United States Department of Agriculture

Proceedings

Mass Timber Research Workshop 2015

USDA Forest Products Laboratory
Madison, Wisconsin, USA
November 3–4, 2015

Forest Service | Forest Products Laboratory | General Technical Report FPL–GTR–241 | March 2016

Abstract

This report summarizes the proceedings, including key points and identified research needs, that evolved from the Mass Timber Research Workshop, which was held at the USDA Forest Products Laboratory (FPL), November 3–4, 2015. The purpose of the workshop was to bring design professionals, researchers, and industry leaders together to examine the state-of-the-art in mass timber construction, with an emphasis on cross-laminated timber, and to identify technical barriers to the broader use of wood in engineered structures that need to be addressed. Following a plenary session on mass timber in North America, some 120 scientists, engineers, and industry leaders heard presentations organized in four technical areas: (1) resistance to lateral loads, (2) building performance—durability, sound, vibration, and life cycle assessment, (3) fire safety, and (4) material resources and other research topics. Breakout sessions aimed at identifying future research objectives were then held for each of the four technical areas, followed by a prioritization of future research needs. Included in these proceedings are abstracts from each presentation, copies of all presentations and a summary of research needs.

Keywords: Mass timber, cross-laminated timber, wood construction, engineered wood structures

March 2016

Williamson, Tom; Ross, Robert J. 2016. (Eds.) Proceedings: Mass Timber Research Workshop 2015. General Technical Report FPL-GTR-241. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 364 p.

A limited number of free copies of this publication are available to the public from the Forest Products Laboratory, One Gifford Pinchot Drive, Madison, WI 53726–2398. This publication is also available online at www.fpl.fs.fed.us. Laboratory publications are sent to hundreds of libraries in the United States and elsewhere.

The Forest Products Laboratory is maintained in cooperation with the University of Wisconsin.

The use of trade or firm names in this publication is for reader information and does not imply endorsement by the United States Department of Agriculture (USDA) of any product or service.

In accordance with Federal civil rights law and U.S. Department of Agriculture (USDA) civil rights regulations and policies, the USDA, its Agencies, offices, and employees, and institutions participating in or administering USDA programs are prohibited from discriminating based on race, color, national origin, religion, sex, gender identity (including gender expression), sexual orientation, disability, age, marital status, family/parental status, income derived from a public assistance program, political beliefs, or reprisal or retaliation for prior civil rights activity, in any program or activity conducted or funded by USDA (not all bases apply to all programs). Remedies and complaint filing deadlines vary by program or incident.

Persons with disabilities who require alternative means of communication for program information (e.g., Braille, large print, audiotape, American Sign Language, etc.) should contact the responsible Agency or USDA's TARGET Center at (202) 720–2600 (voice and TTY) or contact USDA through the Federal Relay Service at (800) 877–8339. Additionally, program information may be made available in languages other than English.

To file a program discrimination complaint, complete the USDA Program Discrimination Complaint Form, AD-3027, found online at http://www.ascr.usda.gov/complaint_filing_cust.html and at any USDA office or write a letter addressed to USDA and provide in the letter all of the information requested in the form. To request a copy of the complaint form, call (866) 632–9992. Submit your completed form or letter to USDA by: (1) mail: U.S. Department of Agriculture, Office of the Assistant Secretary for Civil Rights, 1400 Independence Avenue, SW, Washington, D.C. 20250–9410; (2) fax: (202) 690–7442; or (3) email: program.intake@usda.gov.

USDA is an equal opportunity provider, employer, and lender.

Proceedings

Mass Timber Research Workshop 2015

USDA Forest Products Laboratory
Madison, Wisconsin
November 3–4, 2015

Edited by

Tom Williamson, Managing Partner
Timber Engineering LLC, Vancouver, Washington

Robert J. Ross, Supervisory Research General Engineer
Forest Products Laboratory, Madison, Wisconsin

Contents

Preface, 6

Workshop Overview, 7

Plenary Session—Mass Timber in North America
- Role of WoodWorks in the Technology Transfer of Mass Timber Research, 28
- Importance of Mass Timber Research for the Softwood Lumber Industry, 36
- Cross Laminated Timber in the United States: Past, Present, and Future Issues, 48
- Updates/Overview of the Status of CLT R&D Activities and Tall Wood Buildings in Canada, 55
- The U.S. Tall Wood Building Prize Competition and USDA's Role with Mass Timber, 70

Session 1—Resistance to Lateral Loads
- Coming Soon: Seismic Performance Factors for Cross Laminated Timber Design, 74
- Performance of Mass Timber Structures under Lateral Loads: The Canadian Experience, 96
- Updates and Results from NEES–CLT Planning Project, 116
- The Heavy Timber Buckling Restrained Braced Frame System as a Solution for Commercial Construction in Regions of High Seismicity, 129
- CLT Diaphragm Research and Design in North America, 144

Session 2—Building Performance: Durability, Sound, Vibration, and Life Cycle Analysis
- CLT Systems: Acoustic, Vibration and Creep Performance, 157
- Hygrothermal Performance of Mass Timber Construction, 174
- Acoustic Prediction Models Create Basis for Future Competitive Wooden Structures, 185
- Comparative Life Cycle Assessment of a U.S. CLT Building: Planning and Challenges, 194

Session 3—Fire Safety
- Fire Safe Design of Exposed Mass Timber Buildings, 204
- Performance of Mass Timber Construction in Fire, 213
- Forest Products Laboratory Research on the Fire Performance of Cross Laminated Timber, 226
- Fire Safety of Tall Buildings—Property Protection View, 236

Session 4—Material Resources and Other Topics
- CLT Supply Chain from Forest to Market, 248
- Timber–Concrete Composites, 257
- Mass Timber Construction in Utah: Research, Practice, and Futures, 270
- Blast-Resistant Testing for Massive Timber Exterior Wall: Expanding Timber Opportunities in North America, 295
- Development of a Mass Timber Tornado Safe Room, 303
- More with Less—An Overview of the First CLT Hotel in the United States, 307

Keynote Presentation—Challenges of Building with Mass Timber in the United States, 321

Summary of Breakout Sessions
Breakout Session 1—Resistance to Lateral Loads, 339
Breakout Session 2—Building Performance: Durability, Sound, Vibration, and Life Cycle Analysis, 340
Breakout Session 3—Fire Safety, 341
Breakout Session 4—Material Resources and Other Topics, 343
Close-Out Session to Prioritize Future Research Needs, 344

Appendix 1—Discussion Notes for Breakout Session 1, Resistance to Lateral Loads, 347

Appendix 2—Discussion Notes for Breakout Session 2, Building Performance: Durability, Sound, Vibration, and Life Cycle Analysis, 350

Appendix 3—Discussion Notes for Breakout Session 3, Fire Safety, 353

Appendix 4—Discussion Notes for Breakout Session 4, Material Resources and Other Topics, 358

List of Attendees, 362

Preface

The use of large, solid sawn, and laminated timber members in the design and construction of structures has been a topic of research for over 100 years in North America. That research has resulted in many technical innovations that have yielded structures that have performed admirably in a wide range of applications, with many serving in a variety of capacities for nearly a century. Although heavy timber design principles and construction techniques have been in use worldwide for some time, there is a renewed, growing interest in the design and construction of large, multistory structures with massive engineered timbers, commonly referred to as "mass timber." Cross-laminated timber (CLT) is a relatively new engineered mass timber building product that has sparked considerable research and design activity worldwide.

CLT is a multilayer wooden panel made of lumber. Each layer of boards is aligned perpendicular to adjacent layers and connected by adhesives for increased rigidity and stability. CLT—developed in Europe as an environmentally friendly building product—has been used successfully in multistory applications, such as a nine-story apartment tower in London's East End and four- and seven-story buildings in Växjö, Sweden. CLT is making inroads in North America, but many technical questions have arisen concerning its use. For example, increasing density of modern urban population centers demands buildings that are taller and safer, resilient to natural hazards, and built from sustainable natural resources. CLT is a bio-based product that can achieve these objectives while utilizing low-value lumber stock such as emanating from beetle-killed trees, small-diameter growing stock, and other wood-based materials, rendering it an environmentally friendly engineered timber product. However, basic information needs to be developed to ensure safe designs.

A workshop was held at the USDA Forest Products Laboratory to provide a technical forum on the topic of mass timber research. The objectives of the *Mass Timber Research Workshop*, held November 3–4, 2015, were to (1) bring design professionals, researchers, and industry leaders together to examine the state-of-the-art in mass timber construction, with an emphasis on CLT, and (2) identify technical barriers to the broader use of mass timber in engineered structures that need to be addressed through research.

Following a plenary session on mass timber in North America, more than 120 scientists, engineers, and industry leaders heard presentations organized in four technical areas: (1) resistance to lateral loads, (2) building performance—durability, sound, vibration, and life cycle assessment, (3) fire safety, and (4) material resources and other research topics. Breakout sessions aimed at identifying future research objectives were then held for each technical area, followed by a prioritization of future research needs.

This report summarizes the proceedings, including key points and identified research needs that evolved from the *Mass Timber Research Workshop*. Included in these proceedings are abstracts from each presentation, copies of all presentations, and a summary of prioritized research needs.

Tom Williamson
Robert J. Ross
Editors

Workshop Overview

Michael Ritter, Assistant Director
USDA Forest Products Laboratory, Madison, Wisconsin

Welcome to FPL

Forest Service Seeks to Expand Wood Product Markets
Support Job Creation and Reduce Wildfire Threat

WASHINGTON, Oct. 20, 2015 — The U.S. Forest Service today announced that it is seeking proposals for projects to expand wood energy and wood products markets that support sustainable forest management, especially in areas with high wildfire risks. Grants will be made through the agency's Wood Innovations program.

"Forests on public and private lands face an increasing threat of catastrophic wildfires as vegetative fuels build to unprecedented levels," said Forest Service Chief Tom Tidwell. "The grants provided through this program not only help reduce hazardous fuels and improve forest health, but also create jobs to promote economic vitality in our communities."

For Fiscal Year 2016, the program will invest up to $5 million in projects designed to have a long-term impact on the National Forest System and other forested lands by leveraging the market for low value wood.

Funding is available for a diverse range of activities, from completion of a final engineering design for a renewable wood energy system to a demonstration of wood as a primary building material in commercial construction. Funding may also support business planning and other efforts to accelerate the manufacturing, market adoption and demonstration of innovative wood products.

Since 2005, more than 200 grants have been awarded to small businesses, non-profits, Tribes, States, and local governments to improve forest health while creating jobs, renewable energy and healthy communities. Since 2013, this funding has also helped establish 20 Statewide Wood Energy Teams and five Statewide Wood Utilization Teams that collectively expand and support wood energy and wood products markets.

The deadline for proposals is Jan. 15, 2016. Information on how to apply is available in the Federal Register Notice.

Workshop Objectives

- Better understand what research is currently in progress for mass timber
- Identify research gaps that must be filled to further advance mass timber structural systems
- Formulate an international network to share research information and compile non-refereed research in progress summaries

Thank You

- Timber Engineering LLC
  - Tom Williamson
- Softwood Lumber Board
  - Steve Lovett, Cees de Jager
- WoodWorks
  - Jennifer Cover, Jaime Krohn, Dawn Condotti, Karen Droste
- FPL Staff
  - Karen Martinson, Steve Schmieding, Bruce Smith, Karen Nelson, Bill Ireland, Jim Godfrey, Karla Cunningham

FPL Mission

"…to improve people's lives by helping to sustainably use our Nation's forest natural resources through leading-edge science, technology development and information delivery."

