Protective Design in Mass Timber Construction

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Course Description

Local and federal government agencies are increasingly pursuing mass timber for their building projects—inspired by the sustainability and aesthetic of these innovative wood materials, as well as their strength and dimensional stability. This presentation will provide a detailed look at the variety of mass timber products available, their structural performance, fire resistance, acoustics, and energy efficiency. Intended for design teams that work on government projects, it will also include an overview of the current protective design landscape as it applies to some of the larger federal agencies. We'll review applied research that is pertinent to the protective design of mass timber construction, design aids and resources for teams whose projects have to meet protective design requirements, and construction details that have performed well during blast testing and have been implemented in mass timber construction design for blast loading.

Learning Objectives

1. Identify mass timber products available in North America and consider how they can be used under current building codes and standards.

2. Discuss benefits of using mass timber products, including structural versatility, prefabrication, lighter carbon footprint, and reduced labor costs.

3. Understand recent developments for protective design requirements in the built environment.

4. Explore mass timber design aids and construction details that can be utilized when a job has protective design requirements.

Agenda

- Mass Timber Systems and Products
- Fire Resistance
- Acoustics
- Market Drivers
- Protective Design

Photo: John Stamets

Agenda

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Photo: Ema Peter

HEAVY TIMBER

Federal Center South, Seattle, WA
Photo: Benjamin Benschneider

MASS TIMBER

Bullitt Center, Seattle, WA
Photo: John Stamets

Glue Laminated Timber (Glulam)
Beams & columns

Cross-Laminated Timber (CLT)
Solid sawn laminations

Cross-Laminated Timber (CLT)
SCL laminations

Photo: Freres Lumber

Photo: StructureCraft

Photo: LendLease

Photo: LEVER Architecture

Dowel-Laminated Timber (DLT)

Photo: StructureCraft

Nail-Laminated Timber (NLT)

Photo: Think Wood

Glue-Laminated Timber (GLT)

Plank orientation

Photo: StructureCraft

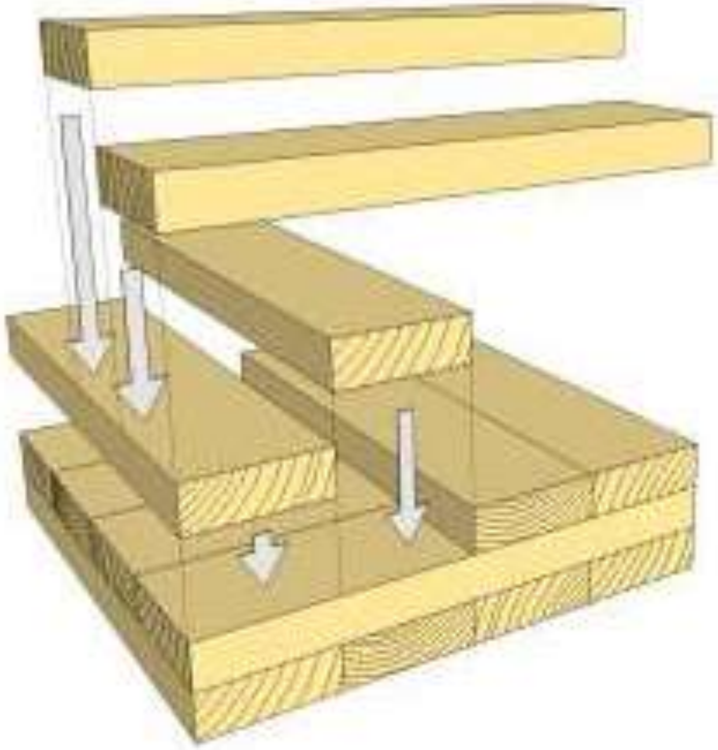
Photo: StructureCraft

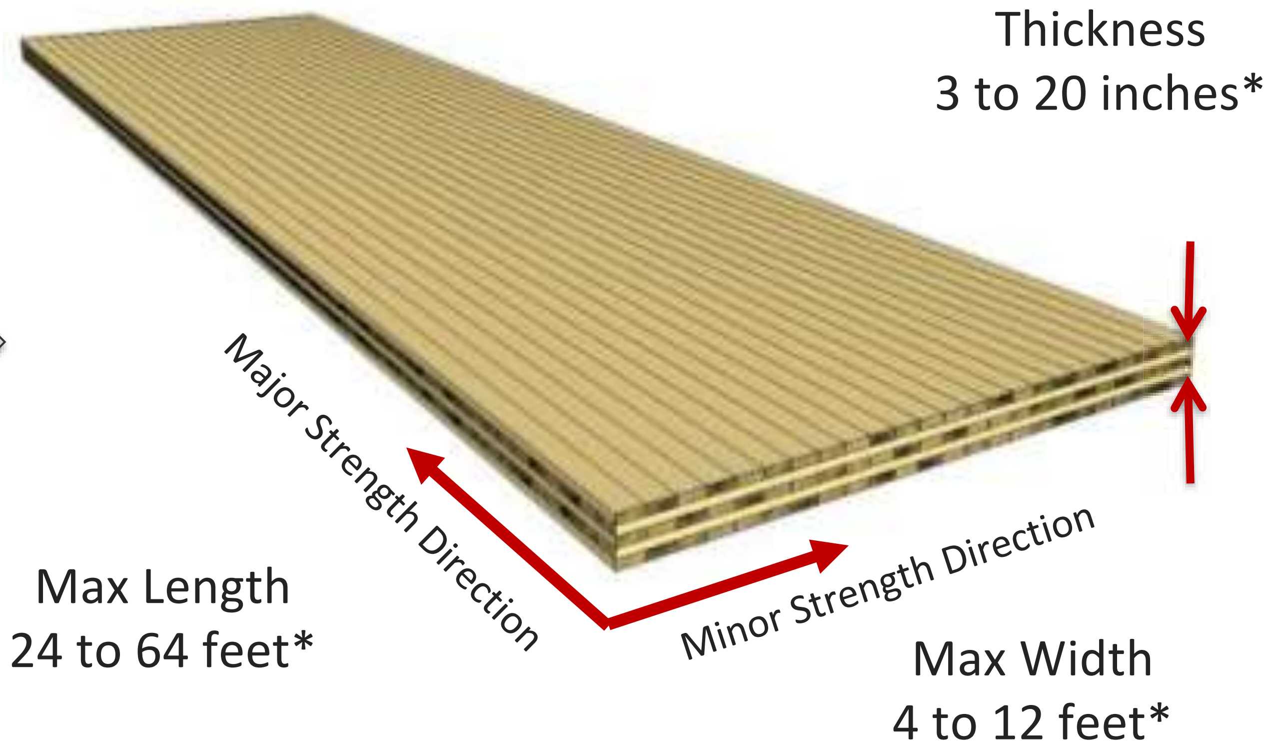
Photo: Ema Peter

Photo: Manasc Isaac Architects/Fast + Epp

What is CLT?

3+ layers of laminations
Typically Solid Sawn Laminations
Cross-Laminated Layup
Glued with Structural Adhesives





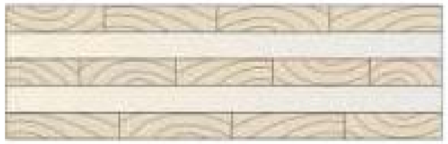
*All dimensions are approximate.
Consult with manufacturers

Common CLT Layups

Most Designs
Least $/sf

3-ply 3-layer

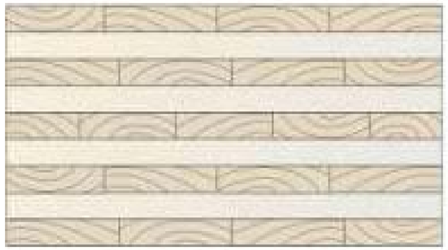
5-ply 5-layer

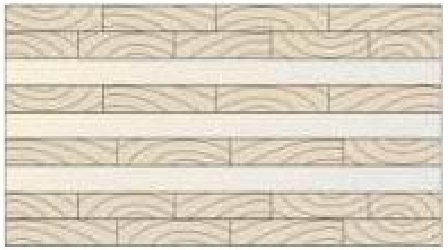


7-ply 7-layer

7-ply 5-layer

9-ply 9-layer



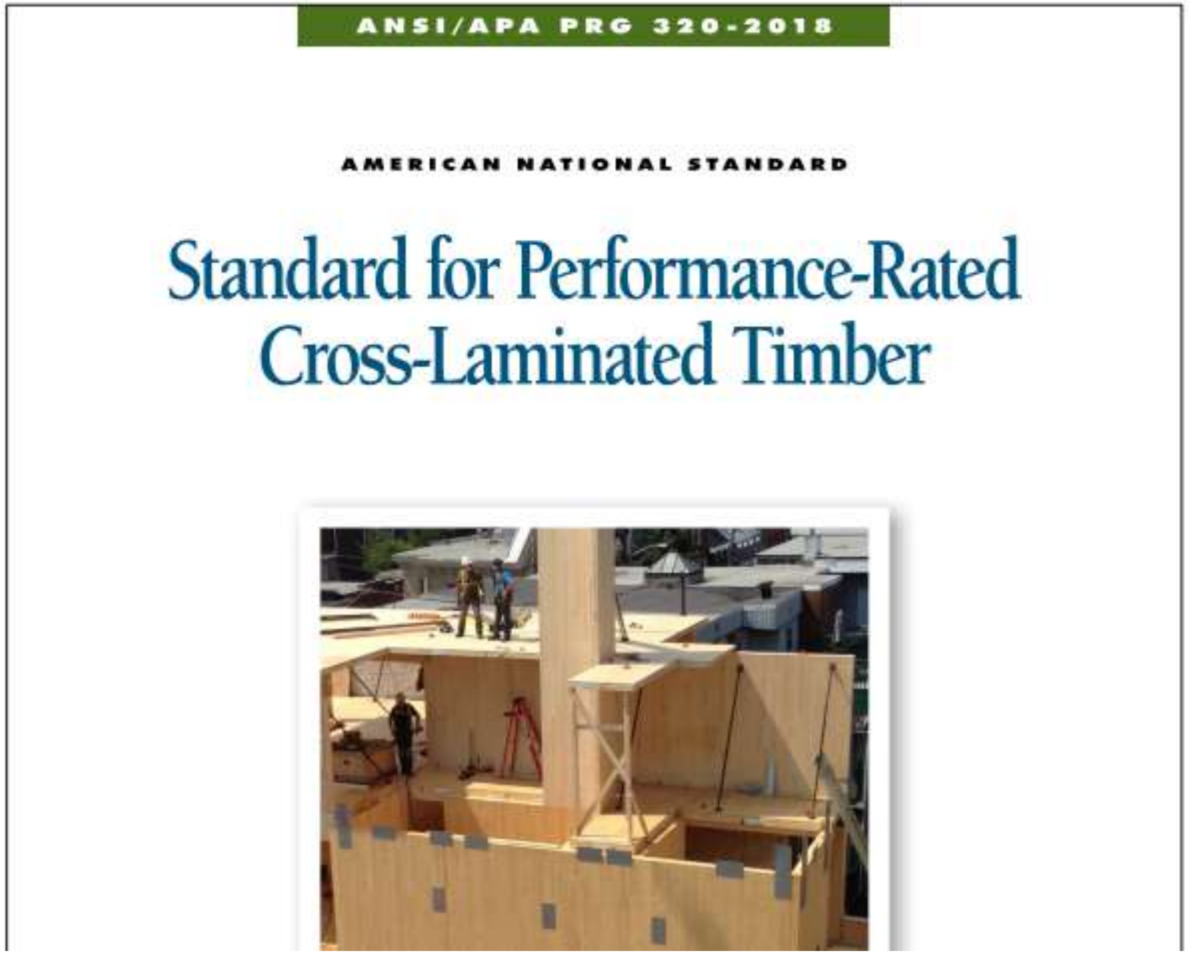


9-ply 7-layer

Model Building Code Acceptance

2015 International Building Code

North American CLT Product Standard

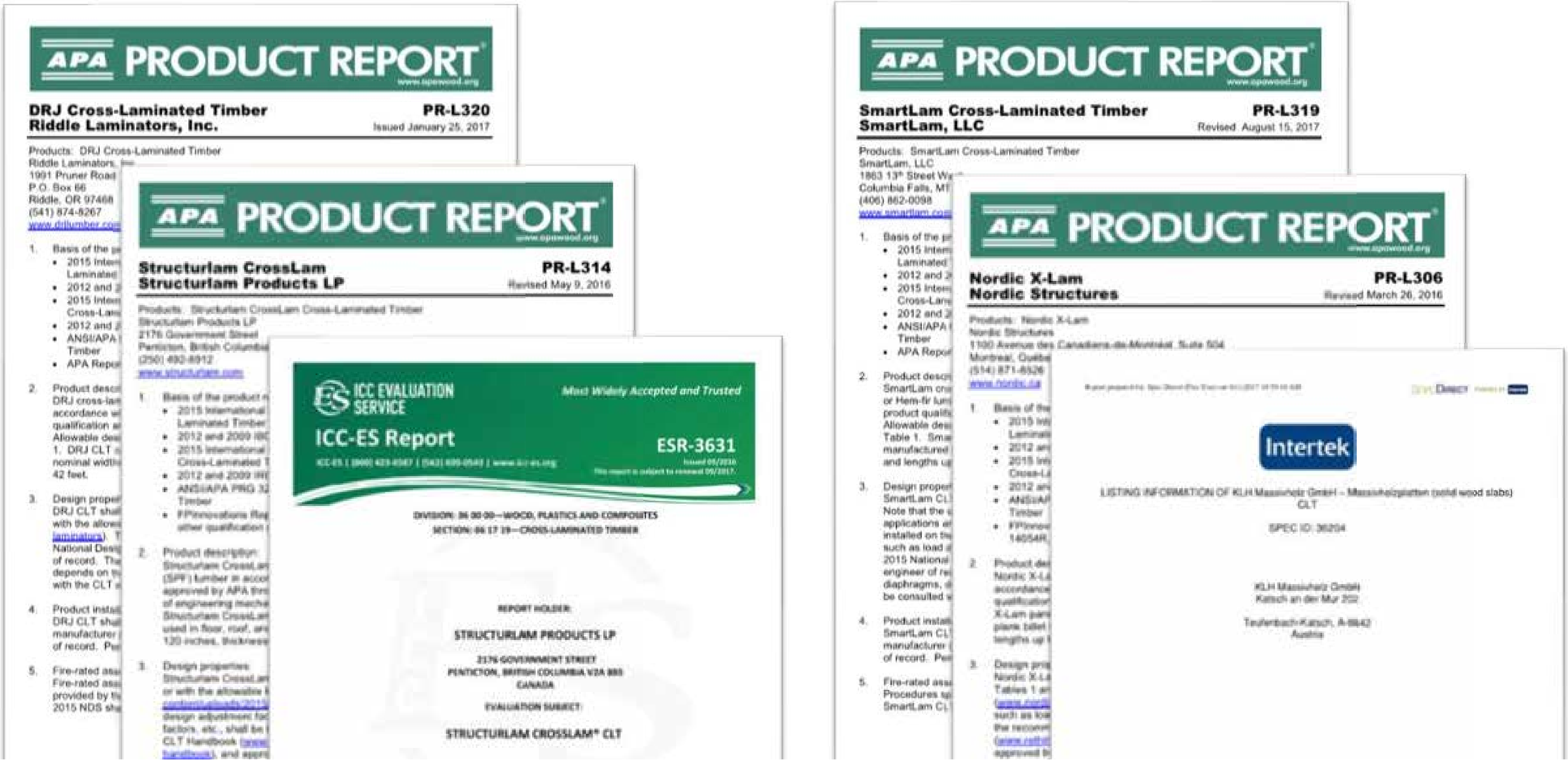


ANSI/APA PRG 320 Standard for Performance-Rated Cross-Laminated Timber

The Standard Covers:

- U.S. and Canada Use
- Panel Dimensions and Tolerances
- Component Requirements
- Structural Performance Requirements
- Panel and Manufacturing Qualification
- Marking (Stamping)
- Quality Assurance

3rd Party Product Qualification of CLT



CLT Product Reports

CLT Grade (basic or custom)

Layup

Panel Properties

Table 1. Allowable Design Properties[a] for Lumber Laminations Used in SmartLam CLT (for Use in the U.S.)

CLT Grade	Major Strength Direction						Minor Strength Direction					
	$F_{b,0}$ (psi)	E_0 (10^6 psi)	$F_{t,0}$ (psi)	$F_{c,0}$ (psi)	$F_{v,0}$ (psi)	$F_{s,0}$ (psi)	$F_{b,90}$ (psi)	E_{90} (10^6 psi)	$F_{t,90}$ (psi)	$F_{c,90}$ (psi)	$F_{v,90}$ (psi)	$F_{s,90}$ (psi)
SL-V4	775	1.1	350	1,000	135	45	775	1.1	350	1,000	135	45

For SI: 1 psi = 0.006895 MPa

[a] Tabulated values are allowable design values and not permitted to be increased for the lumber flat use or size factor in accordance with the NDS. The design values shall be used in conjunction with the section properties provided by the CLT manufacturer based on the actual layup used in manufacturing the CLT panel (see Tables 2 and 3).

Table 2. Allowable Design Capacities[a] for SmartLam Balanced CLT (for Use in the U.S.)

CLT Grade	Layup #	Thick-ness (in.)	Lamination Thickness (in.) in CLT Layup									Major Strength Direction				Minor Strength Direction			
			=	⊥	=	⊥	=	⊥	=	⊥	=	$F_bS_{eff,0}$ (lbf-ft/ft)	$EI_{eff,0}$ (10^6 lbf-in.²/ft)	$GA_{eff,0}$ (10^6 lbf/ft)	$V_{s,0}$ (lbf/ft)	$F_bS_{eff,90}$ (lbf-ft/ft)	$EI_{eff,90}$ (10^6 lbf-in.²/ft)	$GA_{eff,90}$ (10^6 lbf/ft)	$V_{s,90}$ (lbf/ft)
	3-alt	4 1/8	1 3/8	1 3/8	1 3/8							1,800	74	0.41	1,430	245	2.9	0.41	495
	4-maxx	5 1/2	1 3/8	1 3/8 x 2	1 3/8							2,925	161	0.49	1,740	975	23	0.85	990
	5-alt	6 7/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8					4,150	286	0.83	1,980	2,120	74	0.83	1,430
	5-maxx	6 7/8	1 3/8 x 2	1 3/8	1 3/8 x 2							5,150	355	1.4	2,460	245	2.9	0.86	495
SL-V4[b]	6-maxx	8 1/4	1 3/8 x 2	1 3/8 x 2	1 3/8 x 2							7,200	596	1.2	2,875	975	23	1.3	990
	7-alt	9 5/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8			7,325	707	1.2	2,500	4,825	283	1.2	1,960
	7-maxx	9 5/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8					9,425	909	1.7	3,200	2,120	74	1.3	1,430

NEW MASS TIMBER DESIGN MANUAL

10+ new case studies, technical resources, Q&A and more. Links directly to many additional resources.

