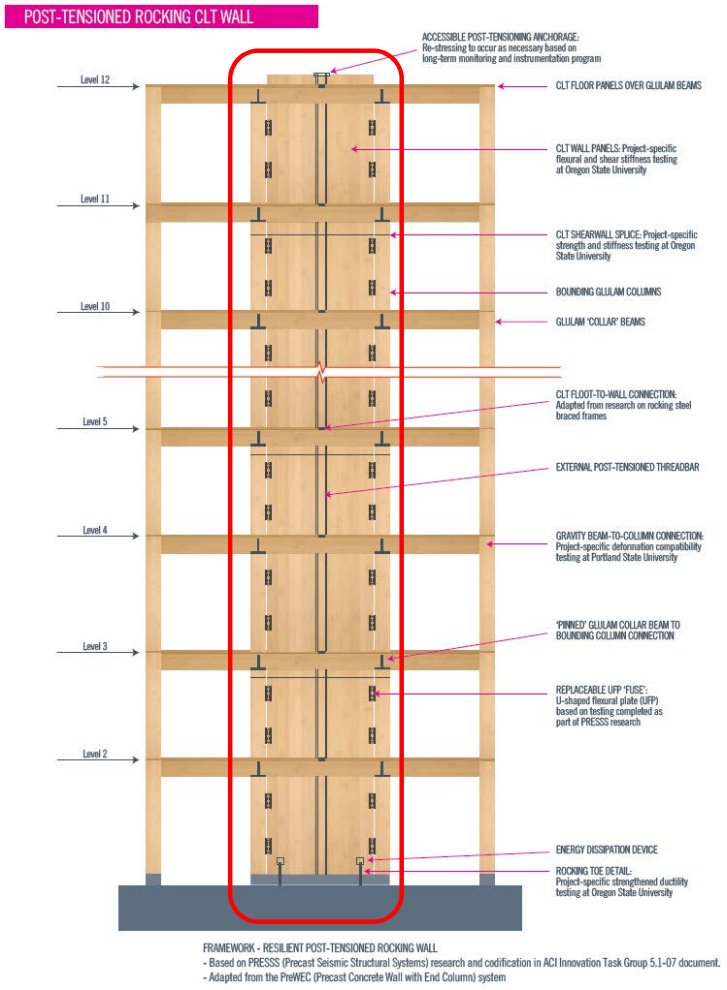
Notes
1. Cracked section modifiers for concrete taken as 0.5 for EI_{eff} and 1.0 for GA_{eff}.
2. GA_{eff} for CLT based on Flaig and Blaß (2013) and Brandner et al. (2015)

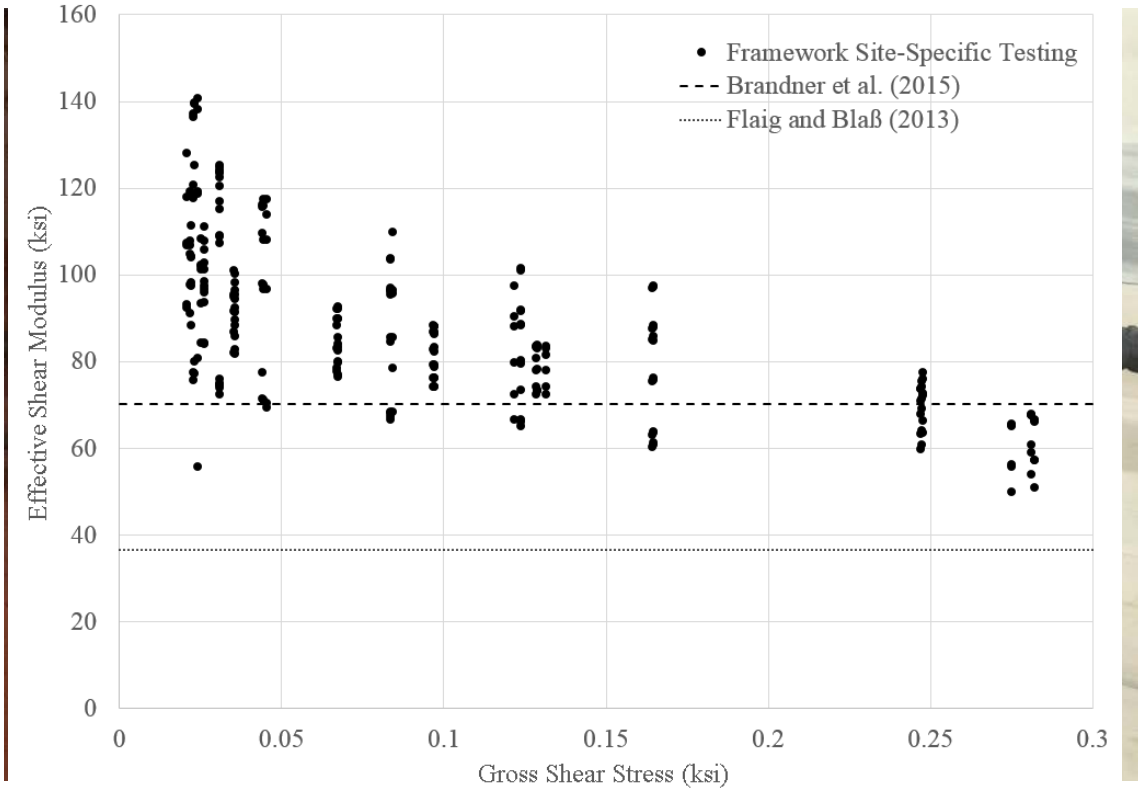


Figures taken from "Shear Properties of Cross Laminated Timber (CLT) under in-plane load: Test Configuration and Experimental Study" by P. Dietsch.



BARE WALL TESTING





SHEAR CAPACITY AND DEMAND OF CLT WALLS

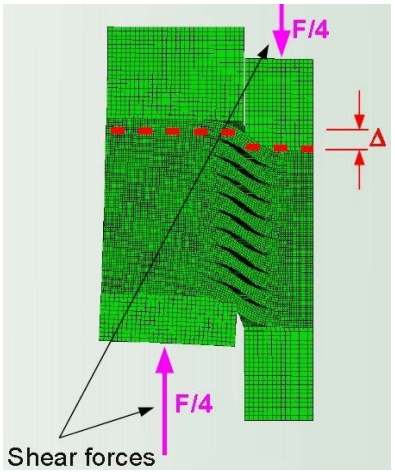


Figure taken from "Verification of CLT-plates under loads in plane" by Bogensperger, Moosbrugger and Silly.

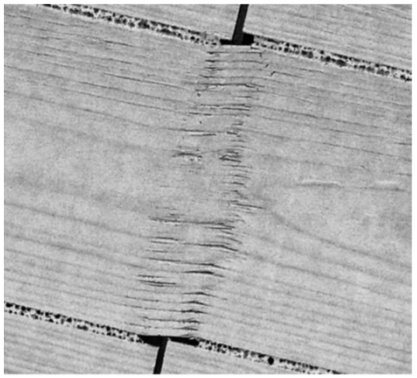
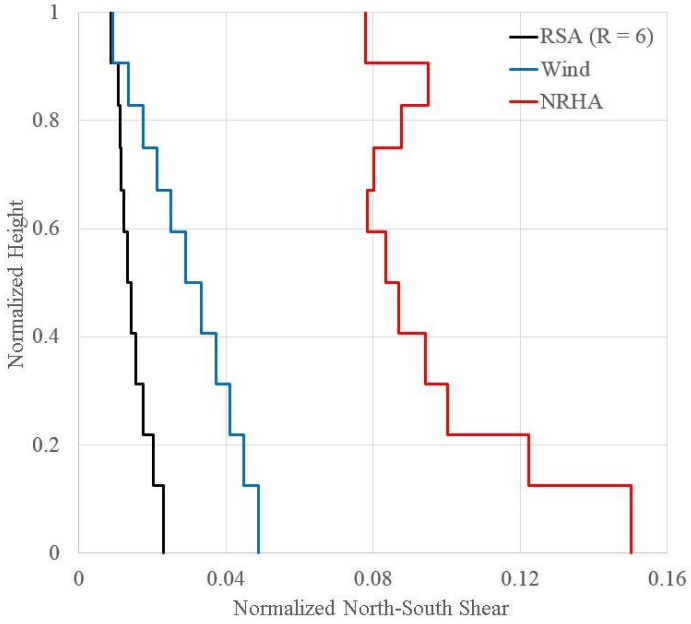


Figure taken from "Shear Properties of Cross Laminated Timber (CLT) under in-plane load: Test Configuration and Experimental Study" by P. Dietsch.