Guiding Principles

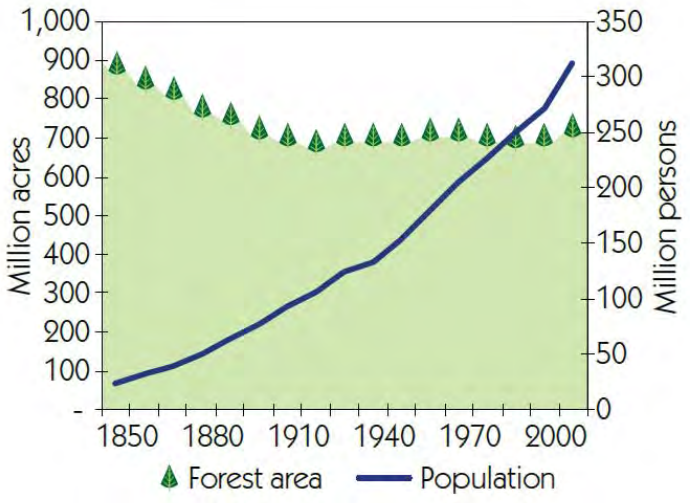
- America's forests are a major strategic asset that provide environmental, social, and economic benefits
- The US cannot maintain healthy, diverse, productive and sustainable forests without an equally healthy, diverse, productive and competitive forest products industry
- Forest products contribute to the Triple Bottom Line
  - Environmental Stewardship
  - Social Responsibility
  - Economic Prosperity (e.g. jobs and Gross Domestic Product)

Healthy and Sustainable Forests

"….. A key element in maintaining healthy, resilient forests is our ability to provide value-added products from the full complement of forest biomass."

Michael T. Rains
Director of the Forest Products Laboratory and Northern Research Station

U.S. Forest Land



Forest area and population trends in the United States, 1850–2010.

Why Mass Timber is Important

- Contributes to healthy, sustainable forests
- Improves utilization of forest mortality
- Helps keep working forests working
- Provides economic and employment opportunities
- Contributes to greenhouse gas mitigation
- Develops the potential using the urban wood resources

Healthy and Sustainable Forests

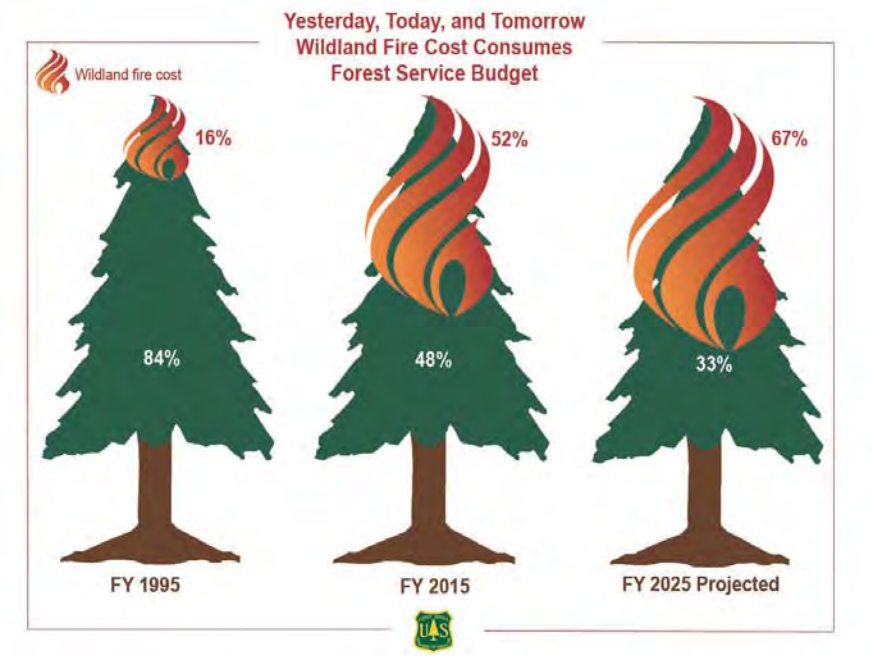
Healthy and Sustainable Forests

Healthy and Sustainable Forests

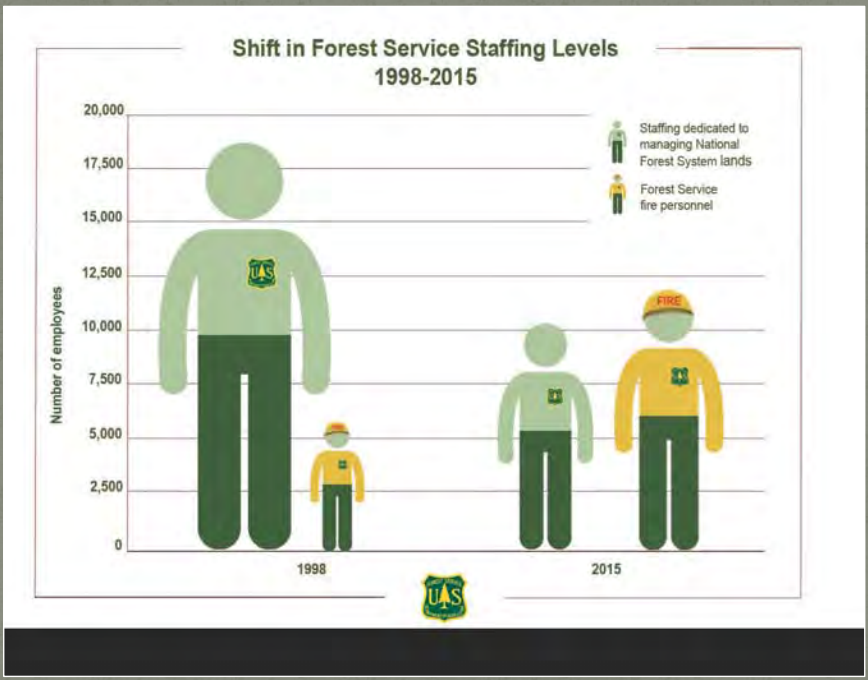
Healthy and Sustainable Forests

Fire readiness and suppression has gone from 20% of the FS budget in 2001 to 52% in 2015. It is not uncommon to spend $1 million per hour fighting fires.

Healthy and Sustainable Forests



Healthy and Sustainable Forests



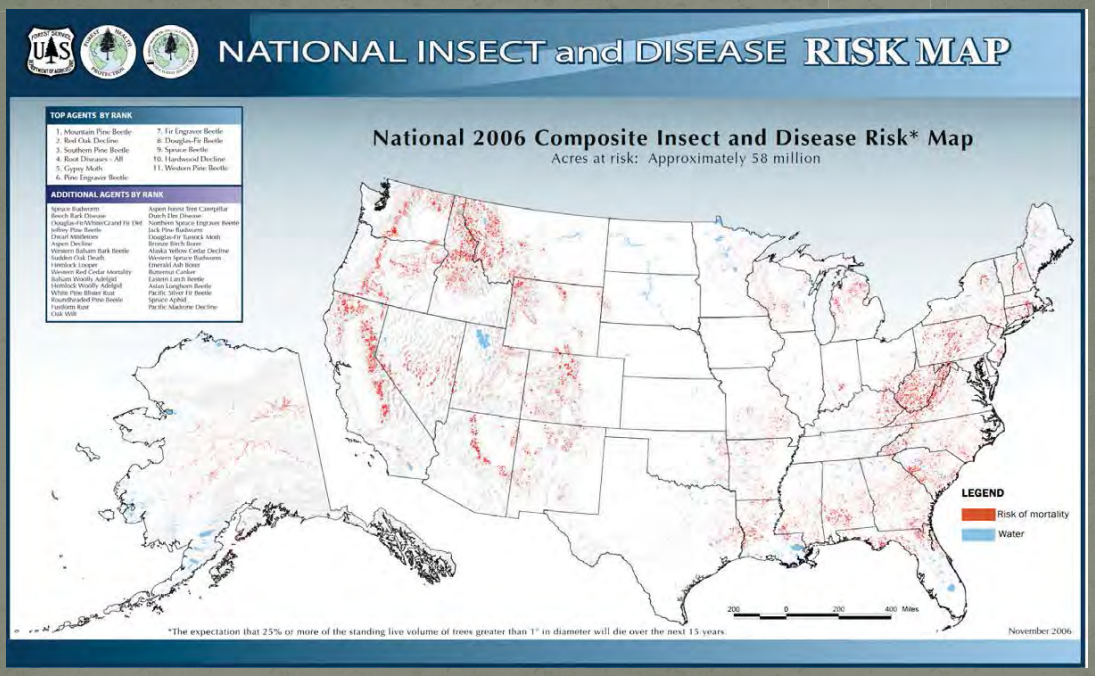
Healthy and Sustainable Forests

- **Opportunity:**
  Improve the health and resiliency of our forests and stimulate rural economies

- **Challenge:**
  Provide a consistent, sustainable material supply

Utilization of Forest Mortality

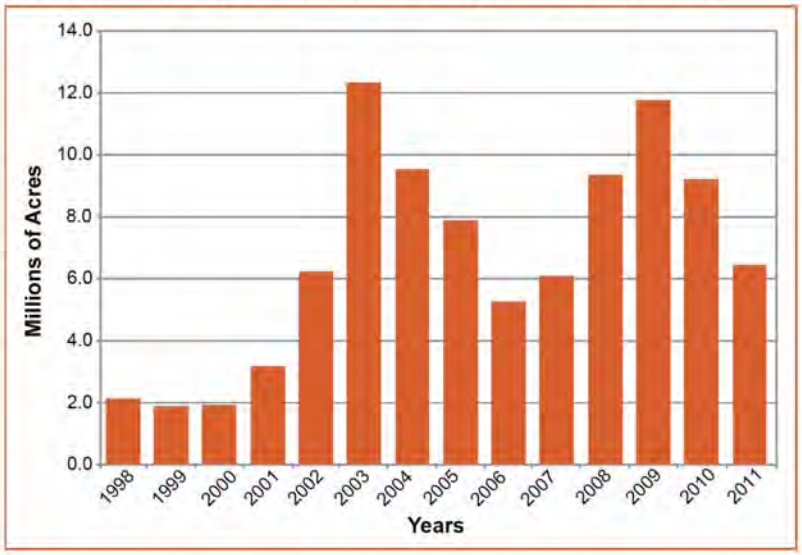
Utilization of Forest Mortality



Utilization of Forest Mortality

Utilization of Forest Mortality

Figure 1.—*Surveyed acres of mortality from 1998 to 2011.*



Utilization of Forest Mortality

Utilization of Forest Mortality

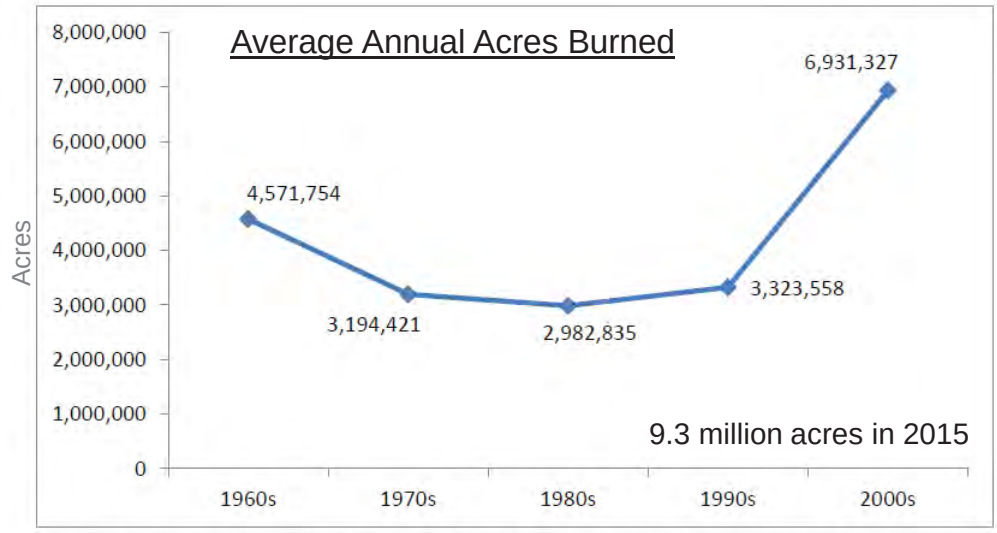


Figure 2 - Average annual acres burned, by decade. Rising firefighter effectiveness and other factors steadily lowered the number of acres burned until the 1990s, when a slight rise was followed by a sharp increase in the 2000s due to fuel buildups and worsening fire weather conditions.