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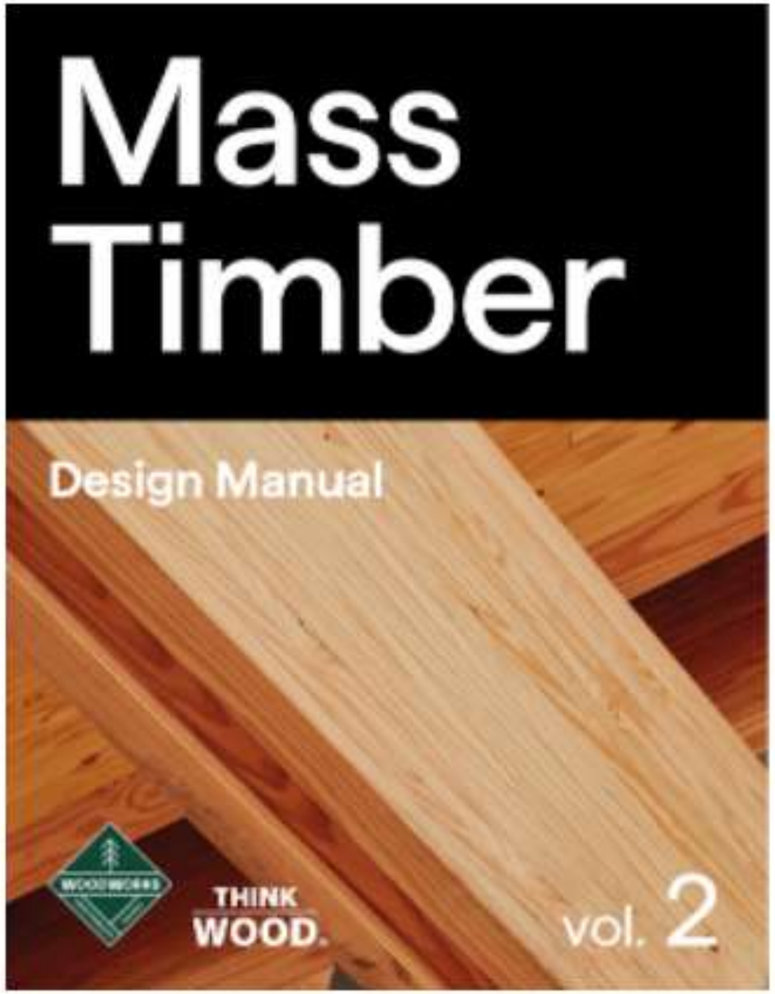


https://info.thinkwood.com/masstimberdesignmanual

Construction Types

Allowable mass timber building size for group B occupancy with NFPA 13 Sprinkler

Type III: 6 stories

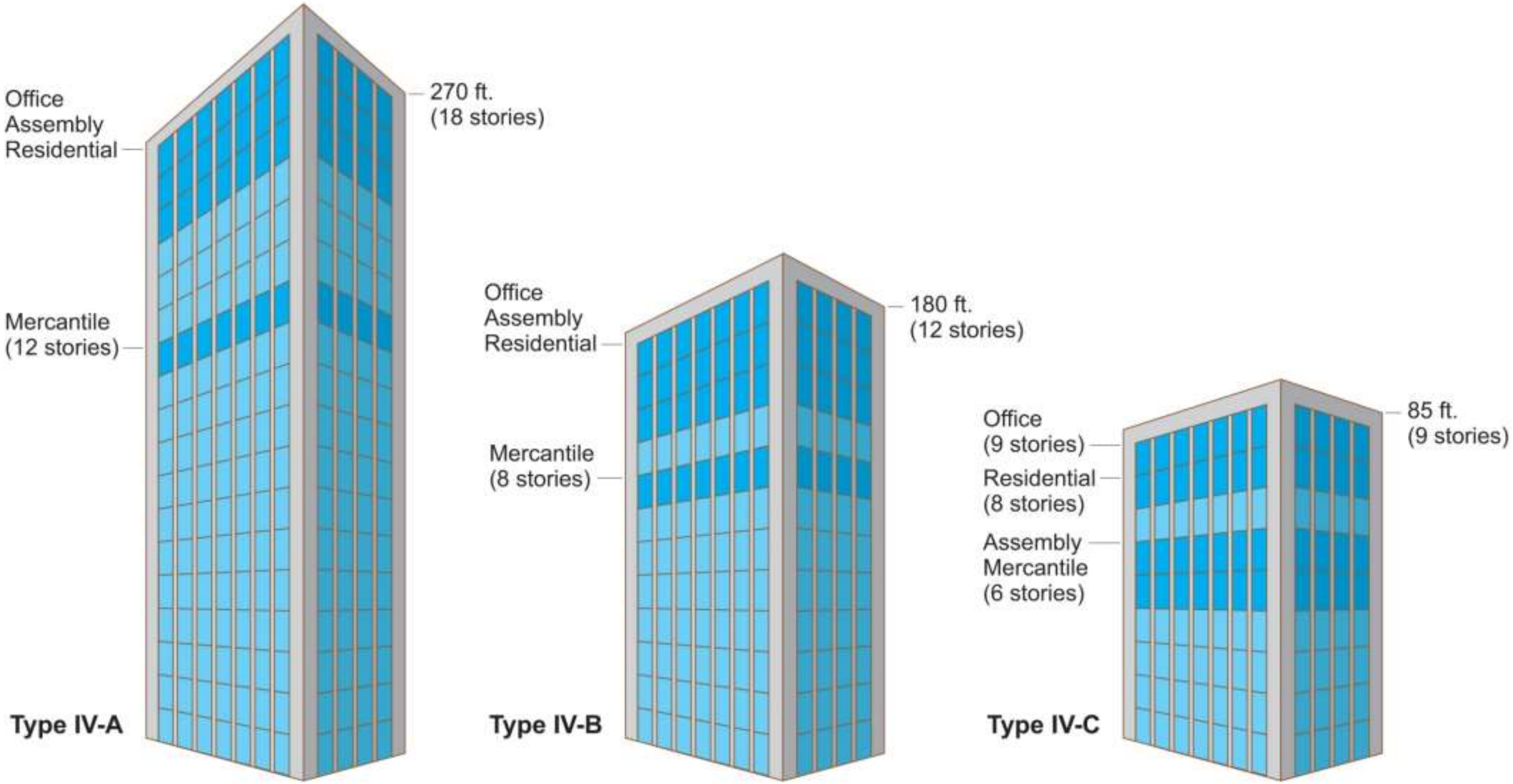
Credit: Ema Peter

Type IV: 6 stories

Credit: Christian Columbres Photography

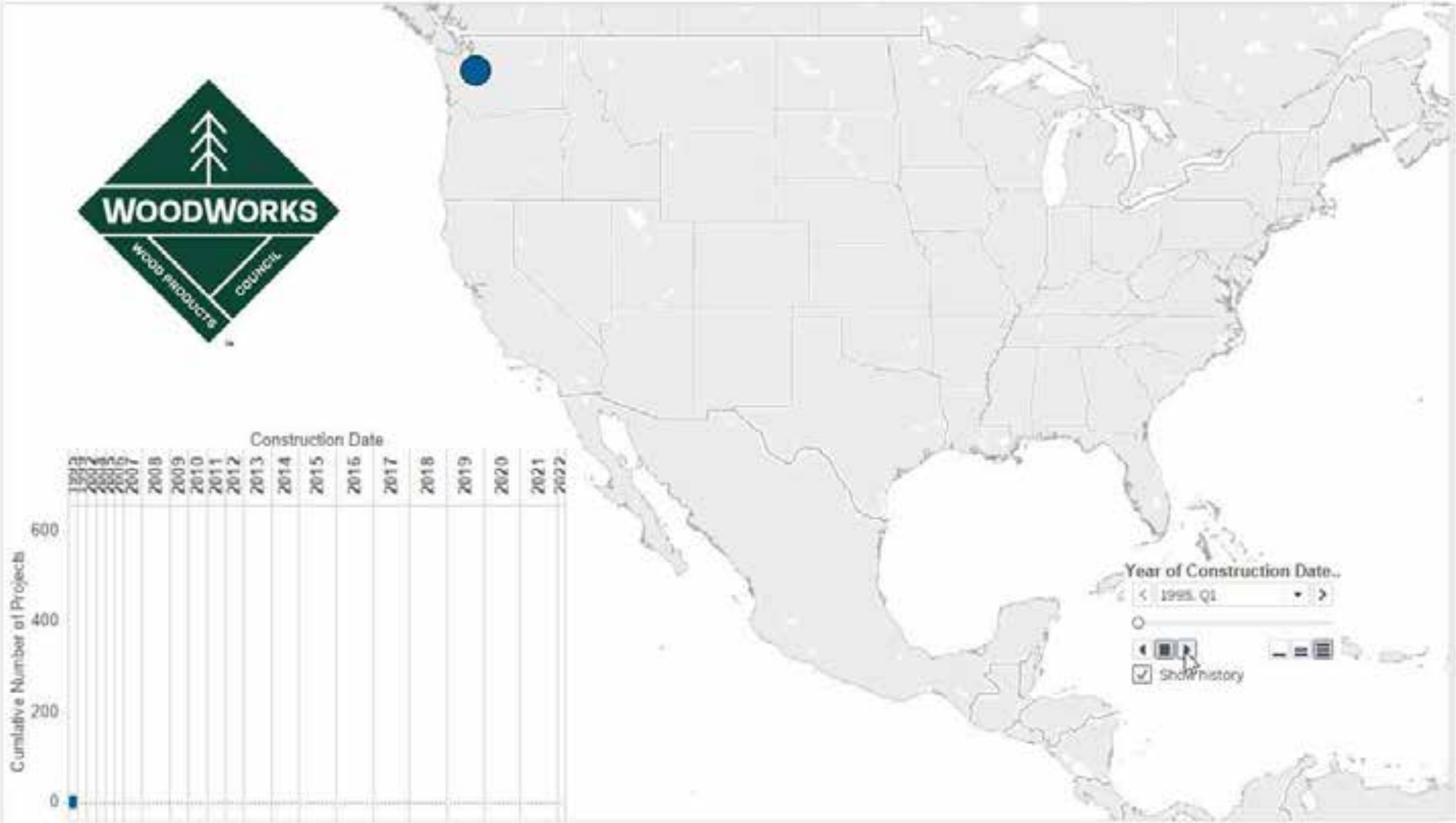
Type V: 4 stories

Tall Mass Timber: Up to 18 Stories in Construction Types IV-A, IV-B or IV-C



Current State of Mass Timber Projects

As of March 2022, in the US, **1,384** multi-family, commercial, or institutional projects have been constructed with, or are in design with, mass timber.



Agenda

» Mass Timber Systems and Products

› Fire Resistance

» Acoustics

» Market Drivers

» Protective Design

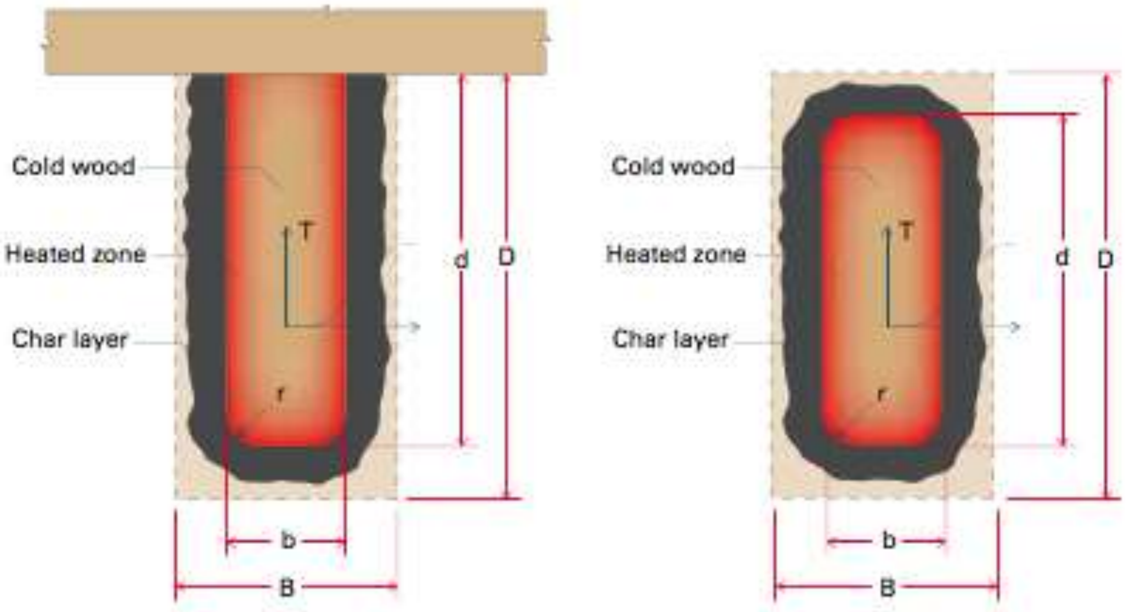
Photo: Ema Peter

Mass Timber's Fire-Resistive Performance is Well-Tested, Documented and Recognized via Code Acceptance

Table 16.2.1A Char Depth and Effective Char Depth (for β_n = 1.5 in./hr.)

Required Fire Resistance (hr.)	Char Depth, a_{char} (in.)	Effective Char Depth, a_{eff} (in.)
1-Hour	1.5	1.8
1½-Hour	2.1	2.5
2-Hour	2.6	3.2

Source: AWC's NDS



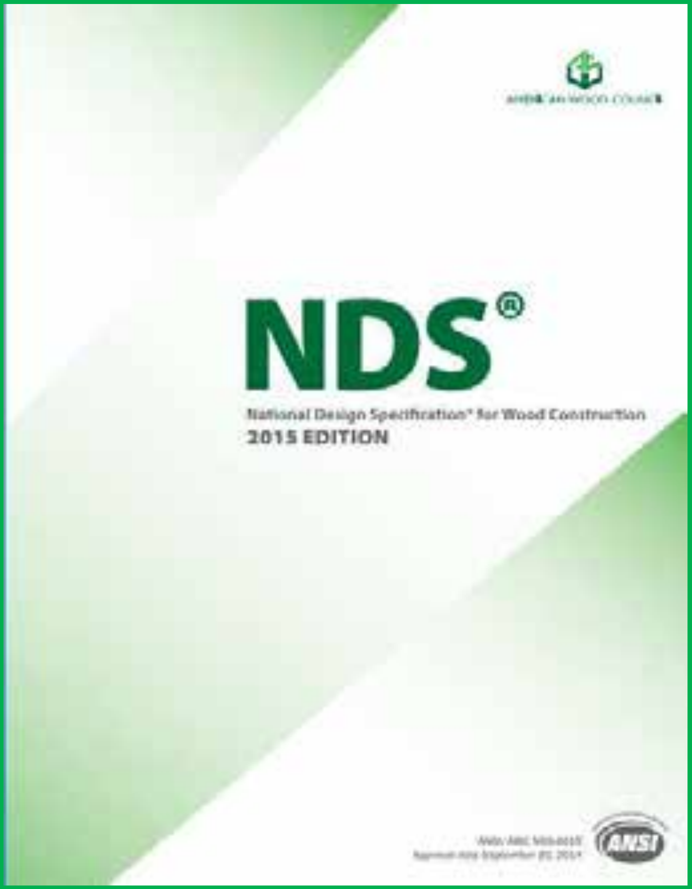
Source: AWC's TR 10

Credit: David Barber, ARUP

Mass timber design

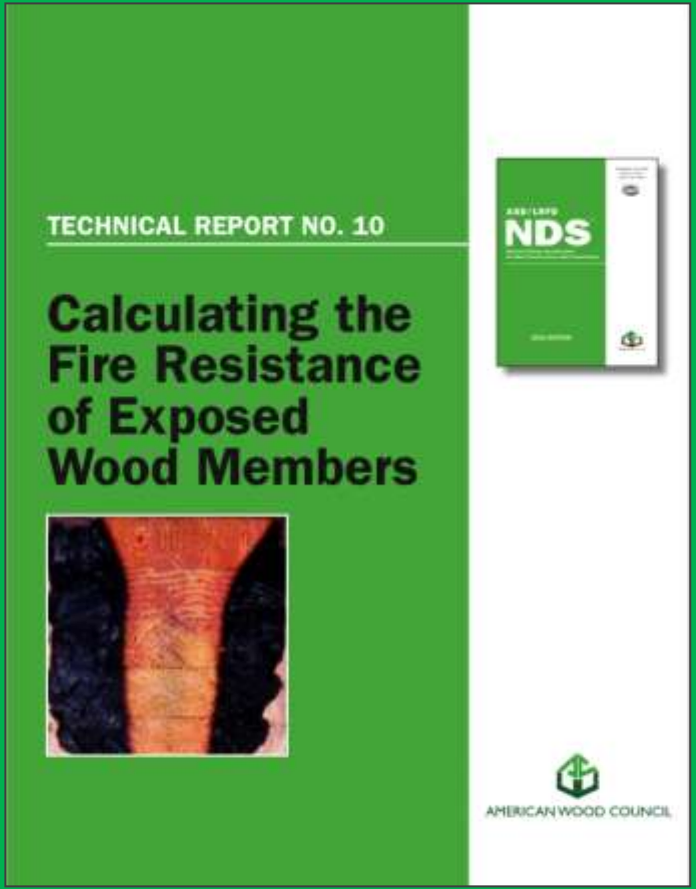
Fire resistance

For Exposed Wood Members: IBC 722.1 References AWC's NDS Chapter 16 (AWC's TR 10 is a design aid to NDS Chapter 16)



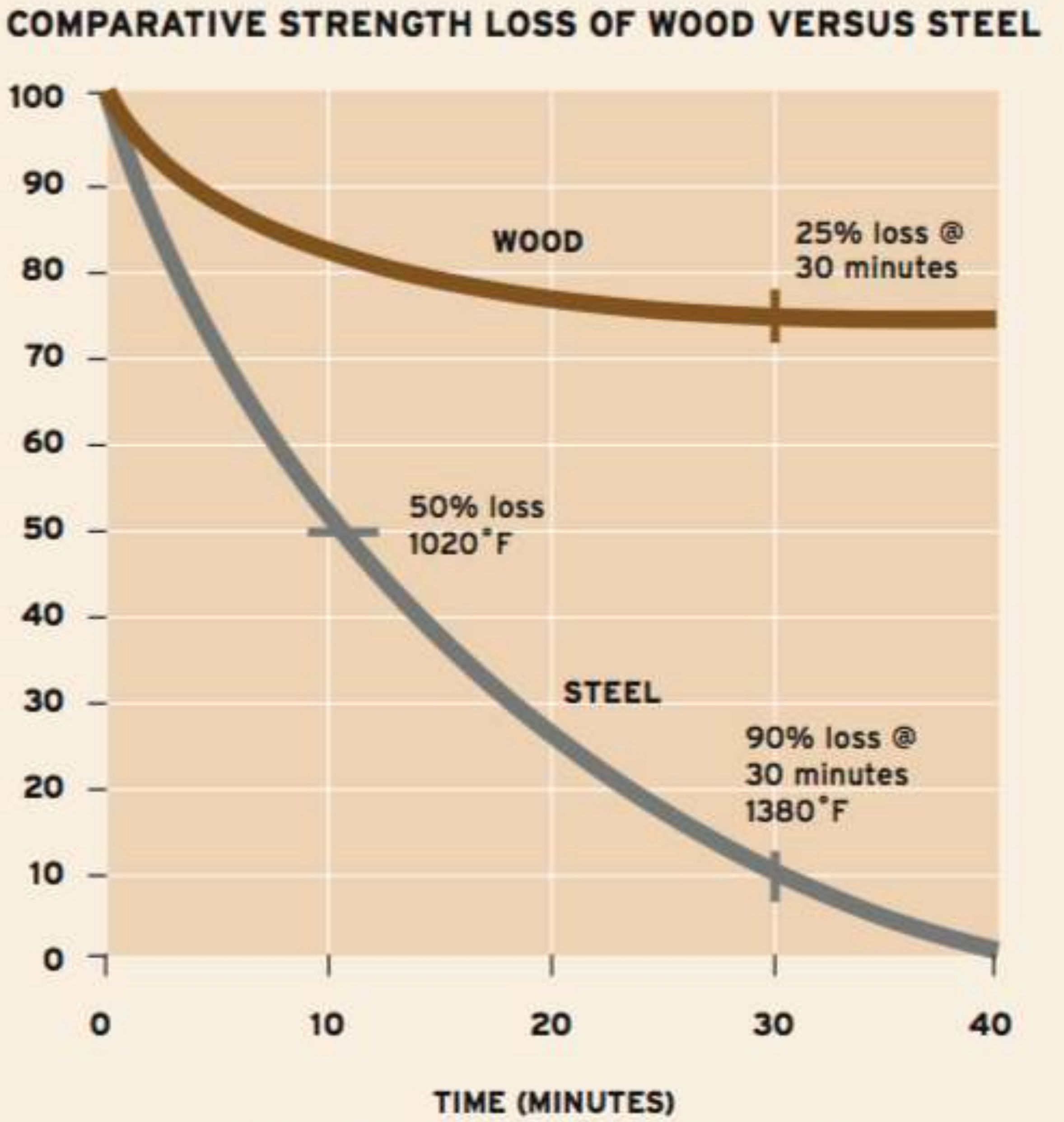
FIRE DESIGN OF WOOD MEMBERS

16



MASS TIMBER DESIGN

FIRE RESISTANCE



Results from test sponsored by National Forest Products Association at the Southwest Research Institute

SOURCE: AITC

KEY EARLY DESIGN DECISIONS

Inventory of Fire Tested MT Assemblies

Table 1: North American Fire Resistance Tests of Mass Timber Floor / Roof Assemblies