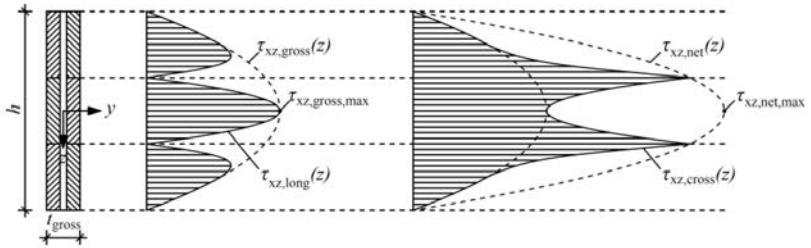
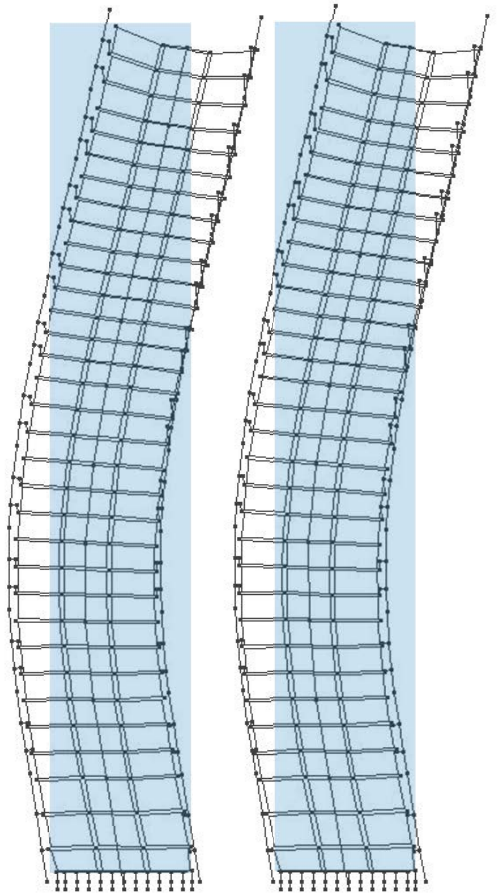
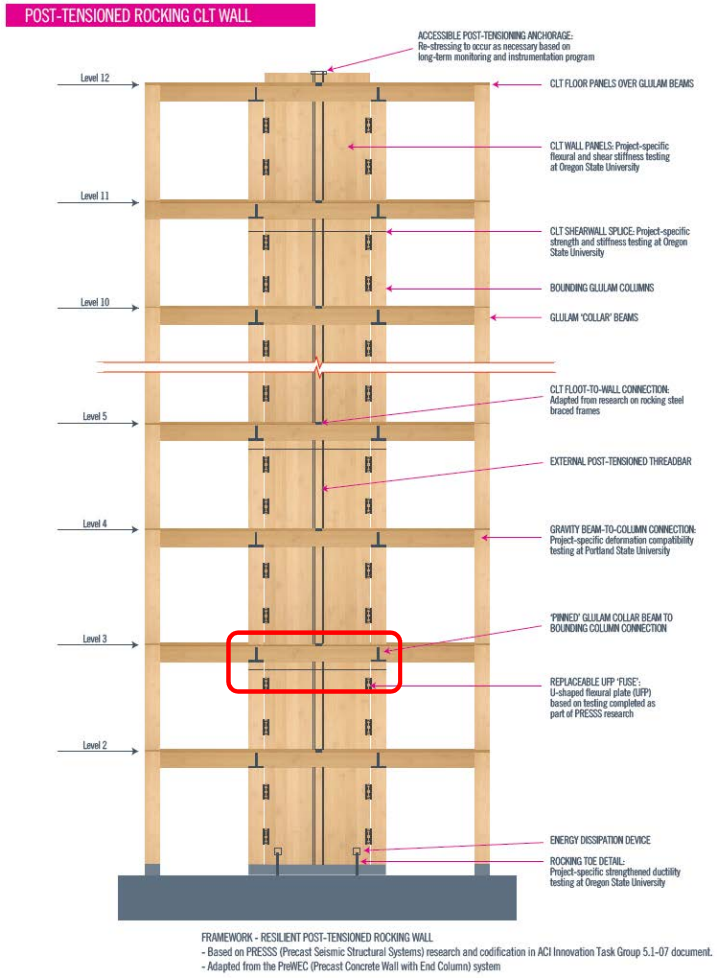


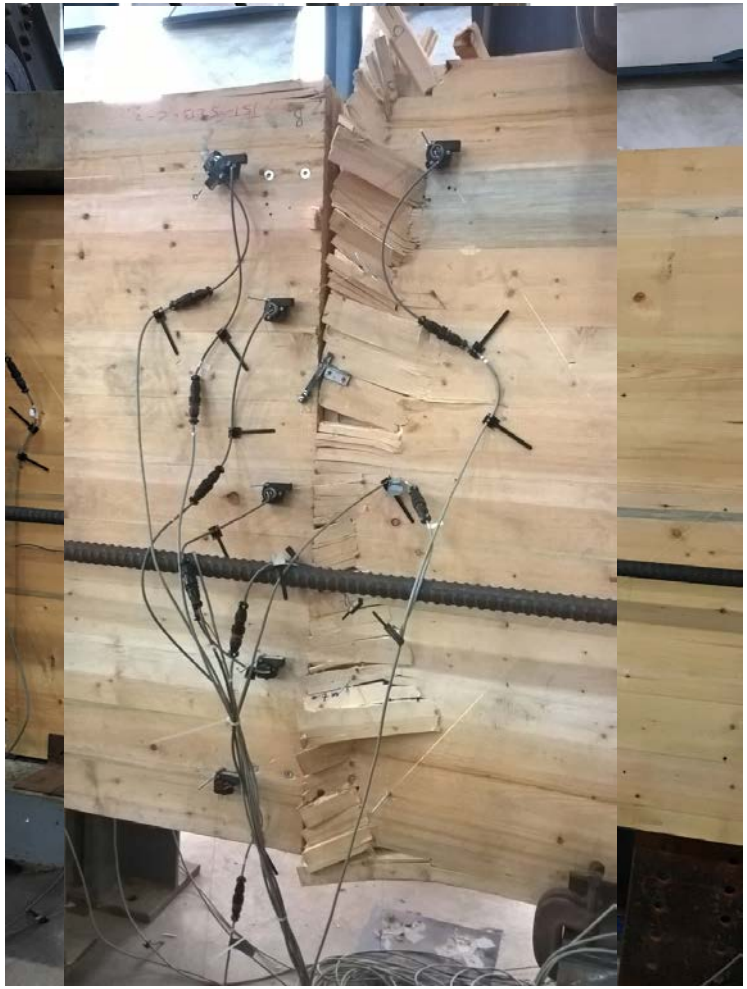
Figure taken from "Shear strength and shear stiffness of CLT-beams loaded in plane" by Flaig and Blab.