Utilization of Forest Mortality

- **Opportunity:**
  Improve forest health and regeneration and access an abundant, low cost resource

- **Challenge:**
  Harvest material before it deteriorates and economically harvest and transport logs

Keep Working Forests Working

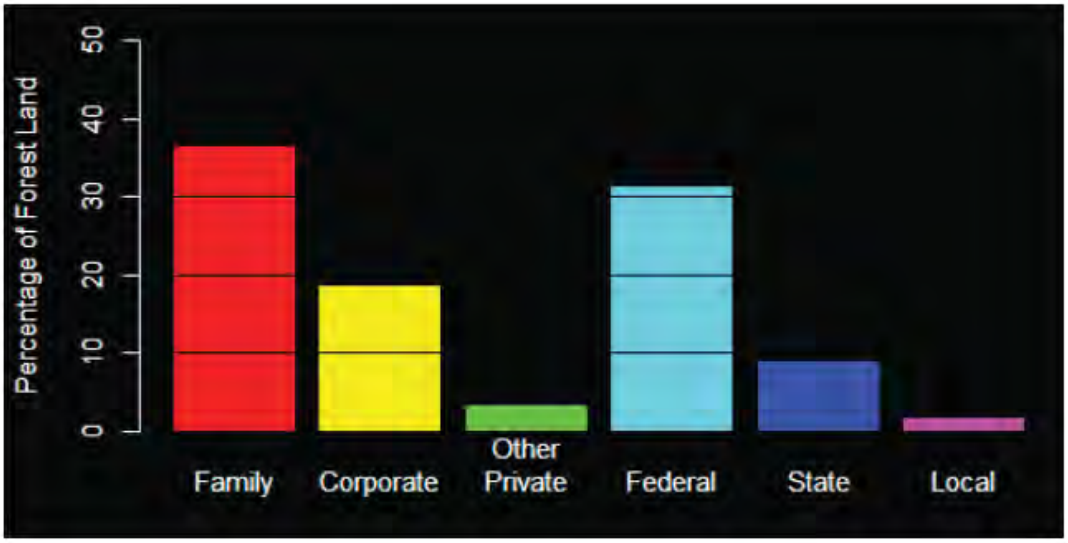


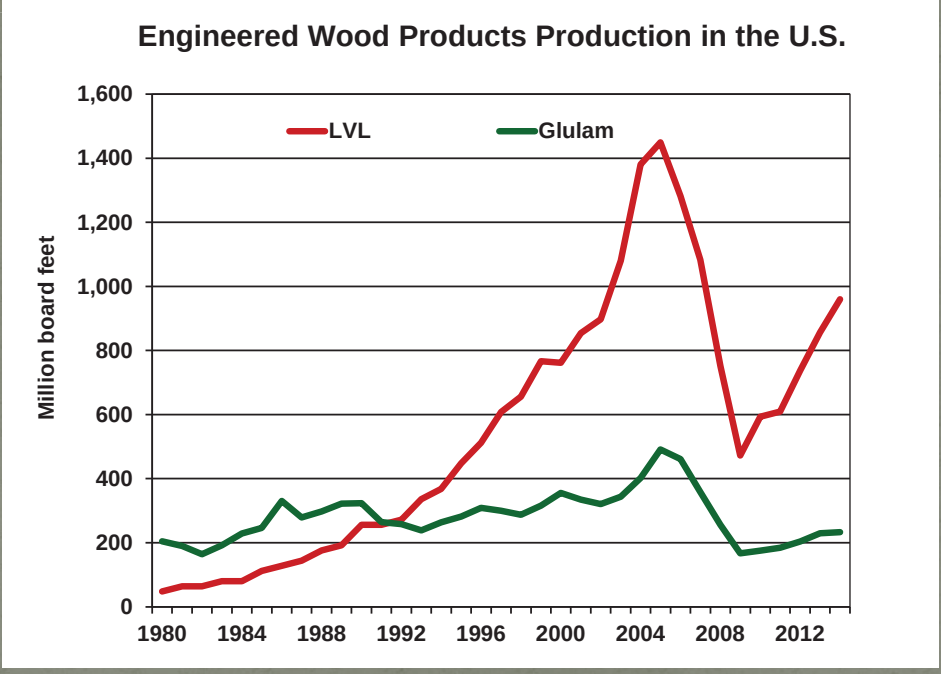
FIGURE 2-1 U.S. forestland ownership by class, 2011.
SOURCE: Available: http://www.fia.fs.fed.us/nwos [May 2014].

Keep Working Forests Working

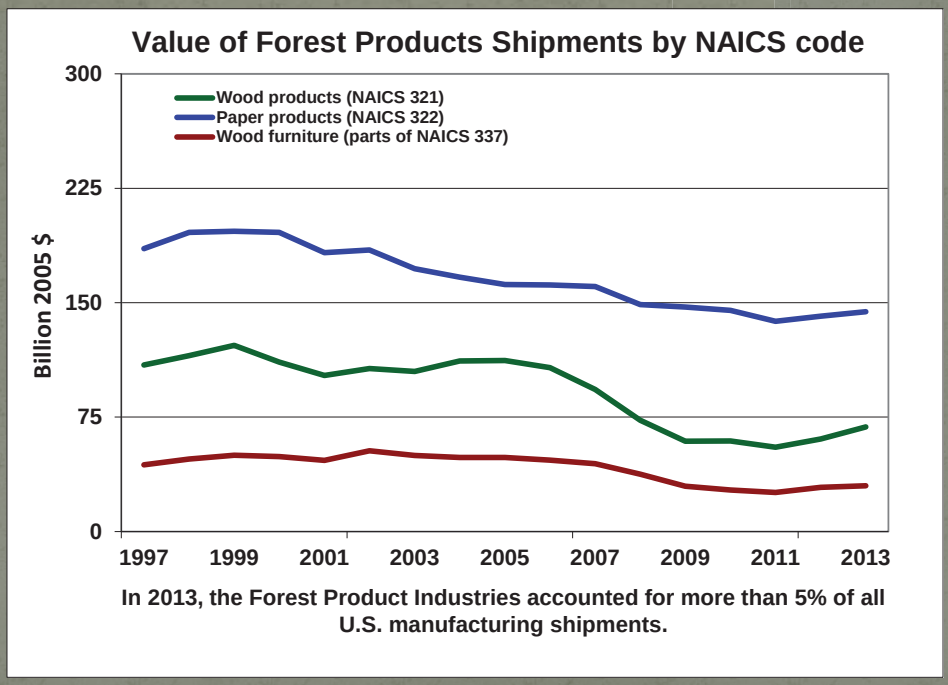
Keep Working Forests Working

- **Opportunity:**
  Family owned working forests provide an expanded source of material supply
- **Challenge:**
  Educate landowners on the advantages of forest management and sustainable harvesting

Economy and Employment

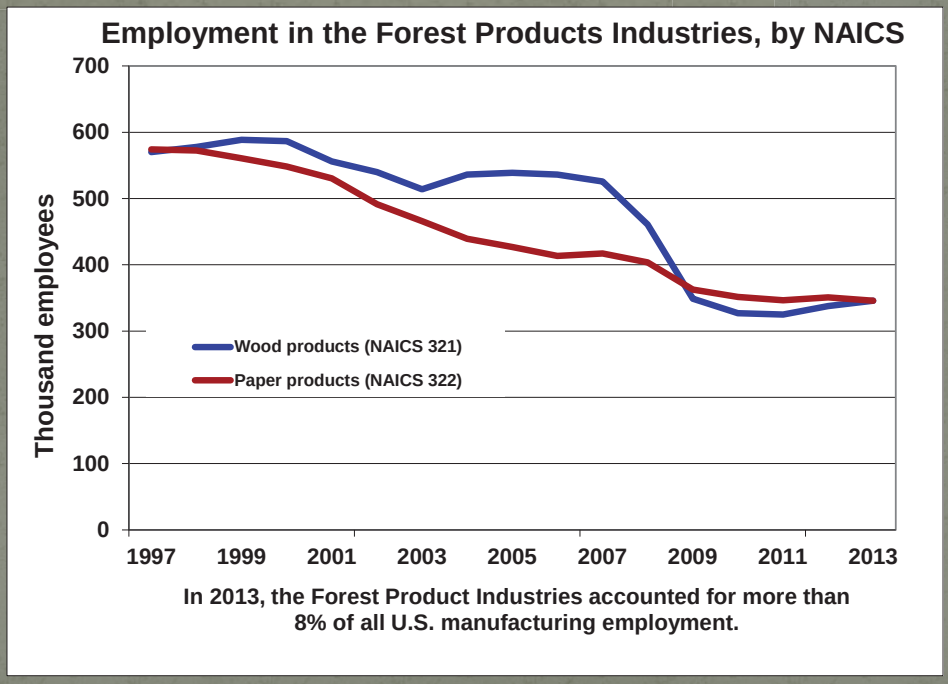


Economy and Employment



In 2013, the Forest Product Industries accounted for more than 5% of all U.S. manufacturing shipments.

Economy and Employment

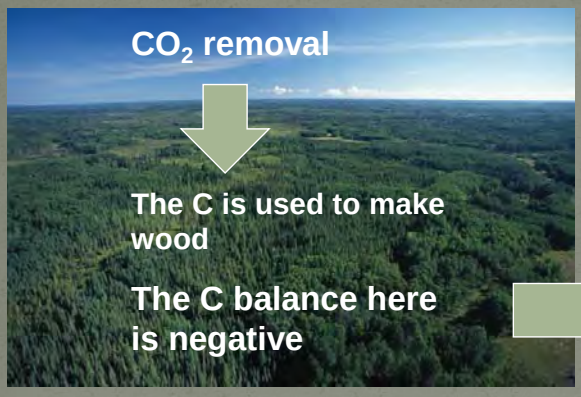


In 2013, the Forest Product Industries accounted for more than 8% of all U.S. manufacturing employment.

Economy and Employment

- **Opportunity:**
  Contribute to the local and national economies and provide jobs for rural development
- **Challenge:**
  Increase demand for mass timber

Greenhouse Gas Mitigation



CO_2 emissions due to harvesting, manufacturing, transportation +

Net C is NEGATIVE: more C is in the product than was emitted to atmosphere in making the product

Graphics from FPInnovations and the Athena Institute

Greenhouse Gas Mitigation

- 2.4 tons of CO_2 are absorbed to create 100 ft^3 of wood
- 100 ft3 of wood contains:
  - 0.65 tons of carbon
  - 0.55 tons of oxygen
  - 0.1 tons of hydrogen
  - minor amounts of other elements

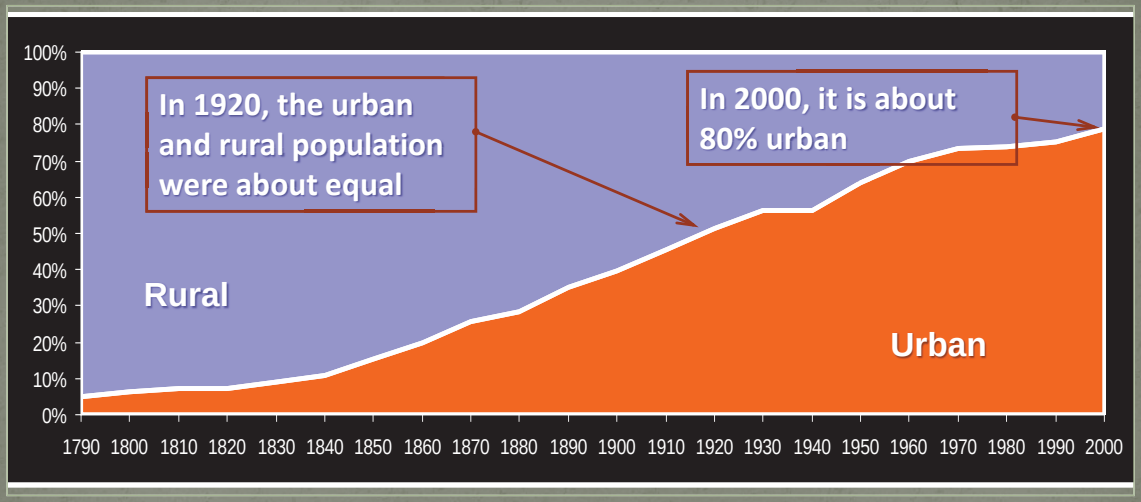
From: Building with wood = Proactive climate protection
Dovetail, BSLB, SUNY

Greenhouse Gas Mitigation

- Opportunity:
  Sequester carbon to mitigate greenhouse gas emissions and reduce the potential for climate change
- Challenge:
  Educate users on the environmental advantages of using mass timber

Urban Wood Utilization

Urban and Rural Population in the United States (1790 to 2000)



Urban Wood Utilization

Urban Wood Utilization

Urban Wood Utilization

Urban Wood Utilization

Demolition

Deconstruction

Urban Wood Utilization

- **Opportunity:**
  Provide an opportunity to utilize large quantities of urban wood that would otherwise be landfilled
- **Challenge:**
  Develop an infrastructure for harvesting, processing and marketing urban wood.