Mass Timber Panel	Manufacturer	CLT Grade or Timber Grade	Ceiling Protection	Panel Connection	Floor Topping	Load Rating	Fire Resistance Achieved (Hours)	Source	Testing Lab
3-ply CLT (114mm 4.488 in)	Nordic	SPF 1650 Fb 1.5E MSR x SPF #3	2 layers 1/2" Type X gypsum	Half-Lap	None	Reduced 36% Moment Capacity	1	1 (Test 1)	NRC Fire Laboratory
3-ply CLT (105mm 4.133 in)	Structurlam	SPF #1/#2 x SPF #1/#2	1 layer 5/8" Type X gypsum	Half-Lap	None	Reduced 75% Moment Capacity	1	1 (Test 5)	NRC Fire Laboratory
5-ply CLT (175mm 6.875")	Nordic	E1	None	Topside Spline	2 staggered layers of 1/2" cement boards	Loaded, See Manufacturer	2	2	NRC Fire Laboratory March 2016
5-ply CLT (175mm 6.875")	Nordic	E1	1 layer of 5/8" Type X gypsum under Z-channels and furring strips with 3 5/8" fiberglass batts	Topside Spline	2 staggered layers of 1/2" cement boards	Loaded, See Manufacturer	2	5	NRC Fire Laboratory Nov 2014
5-ply CLT (175mm 6.875")	Nordic	E1	None	Topside Spline	3/4 in. proprietary gypcrete over Maxxon acoustical mat	Reduced 50% Moment Capaciy	1.5	3	UL
5-ply CLT (175mm 6.875")	Nordic	E1	1 layer 5/8" normal gypsum	Topside Spline	3/4 in. proprietary gypcrete over Maxxon acoustical mat or proprietary sound board	Reduced 50% Moment Capaciy	2	4	UL
5-ply CLT (175mm 6.875")	Nordic	E1	1 layer 5/8" Type X gyp under Resilient Channel under 7 7/8" I-Joists with 3 1/2" Mineral Wool between Joists	Half-Lap	None	Loaded, See Manufacturer	2	21	Intertek 8/24/2012
5-ply CLT (175mm 6.875")	Structurlam	E1 M5 MSR 2100 x SPF #2	None	Topside Spline	1-1/2" Maxxon Cyp-Crete 2000 over Maxxon Reinforcing Mesh	Loaded, See Manufacturer	2.5	6	Intertek, 2/22/2016
5-ply CLT (175mm 6.875")	DR Johnson	V1	None	Half-Lap & Topside Spline	2" gypsum topping	Loaded, See Manufacturer	2	7	SwRI (May 2016)
5-ply CLT (175mm 6.875")	Nordic	SPF 1950 Fb MSR x SPF #3	None	Half-Lap	None	Reduced 59% Moment Capacity	1.5	1 (Test 3)	NRC Fire Laboratory
5-ply CLT (175mm 6.875")	Structurlam	SPF #1/#2 x SPF #1/#2	1 layer 5/8" Type X gypsum	Half-Lap	None	Unreduced 101% Moment Capacity	2	1 (Test 6)	NRC Fire Laboratory
7-ply CLT (245mm 9.65")	Structurlam	SPF #1/#2 x SPF #1/#2	None	Half-Lap	None	Unreduced 101% Moment Capacity	2.5	1 (Test 7)	NRC Fire Laboratory
5-ply CLT	SmartLam	SL-V4	None	Half-Lap	1/2" plywood with 8d nails	Loaded,	2	12	Western Fire Center

https://www.woodworks.org/resources/inventory-of-fire-resistance-tested-mass-timber-assemblies-penetrations/

Agenda

- Mass Timber Systems and Products
- Fire Resistance
- Acoustics
- Market Drivers
- Protective Design

Photo: Ema Peter

Mass timber design

Acoustics – IBC 1207

No acoustical code requirements for many mass timber building types such as offices and assembly. However, many owners require a minimum level of performance

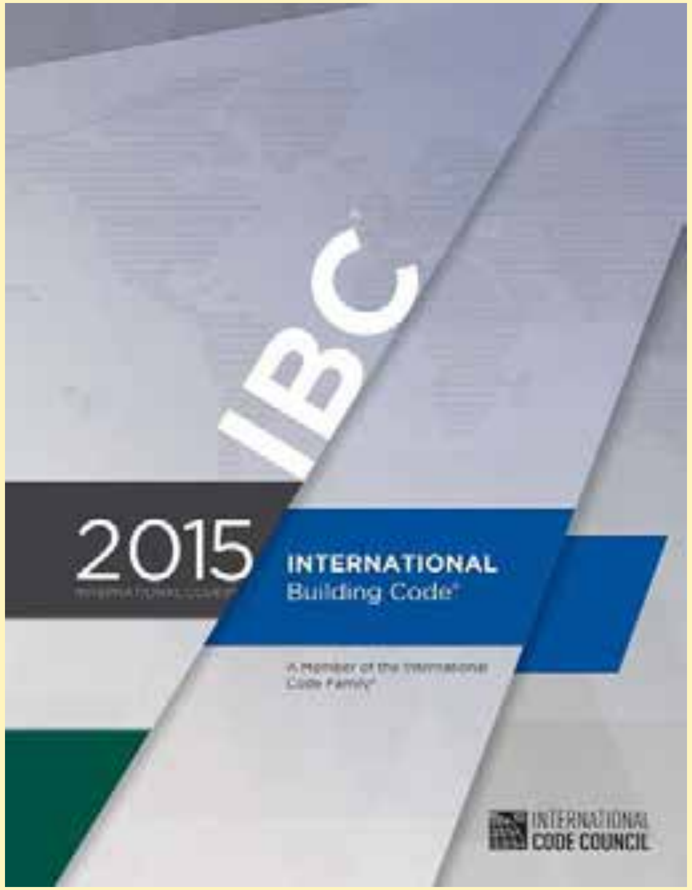
Code requirements for residential occupancies:

Min. STC of 50:

- Walls, Partitions, and Floor/Ceiling Assemblies

Min. IIC of 50 for:

- Floor/Ceiling Assemblies



Mass timber design

Acoustics

Sound Insulation of Bare CLT Floors and Walls

Examples of Acoustically-Tested Mass Timber Panels

Mass Timber Panel	Thickness	STC Rating	IIC Rating
3-ply CLT wall[4]	3.07"	33	N/A
5-ply CLT wall[4]	6.875"	38	N/A
5-ply CLT floor[5]	5.1875"	39	22
5-ply CLT floor[4]	6.875"	41	25
7-ply CLT floor[4]	9.65"	44	30
2x4 NLT wall[6]	3-1/2" bare NLT 4-1/4" with 3/4" plywood	24 bare NLT 29 with 3/4" plywood	N/A
2x6 NLT wall[6]	5-1/2" bare NLT 6-1/4" with 3/4" plywood	22 bare NLT 31 with 3/4" plywood	N/A
2x6 NLT floor + 1/2" plywood[2]	6" with 1/2" plywood	34	33

Source: Inventory of Acoustically-Tested Mass Timber Assemblies, WoodWorks[7]

Mass timber design

Acoustics

Common mass timber floor assembly:

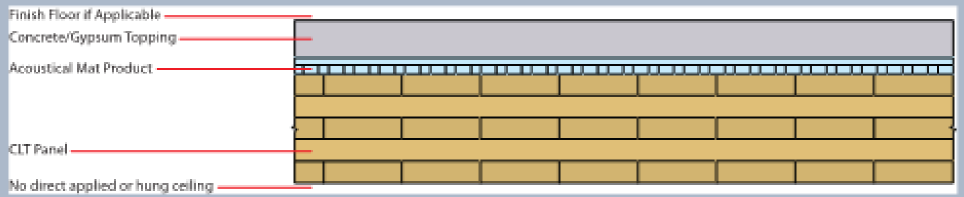
- Finish floor (if applicable)
- Underlayment (if finish floor)
- 1.5” to 3” thick concrete/gypcrete topping
- Acoustical mat
- Mass timber floor panels

Image credit: AcoustiTECH

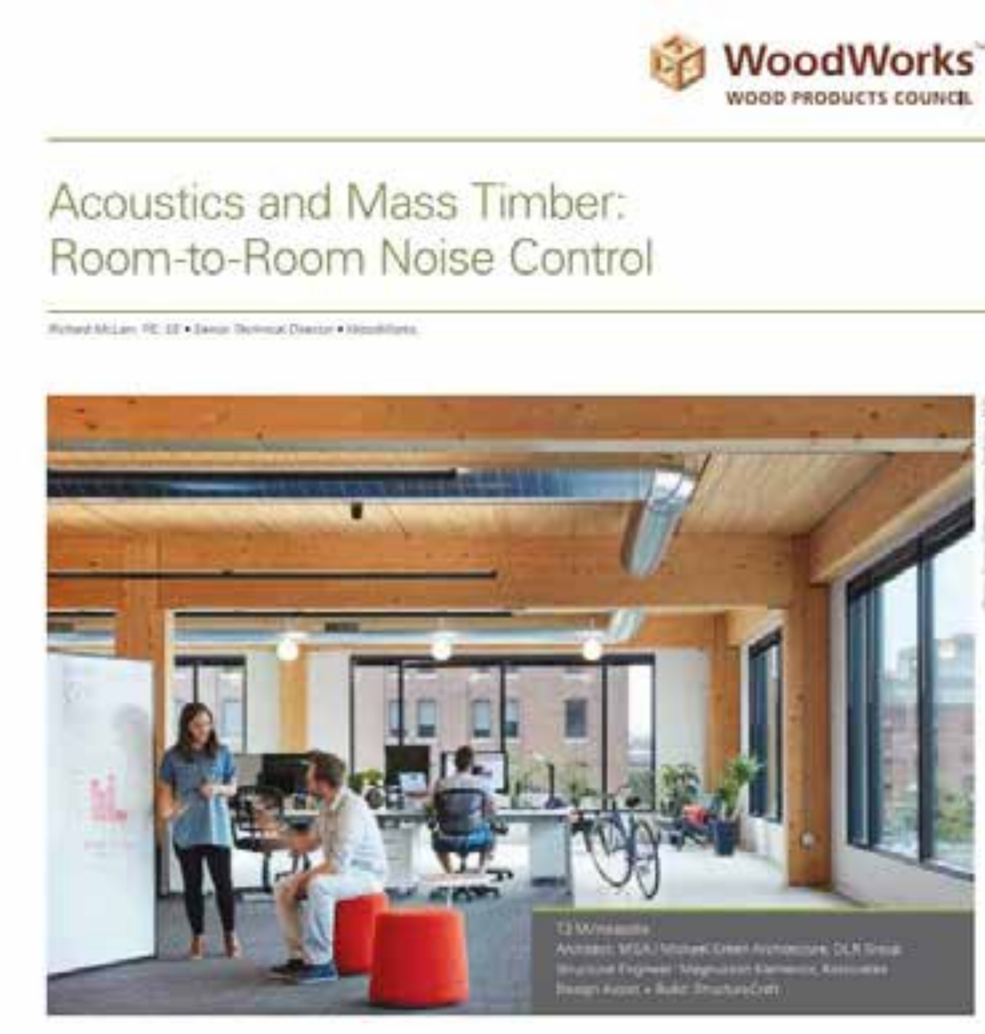
Mass timber design

Acoustics

Table 1: CLT Floor Assemblies with Concrete/Gypsum Topping, Ceiling Side Exposed



CLT Panel	Concrete/Gypsum Topping	Acoustical Mat Product Between CLT and Topping	Finish Floor	STC[1]	IIC[1]	Source
CLT 3-ply (3.5")	3" concrete	Maxxon Acousti-Mat® 3/4	None	53[2] ASTC	45[2] FIIC	72
CLT 3-ply (4.125")	2" concrete	Pliteq GenieMat™ FF25	None	54	44	89
			LVT on GenieMat RST05	53	48	90
			Eng Wood on GenieMat RST05	53	46	91
			Carpet Tile	52	50	92
	3" concrete	Kinetics® RIM-33L-2-24 System with ¾" Plywood	None	57	45	103
			LVT	-	58	104
			2 layers of ¼" USG Fiberock® on Kinetics® Soundmatt	55	55	105
			LVT on 2 layers of ¼" USG Fiberock® on Kinetics® Soundmatt	-	59	106
		Kinetics® Ultra Quiet SR with synthetic roofing felt	None	57	46	107
			LVT	-	55	108
			2 layers of ¼" USG Fiberock® on Kinetics® Soundmatt	57	53	109
			LVT on 2 layers of ¼" USG Fiberock® on Kinetics® Soundmatt	-	50	110
	4" concrete	Kinetics® RIM-33L-2-24 System with ¾" Plywood	None	60	53	111



https://www.woodworks.org/resources/inventory-of-acoustically-tested-mass-timber-assemblies/

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Photo: Ema Peter

MARKET DRIVERS FOR MASS TIMBER

PRIMARY DRIVERS

- » Construction Efficiency & Speed
- » Construction site constraints – Urban Infill
- » Innovation/Aesthetic

SECONDARY DRIVERS

- » Carbon Reductions
- » Structural Performance – lightweight

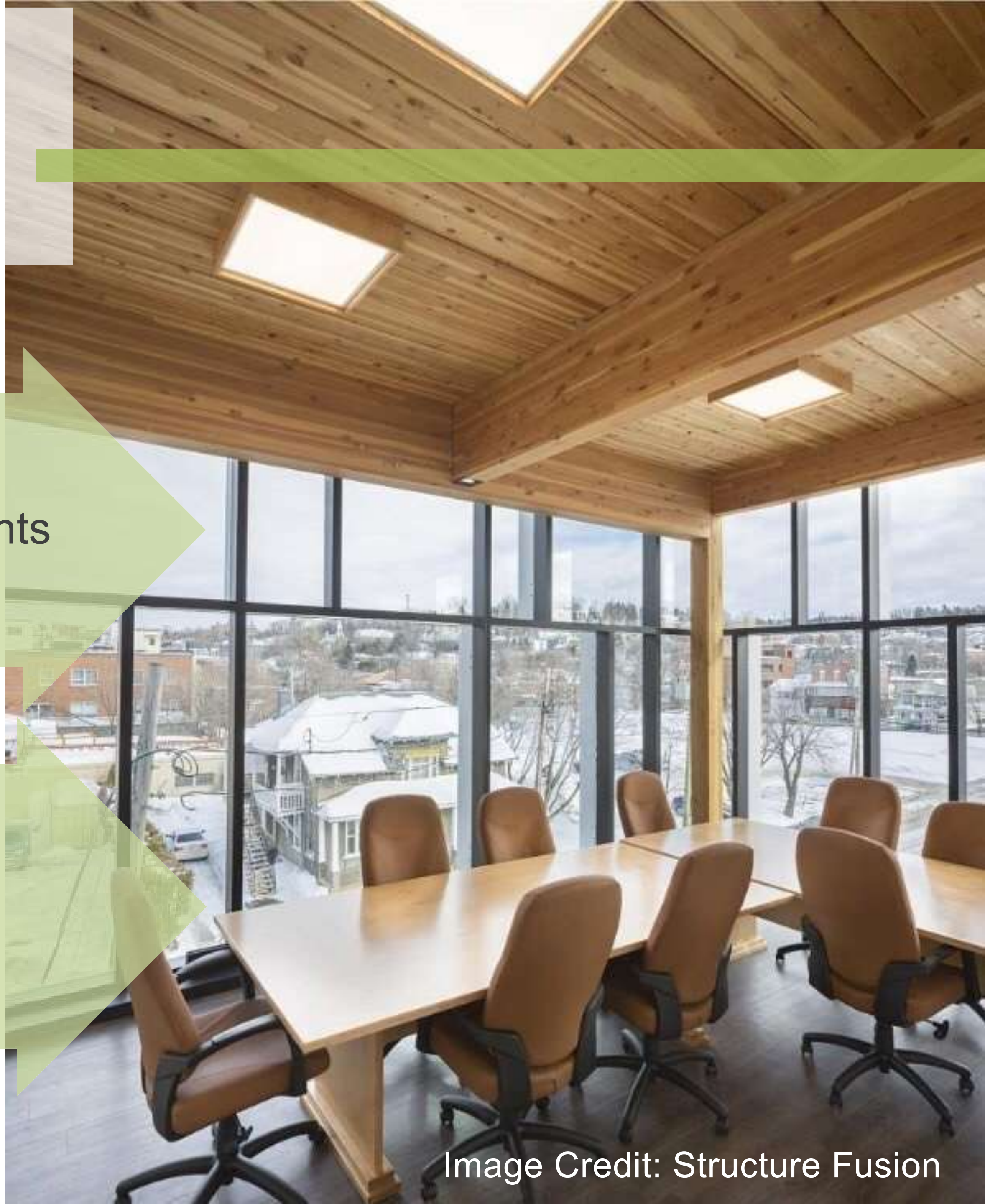


Image Credit: Structure Fusion

Mass timber appeal

Reduced construction time

1 Floor = 3 Days
17 Floors Erected in 9.5 Weeks

Traditional methods:
100 people on site
7-10 day floor cycle + temp shoring and curing

Brock Commons:
20-30 people on site
3 day floor cycle
no shoring no curing

Brock Commons, Vancouver, BC
Source: naturally:wood[5]

Mass timber appeal

Reduced embodied carbon

ESTIMATED ENVIRONMENTAL IMPACT OF WOOD USE

Volume of wood products used:
2,233 cubic meters of CLT and Glulam

U.S. and Canadian forests grow this much wood in:
6 minutes

Carbon stored in the wood:
1,753 metric tons of CO_2

Avoided greenhouse gas emissions:
679 metric tons of CO_2

Total potential carbon benefit:
2,432 metric tons of CO_2

THE ABOVE GHG EMISSIONS ARE EQUIVALENT

511 cars off the road for a year

Energy to operate a home for 222 years

**Estimated by the Wood Carbon Calculator for Buildings, based on research by Sathre, R. and J. O'Connor, 2010, A Synthesis of Research on Wood Products and Greenhouse Gas Impacts, FPInnovations (this relates to carbon stored and avoided GHG).*

**CO2 in this case study refers to CO2 equivalent*

Source: Naturally:wood[9]

Brock Commons, Vancouver, BC

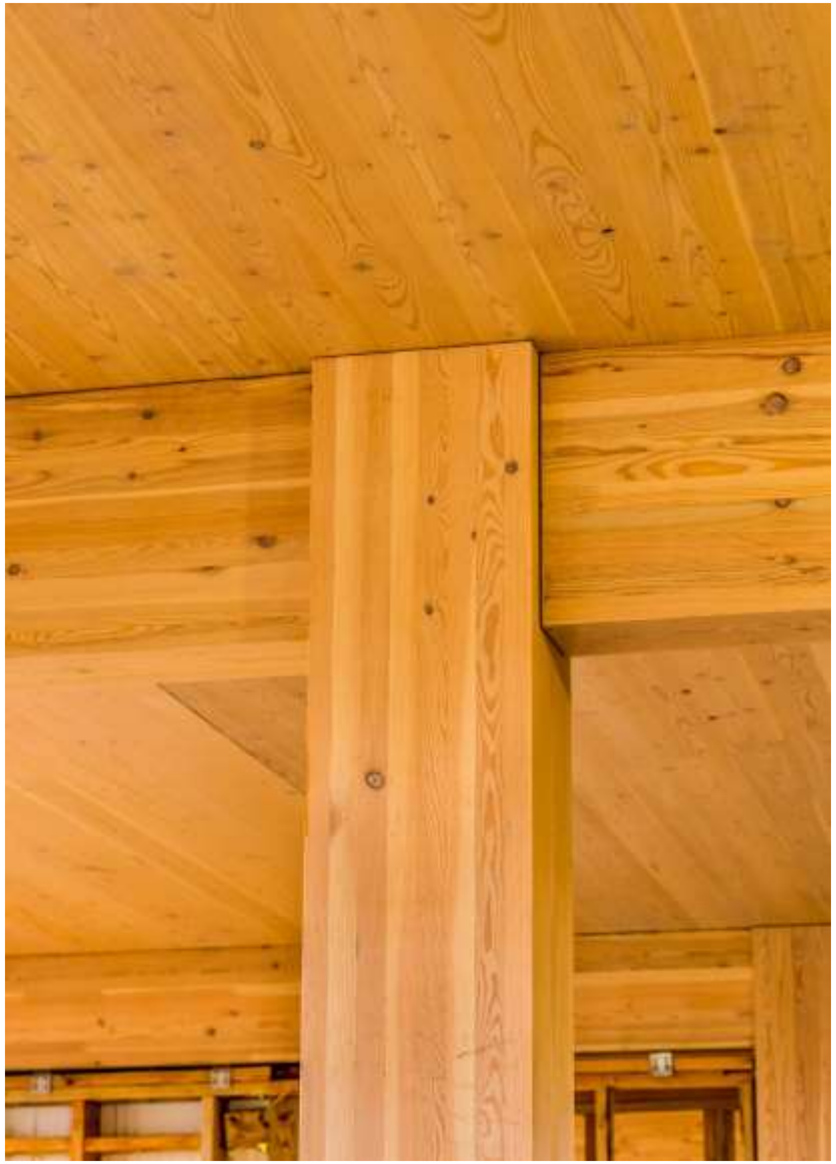
Photo credit: acton ostry architects

MASS TIMBER APPEAL

MATERIAL MASS

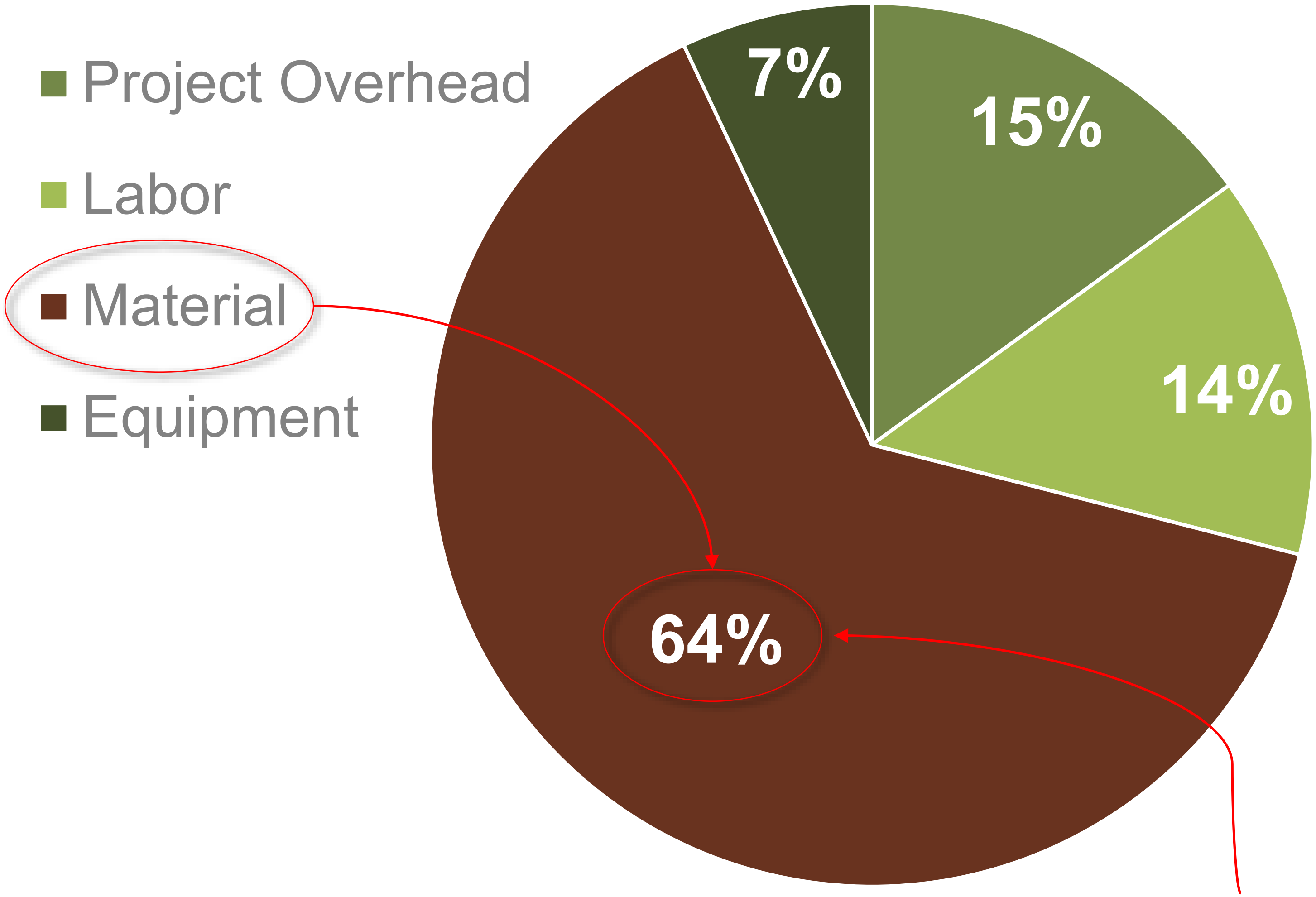
75% LIGHTER WEIGHT THAN CONCRETE

Mass Timber: Structure Often is Finish



Photos: Baumberger Studio/PATH Architecture/Marcus Kauffman | Architect: PATH Architecture