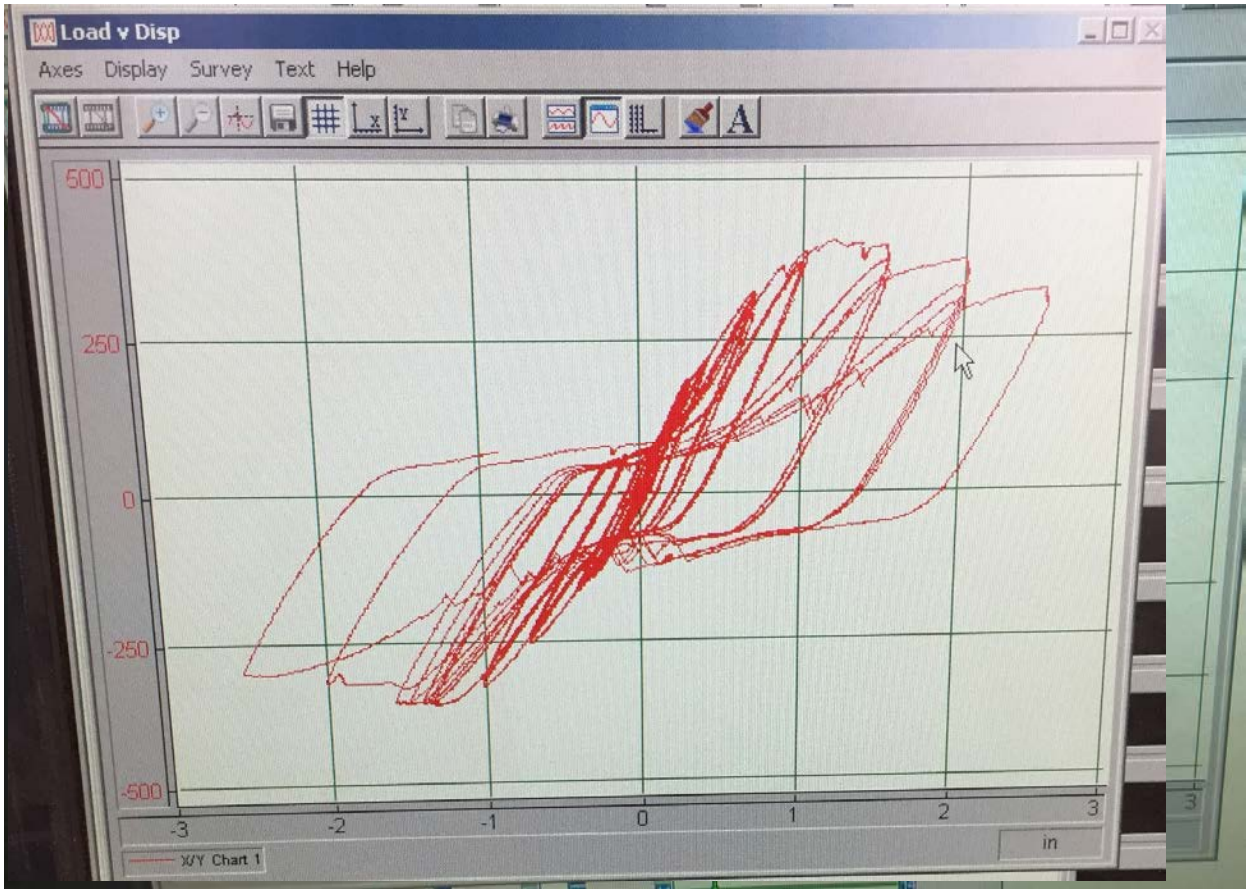


WALL SPLICE TESTING



WALL SPLICE TESTING





UNIQUE CONSIDERATIONS FOR TALL MASS TIMBER

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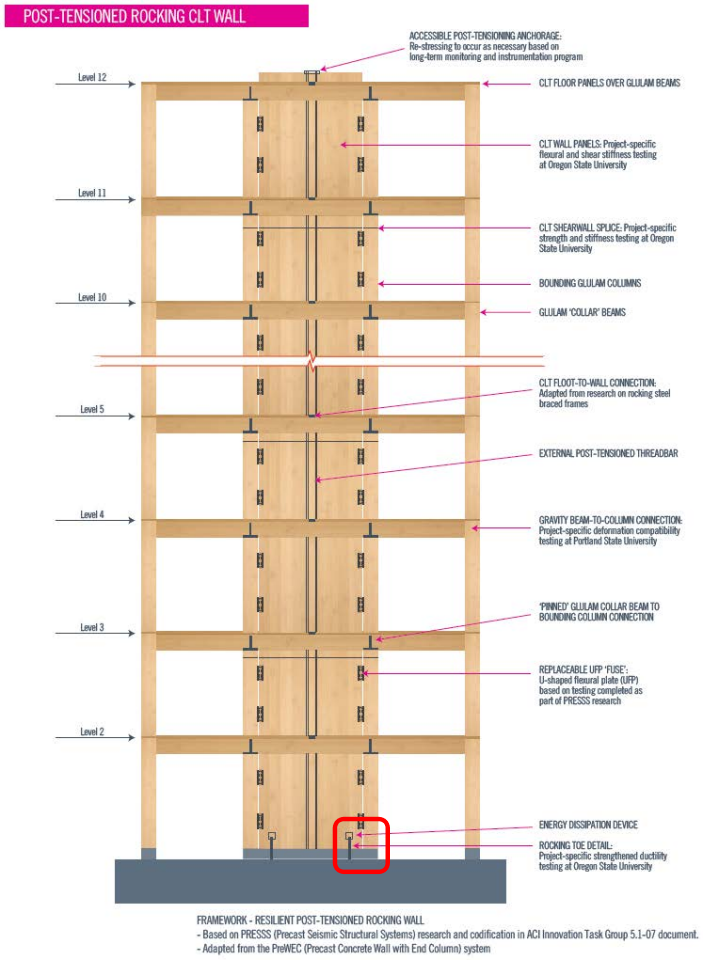
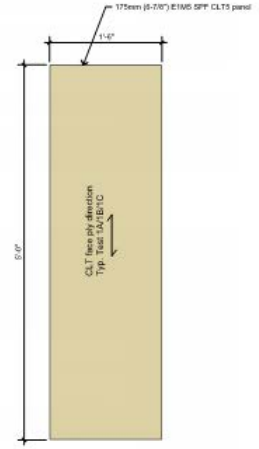
8. LRFD and Expected Properties of Wood
9. Post-Tensioning Loss
10. Fire Rating and Char Depth

CLT CRUSHING TESTING

Oregon State UNIVERSITY





STRUCTURAL TEST 1A
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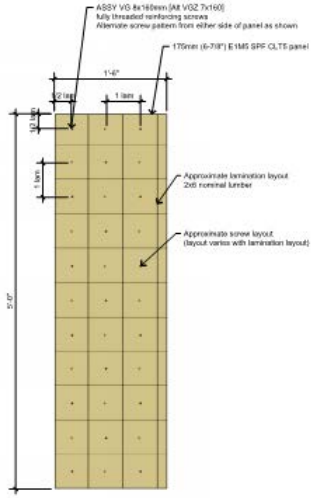