Conclusions I

The growth in demand for mass timber will help to foster environmental stewardship, social responsibility and economic development. To fully develop this potential, there must be a sustainable wood supply that can be harvested, transported and manufactured in a cost effective manner……..

Conclusions II

- *Requirements for design and construction of mass timber structures, as well as the availability of forest resources, varies by country and can vary within a country.*
- *Both research and technology transfer are critical to overcome barriers that hinder widespread mass timber use.*
- *Communicating research activities and identifying research needs and priorities will help us all achieve objectives in a more efficient, cost effective manner.*

Plenary Session—Mass Timber in North America

Role of WoodWorks in the Technology Transfer of Mass Timber Research

Jennifer Cover, Executive Director
WoodWorks, Washington, D.C.

As the only national program dedicated to educating architects and engineers on the use of wood as a structural building material in commercial, multifamily/midrise and taller wood construction, WoodWorks plays a central role related to mass timber technology transfer. As a “go-to” resource for designers, WoodWorks helps take innovative advancements from the research environment and place them in the hands of the design community so they can be applied to real-world projects, opening new markets and applications for wood products as quickly as possible. This presentation will cover the organization’s multifaceted approach to education and project support, which results in knowledgeable “wood champions” who are then well-positioned to make cost-effective material choices that reduce the carbon footprint of their projects. Examples of WoodWorks’s broad efforts related to mass timber market development will be highlighted, including two national tall wood symposia, efforts to open a market for wood use on military projects, and support for projects such as the Integrated Design Building at the University of Massachusetts, currently under construction.

WoodWorks Technical Staff

Wood Project Assistance

help@woodworks.org

Project Support Resources

WoodWorks™
WOOD PRODUCTS COUNCIL

Educational Outreach

Practitioner Education Hours

Jan to Sept 2015

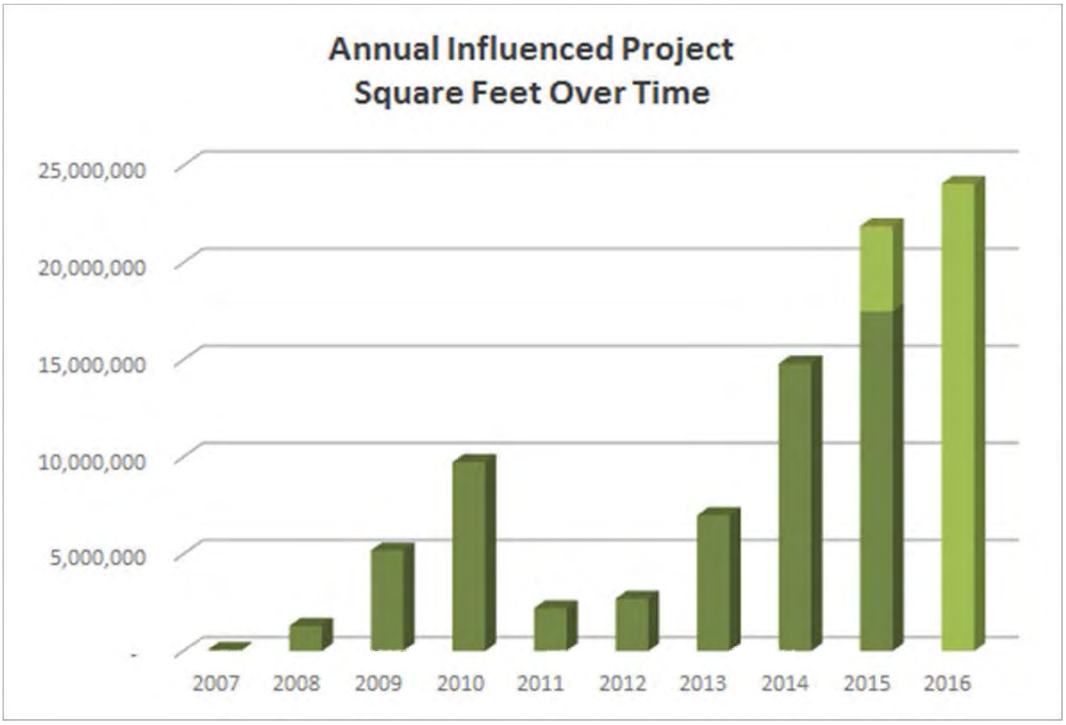
31,000

- *3 Wood Solution Fairs*
- *17 Workshops*
- *51 Lunch Seminars*
- *9 Webinars*
- *124 Lunch & Learns*
- *1 Tour*
- *48 Third Party Speaking Engagements*

WoodWorks™
WOOD PRODUCTS COUNCIL

Wood Design Provides Solutions

Impacting Projects – 330 YTD



WoodWorks™
WOOD PRODUCTS COUNCIL

Taking Wood Projects Taller

How do we get there in the U.S.?

- Creative Architects
- Engineering Advancements
- Code Advancements
- Innovative Wood Materials

Forté
Melbourne, Australia
10 stories
105.5 ft
Developer : Lend Lease
Completed 2012

Mass Timber Panels

Nail Laminated Timber (NLT)

Glue Laminated Timber (GLT)

Laminated Veneer Lumber (LVL)

Cross Laminated Timber (CLT)

Images Source: Structurecraft

Not shown: Laminated Strand Lumber (LSL)

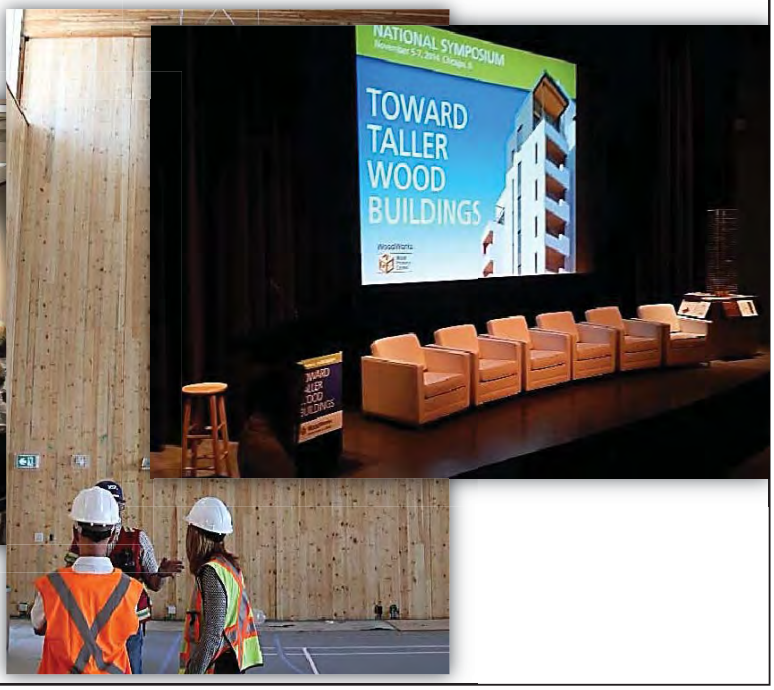
U.S. Tall Wood Building Prize Competition

Framework
Portland, OR
12 stories / 130 feet tall
Retail/office/apartments

475 West 18th Street
Manhattan, NY
10 stories / 120 feet tall
Commercial / condominiums

WoodWorks Creating Market Demand

18,700 hours of Tall Wood/Mass Timber education delivered



WoodWorks™
WOOD PRODUCTS COUNCIL

WoodWorks Project Support – Mass Timber

Franklin Elementary School (45,200 sq ft)
Franklin, WV

Paccar Environmental Technology Building at Washington State University (WSU)

WoodWorks™
WOOD PRODUCTS COUNCIL

Team providing assistance on ***12*** projects over 7 stories

Opening New Markets for Mass Timber

Department of Defense - Blast Testing of Mass Timber

Karagozian & Case completes a blast test of a curtain wall system for the government.

Redstone Hotel
Huntsville, AL
Photo Credit: Lend Lease

WoodWorks™
WOOD PRODUCTS COUNCIL

2016 Education Program Plan

Q1

- **32 Total Events**
- 1 WSF (Minneapolis)
- 11 Workshops (4 Series)
- 17 Lunch Seminars
- 3 Webinars

Q2

- **46 Total Events**
- 2 Wood Solutions Fairs (Portland & Oakland)
- 9 Workshops (4 Series)
- 23 Lunch Seminars
- 4 Interactive Design Sessions
- 1 Tour
- 4 Small Tours
- 3 Webinars

Q3

- **37 Total Events**
- 1 Wood Solutions Fairs (Houston)
- 5 Workshops (2 Series)
- 23 Lunch Seminars
- 1 Tour
- 4 Small Tours
- 3 Webinars

Q4

- **35 Total Events**
- 2 Wood Solutions Fairs (Philadelphia & Orlando)
- 7 Workshops (2 Series)
- 20 Lunch Seminars
- 1 Tour
- 2 Interactive Design Sessions
- 3 Webinars

150 branded events + over **200** Lunch 'n Learns = over **38,000** education hours

WoodWorks™
WOOD PRODUCTS COUNCIL

2016 Wood Solution Fairs

Six Wood Solution Fairs

- Minneapolis (Q1)
- Portland (Q2)
- Oakland (Q2)
- Houston (Q3)
- Philadelphia (Q4)
- Orlando (Q4)

Program Support

SLB SOFTWOOD LUMBER BOARD

FOREST SERVICE US DEPARTMENT OF AGRICULTURE

Canada

Forestry Innovation Investment

Wood Project Assistance
help@woodworks.org

WoodWorks Website
www.woodworks.org

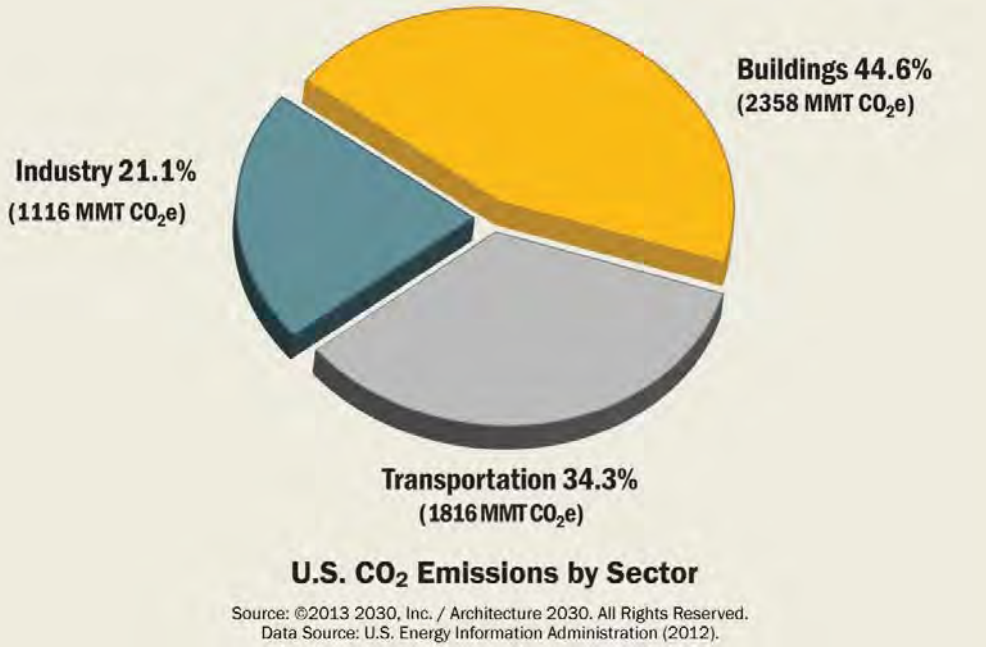
Importance of Mass Timber Research for the Softwood Lumber Industry

Steve Lovett, CEO
Softwood Lumber Board, Washington, D.C.

This presentation will cover the Softwood Lumber Board's (SLB's) purpose and programs emphasizing mass timber, SLB's interest in the conference, why it was important for SLB to partner with FPL as a sponsor, and what SLB hopes to gain from the conference. Finally, it will summarize how and why the conference and the follow-on activities will be important to all participants.