Higher Material Cost | Lower Construction Costs



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

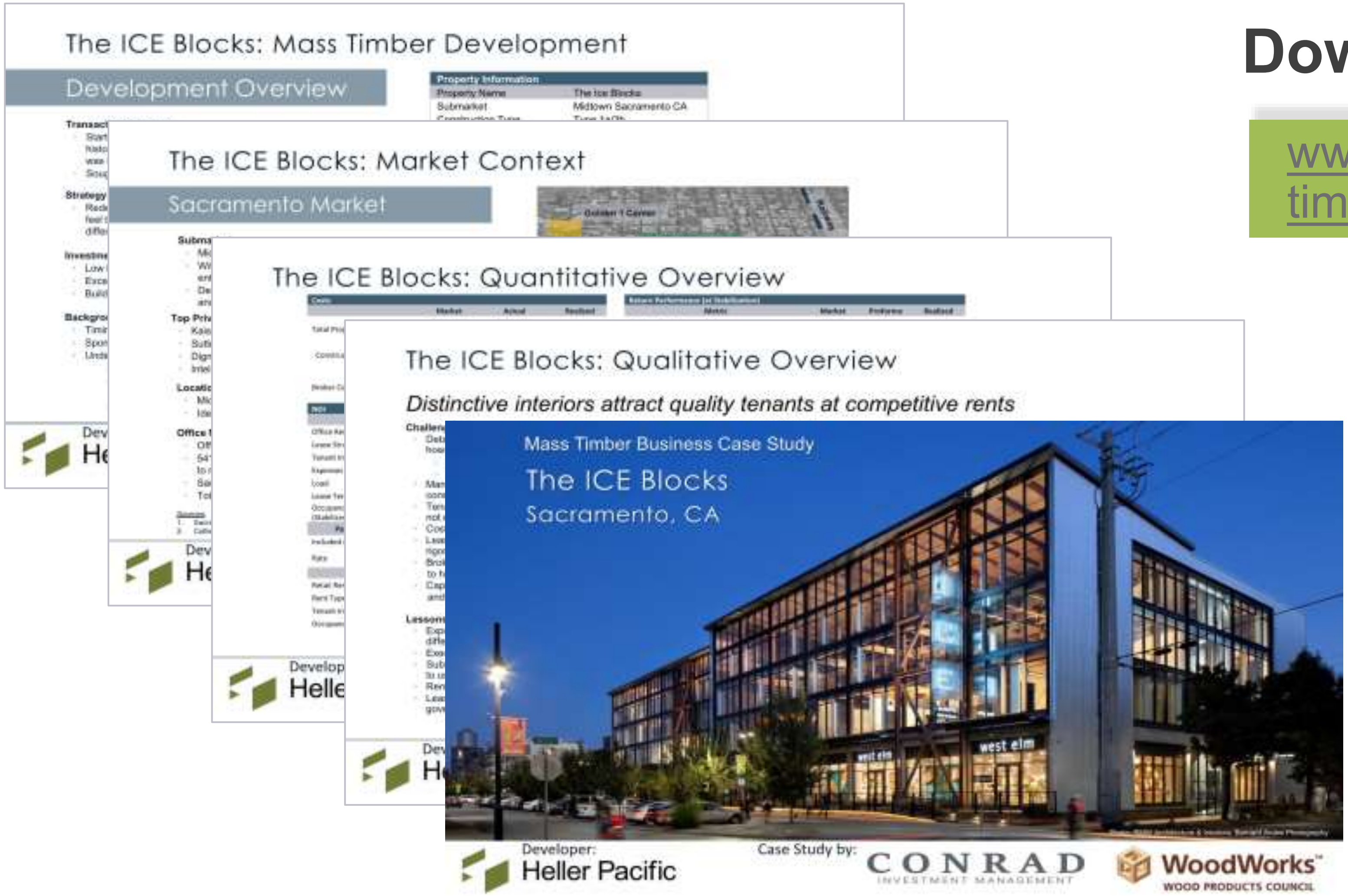
Source: Swinerton

Mass Timber Costs

Factors relevant to the cost conversation:

- Cure time: mass timber has none. It can be worked on immediately after being placed
- Crane size: mass timber is lighter than traditional materials. Smaller crane = potential savings
- Smaller seismic forces & foundations = potential savings
- Fewer finishes = labor and material savings
- Construction speed: estimated to be 25% faster. Sooner completion = sooner occupancy = sooner revenue and less general conditions
- Less construction traffic, prefabricated & precise – goes together smoothly
- Labor costs are lower

NEW MASS TIMBER BUSINESS CASE STUDIES



Download online at

www.woodworks.org/mass-timber-business-case-studies

- Includes financial return performance data on mass timber projects
- Developers share lessons learned, challenges and successes

The Canyons VE Exercise

Total Change to Light Framing

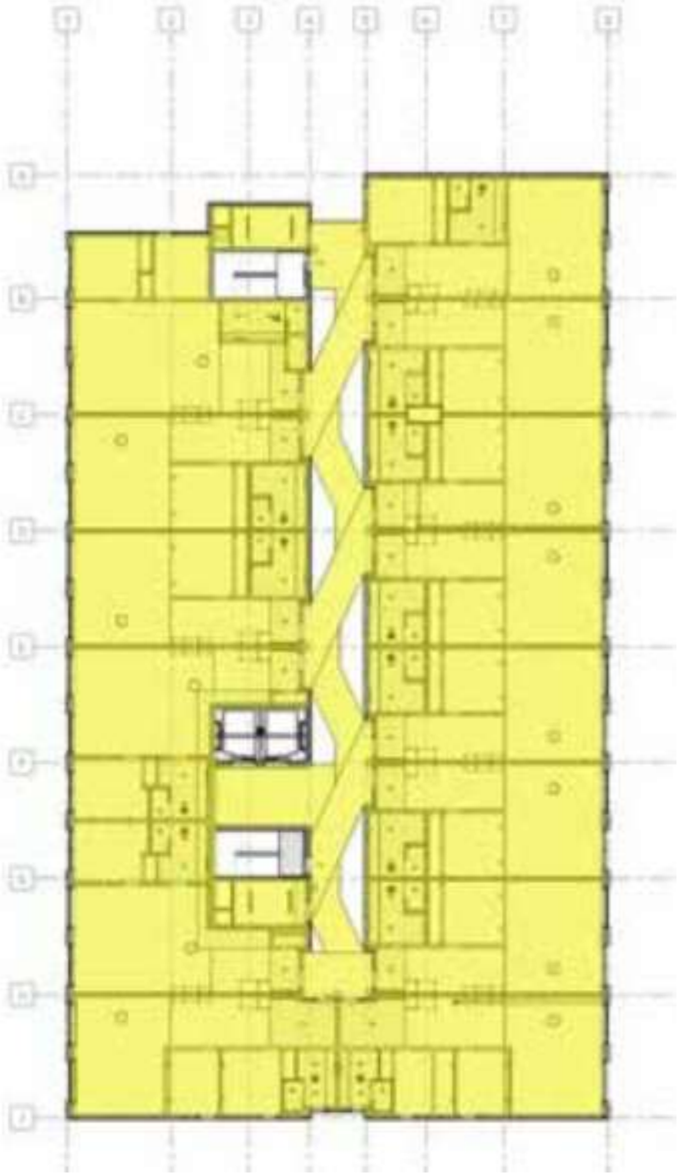
- TOTAL BUILDING COST SAVINGS save $278,600

Value Lost

- Ceiling height reduced 6” or building height decreased by 30”
- Potential to loose a floor. We are at max height limit.
- Loss of exposed wood ceilings.
- Lower lease rates
- Market differentiation

Building Value vs Building Cost.

The Canyons – CLT vs Light Framing



Schedule Impact on Cost | Value of Time

A large-scale MT project can be up to 2% higher in direct costs, but a minimum of 20% lower in project overhead costs. The net result is cost-neutrality and higher value.

Source: Swinerton
Photo: Alex Schreyer

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- **Protective Design**

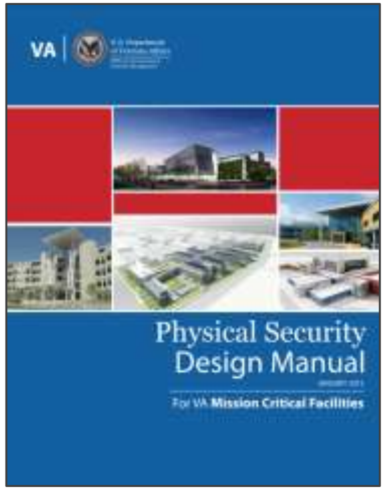
Photo: Ema Peter

Current Protective Design Requirements

- Protective design
  - Physical measures to mitigate the consequences of adverse events to people and other critical assets
- Traditionally, protective design has focused on countering four threats:
  - Blast
  - Ballistic
  - Forced Entry
  - Progressive Collapse
- Many Government entities have some form of protective design requirements

Antiterrorism Criteria

- Following 9/11, most federal agencies instituted protective design requirements for antiterrorism
  - Department of Defense
    - UFC 4-010-01
  - Department of State
    - OBO Building Code
    - SD-STD-01.01
  - Department of Veterans Affairs
    - Physical Security Design Manual
  - Other Non-Military Federal Government
    - Interagency Security Council Risk Management Process
- Other non-federal agencies also have requirements, e.g.:
  - New York City Port Authority
  - Judicial Council of California



Recent Developments

- Some of these requirements have been scaled back within the past 5 years
  - Particularly **blast** design requirements for less critical DoD, GSA, & VA facilities
  - For example, UFC 4-010-01
    - Prior to December 2018: CLT had to be designed for blast loads
    - December 2018 UFC 4-010-01 version (and subsequent versions): No blast design unless a Medium or High Level of Protection (LOP) is needed
- Most ballistic, forced entry, and progressive collapse requirements have stayed in place
  - Ballistic and FE requirements only necessary when Medium or High LOP

UNIFIED FACILITIES CRITERIA (UFC)

DoD MINIMUM ANTITERRORISM STANDARDS FOR BUILDINGS

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Table B-2 Conventional Construction Standoff Distances

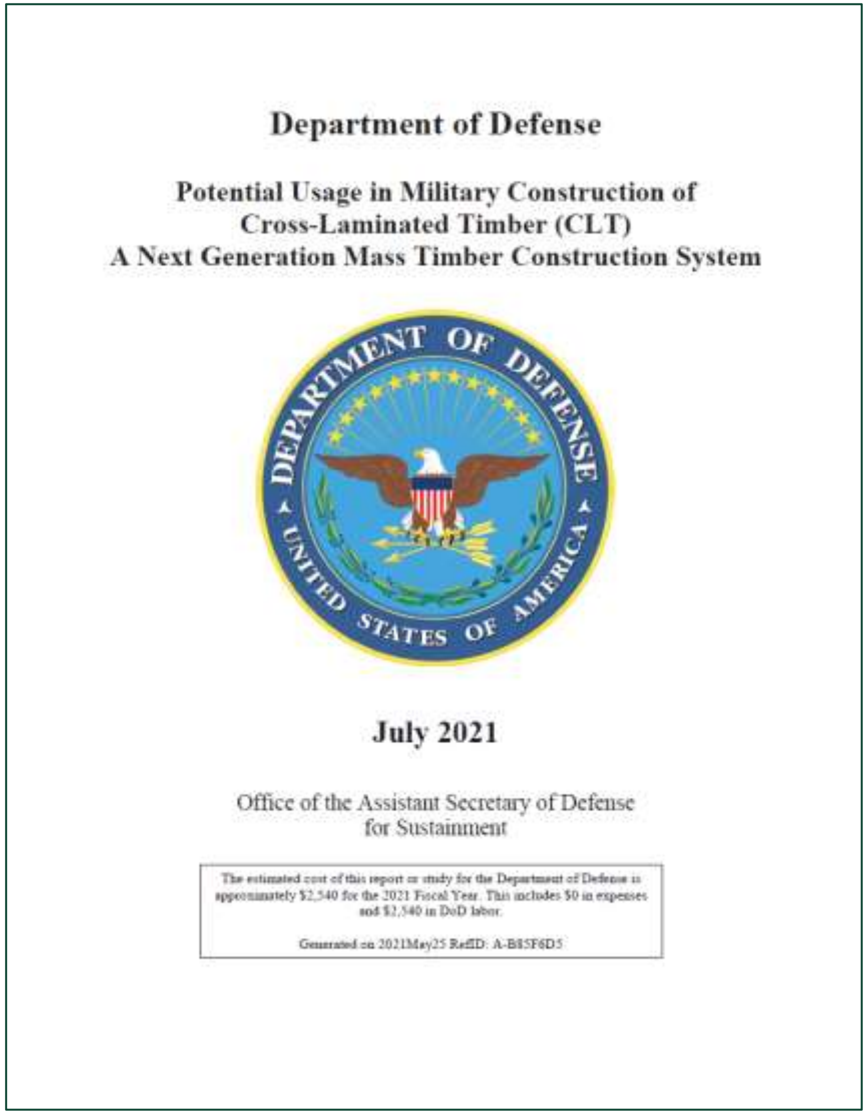
NO LONGER REQUIRED FOR LLOP OR VLLOP FACILITIES

Wall Type	Column Letter							
	Without Controlled Perimeter Applicable Explosive Weight I				Within Controlled Perimeter Applicable Explosive Weight II			
	Load Bearing Walls		Non-Load Bearing Walls		Load Bearing Walls		Non-Load Bearing Walls	
	A PG & BIL LLOP	B INHAB VLLOP	C PG & BIL LLOP	D INHAB VLLOP	E PG & BIL LLOP	F INHAB VLLOP	G PG & BIL LLOP	H INHAB VLLOP
Wood Studs – Brick Veneer	105 ft (32 m)	105 ft (32 m)	79 ft (24 m)	65 ft (20 m)	36 ft (11 m)	36 ft (11 m)	23 ft (7 m)	16 ft (5 m)
Wood Studs – EIFS	207 ft (63 m)	207 ft (63 m)	164 ft (50 m)	141 ft (43 m)	86 ft (26 m)	86 ft (26 m)	66 ft (20 m)	56 ft (17 m)
Metal Studs – Brick Veneer	187 ft (57 m)	187 ft (57 m)	207 ft[3] (63 m)	187 ft[3] (57 m)	75 ft (23 m)	75 ft (23 m)	82 ft[3] (25 m)	75 ft[3] (23 m)
Metal Studs – EIFS	361 ft (110 m)	361 ft (110 m)	420 ft (128 m)	361 ft[3] (110 m)	151 ft (46 m)	151 ft (46 m)	167 ft[3] (51 m)	151 ft[3] (46 m)
Metal Panels	n/a[2]	n/a[2]	151 ft (46 m)	108 ft (33 m)	n/a[2]	n/a[2]	56 ft (17 m)	39 ft (12 m)
Girts	n/a[2]	n/a[2]	115 ft (35 m)	59 ft (18 m)	n/a[2]	n/a[2]	23 ft (7 m)	16 ft (5 m)
Reinforced Concrete	66 ft (20 m)	66 ft (20 m)	26 ft (8 m)	20 ft (6 m)	16 ft (5 m)	16 ft (5 m)	13 ft (4 m)	13 ft (4 m)
Unreinforced Masonry[4]	262 ft (80 m)	262 ft (80 m)	125 ft (38 m)	33 ft (10 m)	80 ft (24 m)	80 ft (24 m)	26 ft (8 m)	16 ft (5 m)
Reinforced Masonry	86 ft (26 m)	86 ft (26 m)	30 ft (9 m)	20 ft (6 m)	30 ft (9 m)	30 ft (9 m)	13 ft (4 m)	13 ft (4 m)
European Block	164 ft (50 m)	164 ft (50 m)	59 ft (18 m)	30 ft (9 m)	39 ft (12 m)	39 ft (12 m)	23 ft (7 m)	16 ft (5 m)
\1\ Roof Construction in Table 2-3 /1/	20 ft (6 m)				13 ft (4 m)			

Recent Developments

- Planned release of new standards in 2022
  - SD-STD-01.01, Rev. H (released in 2020 but to become effective this year)
    - FE/BR requirements for DoS facilities
    - Removed grandfathering
      - Requires that all FE/BR products be recertified
  - ASCE/SEI 59
    - Blast Protection of Buildings
    - Update of 2011 version
  - ASCE/SEI 76
    - Mitigation of Disproportionate Collapse Potential in Buildings and Other Structures
    - New standard

Recent Developments


Department of Defense

Potential Usage in Military Construction of
Cross-Laminated Timber (CLT)
A Next Generation Mass Timber Construction System

July 2021

Office of the Assistant Secretary of Defense
for Sustainment

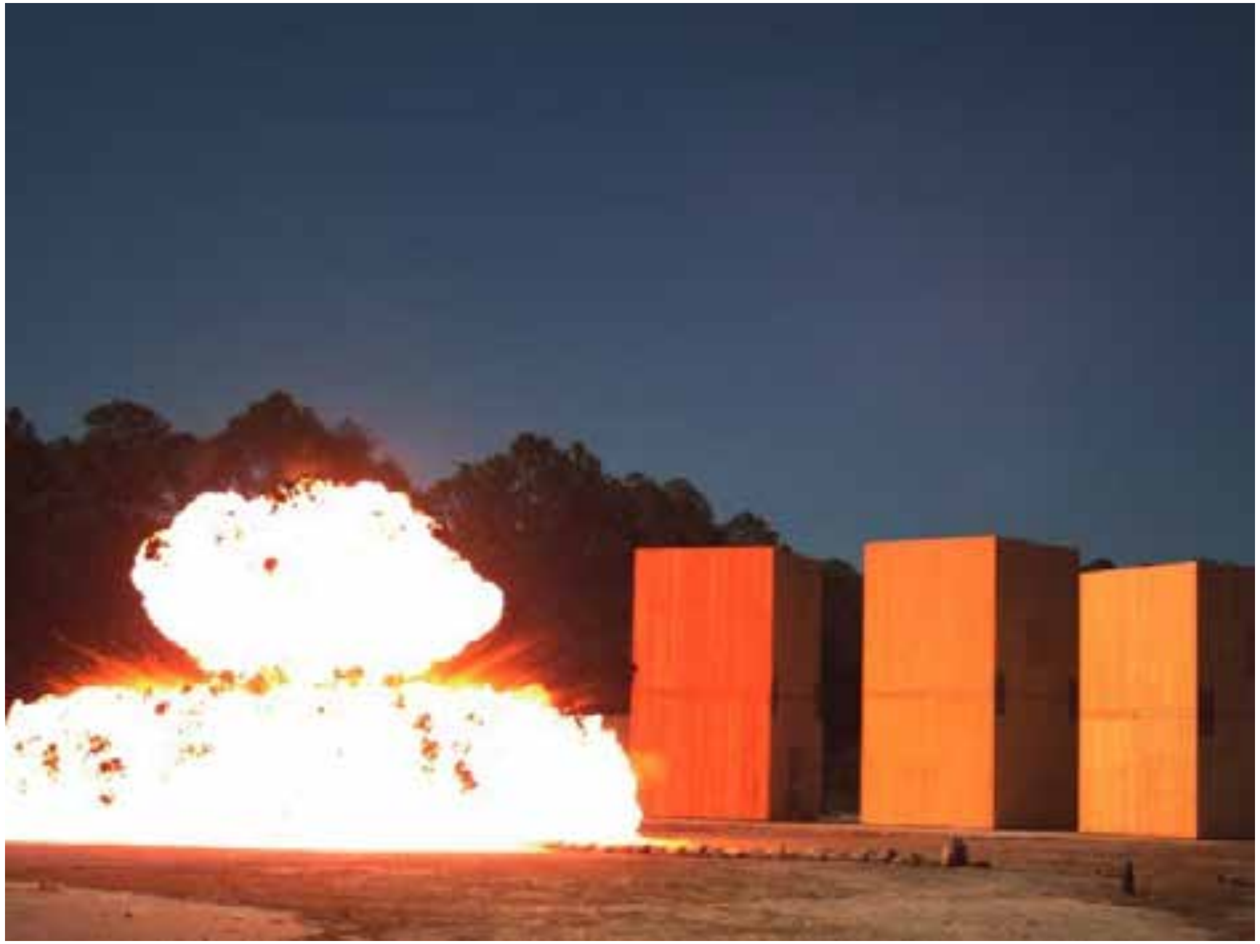
The estimated cost of this report or study for the Department of Defense is approximately $2,540 for the 2021 Fiscal Year. This includes $0 in expenses and $2,540 in DoD labor.