STRUCTURAL TEST 1B
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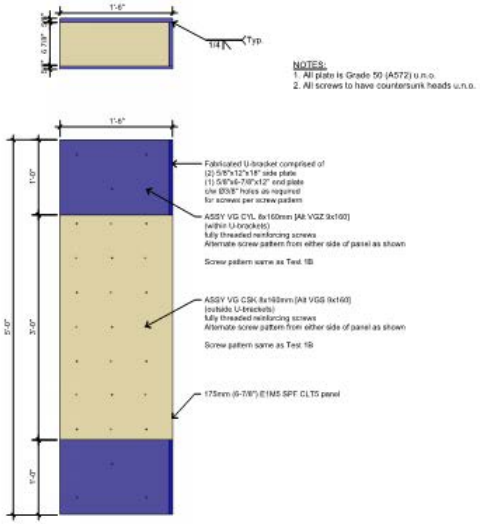

STRUCTURAL TEST 1C
QTY:3

UNIQUE CONSIDERATIONS FOR TALL MASS TIMBER

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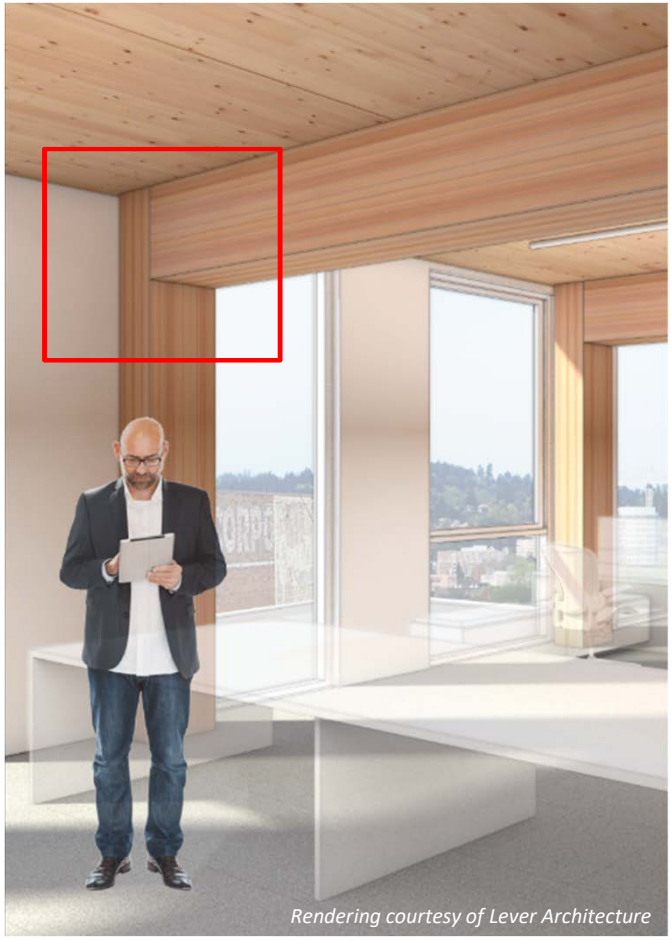
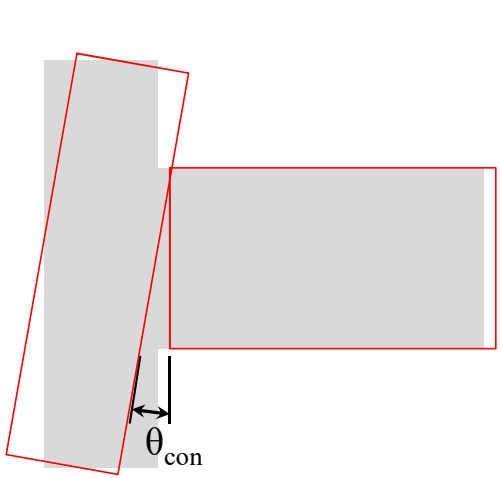
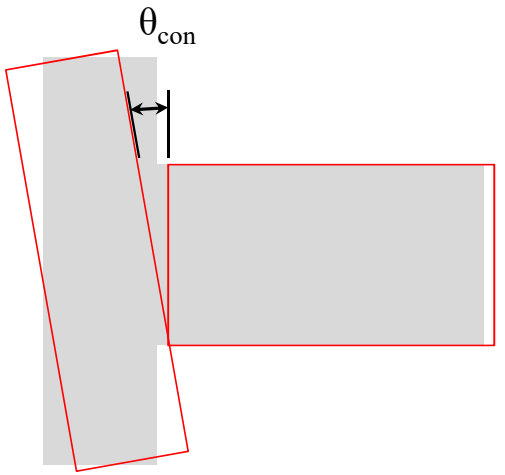
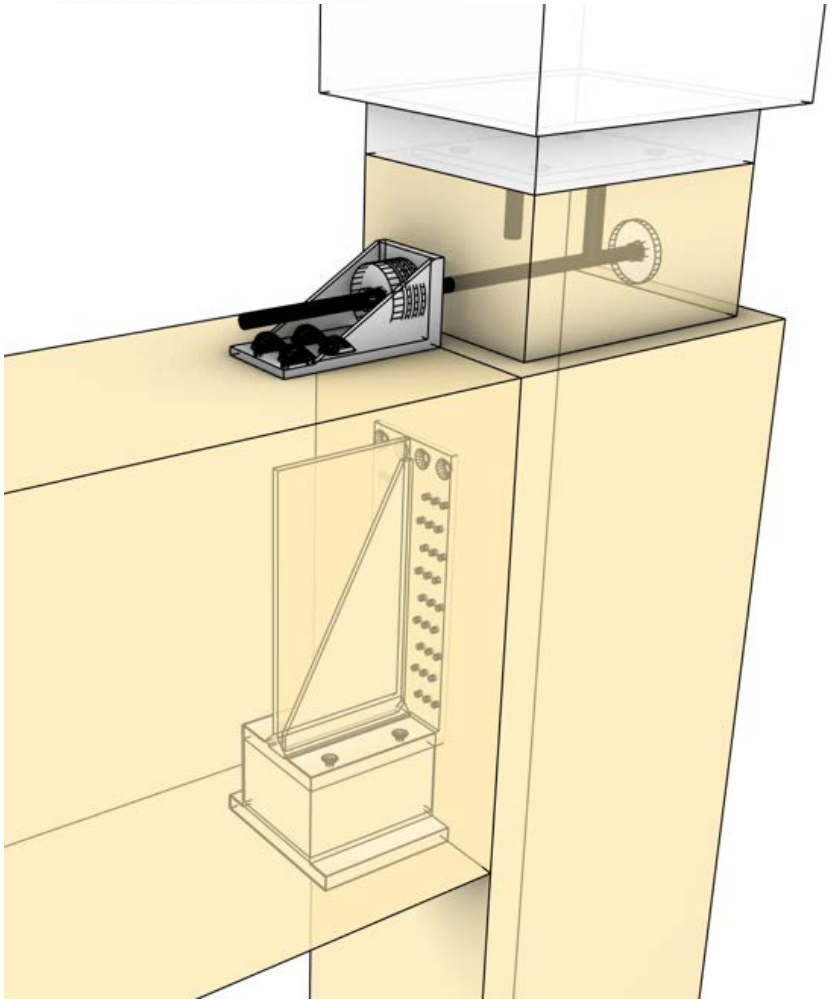
DEFORMATION COMPATIBILITY AND BEAM ELONGATION