Global Climate Change

Buildings are responsible for nearly half of US CO2 emissions.



U.S. CO_2 Emissions by Sector

Source: ©2013 2030, Inc. / Architecture 2030. All Rights Reserved.
Data Source: U.S. Energy Information Administration (2012).

Global Climate Change

A Yale University-led study has found that using more wood and less steel and concrete in building and bridge construction would substantially reduce global carbon dioxide emissions and fossil fuel consumption.

--Yale News, March 31, 2014

Yale School of Forestry & Environmental Studies
University of Washington College of the Environment

Changing Attitudes

SLB SOFTWOOD LUMBER BOARD

"With a carbon footprint that's 75% less than that of concrete or steel, is it any wonder that wood has become a top contending material for green builders?"

US Green Building Council

ARTICLES

Sustainable building: Why wood is our most valuable resource

Published on 21 Aug 2015 Written by Tara Martinez Posted in Industry

SUSTAINABLE BUILDING

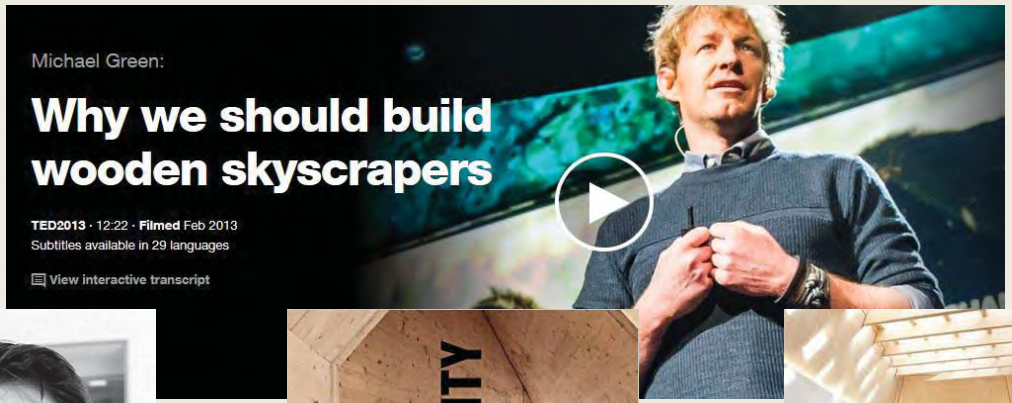
In some small way, each of us knows the value of wood as a resource. In fact, we use it every day—it heats our homes, makes our stationery, lines our floors. But in spite of all of its uses, wood is still a taboo material where building is concerned. Instead, we use concrete and steel in the hopes that our buildings (which are often our biggest investments) will remain strong and stable.

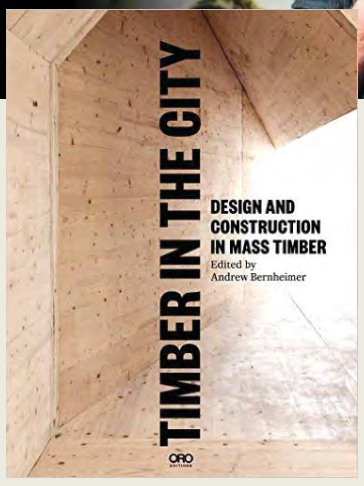
We tell ourselves that wood is too weak to sustain anything more than a few stories; that it'll succumb to any number of elements–fire, water, you name it. But is any of this really true? While we prompt each other to 'save the trees' and find ways to eliminate wood from our construction processes, others are using this resource to develop and maintain *sustainable* building practices that will help us all in the long run.

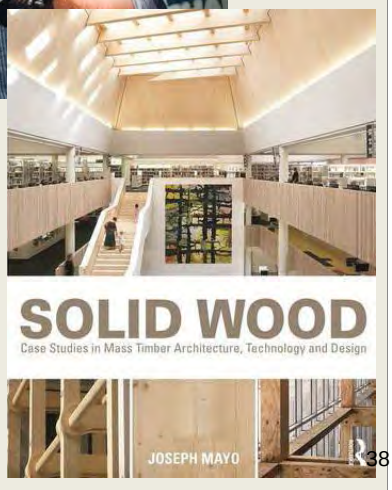
While sustainable building–or green building–dates back centuries, it really came into focus during the 1970's when environmentally conscious groups forged a movement that expressed a strong

Changing Attitudes

SLB SOFTWOOD LUMBER BOARD

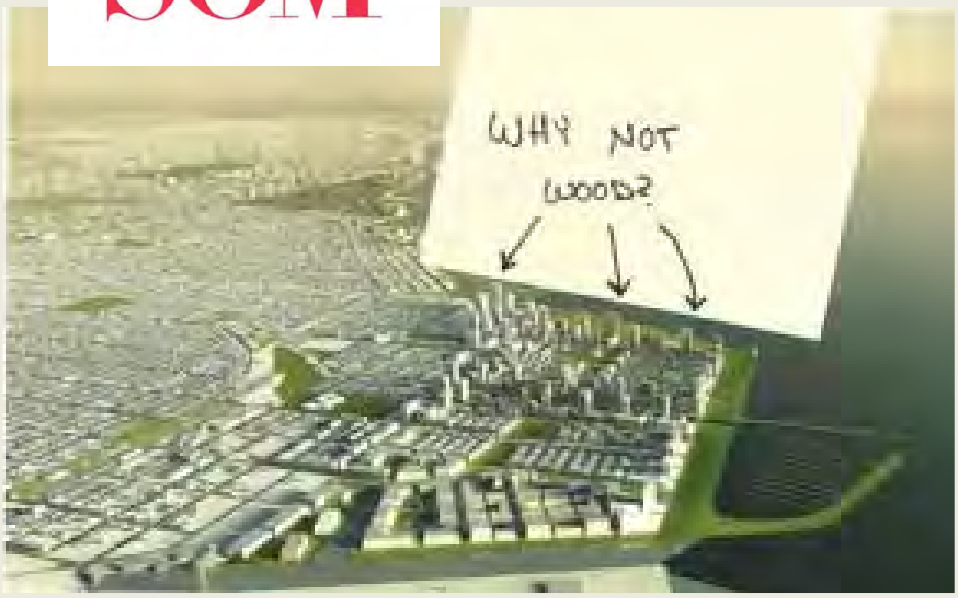






Innovation – Why Tall Wood Matters

SOM



Chicago, US
42 stories hybrid
Proof of concept

Innovation – Tall Wood

US Tall Wood Competition

- Support early adopters
- Foster innovation
- Generate broad awareness and understanding of wood's value proposition.
- **Budget: $3 million** (includes $1 million from USDA)

Innovation – Tall Wood

USDA Tall Wood Competition

FrameWork

Portland, OR

- Pearl district
- 12 stories – 130’
- Mixed use (retail/residential)
- Expected start: Jan ’16
- CLT plus glulam using NZ technology to address seismic issues.
- $1.5 million Prize

USDA Tall Wood Competition

West Chelsea

New York, NY

- Adjacent to Highline
- 11 stories – 120’
- Mixed use (retail/residential)
- Expected start: Dec ’16
- Team includes SHOP architecture: “most innovative firm in the world”
- $1.5 million Prize

USDA Tall Wood Competition

Carbon 12

Portland, OR

- 8 stories – 85’
- Mixed use (retail + office)
- Expected start: Fall ’15
- $250,000 funding for 6 research projects.

USDA Tall Wood Competition

SLB SOFTWOOD LUMBER BOARD

T3 - Hines

Minneapolis, MN

- 7 stories – 85’
- High end office space
- 220,000 square feet
- Post & beam with NLT
- Under Construction
- **$0 funding**
- Next project planned for Atlanta, GA

Innovation – Cross Laminated Timber

SLB SOFTWOOD LUMBER BOARD

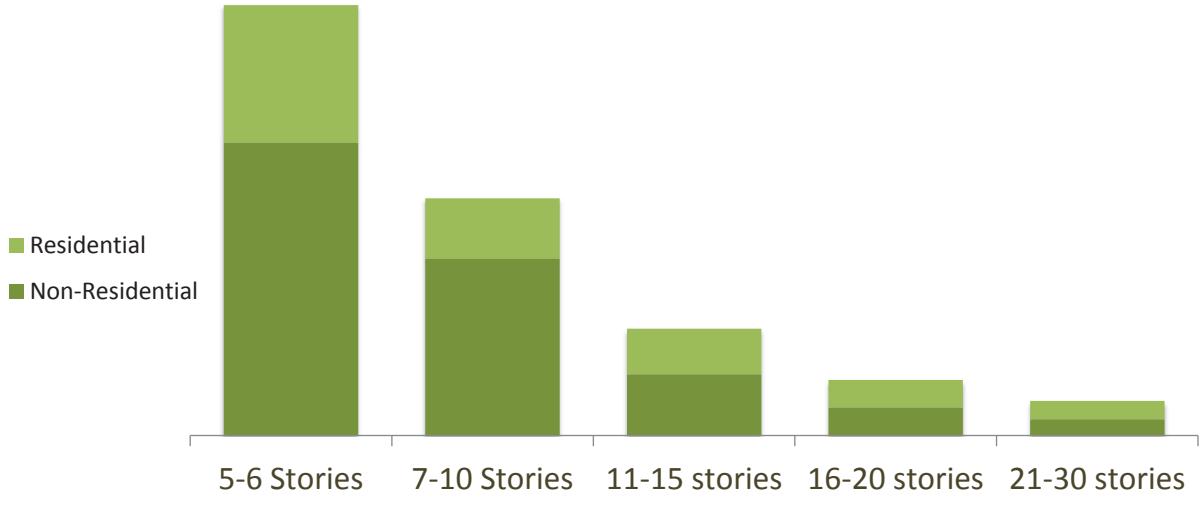
Innovation – NLT

SLB SOFTWOOD LUMBER BOARD

Innovation – Building Systems

Opportunity – Tall Wood

Incremental Volume: 5.0 BBF/Year



Non-Res	2.035 bbf	1.229 bbf	.425 bbf	.195 bbf	.113 bbf
Residential	.958 bbf	.420 bbf	.318 bbf	.192 bbf	.129 bbf
Total	**2.003 bbf**	**1.649 bbf**	**.743 bbf**	**.387 bbf**	**.242 bbf**

Ongoing Initiatives

- Construction site fire mitigati
- Coatings: Fire perfor ce.
- Lateral desig oise r ic
- Ener icient uildi s tems & t life ycle co t.
- Ma et l gence: l trial segment & co ructio ts
- Data and metrics support

ON HOLD

Research Projects

Database Development Project: Vision

- Database of research in wood building products and systems
- Focus on mass timber
- Create best in-class database and user focused interface

Database Project: Purpose

To set up a process to create a continuously updating inventory of the current landscape of research in wood building products and wood building systems from key markets around the world.