Generated on 2021May25 RefID: A-B85F6D5

- Various Government organizations investigating ways to get CLT into their infrastructure
  - Renewable material / carbon footprint reduction
  - Augmented speed of construction
  - Innovative use of materials
- Department of Defense
  - *Potential Usage in Military Construction of CLT* Report
  - U.S. Army Small Business Technology Transfer (STTR) Effort: *Modeling and Design Tool for Bio-Based Construction Products*
- Department of State
  - *Application of Mass Timber and Climate Resiliency in Diplomatic Buildings* Effort

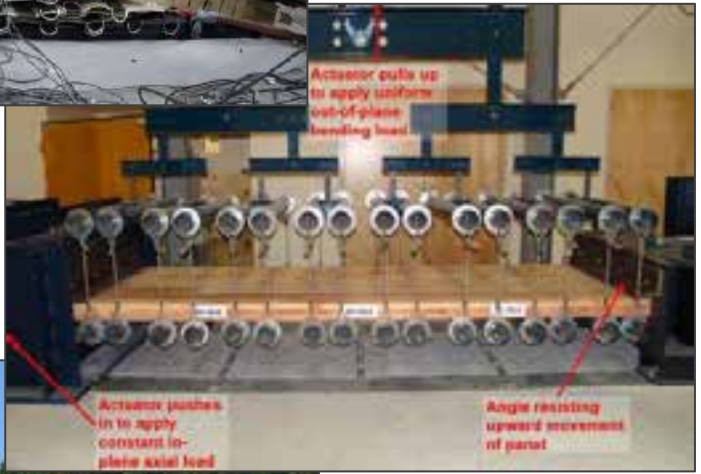
Protective Design Applied Research for Mass Timber
Overview

- Blast
  - WoodWorks Blast Testing
  - ISIEMS Test on 7-Ply CLT Panel
  - USACE PDC CLT Shock Tube Testing
  - UOttawa CLT Shock Tube Testing
  - WoodWorks NLT Shock Tube Testing
- Ballistic
  - Georgia Tech Ballistic Testing
  - Reinforced CLT Development
    - Ballistic Testing
    - Quasi-Static Full-Size Panel Testing
- Forced Entry
  - DOS Forced Entry Test



WoodWorks Blast Testing

Quasi-Static Testing of CLT Panels (2016)



Quasi-Static Testing of Axially-Loaded CLT Panels (2017)

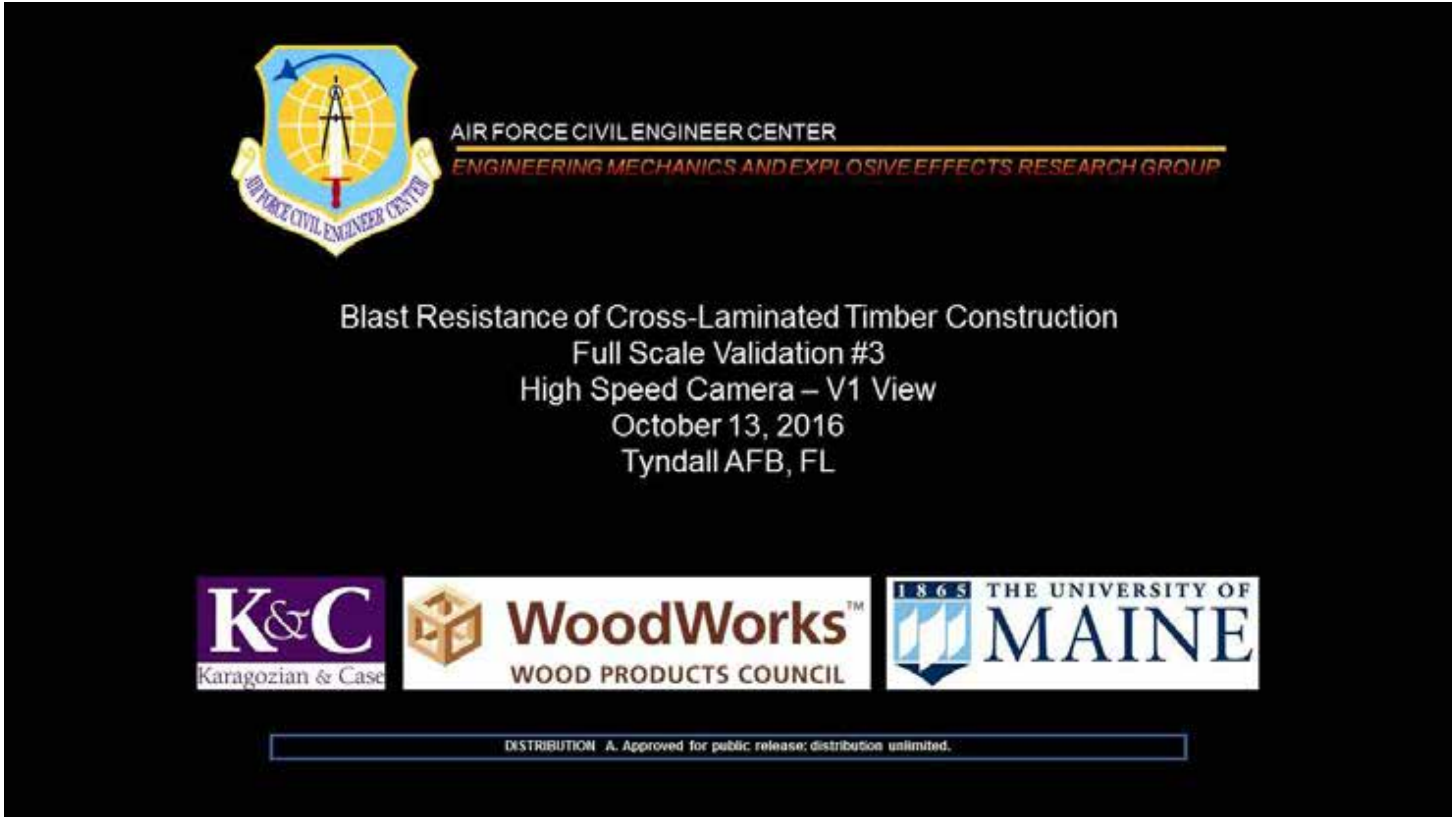
Full-Scale Blast Testing of CLT Panels (2016-2017)

- 3-year testing program to investigate response of CLT and NLT to blast loads

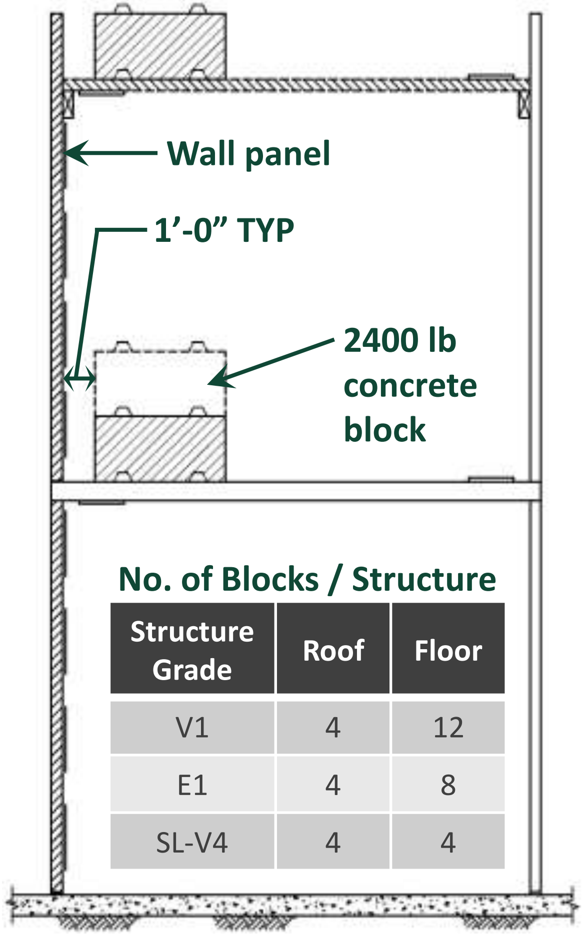
- DoD antiterrorism blast loading conditions
  - UFC 4-010-01 (pre-2018)

- Testing performed
  - 31 quasi-static panel tests w/o axial load
  - 24 quasi-static panel tests w/ axial load
  - 7 arena blast tests on full-scale structures
  - Can obtain reports documenting testing through WoodWorks
    - https://www.woodworks.org/learn/mass-timber-clt/protective-design/

Mass Timber Structures Can Be Designed to Efficiently Resist Blast Loading



Axial Load Impact



No. of Blocks / Structure

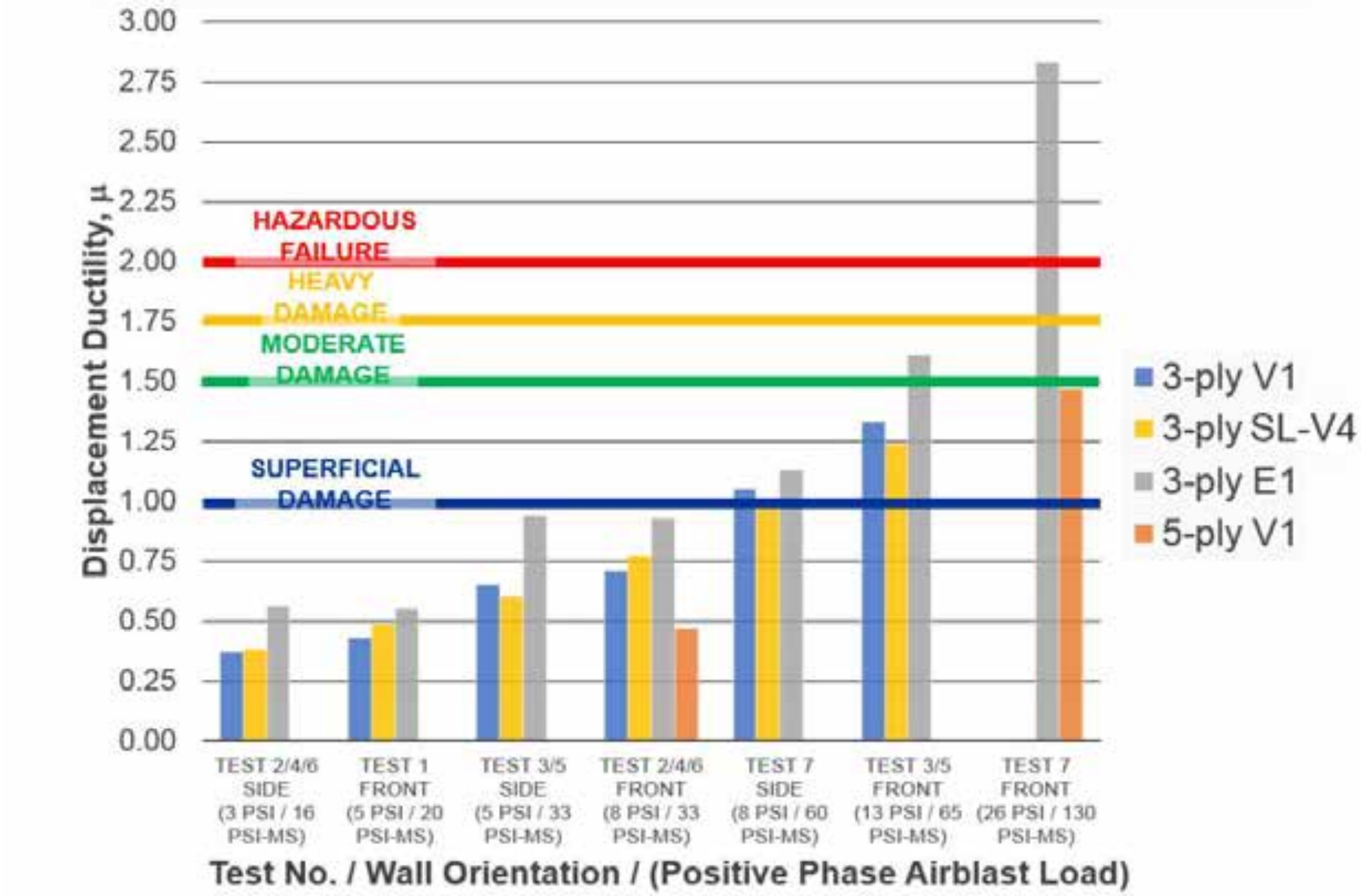
Structure Grade	Roof	Floor
V1	4	12
E1	4	8
SL-V4	4	4

With Axial Load

Without Axial Load

Summary of WoodWorks Blast Testing Results

- Where can CLT be used in DOD construction?
  - Based on the facility's Level of Protection (LOP)
    - Very Low / Low LOP: Yes
    - Medium / High LOP: Must exhibit Superficial Damage (i.e., remain elastic)



Load Bearing Wall Comparison from a Blast Perspective

Wall Type	Sections	Span	Min. Static Material Strength	Explosive Weight I Standoff Distance	Explosive Weight II Standoff Distance
Reinforced Concrete	≥ 6”	12’ – 20’	3,000 psi	**66**	**16**
Reinforced Masonry	8” – 12”	10’ – 14’	1,500 psi	**86**	**30**
CLT	**3-ply**	**10’ – 12’**	**Grades E1, V1, and SL-V4**	**90**	**35**
Steel Stud	600S162-43; 600S162-54; 600S162-68	8’ – 12’	50,000 psi	**361**	**151**

1 Table shows proposed conventional construction standoff distances (CCSDs) for CLT assuming a LLOP based on a response limit of $\mu < 1.5$. This table has not been reviewed or approved by USACE.

2 Table does not consider openings; localized reinforcement may be required around openings for the CCSDs shown.

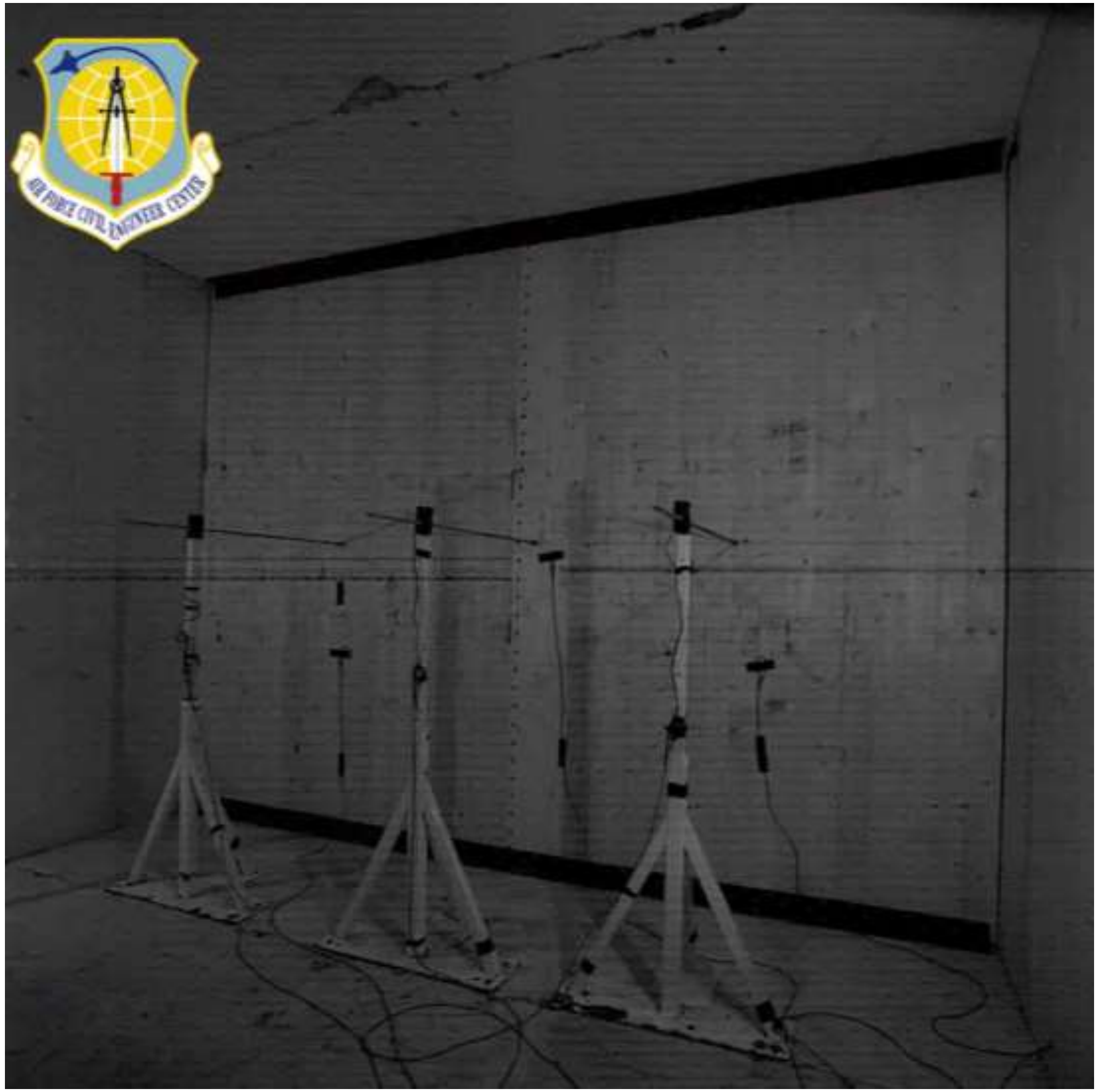
3 Assumed COV: 0.40 for Grades V1 and SL-V4; 0.10 for Grade E1

4 Assumed panel density: 35 pcf for Grade V1; 32.5 pcf for Grade E1; 30 pcf for Grade SL-V4

5 Assumed supported weight: 10 psf

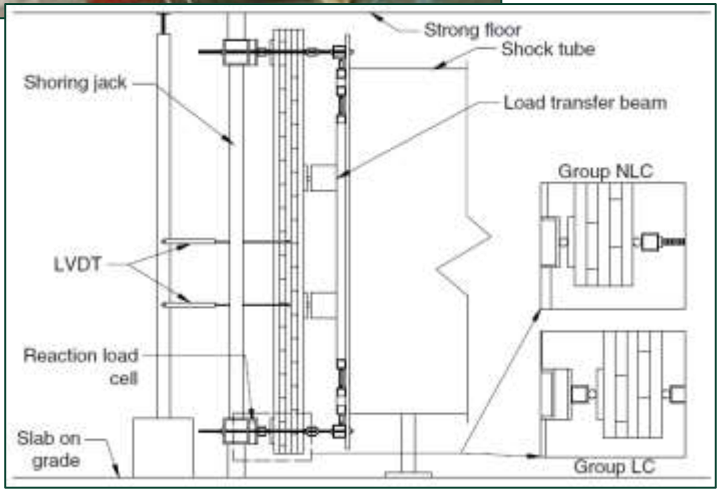
ISIEMS Test on 7-Ply CLT Panel

- 7-ply SL-V4 panel
  - No. 2 SPF-S in both major and minor strength directions
- Blast load: 80.5 psi / 216 psi-ms
- Peak displacement measured in test compares well w/ that computed using PDC-TR 18-02
- Computed displacement ductility using PDC-TR 18-02: 2.93