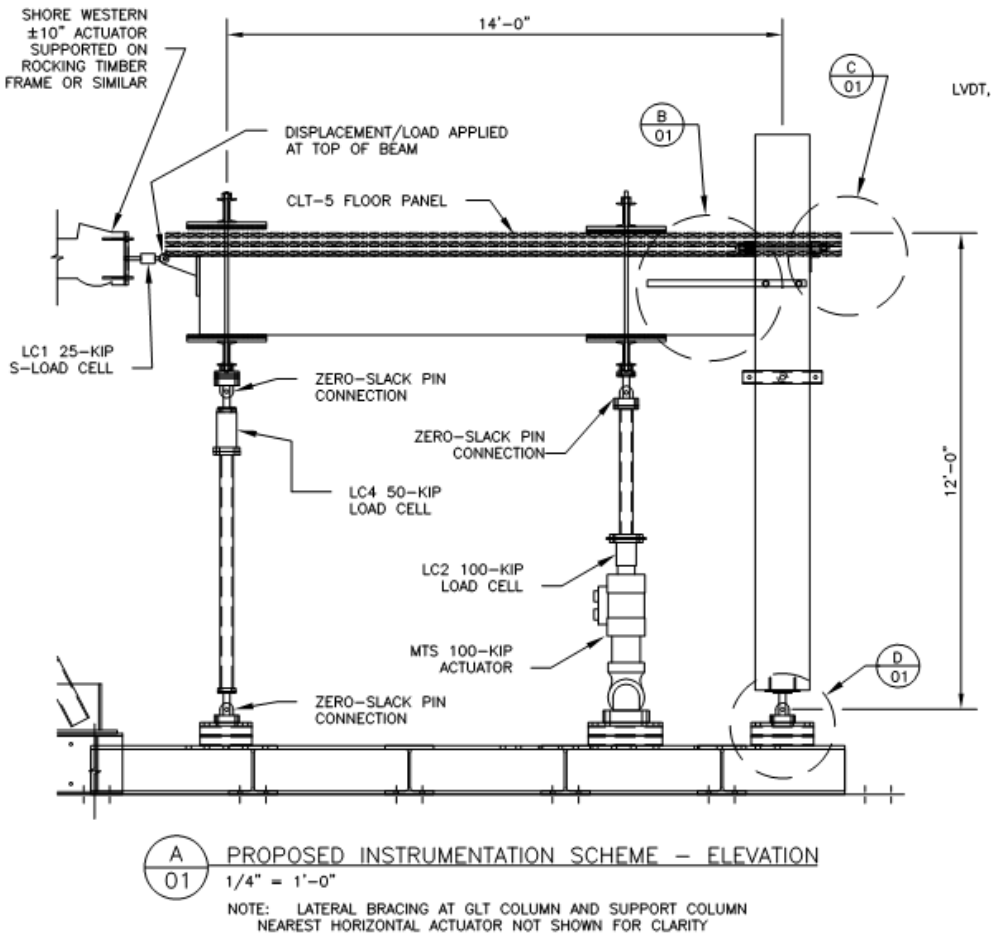






BEAM-COLUMN SUBASSEMBLY TESTING





Framework

Full Scale Beam-Column Connection Testing

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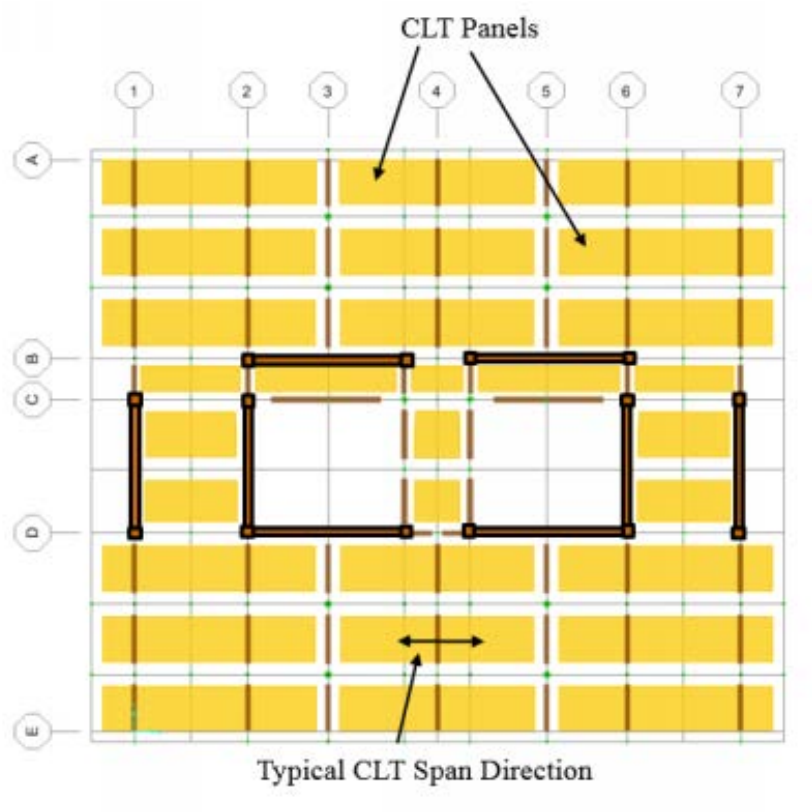
CLT DIAPHRAGMS

WCTE 2016
World Conference on Timber Engineering
August 22-25, 2016 | Vienna, Austria

AN APPROACH TO CLT DIAPHRAGM MODELING FOR SEISMIC DESIGN WITH APPLICATION TO A U.S. HIGH-RISE PROJECT

Scott Breneman[1], Eric McDonnell[2], Reid B. Zimmerman[3]