Research Projects

Database Project Goals

1. To compile a continuously updating inventory of research
2. To display the current status of research
3. To identify specific knowledge gaps
4. To identify researchers best able to fill gaps
5. To make the database public
6. Promote database as a resource for researchers, design/build professionals and funders

A Solution for the 21st Century

SLB SOFTWOOD LUMBER BOARD

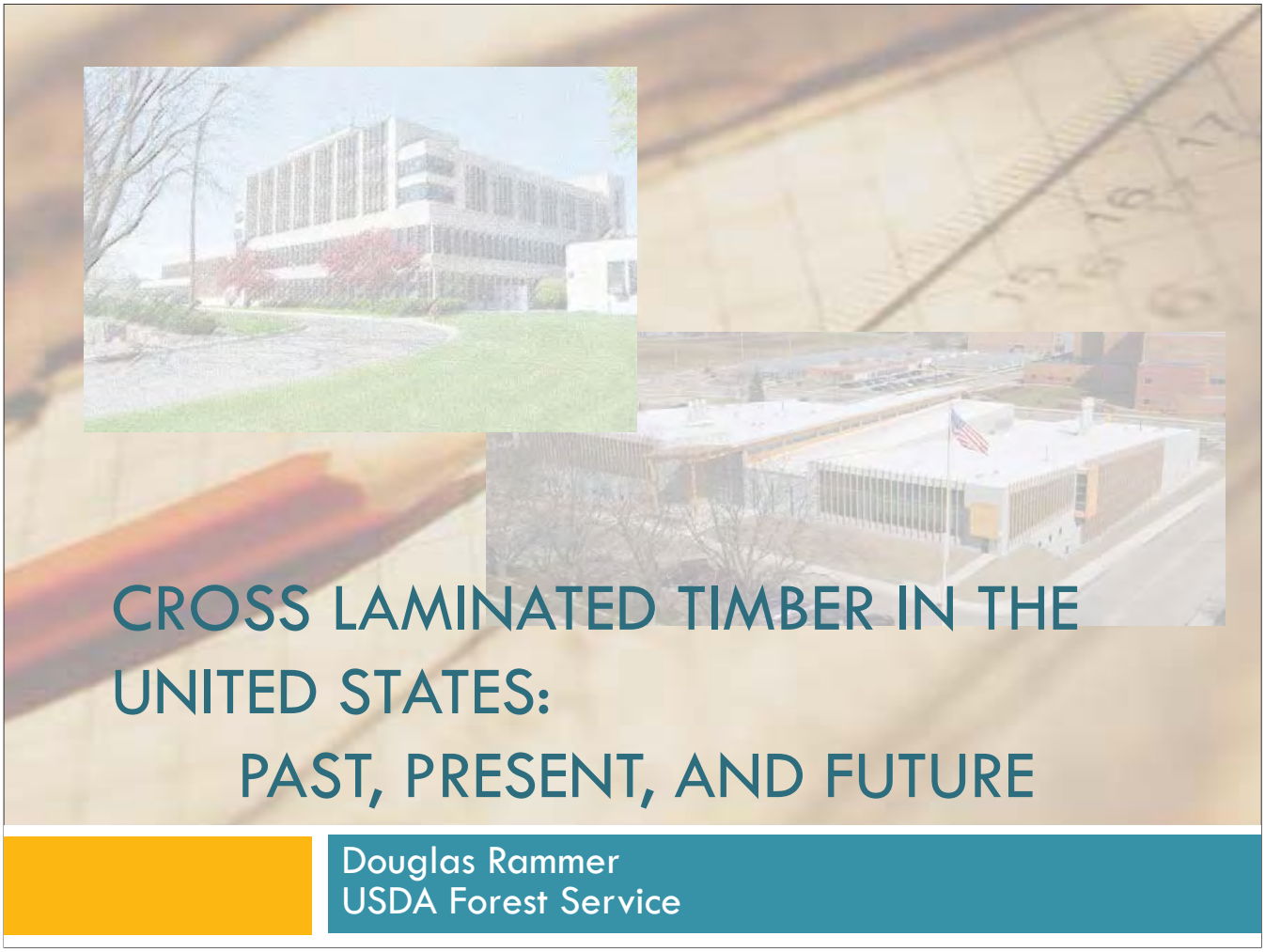
"If the 19th Century was the century of steel, and the 20th century the century of concrete, then the 21st century is about timber."

Alex de Rijke
dRMM Architects

Cross Laminated Timber in the United States: Past, Present, and Future Issues

Douglas Rammer, Research General Engineer
USDA Forest Products Laboratory, Madison, Wisconsin

Cross laminated timber (CLT) is making inroads into the United States building construction market, but research and design needs still limit expanded use. Two of the first significant advancements were the development and adoption of ANSI/APA PG 320 in 2012 and the publishing of the *U.S. CLT Handbook* in 2013. This talk will briefly discuss the past efforts, along with the more recent developments of inclusion of the CLT design specification in the National Design Specification and Oregon Building Code. Broad design issues using CLT in the U.S. construction market will be presented. Finally, ongoing USDA and Forest Service research efforts to further CLT use in the United States will be highlighted.



Benefits of Mass Timber

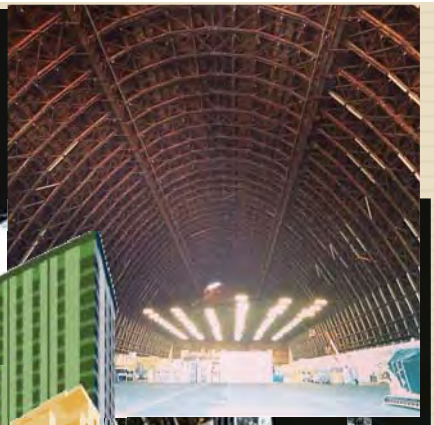
- Sustainable
- Low Carbon Footprint
- Rapid Construction
- Less Waste
- Thermal Performance/Energy Efficient
- Fire Protection
- Cost Effectiveness

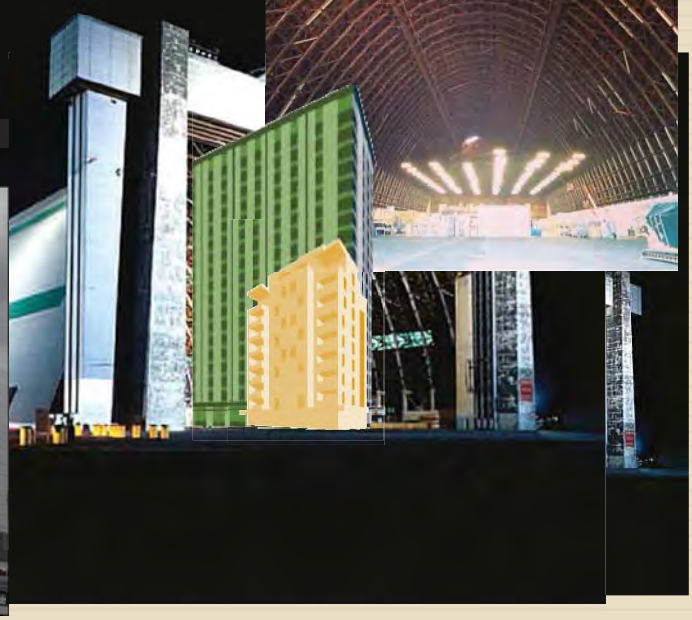
TALL WOOD BUILDINGS !!!!!

Tall Wood Buildings in US

Tall Wood Buildings in US

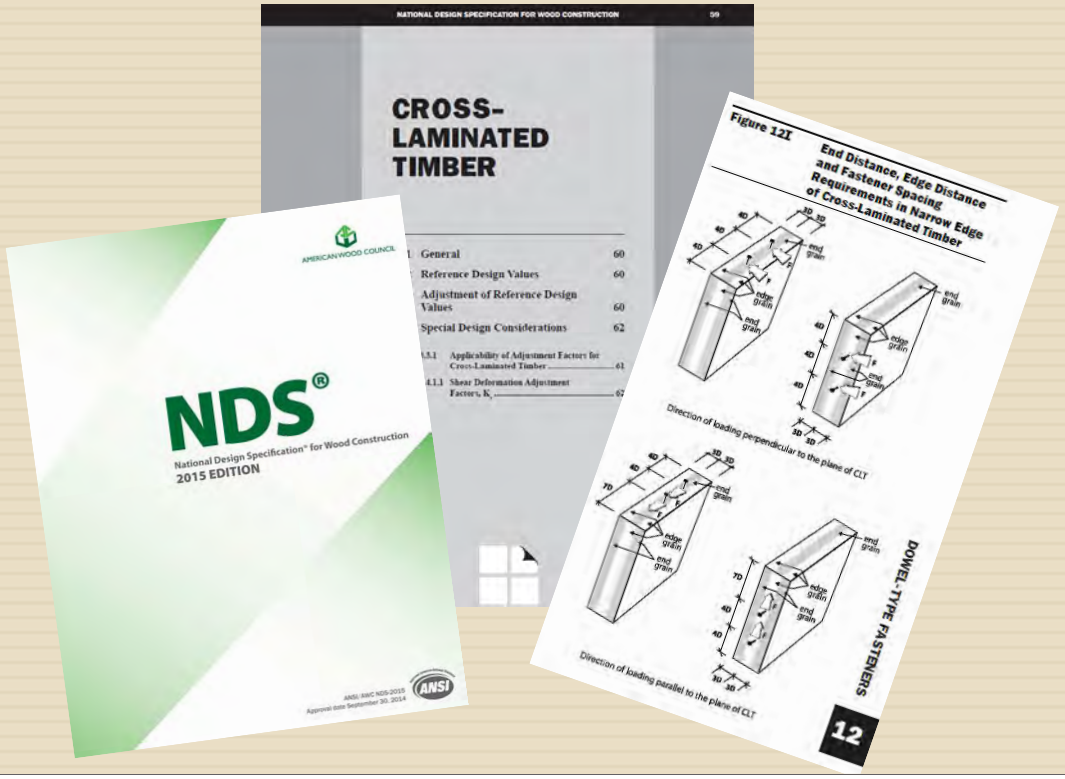
- 1,025' X 235' footprint
- 183' High





Recent Developments

Design Milestones



Design Milestones

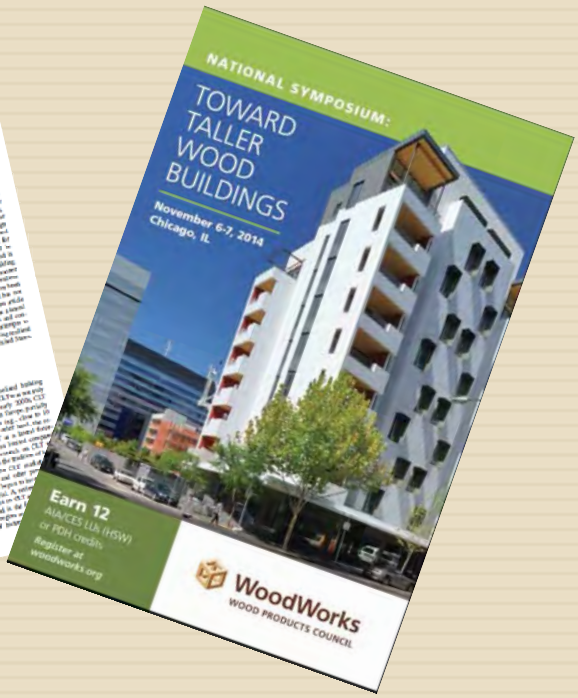
- CLT is recognized as Type IV Construction

- ICC Board

Future of U.S. Tall Wood Buildings

Forum

Cross-Laminated Timber for Seismic Regions: Progress and Challenges for Research and Implementation



Future of U.S. Tall Wood Buildings

US CLT Research

- USDA NIFA
- ARS
- FPL - CAWS
  - Performance Based Design of CLT
  - NEES-Soft CLT Repair Option
  - Seismic Design Parameters for CLT
  - Rocking Shear Walls (UW-Milwaukee)
  - Mechanically Laminated CLT
  - Instrumentation of Promega Building
  - LCA of CLT
  - Supply Chain Analysis
- Forest Service Wood Innovation Awards
- NEEScr - CLT

Where is the future?

Topics Areas for Workshop

- **Resistance to Lateral Loads**
- **Building Performance:**
  - **Durability**
  - **Sound,**
  - **Vibration**
  - **LCA**
- **Fire Safety**
- **Material Resources and Other Research Topics**

Tallest US Wood Structures

Updates/Overview of the Status of CLT R&D Activities and Tall Wood Buildings in Canada

Mohammad Mohammad, Research Leader/Senior Industrial Advisor
FPInnovations, Ottawa, Ontario, Canada

A summary of recent research activities at Canadian research institutes, including FPInnovations, National Research Council (NRC), and universities, on various performance attributes (e.g., structural, fire, acoustics, etc.) of CLT products and assemblies and status of CLT in Canadian codes and standards will be provided. Recent developments and initiatives related to Canadian tall wood buildings demonstration projects that incorporate CLT, and the specific research and development activities conducted in support of the proposed design concepts and regulatory approval of those tall mass timber projects, will be presented.