USACE PDC / UOttawa CLT Shock Tube Testing

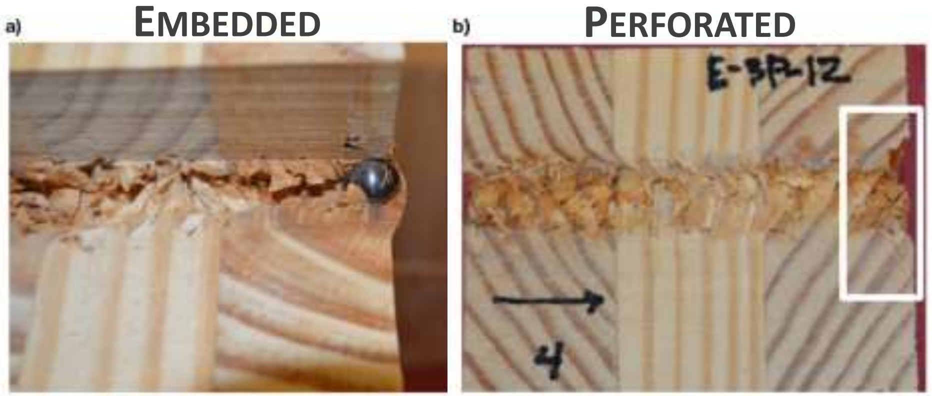
- 3-, 5-, and 7-ply Grade E1 specimens
- Specimens hit multiple times in some cases if no signs of rupture
- Shock tube test reports indicate a dynamic increase factor of between 1.2 and 1.35 for CLT

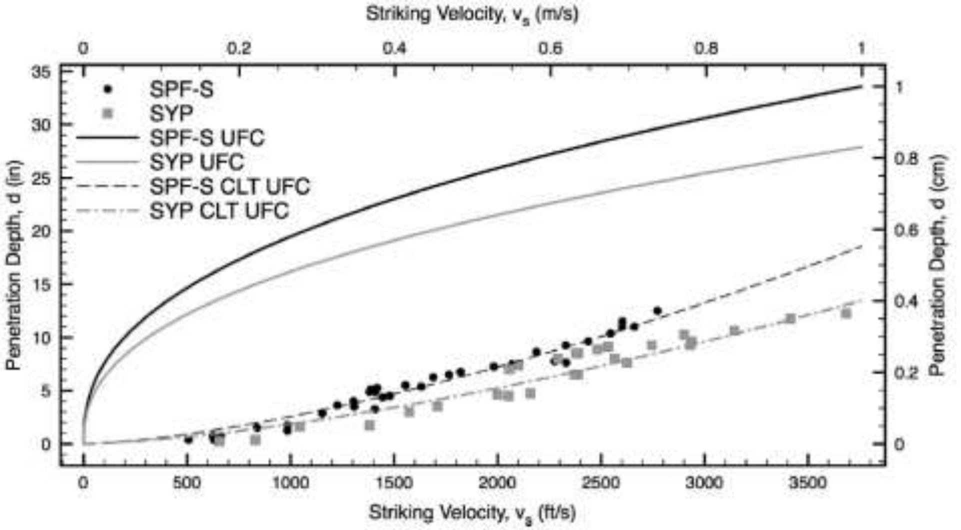


WoodWorks NLT Shock Tube Testing

- 6 tests on 2x4 and 2x6 NLT (No. 2 or better SPF) + ½" plywood
- Blast loads were selected to induce 0.75, 1.00, and 1.25 ductility ratios in NLT panels
  - Ductility: ratio of actual displacement response over theoretical elastic response
- Doesn't benefit from 2-way redistribution of load like CLT

Georgia Tech Ballistic Testing



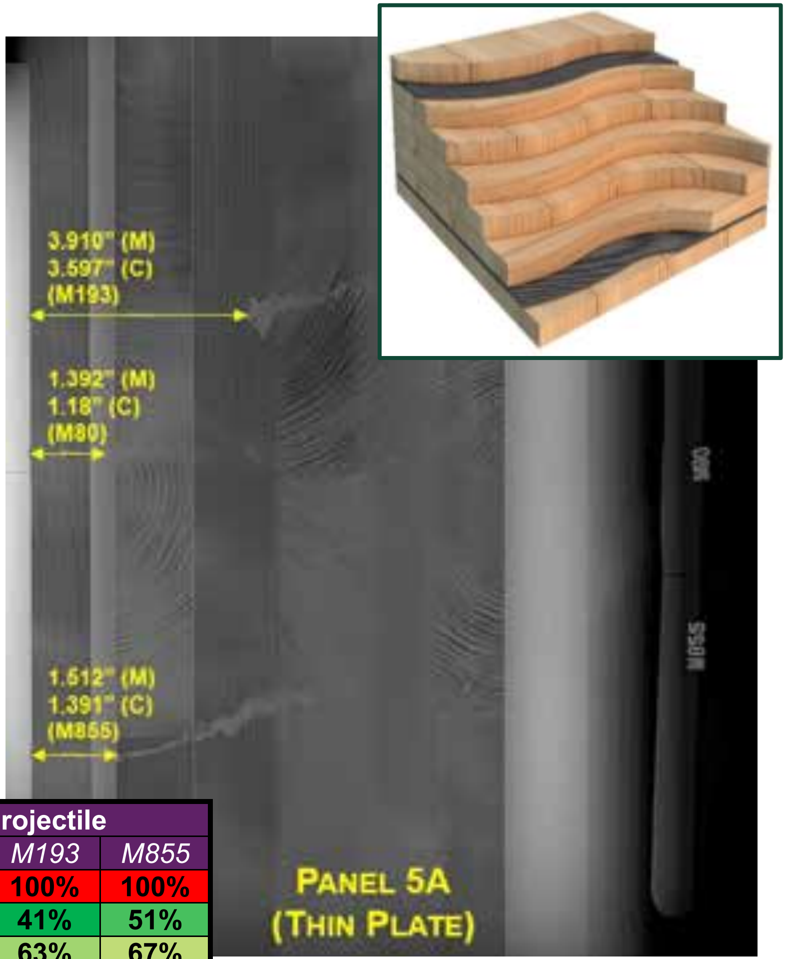


International Journal of Impact Engineering 128 (2019) 11–23

- Sanborn et al. (2019) performed 122 ballistic tests on Spruce Pine Fir – South (SPF-S) (i.e., SL-V4) and Southern Yellow Pine (SYP) CLT tiles of various thicknesses
- ½” diameter sphere projectile
- Indicates UFC 4-023-07 is very conservative (for this nose shape)
- Refit UFC equation based on test data for SPF-S & SYP (mean squared error = 0.33)

Reinforced CLT – Ballistic Testing

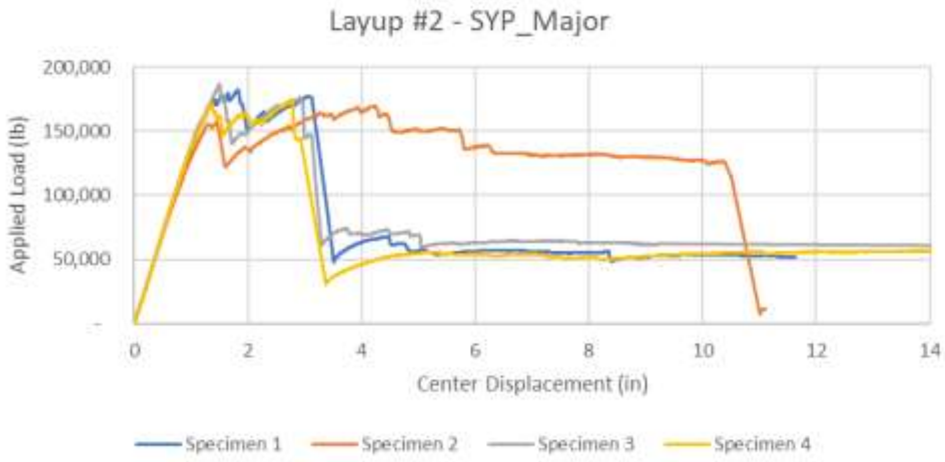
- Ballistic testing effort indicated feasibility of embedding steel plates within CLT panel layup from a cost / weight / performance perspective
  - 72 tests performed on 18” x 18” tiles
  - Varied wood species and non-wood interlayers in 8 candidate layups
  - DOS ballistic design basis threat (SD-STD-01.01, Rev. G)
  - Good adhesion between steel and wood
    - Failure in wood fiber rather than at bond line in simple shear tests



ID	Description	Projectile		
		M80	*M193*	*M855*
1	Baseline	100%	100%	100%
2	All Hardwood	88%	41%	51%
3	Hardwood + Softwood	100%	63%	67%
4	Interlocking + Softwood	100%	100%	100%
5	Thin Plate	85%	63%	78%
6	Fine Mesh	100%	49%	58%
7	Coarse Mesh	84%	59%	65%
8	Thick Plate	61%	43%	72%

Reinforced CLT – Quasi-Static Bending Testing

- 12 tests on 3 different reinforced CLT layups
- Demonstrated feasibility of manufacturing full-scale reinforced CLT panels cost effectively
- Excellent steel-to-wood bond
- Predominant failure mode rolling shear
  - Significant post-peak ductility even w/ rolling shear failure



x64 speedup

Specimen 1, Northeast Corner

DOS Forced Entry Test

- 1 test performed on 7-ply panel w/ SPF-South laminations in each direction ($9^5/_8$" total panel thickness)
  - Only known FE test on CLT
- DOS 60-minute FE design basis threat (SD-STD-01.01, Rev. G)
- Panel resisted FE attack for over 40 minutes

Ongoing Testing

- OBO Mass Timber Study (2022-2023)
  - Blast, FE/BR, Progressive Collapse testing to incorporate CLT in DOS diplomatic buildings
- Additional Reinforced CLT testing (2022-2023)
  - Blast testing of panels
  - Moisture transport studies

Available Design Aids

- WoodWorks Protective Design Website
- Protective Design Center-Technical Report (PDC-TR) 18-02
  - Analysis Guidance for Cross-Laminated Timber Construction Exposed to Airblast Loading
- Unified Facilities Criteria (UFC) 4-023-07
  - Design to Resist Direct Fire Weapons Effects
- Progressive Collapse Strategies

WoodWorks Protective Design Website

- Repository of information and videos related to mass timber and protective design

Learn Tools Events Award Gallery Why Wood? About

WOODWORKS

Protective Design

Home > Learn > Mass Timber / CLT > Protective Design

https://www.woodworks.org/learn/mass-timber-clt/protective-design/

Blast, Ballistic and Forced Entry Test Reports

- Quasi-Static Out-of-Plane Testing of CLT and NLT Panels
  Research
- Blast-Resistant Testing for Mass Timber Exterior Walls – Final Accomplishment Report
  Research
- Results from Blast Tests of Full-Scale CLT Structures
  Research
- Results from Phase 2 Blast Tests of Full-Scale CLT Structures
  Research
- High-Fidelity Physics-Based Modeling of CLT
  Research
- Development of a Cost-Effective CLT Panel Capable of Resisting DOS/DOD Design Basis Threats – Final Report
  Research

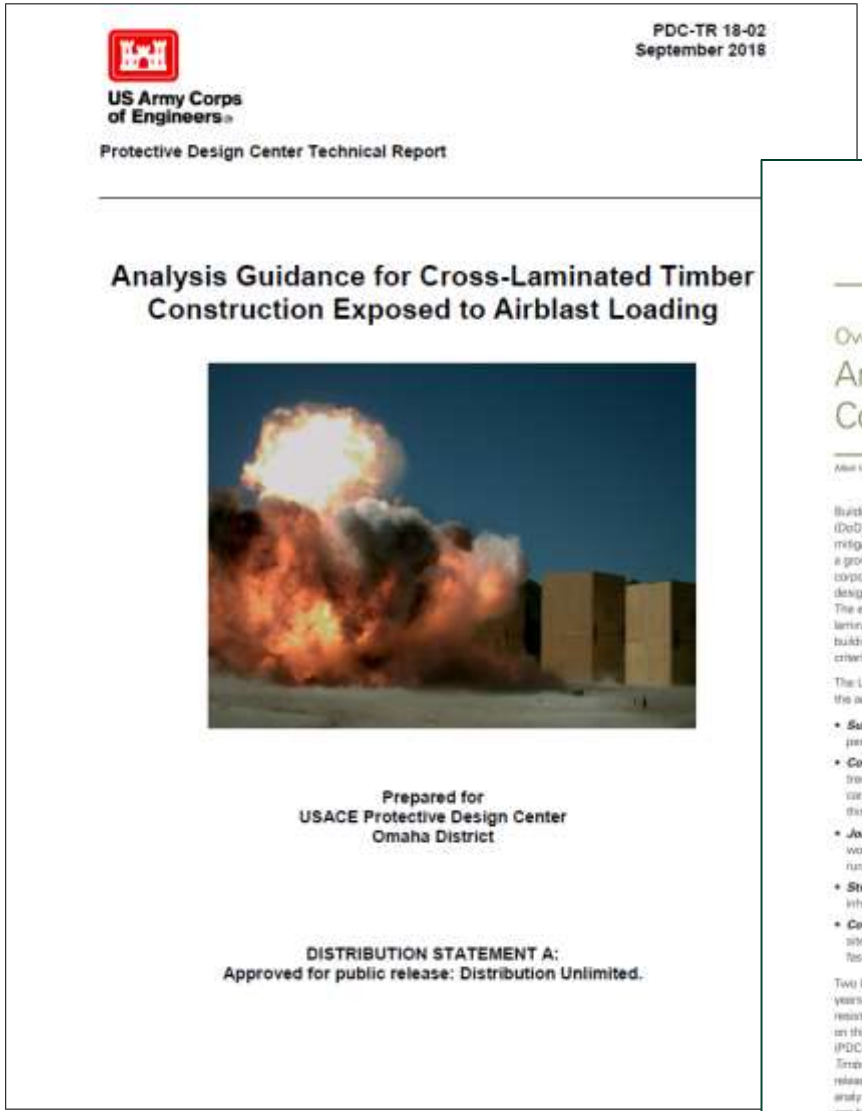
Blast & Forced Entry/Ballistic Protection

Buildings that house critical assets often have to meet blast as well as forced entry/ballistic resistance (FE/BR) design requirements to mitigate the hazardous effects associated with terrorism. Historically, these buildings have been constructed using concrete and steel. A significant amount of testing has been performed to demonstrate the ability of these building materials to resist blast and FE/BR threats. Fewer tests have been performed on wood construction for similar threats. At least part of this stems from the relative difficulty of designing light-frame wood construction to resist these threats efficiently and economically.

However, the emergence of mass timber construction, and cross-laminated timber (CLT) in particular, both in the U.S. and internationally, presents an opportunity to provide a sustainable building material alternative to owners and architects developing high-security buildings. The solid, panelized nature of CLT allows for both inherent strength and ease of construction. Further, as connections for CLT panels typically consist of steel and timber elements, ductile energy-absorbing

PDC-TR 18-02

Analysis Guidance for Cross-Laminated Timber Construction Exposed to Airblast Loading


US Army Corps of Engineers

Protective Design Center Technical Report

PDC-TR 18-02
September 2018

Analysis Guidance for Cross-Laminated Timber Construction Exposed to Airblast Loading

Prepared for
USACE Protective Design Center
Omaha District

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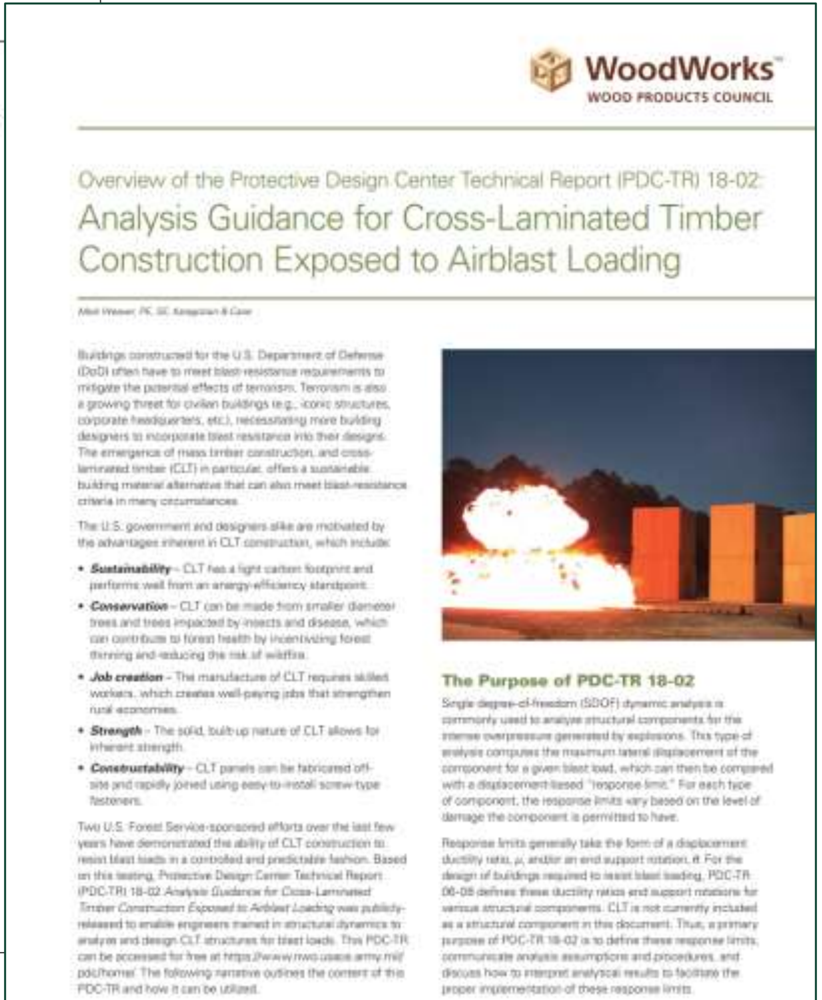
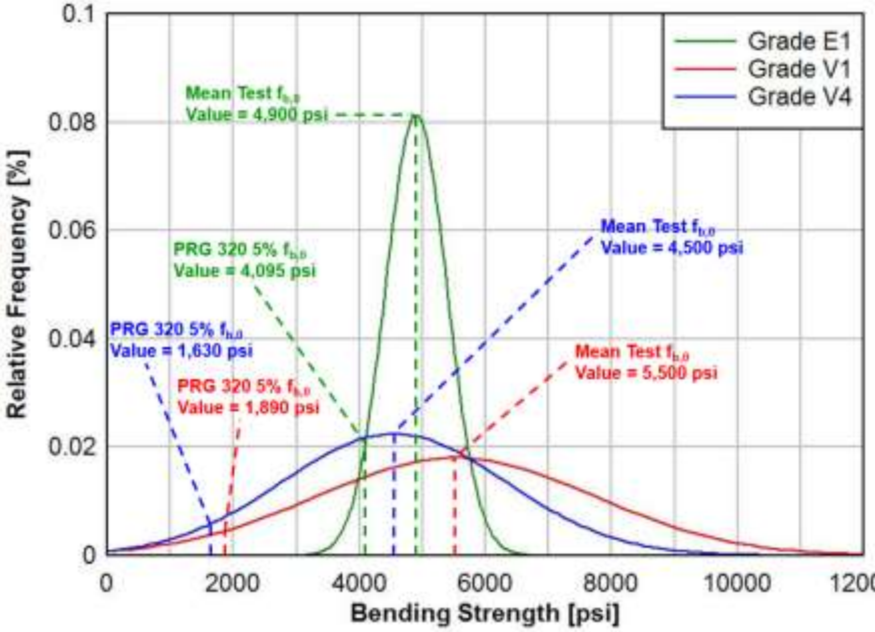

WoodWorks
WOOD PRODUCTS COUNCIL

Overview of the Protective Design Center Technical Report (PDC-TR) 18-02:

Analysis Guidance for Cross-Laminated Timber Construction Exposed to Airblast Loading

The Purpose of PDC-TR 18-02

- Blast design guidance for CLT for structural engineers
  - WoodWorks released an overview of PDC-TR 18-02
- Considers inherent variation in wood and how this impacts blast resistance



UFC 4-023-07

Design to Resist Direct Fire Weapons Effects

- Equations to assess ballistic response of wood panels
  - Perforation
  - Residual Velocity

https://www.wbdg.org/ffc/dod/unified-facilities-criteria-ufc/ufc-4-023-07

Equation 5-1. Wood Thickness to Prevent Projectile Perforation

$$T_W = 9837\left(\frac{v^{0.4113}w^{1.4897}}{\rho\left(\frac{\pi D^2}{4}\right)^{1.3596}H^{0.5414}}\right)$$

Where:
T_W = thickness of wood necessary to prevent perforation (in)
v = projectile impact velocity (ft/s) (conservatively use muzzle velocity in Appendix C
w = projectile weight (lbs) (see Appendix C)
D = projectile diameter (in2)
ρ= wood density (lbs/ft3) (see Table 5-5)
H = wood hardness (lbs) (see Table 5-5)

Table 5-5 Wood Properties

Species		Density (lbs./ft³)	Hardness (pounds)
Pine	Dry	23.5	38.7
	Wet	30	51.1
Maple	Dry	35	76.9
	Wet	40	72
Green Oak	Dry	55	88.1
	Wet	55	72.1
Marine plywood	Dry	37	68.7
	Wet	37	58.8
Balsa	Dry	6	21
	Wet	6	61.5
Fir plywood	Dry	30	75
	Wet	30	68.9
Hickory	Dry	50	74.3
	Wet	55	63.5