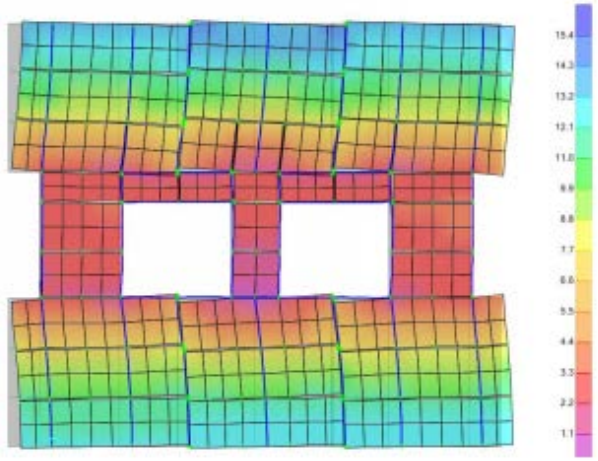


Figure 16: *Diaphragm Deflection to E-W Load (mm scale)*

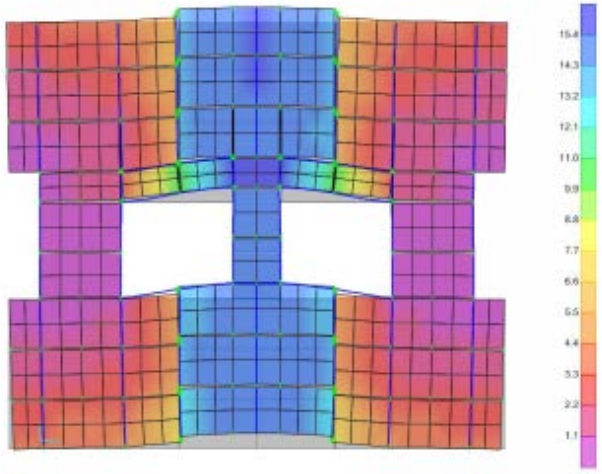
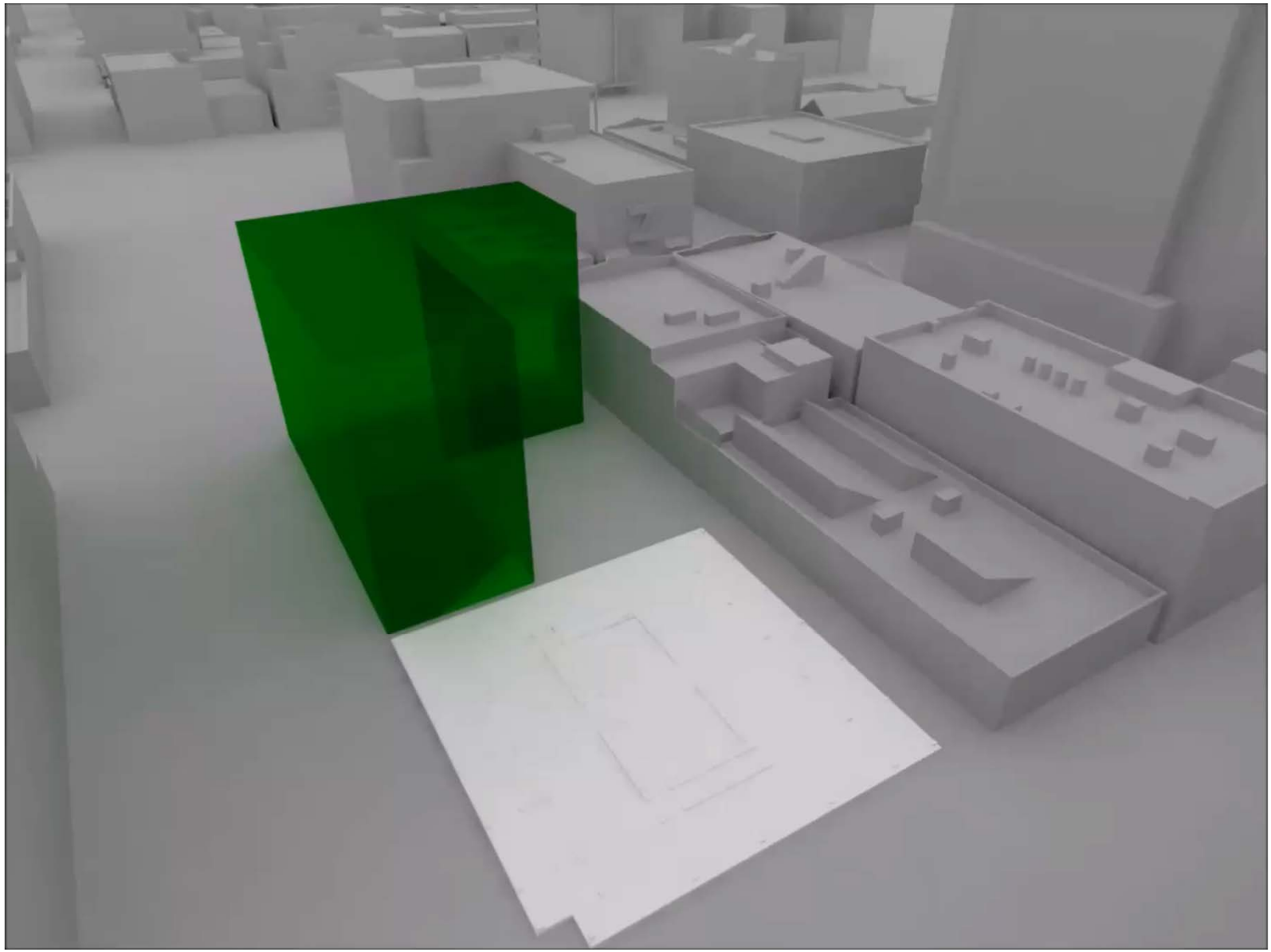
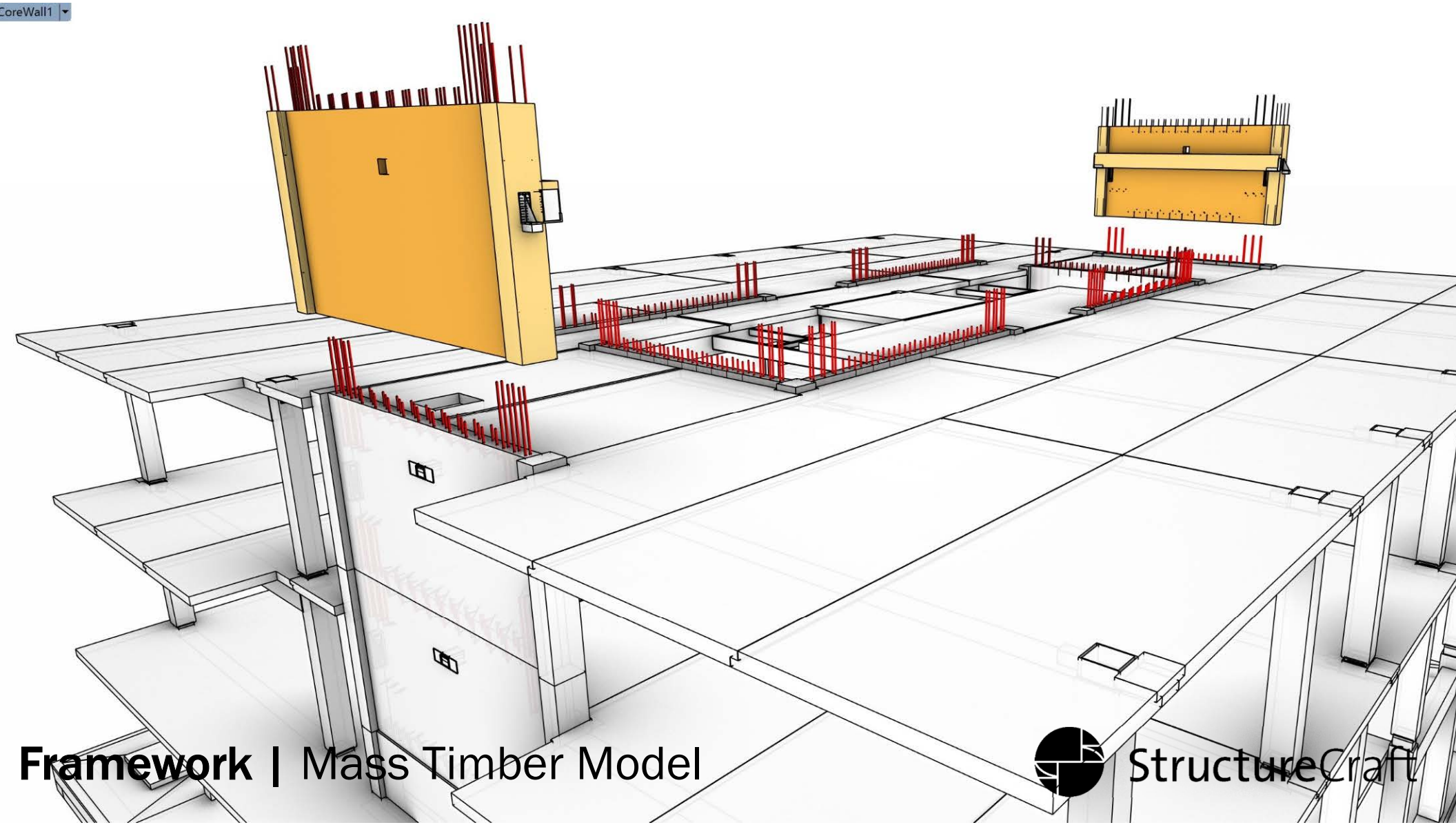