Recent Trends/Opportunities

Strong interest to re-specify wood in non-res. & mid- & high-rise buildings (i.e., renaissance in wood construction)

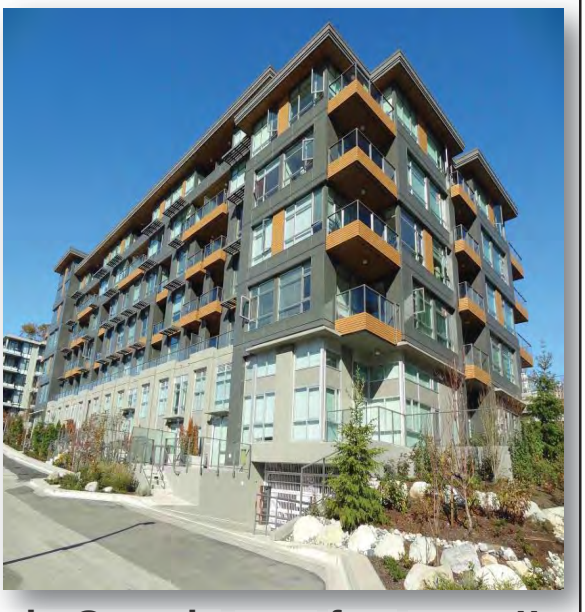
- **Key drivers:**
  - Availability of new generation of innovative EWP, connection systems, design tools & advanced prefab. technologies
  - Recent changes to building codes
  - Environmental concerns (i.e., climatic changes)- favors wood
  - Development of CLT

© 2013 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

FPInnovations

Midrise Wood Frame Construction in Canada: the Journey…

- 2009: BC Building Code revised to increase height limit for wood-frame construction from 4 to 6 storeys
- 2013: Régie du Bâtiment du Québec (RBQ)
- 2015: Ontario Building Code
- 2015: Alberta Building Code
- 2015 National Building Code of Canada



Expecting 1000's of midrise buildings in Canada next few years!!

© 2013 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

FPInnovations

Rediscovered Tall Wood Buildings

The Landing
Vancouver, 1905
Height: 30 m

National Building Code

NBCC 1941 (7)

NBCC 2015 (6)

NBCC 1953 (4)

4

© 2013 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

FPInnovations

Status of CLT in Canada

- CLT introduced to Canada in 2006
- Canadian-made CLT is commercially available (2 manufacturers + 1 coming up soon!!)
- Over 40 projects that utilizes CLT, either designed or built across Canada
- Extensive research conducted by FPI, Universities (NEWBuildS), NRC and Industry Associations (CWC)
- Mostly funded by NRCan, industry (BSLC) and provinces (QC, FII)
- Strong interest in CLT among designers, building officials, governments & developers

© 2013 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

5

FPInnovations

CLT in NA Codes and Standards

US: CLT adopted in the 2015 editions of IBC and NDS

Canada: Implementation process in building codes and standards has been generally slow..

- Designers use CLT under « Alternative Solutions»
- CLT proposal discussed at the NBCC (LLRS): Didn't make it for the 2015 edition
- Proposals are being developed by CWC and partners (2020 NBC)
- Quebec: «Pre-approved » Alternative Solution for mass timber including CLT for up to 12 storeys!

© 2013 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

FPInnovations

Quebec's Guide for Mass Timber Construction up to 12 Storeys

- Released in August, 2015
- Quebec: 1st jurisdiction in NA to officially support the construction of tall mass timber bldgs
- "Pre-approved" Alternative Solution to facilitate the design & approval process
- Covers CLT, hybrid and other types of mass timber
- Great interest in the Guide by other jurisdictions in Canada and overseas

Bâtiments de construction massive en bois d'au plus 12 étages

© 2013 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

FPInnovations

CLT in Canadian Codes and Standards

CSA O86: Canadian Timber Design Standard

- Design provisions proposed at CSA O86 (public review ended Oct. 28)
- Targetting the 2016 Supplement of CSA O86
- Comprehesive proposal that covers provisions for :
  - Bending and shear resistance
  - Serviceability (i.e., deflection and vibration)
  - Connections
  - LLRS
  - Fire resistance

tions. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

FPInnovations

Developing Design Guidelines
CLT Handbooks

- FPI's CLT handbooks have been instrumental in providing guidance to designers under AS provisons & in supporting CLT code change proposals in Canada and the US
- Need to update US CLT handbook to be in line with recently implemented IBC and NDS provisions!

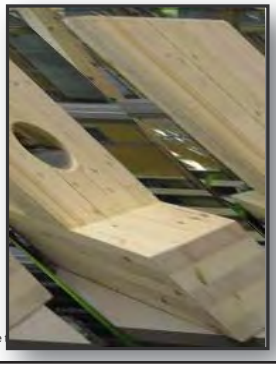
Sponsored by NRCan, BSLC, AWC, USFPL, APA, WoodWorks

© 2013 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

FPInnovations

R&D on Seismic Design in CLT

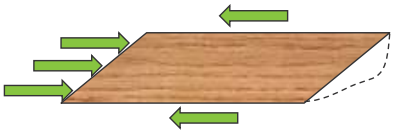
- Short and tall CLT walls & 2-storey CLT assembly tests at FPI & under NEWBuildS
- Evaluation of stiffness of massive wood shearwalls & diaphragms
- Joint research between FPL, FPI & US Universities (WSU, CSU, etc.) on seismic perf. of CLT
- Developing high capacity connections for CLT (i.e., facilitate assembly and disassembly)



FPInnovations

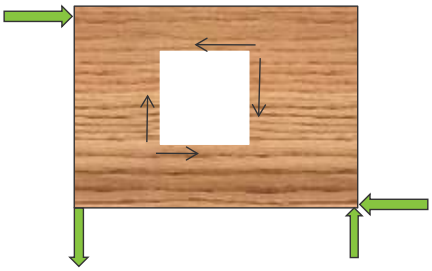
Gravity & Seismic Design in CLT (NEWBuildS/FPI)

- Stability of CLT wall panels under gravity loading
- In-plane stiffness and strength of CLT diaphragms
- Force transfer around openings in walls subjected to in-plane loading



NEWBuildS

UBC

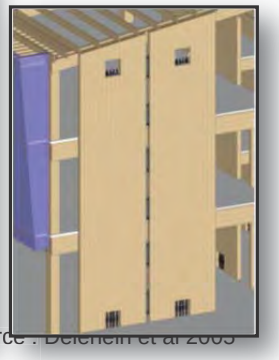


FPInnovations

© 2013 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

Post-tensioning System Applications: Self-centering & Energy Dissipation

- Explore the adoption of self-centering/damage fuse concept to CLT wall construction to resist seismic load (NEWBuildS/FPI)
- FPI acquired the IP for the NZ PT system for NA and an implementation strategy is being developed including supporting R&D research and design guides



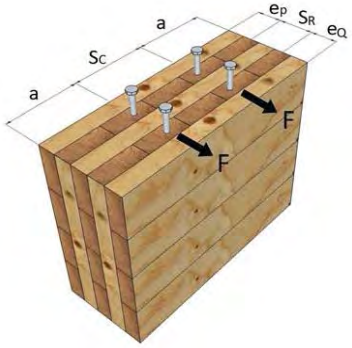
Source : Deierlein et al 2003

© 2013 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

NEWBuildS
FPInnovations

NEWBuildS/FPI: Structural CLT Connections

- Fastener Withdrawal and Embedment Strength in Timber, Glulam and CLT
- Connections for CLT plates in hybrid steel frame structures



NEWBuildS
FPInnovations

© 2013 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

Fire Protection: Research Areas

- Encapsulation (FPI/NRC/CWC)
- Fire Resistance Tests (FPI/NRC: TWBs)
- Surface flammability of mass timber
- Full-Scale CLT Shaft Demonstration Fire (TWBs)
- Composite mass wood-concrete floor systems
- Firestops
- Room fires (Carleton University/NEWBuildS)

© 2013 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

FPInnovations

Nailed Laminated Timber (NLT)

- Great interest in NLT in Canada
- Applications: floor/roof systems in mid-rise non-res & TWBs
- Used in several landmark projects in Canada & overseas
- Comes in various shapes, configurations and patterns
- Some ongoing testing at FPI including hybrid NLT with concrete

T3 Minneapolis Office Building

http://www.structurecraft.com/projects

© 2014 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

FPInnovations

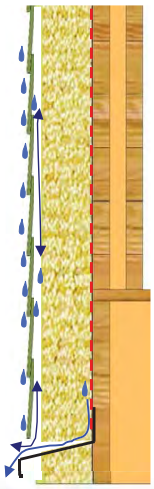
Mass Timber Fire Research

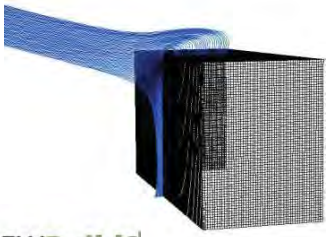
- Mass timber-concrete composite floors
- 2x8 laminated wood deck-concrete
  - truss plates
- 5-ply CLT-concrete – 3 h 34 min
  - Self-tapping wood screws at 45º
- Other tests planned for 2015

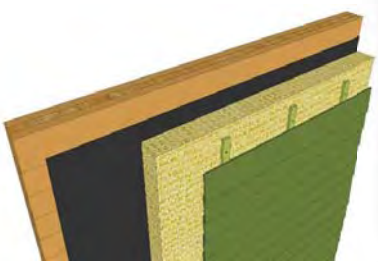
© 2014 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

Building Envelope/Durability of CLT (NEWBuildS/FPI)

- Characterizing wind-driven rain load on mid-rise buildings
- Developing durable building envelope assemblies for CLT construction
- Drying performance of CLT







Serviceability Research

- A challenge to designers & occupants in taller buildings (IIC, STC, floor & building vibrations, etc.)
- Ongoing acoustic, floor & wind-induced vibrations at FPI and NRC in support of FPI's Mid-rise Guide & NRCan's TWBs
- FPI's on-site measurements and monitoring activities (WIDC)

Source: Binder

© 2013 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

FPInnovations

What is Happening in Canada on the TWBs Front?!!

© 2013 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

FPInnovations

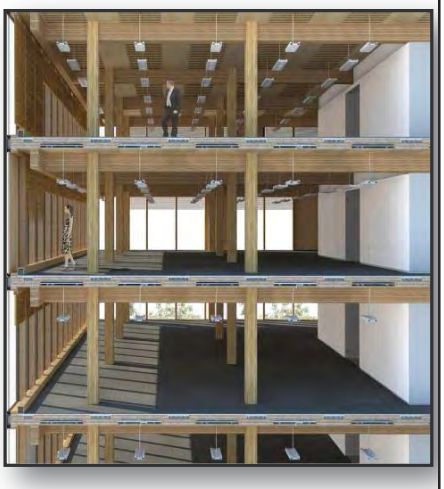
Inspiring Modern Tall Wood Buildings

9-Storey buildings, London, UK
1st storey concrete, 8 storeys CLT

2 @ 8 storeys CLT buildings,
Oslo, Norway

4 CLT residential buildings/social housing
@ 9 storeys, Milan, Italy

© 2013 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.