Equation 5-2. Residual Velocity from Wood Target

$$v_r = v\left[1.0-\left(\frac{t}{T_w}\right)^{0.5791}\right]$$

Where:
v_r = residual velocity (ft/s)
t = actual target thickness (in)

UFC 4-023-07
7 July 2008
Change 1, 1 February 2017

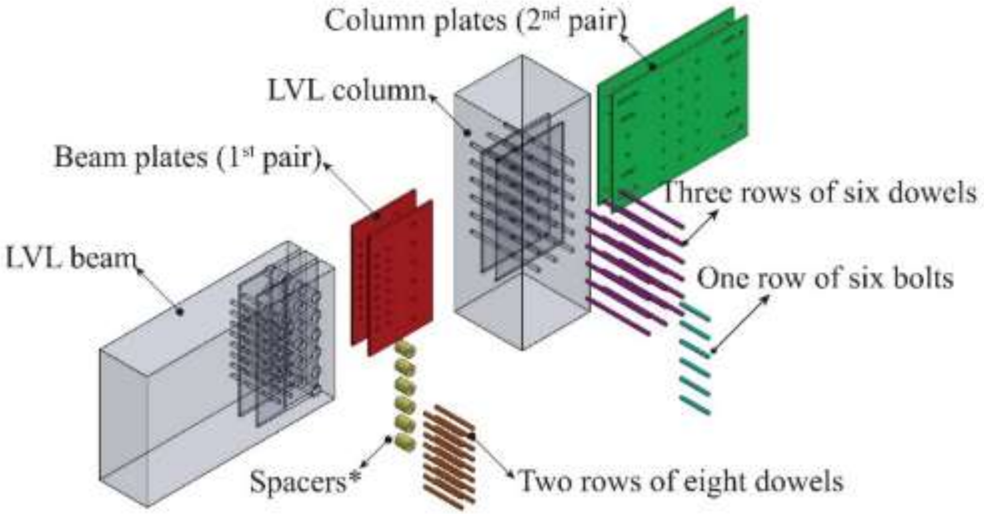
UNIFIED FACILITIES CRITERIA (UFC)

DESIGN TO RESIST DIRECT FIRE WEAPONS EFFECTS

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

Progressive Collapse: State-of-Practice

- Current UFC 4-023-03 provisions for wood structural systems only considers light frame construction
  - Tie force not typically feasible
  - Alternate Path is most common
- Strategies to address progressive collapse requirements
  - CLT walls act as deep beams
  - Continuity plates in beam-column connections (e.g., double plate assembly)
  - Reinforcement in topping for catenary action
- Research in this area is ongoing



Experimental collapse response of post-and-beam mass timber frames under a quasi-static column removal scenario
Lyu et al. (2020)

Connections

- CLT connections are inherently ductile
  - Wood crushing and steel yielding are primary limit states encountered

- Different connection types have been exposed to blast loads via arena testing

WoodWorks Index of Mass Timber Connections

This index is a compilation of connections used in mass timber construction. Mass timber elements are solid wood pieces with inherent fire resistance due to their mass, as defined in the 2021 International Building Code (IBC). Examples of mass timber include but are not limited to cross-laminated timber (CLT), dowel-laminated timber (DLT), nail-laminated timber (NLT), glue-laminated timber (GLT), mass plywood panels (MPP), and structural composite lumber (SCL) products such as laminated veneer lumber (LVL) and laminated strand lumber (LSL). Mass timber can be used as structural floors, roofs, walls, columns and/or beams. The examples in this index illustrate a broad spectrum of connections for use in mass timber construction. Depending on the unique constraints of each project, the connection choice made by the designer may be influenced by aesthetics, load carrying capacity, fire-rating requirements, quality assurance requirements, cost and/or constructability. The purpose of the index is to facilitate the designer's selection of project-appropriate connections.

The index includes structural and architectural connections created for WoodWorks by **KL&A Engineers & Builders** and **Oz Architecture** in cooperation with **Swinerton Builders**. For information on these firms and their mass timber projects, follow the links above to view their profiles on the WoodWorks Innovation Network.

FREE PROJECT SUPPORT | EDUCATION | RESOURCES

For free technical assistance related to mass timber connections, or any aspect of the design, engineering or construction of a commercial or multi-family wood building in the U.S., visit woodworks.org to contact the WoodWorks Regional Director nearest you or email help@woodworks.org.

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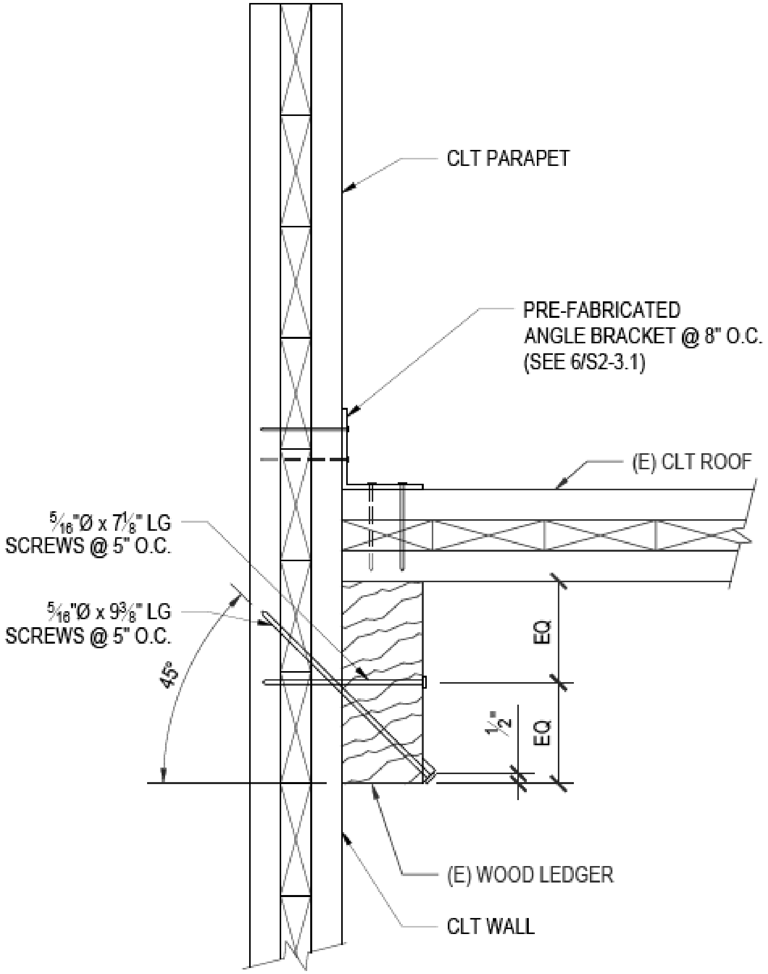
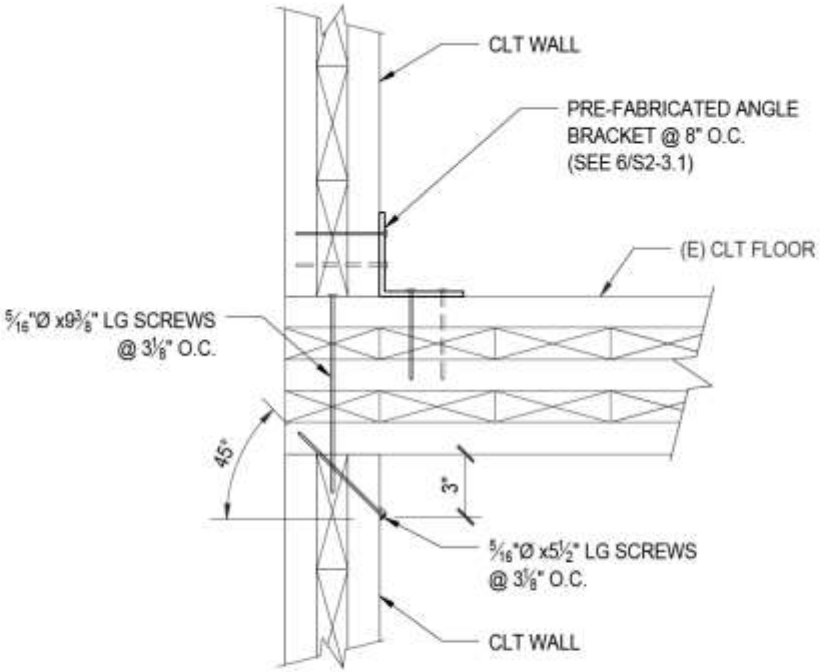
Examples of CLT Connections Exposed to Blast Loading

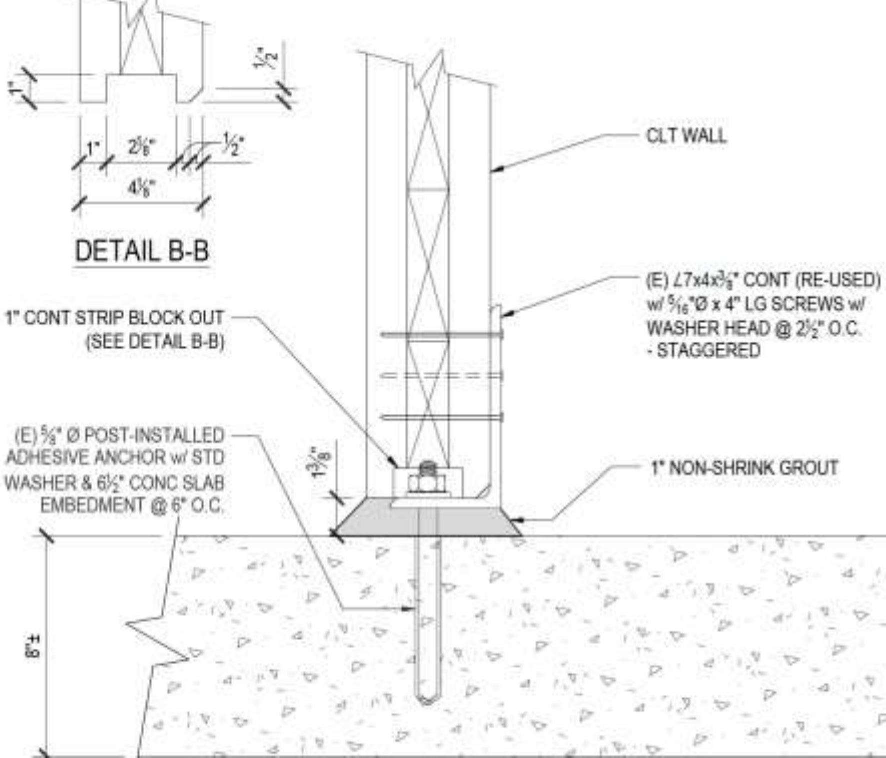
Balloon Framing Condition



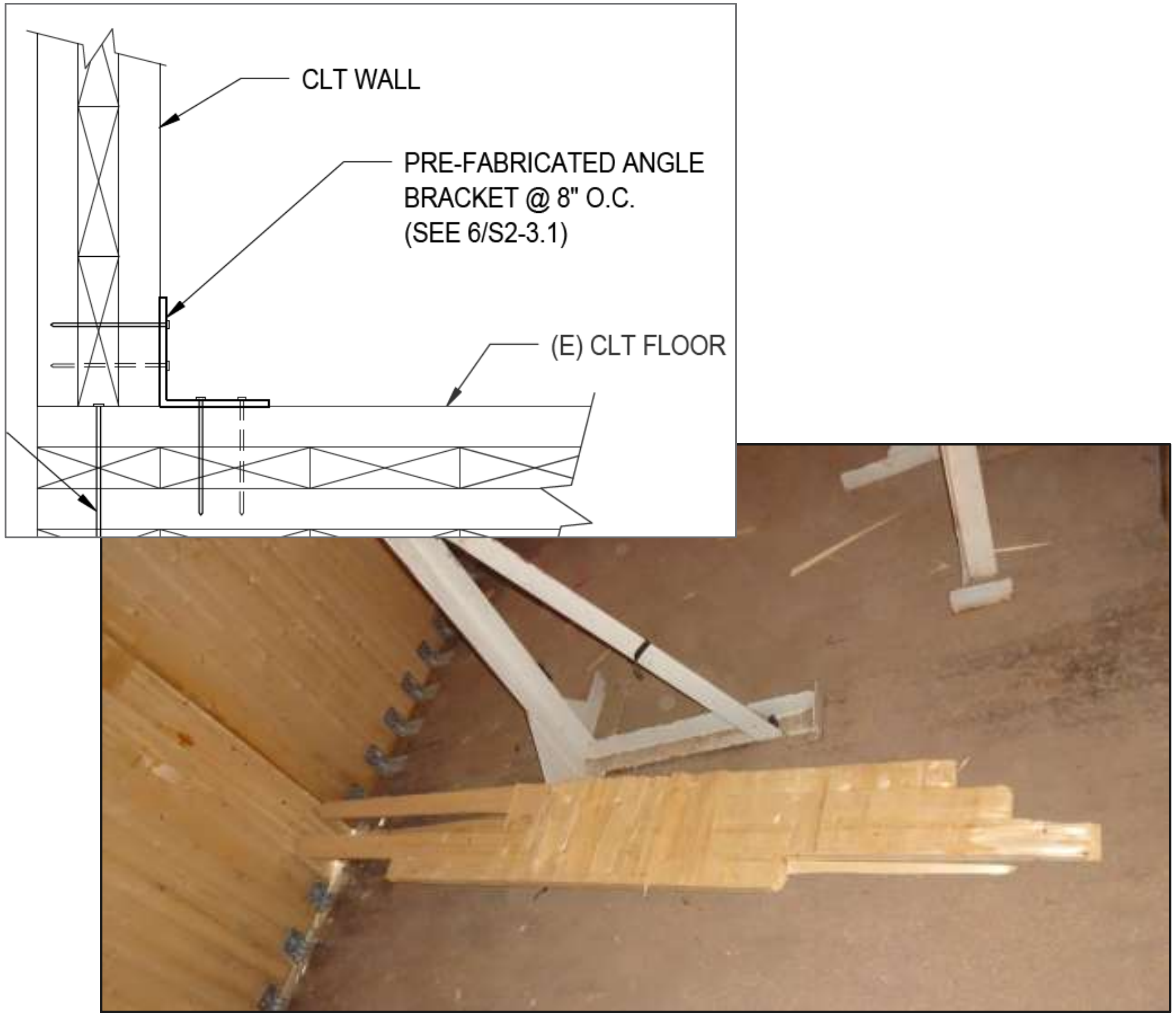
Platform Framing Condition



Base Condition

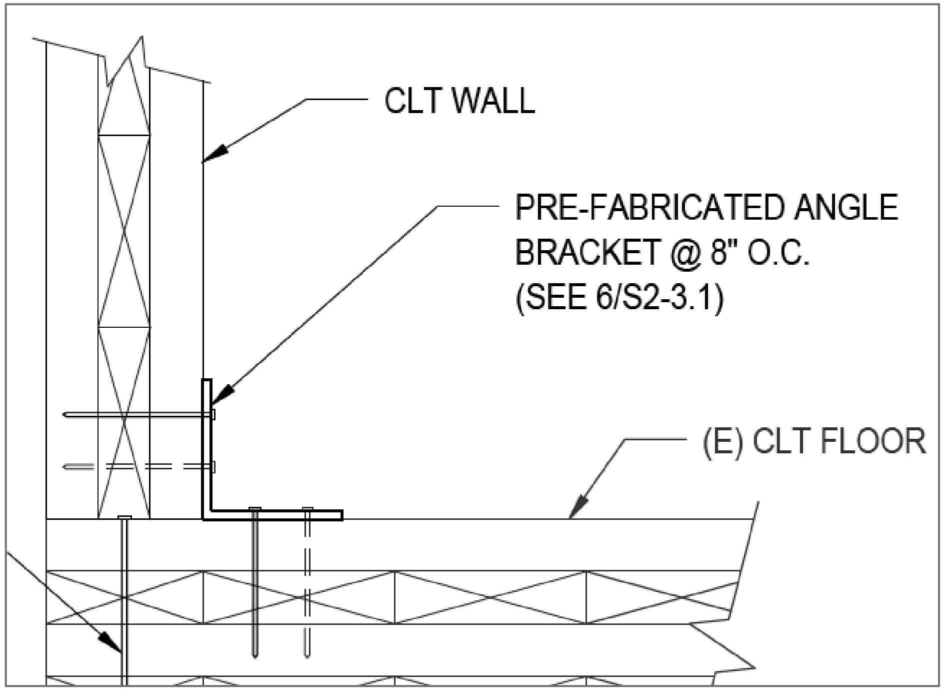


Post-Test Observations: The Good



Designed to develop strength of panel and remains intact even when panel is overloaded

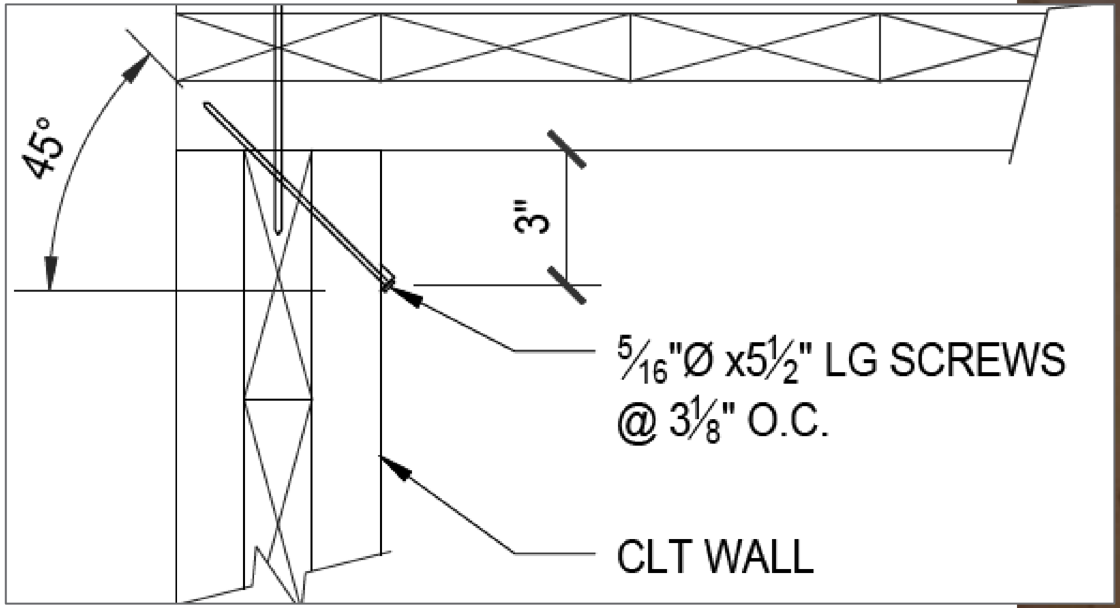
Post-Test Observations: The Bad



Screw with incorrect length (1-1/2" instead of 3-1/2") was installed => screw withdrawal results when panel is overloaded

Post-Test Observations: The Ugly

Designed to develop strength of panel, yet connection fails when panel is overloaded



Case Study

Candlewood Suites

Joint Base Lewis McChord

Photo: IHG – Candlewood Suites

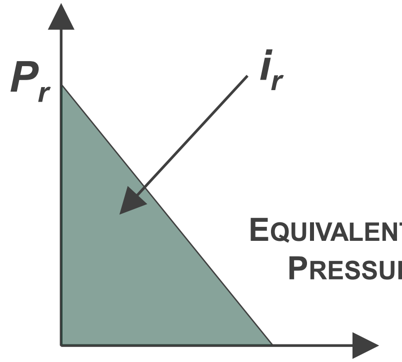
Case Study Overview

- Designed for blast and progressive collapse in accordance w/ UFC 4-010-01 (2013 version)
- Building characteristics
  - 5 stories
  - Load bearing 3 and 4-ply CLT wall panels w/ brick veneer
  - UFC 4-010-01 (2013) required panels exhibit a LLOP for the design blast load
  - Design blast load
    - EWI @ 500’
    - EWII @ 50’ <= this combination controls the blast design
      - 50’ standoff selected to allow for reasonable blast windows (i.e., see Table C-2 of UFC 4-010-01 (2020))
- The slides that follow will go through how the typical wall panel was designed for blast loading