Figure 17: *Diaphragm Deflection to N-S Load (mm scale)*

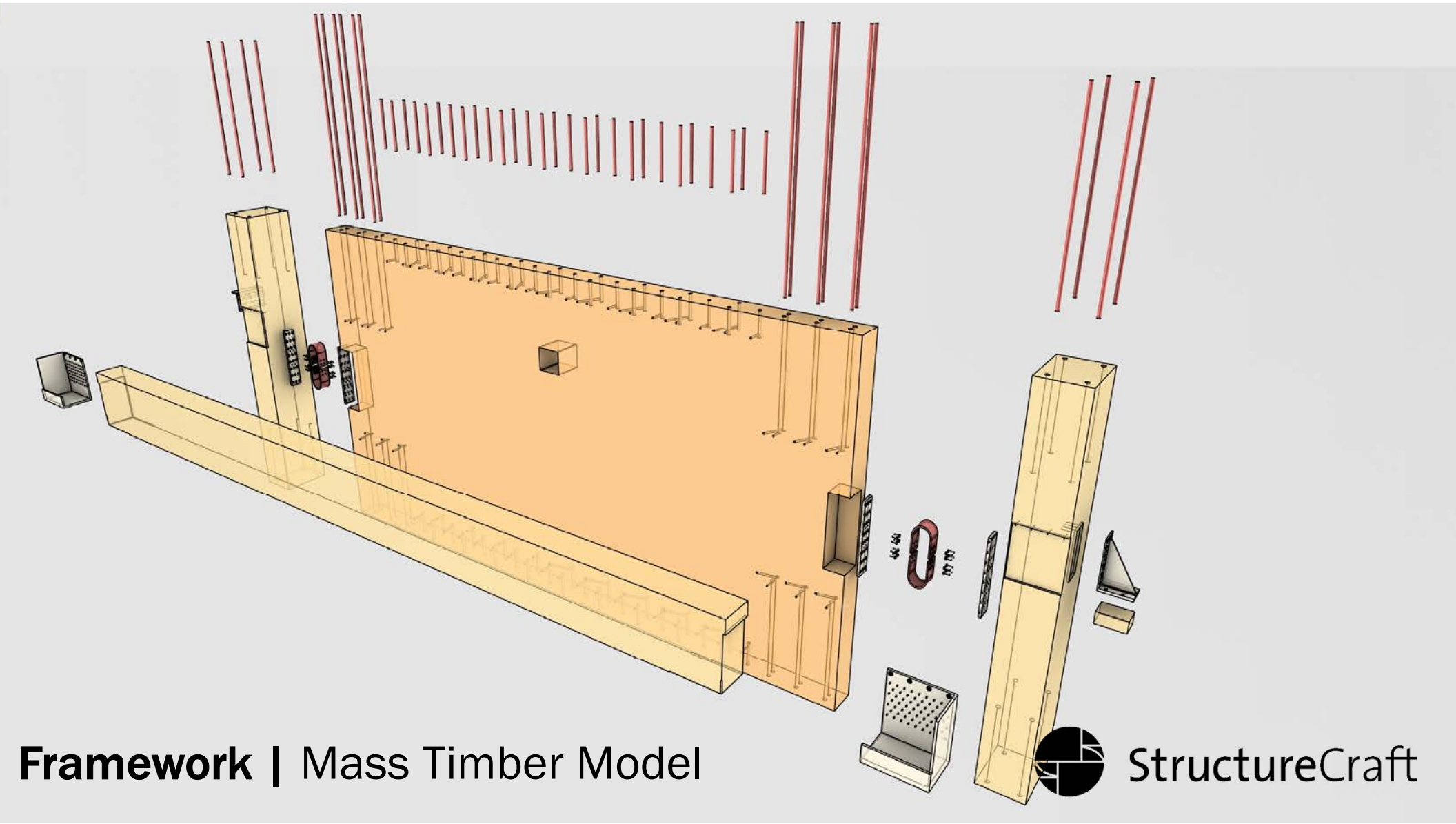
FRAMEWORK – ERECTION STRATEGY





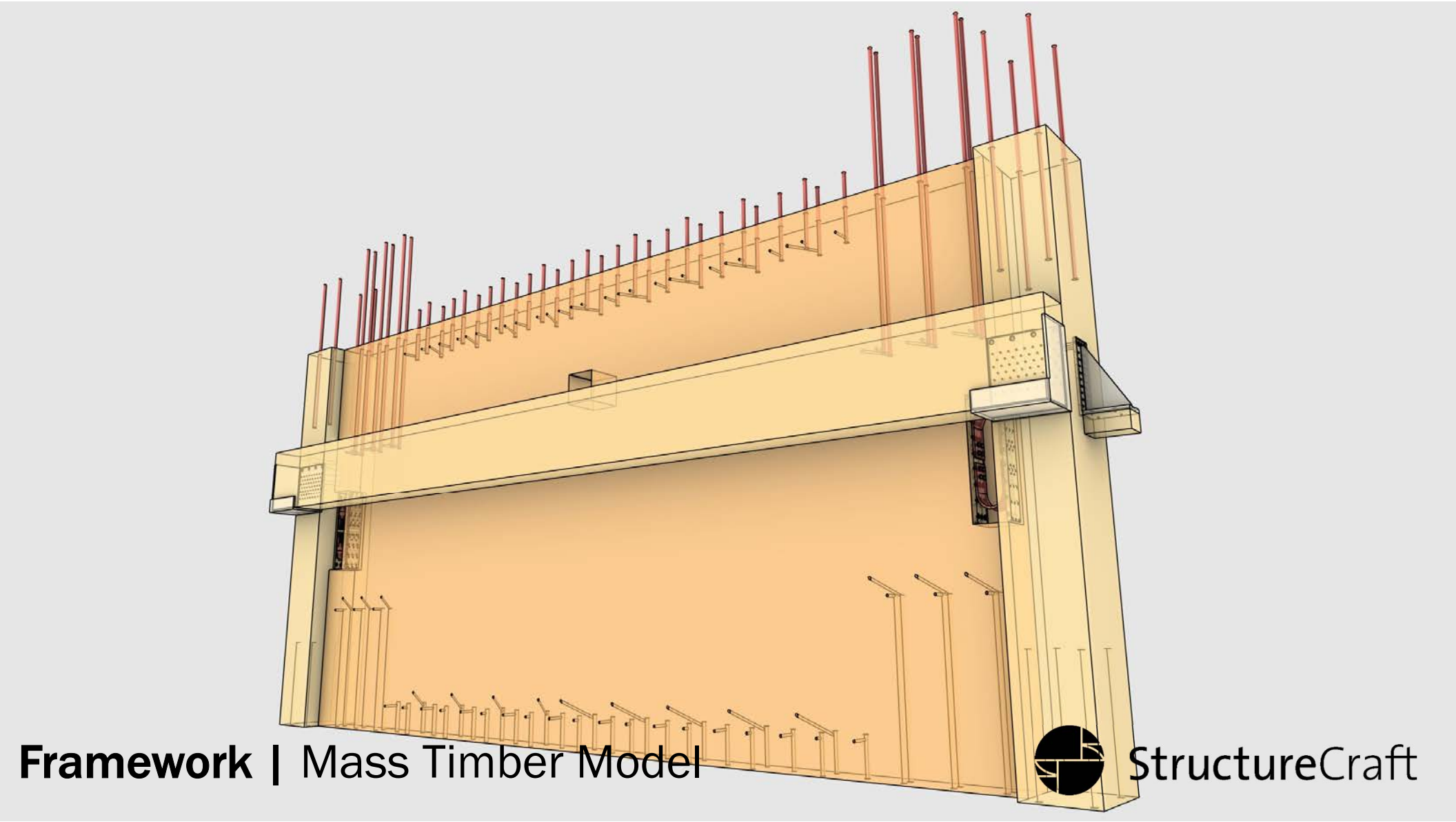
Framework | Mass Timber Model

StructureCraft



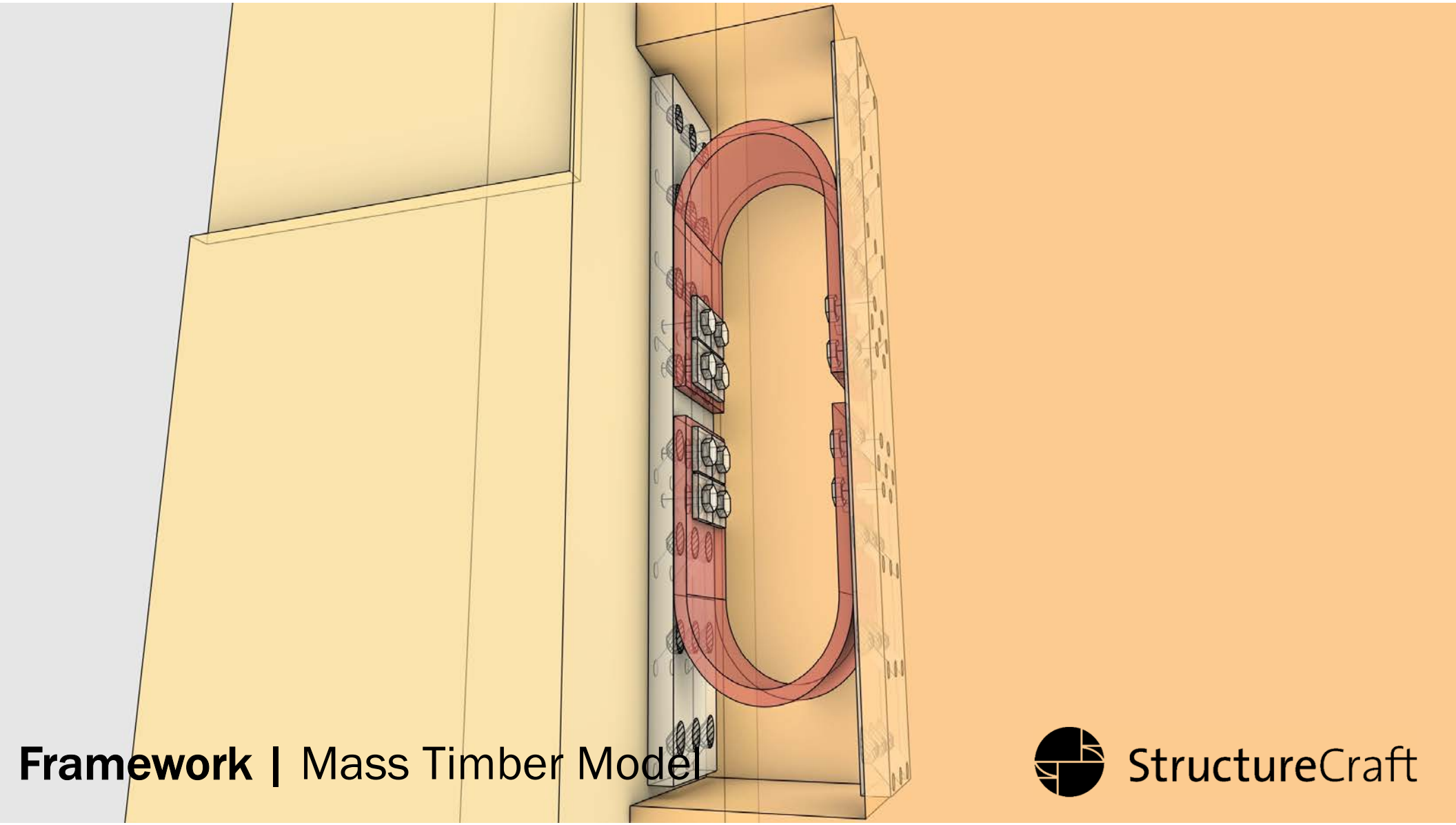
Framework | Mass Timber Model

StructureCraft



Framework | Mass Timber Model

StructureCraft



Framework | Mass Timber Model

StructureCraft

Framework | Mass Timber Model

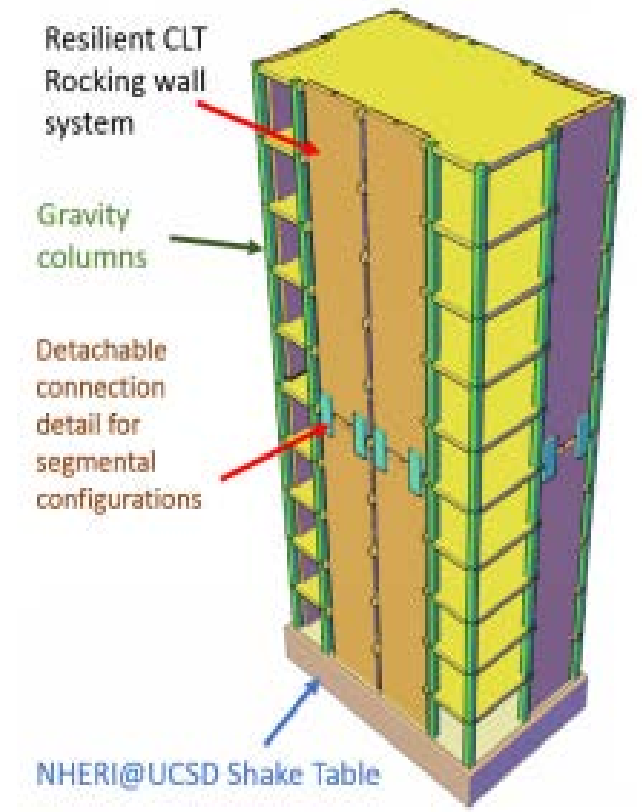
StructureCraft

ONGOING RESEARCH

NSF / NHERI FUNDED COLLABORATIVE RESEARCH

Resilience-Based Seismic Design for Tall Wood Buildings

Collaborative Research: A Resilience-based Seismic Design Methodology for Tall Wood Buildings



NHERI TallWood

Colorado School of Mines — Earth • Energy • Environment

Colorado State University

University of Washington

Washington State University

Lehigh University

University of Nevada, Reno

kpff

USDA Forest Service

FPInnovations

LEVER

PTL Structural Timber Consultants

Red Rocks Community College

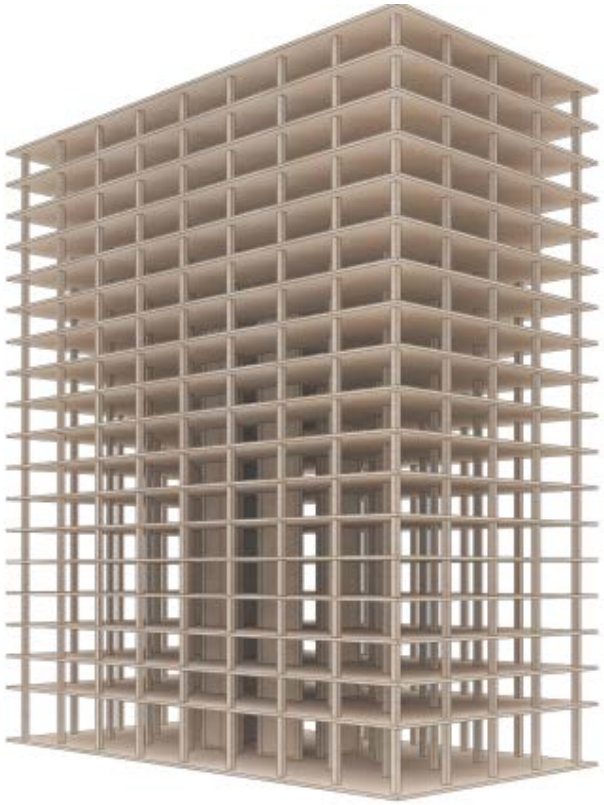
RTMD

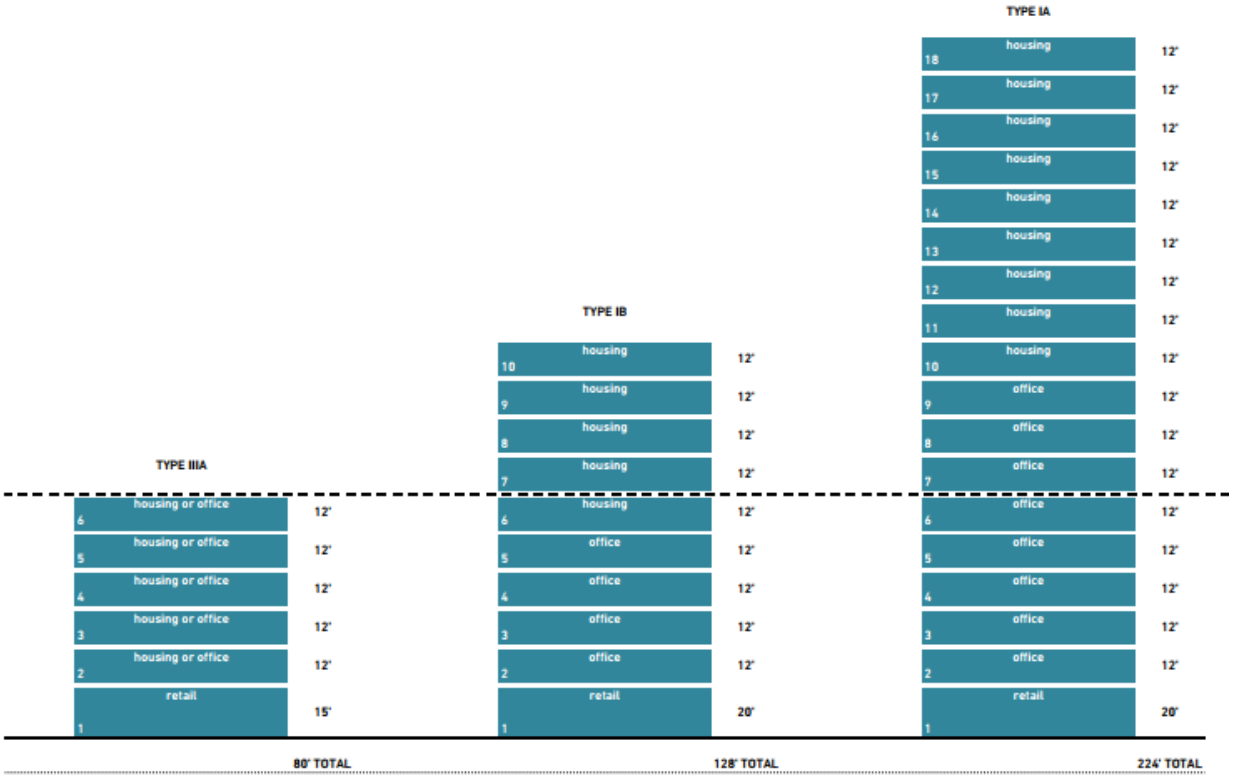
Oregon State University

NHERI@UCSan Diego

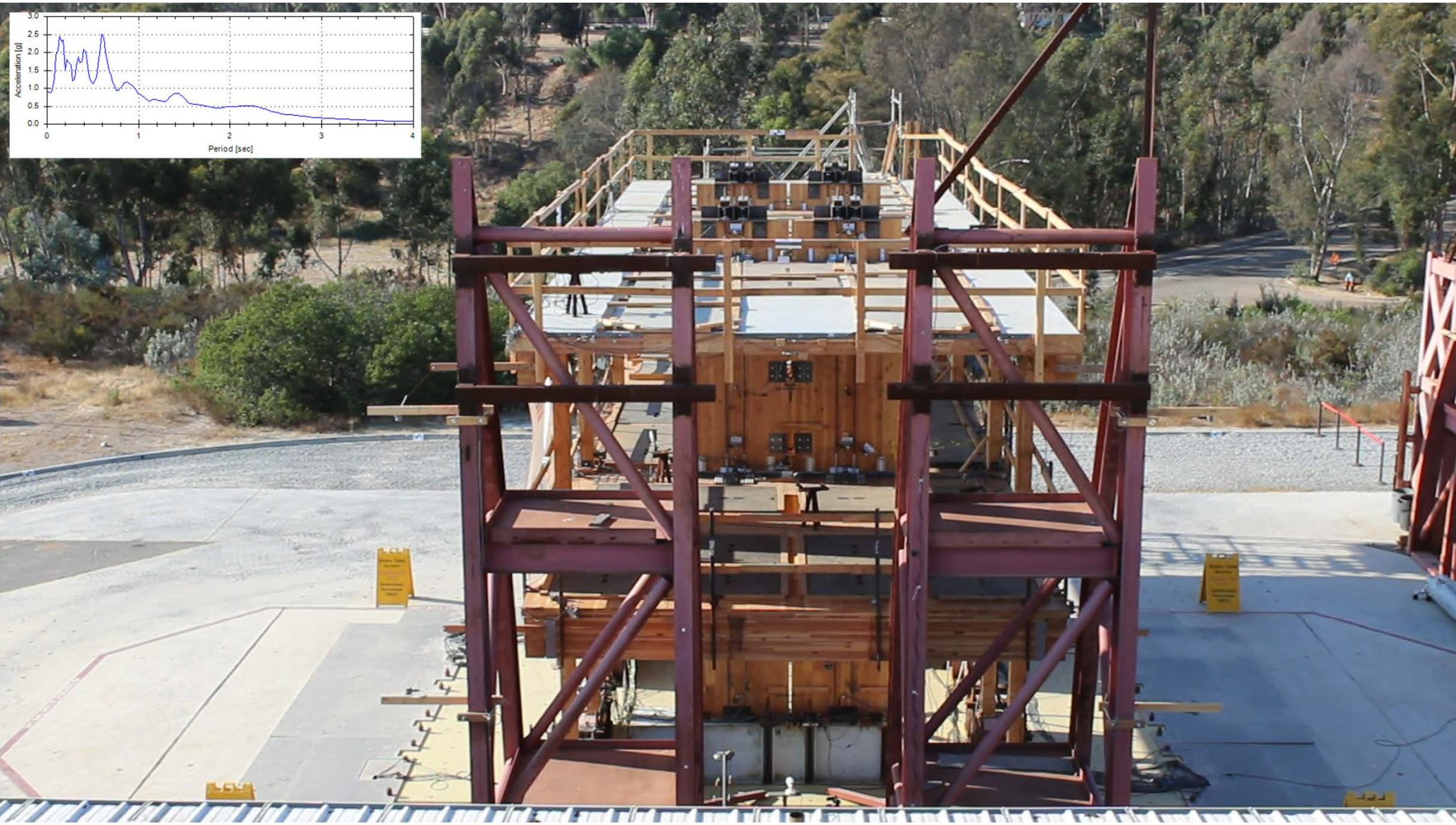
NSF / NHERI FUNDED COLLABORATIVE RESEARCH

Resilience-Based Seismic Design for Tall Wood Buildings





UCSD 2-STORY SHAKE TABLE TEST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1
2
3
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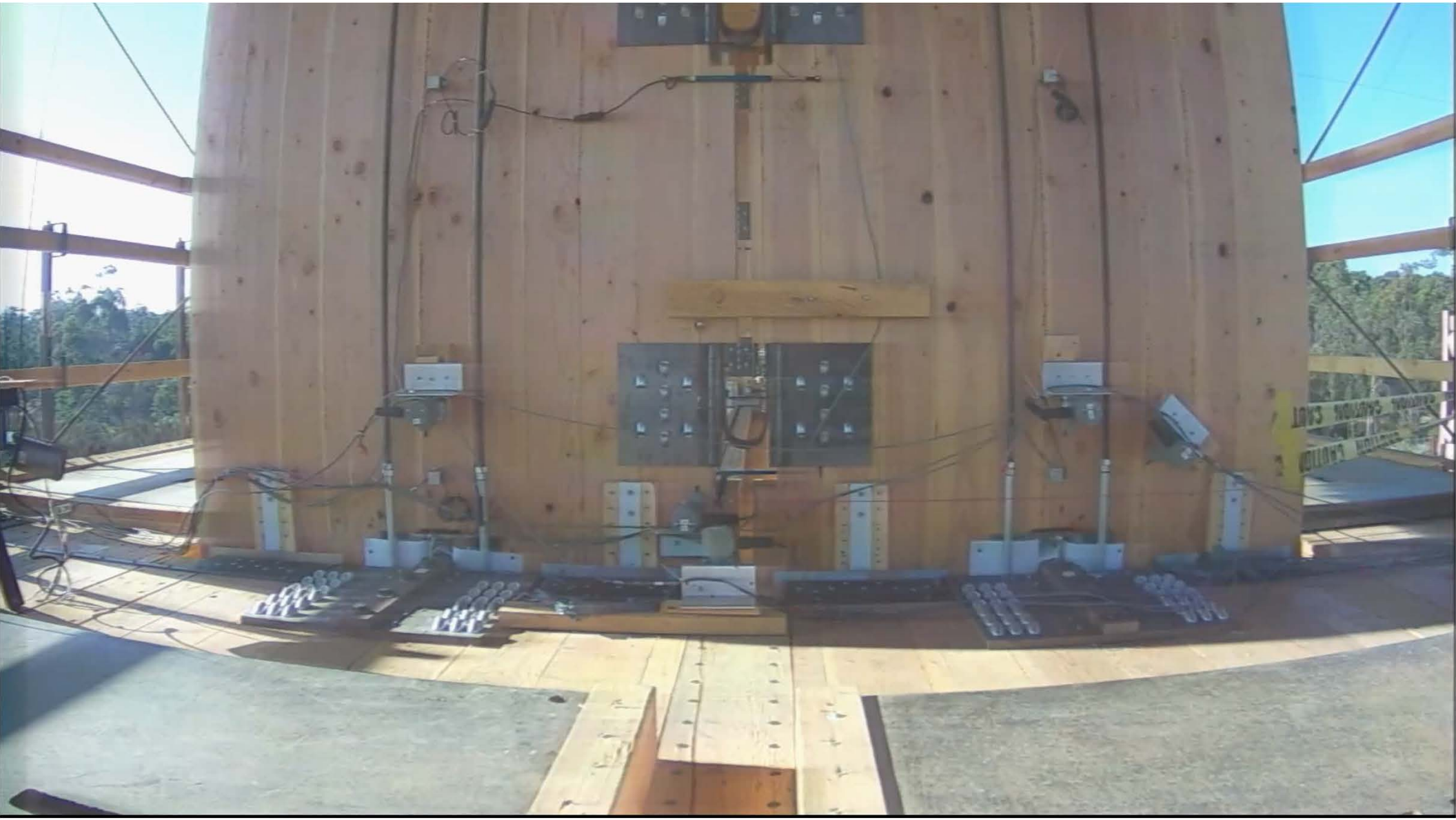

This concludes The American Institute of Architects
Continuing Education Systems Course

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