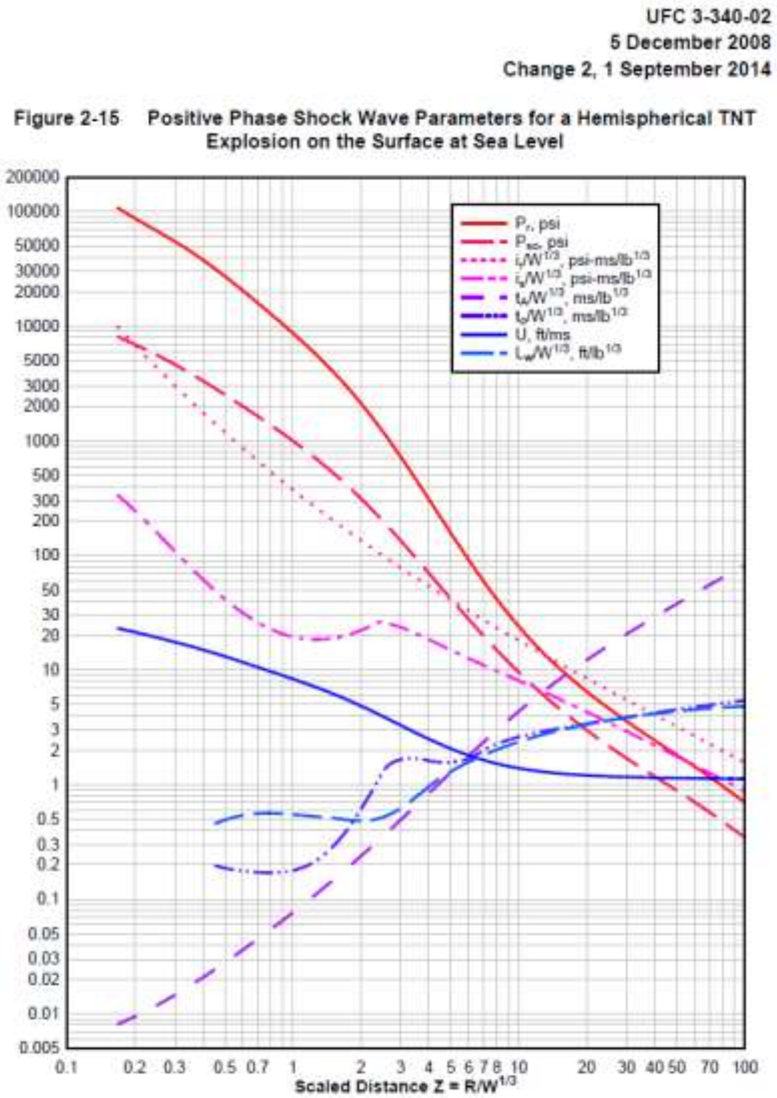
Blast Design Example

Step 1: Determine Design Blast Loads Using Kingery-Bulmash Curves

- Kingery-Bulmash curves for hemispherical (surface) burst included as Figure 2-15 of UFC 3-340-02
- Use Scaled Range, *Z*, to determine positive phase reflected pressure, P_r, and reflected impulse, i_r
    - Blast loads not shown for security reasons
- Construct pressure history
    - Equivalent Triangular, Friedlander, Equivalent Exponential Decay are popular pressure history forms
- May need to consider the following to obtain peak panel response:
    - Negative phase of blast loading for load bearing CLT panels
    - Actual shock wave history



EQUIVALENT TRIANGULAR PRESSURE HISTORY



Blast Design Example

Step 2: Get Panel Stiffness and Strength Properties from APA Report

- PDC-TR 18-02 Reference: Section 7.1
- Example: Properties for 3-ply V4M1 grade panel by SmartLam in ESR-4733
  - $(EI)_{eff,0}$ = 74 x 10^6 lb-in^2/ft
  - $(GA)_{eff,0}$ = 0.41 x 10^6 lb/ft
  - $(F_bS)_{eff,0}$ = 1,800 lb-ft/ft
  - $V_{s,0}$ = 1,490 lb/ft
  - F_c = 1,000 psi

TABLE 4—ASD REFERENCE DESIGN VALUES FOR SMARTLAM BALANCED CLT PANELS[1]

GRADE	LAYUP[2]	THICKNESS t_p[3] (in.)	MAJOR STRENGTH DIRECTION				MINOR STRENGTH DIRECTION			
			$(F_bS)_{eff,f,0}$ (lb-ft/ft)	$(EI)_{eff,f,0}$ (x10^6 lb-in.^{2}/ft)	$(GA)_{eff,f,0}$ (x10^6 lb/ft)	$V_{s,0}$ (lb/ft)	$(F_bS)_{eff,f,90}$ (lb-ft/ft)	$(EI)_{eff,f,90}$ (x10^6 lb-in.^{2}/ft)	$(GA)_{eff,f,90}$ (x10^6 lb/ft)	$V_{s,90}$ (lb/ft)
V4M1[4,5]	3-alt	$4^1/_8$	1,800	74	0.41	1,490	245	2.9	0.41	495
	4-maxx	$5^1/_2$	2,925	161	0.49	1,980	975	23	0.85	990
	5-alt	$6^7/_8$	4,150	286	0.83	2,480	2,120	74	0.83	1,490
	5-maxx	$6^7/_8$	5,150	355	0.85	2,480	245	2.9	0.49	495
	6-maxx	$8^1/_4$	7,200	596	0.83	2,975	975	23	0.83	990
	7-alt	$9^5/_8$	7,325	707	1.2	3,475	4,875	286	1.2	2,480
	7-maxx	$9^5/_8$	9,425	909	1.2	3,475	2,120	74	0.89	1,490

ES ICC EVALUATION SERVICE APA

Joint Evaluation Report **ESR-4733**

Issued December 2020

This report is subject to renewal December 2021.

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DIVISION: 06 00 00—WOOD, PLASTICS AND COMPOSITES
Section: 06 17 19—Cross-laminated Timber

REPORT HOLDER:

SMARTLAM, LLC

EVALUATION SUBJECT:

SMARTLAM CROSS-LAMINATED TIMBER (CLT)

1.0 EVALUATION SCOPE

1.1 Compliance with the following codes:

- 2018, 2015, 2012 and 2009 *International Building Code®* (IBC)
- 2018, 2015, 2012 and 2009 *International Residential Code®* (IRC)

For compliance with codes adopted by Los Angeles Department of Building and Safety (LADBS), see ESR-4733 LABC and LARC Supplement.

Property evaluated:

- Structural
- Fire Resistance

1.2 Evaluation to the following green code(s) and/or standards:

- 2019 California Green Building Standards Code (CALGreen), Title 24, Part 11
- 2015, 2012, and 2008 ICC 700 *National Green Building Standard™* (ICC 700-2015, ICC 700-2012 and ICC 700-2008)

Attributes verified:

- See Section 3.1.

2.0 USES

SmartLam cross-laminated timber (CLT) panels are a certified engineered wood product and are used as a component in floors, roofs, and walls in Type III (interior floors only), Types IV and V Construction; and in roofs in Type I and II Construction of the IBC. The SmartLam CLT panels, when installed under the IRC, require an engineered design in accordance with IRC Section R301.1.3.

3.0 DESCRIPTION

3.1 General:

The SmartLam CLT panels described in this evaluation report comply with requirements noted in Section 2303.1.4 of the 2018 and 2015 IBC, for allowable stress design (ASD) in accordance with 2018 IBC Section 2302.1(1) (2015, 2012 and 2009 IBC Section 2301.2(1)). The panels are fabricated with at least three planed softwood lumber laminations with adjacent laminations glued together at an angle of 90° except that the outermost two layers are permitted to be parallel to each other, as shown in Tables 2 and 3. The panels are fabricated with widths of 12 to 120 inches (305 to 3048 mm), thicknesses of 4⅛ to 12⅜ inches (105 to 314 mm) and lengths up to 52 feet (15.8 m). The SmartLam CLT panels are fabricated by face-bonding each layer of laminations using a structural adhesive, complying with Section 3.2.2 of this evaluation report. The layers are placed in a press to form a dimensionally stable structural element. Refer to Tables 2 and 3 for SmartLam CLT panel layups.

The attributes of the CLT panels have been verified as conforming to the provisions of (i) CALGreen Section A4.404.3 for efficient framing techniques; (ii) ICC 700-2015 Sections 608.1(b), 11.608(b), and 12(A).608.1(b) for resource-efficient materials; (iii) ICC 700-2012 Sections 608.1(2), 11.608.1(2) and 12(A).608.1 for resource-efficient materials; and (iv) ICC 700-2008 Section 607.1(2) for resource-efficient materials. Note that decisions on compliance for those areas rest with the user of this report. The user is advised of the project-specific provisions that may be contingent upon meeting specific conditions, and the verification of those conditions is outside the scope of this report. These codes or standards often provide supplemental information as guidance.

3.2 Material:

3.2.1 Wood Laminations: Wood laminations used in fabricating SmartLam CLT panels must be in accordance with the approved in-plant manufacturing standard and are Spruce-pine-fir (SPF), Spruce-pine fir south (SPF-S), Hem-fir (HF), or Douglas fir-Larch (DF-L) lumbers having ASD reference design values provided in Table 1 of this evaluation report. The outermost SPF, SPF-S, or HF laminations may be permitted to be replaced by DF-L lumber with design properties that are equal to or greater than the corresponding SPF, SPF-S, or HF laminations.

3.2.2 Adhesives: Adhesives used to face-bond layers of SmartLam CLT panels and adhesives used for finger-joints of wood laminations are non-formaldehyde, one-component polyurethane based, exterior-type structural adhesives, conforming to ANSI/APA PRG 320-2019 and the product specifications in the approved quality documentation.

4.0 DESIGN AND INSTALLATION

4.1 General:

Design and installation of SmartLam CLT panels must be in accordance with this evaluation report, the applicable code provisions and the manufacturer's published design and installation instructions. The manufacturer's design and

Blast Design Example

Step 3: Assign Static Increase Factor (SIF) & Dynamic Increase Factor (DIF)

- Transforms *ASD reference design values* to *average expected dynamic* values
- PDC-TR 18-02 Reference: Section 7.2
- Example: SIF for flatwise bending of 3-ply V4M1 panel

$$SIF_b = K_{char} K_{avg} K_{size} = 1.30 * 2.05 * \left(\frac{11.25}{4.125}\right)^{0.29} = 3.56$$

- PDC-TR 18-02 Reference: Section 7.2
  - DIF is defined as 2 for flatwise bending and shear strengths of CLT panel exposed to blast loading

Blast Design Example
Step 4: Check to See if Moment Strength Must Consider Axial Load

- PDC-TR 18-02 Reference: Section 8.2.1
- Example: Ratio of axial stress, f_{dc}, to average expected dynamic compressive strength, F_{dc}, for 3-ply V4M1 grade panel
  - Number of stories: 5
  - Typical Exterior Wall Tributary Width: 7 ft
  - Typical Floor Dead Load: 44 psf
  - Typical Floor Live Load: 40 psf
  - Typical Floor Height: 12 ft
  - Typical Exterior Wall Dead Load: 52 psf

PDC-TR 06-08, Section 4-2

$$P = 5 * 7 * [44 + (0.35 * 40)] + 5 * 12 * 52 = 5{,}150\ lb/ft$$

$$f_{dc} = \frac{P}{A_{parallel}} = \frac{5150}{33} = 156\ psi$$

$$SIF_c = K_{char}K_{avg}K_{size} = 1.20 * 1.40 * 1.00 = 1.68$$

$$F_{dc} = SIF_c * DIF * F_c = 1.68 * 2 * 1000 = 3{,}360\ psi$$

$$\frac{f_{dc}}{F_{dc}} = \frac{156}{3360} = 0.046 < 0.10$$

∴ Axial load does not need to be considered when computing flatwise bending moment strength of panel

Blast Design Example

Step 5: Construct Resistance Function

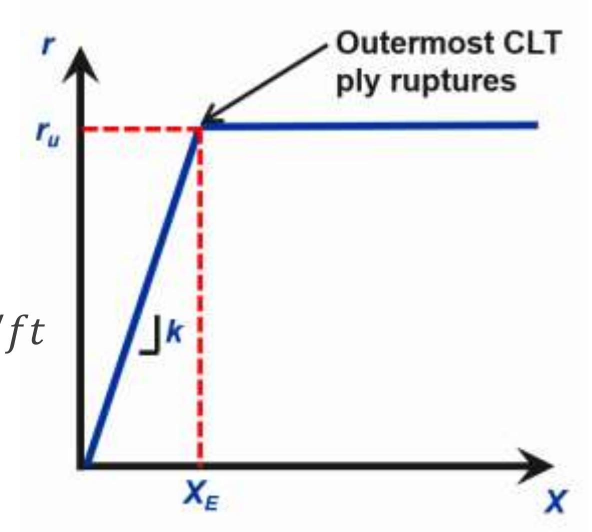
- PDC-TR 18-02 Reference: Section 8
- Example: Ultimate resistance, r_u, and stiffness, k, of 3-ply V4M1 grade panel

$$(EI)_{app} = \frac{(EI)_{eff}}{1 + \frac{K_s (EI)_{eff}}{(GA)_{eff} L^2}} = \frac{74 \times 10^6}{1 + \frac{11.5 * 74 \times 10^6}{0.41 \times 10^6 * 144^2}} = 67.2 \times 10^6 \; lb \cdot in^2/ft$$

$$k = C_{adj\_EI} * \frac{(EI)_{app} b_w}{k_b b L^4} = 1.0 * \frac{67.2 \times 10^6 * 1}{\frac{5}{384} * 12 * 144^4} = \boxed{1.00 \; psi/in}$$

$$M_n = 0.9 * SIF_b * DIF * C_{adj\_b} * (F_b S)_{eff} = 0.9 * 3.56 * 2 * 1 * 1800 = 11.5 \times 10^3 \; lb \cdot ft/ft$$

$$V_n = 0.9 * SIF_s * DIF * C_{adj\_s} * V_s = 0.9 * 2.6 * 2 * 1 * 1490 = 6.97 \times 10^3 \; lb/ft$$



$$r_{u\_v} = \frac{2 V_n b_w}{bL} = \frac{2 * 6.97 \times 10^3 * 1}{12 * 144} = 8.07 \; psi$$

$$X_E = \frac{r_u}{k} = \frac{4.46}{1.00} = \boxed{4.46 \; in}$$

$$r_{u\_b} = \frac{8 M_n}{L^2} = \frac{8 * 11.5 \times 10^3}{144^2} = \boxed{4.46 \; psi}$$

Flatwise bending resistance is smaller than flatwise shear resistance and thus is the ultimate resistance

Blast Design Example
Step 6: Determine Equivalent Mass of Wall Panel

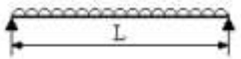
- Example: Mass for 3-ply V4M1 grade panel w/ brick veneer (40 psf)
  - Specific gravity (SG): 0.36 (Spruce-Pine-Fir (South) lumber plies in both directions) (2018 NDS, Table 12.3.3A)
  - Moisture content (MC): 12% (ANSI/APA PRG 320-2019, Section 6.1.5)

$$m_{panel} = \frac{SG * A_{wood} * \gamma_{water} * (1 + MC)}{g} = \frac{0.36 * 4.125 * 0.0361 * (1 + 0.12)}{3.86 \times 10^{-4}} = 156\ psi \cdot ms^2/in$$

$$m = m_{panel} + m_{veneer} = 156 + \frac{40}{144 * 3.86 \times 10^{-4}} = \boxed{876\ psi \cdot ms^2/in}$$

- Because single degree of freedom (SDOF) analysis implicitly assumes all mass and load is “lumped” at the DOF of interest, an equivalent mass must be determined since the mass (and blast load) is distributed over the length of the member. This is done via the load-mass transformation factor, K_{LM}.
  - UFC 3-340-02 provides tables with K_{LM} factors

Table 3-12 Transformation Factors for One-Way Elements

Edge Conditions and Loading Diagrams	Range of Behavior	Load Factor K_L	Mass Factor K_M	Load-Mass Factor K_{LM}
	Elastic Plastic	0.64 0.50	0.50 0.33	0.78 0.66

Blast Design Example
Step 7: Perform SDOF Analysis

- Solve Newton's second law of motion to determine the peak displacement, u_{max}, of the panel
  - Common to ignore damping (velocity) term in blast design

$$p(t) = \underbrace{K_{LM} m}_{\text{Equivalent mass}} \ddot{u}(t) + \underbrace{f_s(u, \dot{u}, t)}_{\text{Resistance function}}$$

Pressure history

- Potential means of solving differential equation
  - UFC 3-340-02 charts (e.g., see right)
  - Fast running tool (e.g., SBEDS, BlaSDOF, etc.)

Natural period of panel

$$T_N = 2\pi\sqrt{\frac{K_{LM} m}{k}} = 2\pi\sqrt{\frac{0.78 * 876}{1.00}} = \boxed{164\ ms}$$

u_{max} = 1.95”

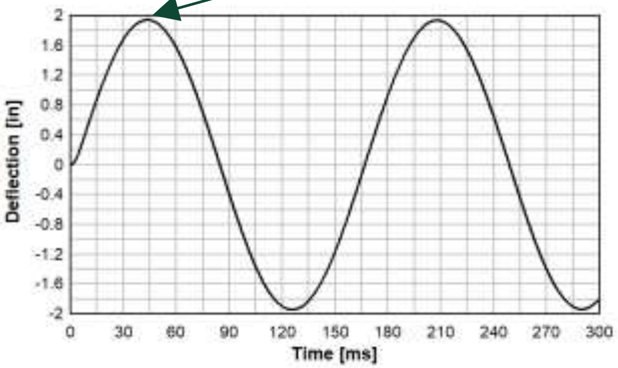
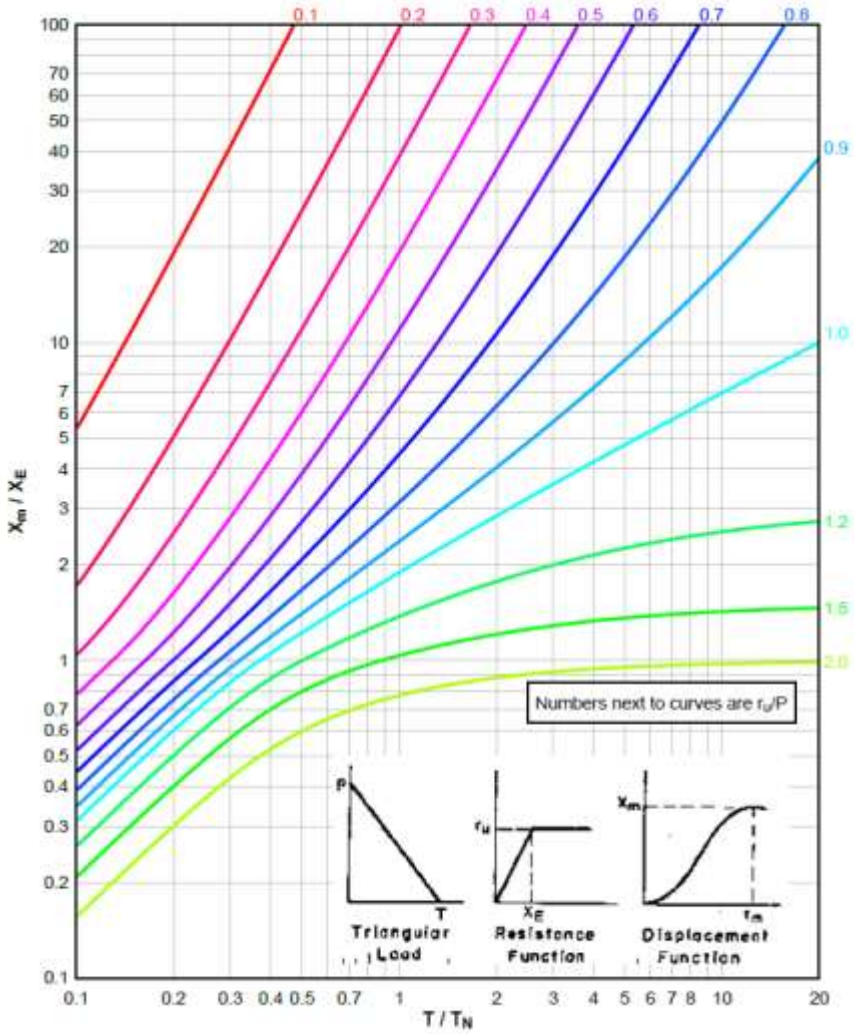


Figure 3-54 Maximum Deflection of Elasto-Plastic, One-Degree-of-Freedom System for Triangular Load



Blast Design Example

Step 8: Compare Peak Displacement w/ Response Limit

- PDC-TR 18-02 Reference: Section 10

Table 5. Response Limits for CLT Construction.

Controlling Limit State	B1		B2		B3		B4	
	μ	θ	μ	θ	μ	θ	μ	θ
Flatwise Bending	1.0	-	1.5	-	1.75	-	2	-
Flatwise Shear	1.0	-	1.5	-	1.75	-	2	-

- Example: Primary component (i.e., load bearing wall) must exhibit moderate damage (i.e., less than the B2 response limit in PDC-TR 18-02) to achieve a low level of protection (LLOP)

$$\mu = \frac{u_{max}}{X_E} = \frac{1.95}{4.46} = 0.44 \ < 1.50 \quad \therefore OK$$

Closing Thoughts

- Many high-security facilities that would benefit from strong, panelized, environmentally friendly building material option
  - Government (DoD infrastructure, embassy)
  - 911 Call Centers
  - Courthouses
- Mass timber has inherent blast / forced entry resistance
  - Two-way action of CLT helps to distribute load, and thus minimize peak response at highest applied load
    - NLT does not share this benefit
- Connections for mass timber systems can be easily designed to exhibit ductile response (i.e., steel yielding, wood crushing)
  - This contrasts with other modular systems (e.g., precast concrete)
- Ballistic resistance of wood is poor
  - Reinforced CLT helps overcome this shortcoming

❯ QUESTIONS?

This concludes The American Institute of Architects Continuing Education Systems Course

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