Courtesy of Equilibrium

NRCan's Tall Wood Demo Buildings Initiative (2013)

- A request for EOI issued by CWC for design teams to use innovative design and build high-rise wood demo projects
- To support the initiative, a "T*echnical Guide for the Design and Construction of Tall Buildings in Canada*" was developed by FPI
- Provinces & industry partnered with NRCan
- A few projects were selected and detailed design & approval by AHJs is underway

© 2013 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

FPInnovations

Origine: Quebec City/Canada

- 13-storey mass timber (12 + 1 concrete podium)
- 800 m² floor area, 40 m tall
- Incorporates a CLT core

- Fire, structural, acoustics, etc.
- Mainly to support the design/approval process

© 2013 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovation

Forêts, Faune et Parcs Québec

FPInnovations

UBC Residence TWB

- 18 Storeys: 1 concrete+ 2 concrete cores supporting 17 storeys of mass timber
- A steel connector allows for a direct load transfer between the columns and also provides a bearing surface for the CLT panels.
- Encapsulated CLT and glulam beams
- The floor comprised of 5-ply CLT panels that are point-supported on glulam columns on a 2.85m x 4.0m grid.
- Mock-up built to verify constructability

CLT floor slabs with glulam columns and steel connectors

partial encapsulation during construction

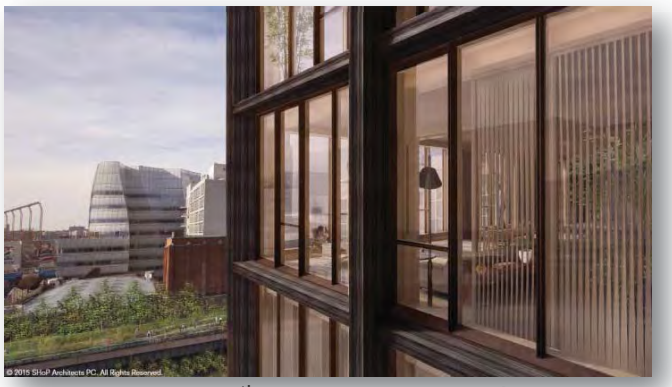
completed construction

UBC TWB Mock-up

© 2013 FPInnovations. All rights reserved. Copying and redistributi ıd logos are t

FPInnovations

US TWB Prize Competition: Winning Buildings (USDA and SLB)



475 West 18th Street, New York
Curtsey SLB

Framework, a 12 storeys, Portland, Oregon
Curtsey SLB

© 2013 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

FPInnovations

Use of CLT in Modern Timber Bridges in Canada

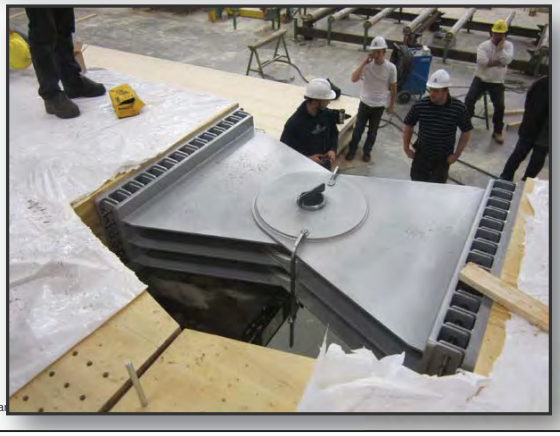
Glulam/CLT Box Girder

© 2013 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

FPInnovations

Hybrid CLT- Glulam Beams

CESM Soccer Stadium in Montreal



SNC-LAVALIN

© 2013 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos a

Final Remarks

- Taller and larger buildings are demanding more from wood products and systems
- And that is creating new opportunities for new products and systems both in Canada and the US
- Continue and enhance joint research ventures between Canada and the US in support of the design and construction of taller and larger wood buildings

© 2013 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

The U.S. Tall Wood Building Prize Competition and USDA's Role with Mass Timber

Patrick Holmes, Senior Advisor
USDA Office of the Secretary, Washington, D.C.

Through Secretary Tom Vilsack's Leadership, USDA has launched a series of initiatives aimed at advancing commercialization of mass timber technologies and enhancing wood use in the commercial and multistory building sectors. New innovations in mass timber and other wood use can help support USDA's goals for rural economic development, improving the health and resiliency of the Nation's forests and enhancing the role of forests and wood products in mitigating the impacts of climate change. This presentation will share Secretary Vilsack's vision; discuss key efforts such as the White House Rural Council Workshop: Building with Wood, Jobs and the Environment; and highlight the winning projects of the U.S. Tall Wood Building Prize Competition.

17
TALL
WOOD
BUILDINGS
(7 STORIES OR TALLER)
HAVE
BEEN
BUILT
IN THE
PAST
5
YEARS
AND
COUNTING
TREET
Bergen, Norway
14 Stories
2015
Trafalgar Place
London, UK
10 Stories
2015
Forté
Melbourne, Australia
10 Stories
2012
Banyan Wharf
London, UK
10 Stories
2015
Cenni di Cambiamento
Milan, Italy
9 Stories
2013
Strandparken
Stockholm, Sweden
8 Stories
2014
Puukuokka
Jyväskylä, Finland
8 Stories
2015
Wood Innovation Design Centre
British Columbia, Canada
8 Stories
2014
St. Dié-des-Vosges
St. Dié-des-Vosge, France
8 Stories
2014
Pentagon II
Oslo, Norway
8 Stories
2013
LifeCycle Tower One
Dornbirn, Austria
8 Stories
2012
Holz8
Bad Aibling, Germany
8 Stories
2011
Contralaminada
Lleida, Spain
8 Stories
2014
Bridport House
London, UK
8 Stories
2010
Wagramerstrasse
Vienna, Austria
7 Stories
2013
Panorama Giustinelli
Triste, Italy
7 Stories
2013
Maison de l'Inde
Paris, France
7 Stories
2013

TALL WOOD BUILDING
PRIZE COMPETITION
WINNER

TALL WOOD BUILDING
PRIZE COMPETITION

© 2015 SHoP Architects PC. All Rights Reserved.

© 2015 SHoP Architects PC. All Rights Reserved.

CONGRATULATIONS
NEW YORK
(FOR KEEPING UP WITH OREGON)
OregonForests.org/tallwood
OSU
OREGON

Session 1—Resistance to Lateral Loads

Coming Soon: Seismic Performance Factors for Cross Laminated Timber Design

John W. van de Lindt, Professor
M. Omar Amini, Ph.D. Candidate
Colorado State University, Fort Collins, Colorado

Douglas Rammer, Research General Engineer
USDA Forest Products Laboratory, Madison, Wisconsin

Phil Line, Director, Structural Engineering
American Wood Council, Leesburg, Virginia

Shiling Pei, Assistant Professor
Colorado School of Mines, Golden, Colorado

Marjan Popovski, Principal Scientist
FPInnovations, Vancouver, British Columbia, Canada

Cross-laminated timber (CLT) based Seismic Force Resisting Systems (SFRS) are not yet recognized in U.S. design codes, and therefore seismic design can be performed only through alternative methods. The purpose of this Forest Products Laboratory funded research project currently underway at Colorado State University is to identify seismic performance factors for CLT as a SFRS. The study is based on the FEMA P-695 methodology that provides a systematic, logical, and relative approach consisting of nonlinear static and dynamic analyses. There are several phases to the project, including development of the archetypes, design methodology, testing, modeling, and the full P-695 analysis procedure itself. This presentation includes a brief description of the FEMA P-695 methodology along with recent progress on the test program. CLT archetypes developed as part of this study and nonlinear models used to simulate CLT behavior at the connector, wall, and system levels are presented. Some examples of several performance groups within the methodology will be presented in their preliminary form, and the procedure to determine the collapse margin ratio will be explained. The timeline to completion has been updated and will be provided.

Coming Soon: Seismic Performance Factors For Cross Laminated Timber Design Oct 30, 2015

Colorado State University

Department of Civil and Environmental Engineering

Project Members

Colorado State University

M. Omar Amini & John W. van de Lindt

Colorado State University

Shiling Pei

COLORADO SCHOOL OF MINES
EARTH • ENERGY • ENVIRONMENT

Douglas Rammer

100 Years of Service
USDA Forest Products Laboratory
1910–2010

Phil Line, *American Wood Council*

AMERICAN WOOD COUNCIL

Marjan Popovski, *FPInnovations*

FPInnovations

Charlie Kircher, Ph.D., P.E.
Principal and Owner
Charles Kircher & Associates

J. Daniel Dolan, Ph.D., P.E.
Professor Department of Civil and Environmental Engineering
Washington State University

Kelly Cobeen, S.E.
Associate Principal
Wiss, Janney, and Elstner Associates, Inc.

Outline

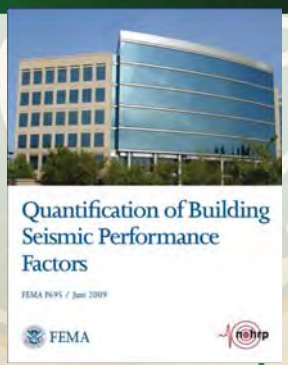
Colorado State University

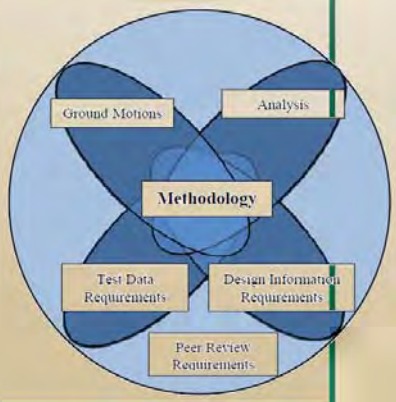
- FEMA P695 methodology
- Index buildings
  - Archetypes
- Testing
- Modeling
- Illustrative example
- Next steps

FEMA P-695: Quantification of Building Seismic Performance Factors

Colorado State University

- A Methodology that allows a team to identify seismic performance factors for a new SFRS.
- The Methodology is consistent with the primary “life safety” performance objective of seismic regulations in model building codes.
- Peer review throughout is key
- Archetypes
- Design methodology
- Nonlinear time history analysis
- Performance evaluation
  - CMR





Archetype Development

Colorado State University

Design Space

Representative of typical residential and commercial structures in the U.S.

Archetype Configurations

Prototypical representation of a seismic-force-resisting system

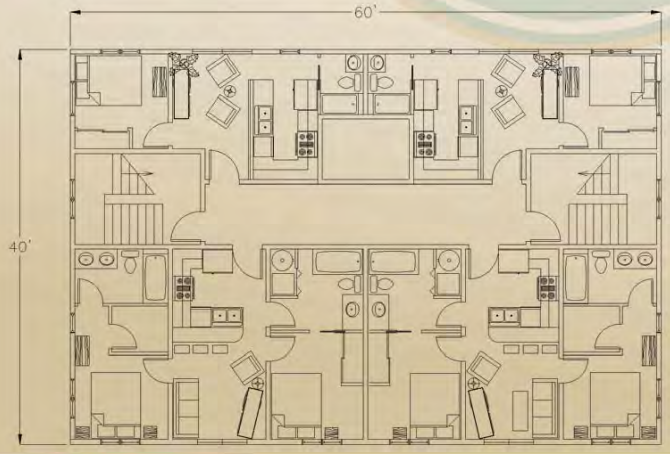
Archetype Designs

Index archetype configurations designed and detailed using the design requirements

Archetype Models

Mathematical idealization of the proposed system

Configuration Design Variables	Seismic Behavioral Effects
Occupancy and Use	Strength
Elevation and Plan Configuration	Stiffness
Building Height	Inelastic-deformation Capacity
Structural Component Type	Seismic Design Category
Seismic Design Category	Inelastic-system Mobilization
Gravity Load	



Index Buildings

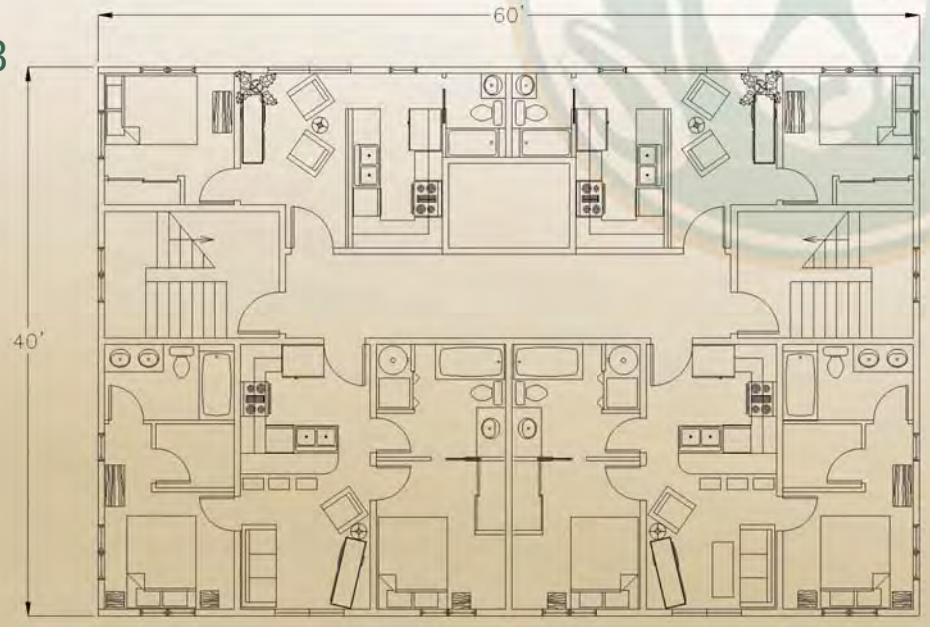
Colorado State University

Index Bldg.	Type	Stories
1	Single Family (SF)	-
2	SF	-
3	SF	-
4	Multi-family (MF)	4, 6, 8
5	MF	2
6	MF	2
7	MF	3
8	MF	6, 8
9	MF	8, 10
10	MF	8, 10, 12
11	Commercial	8, 10, 12

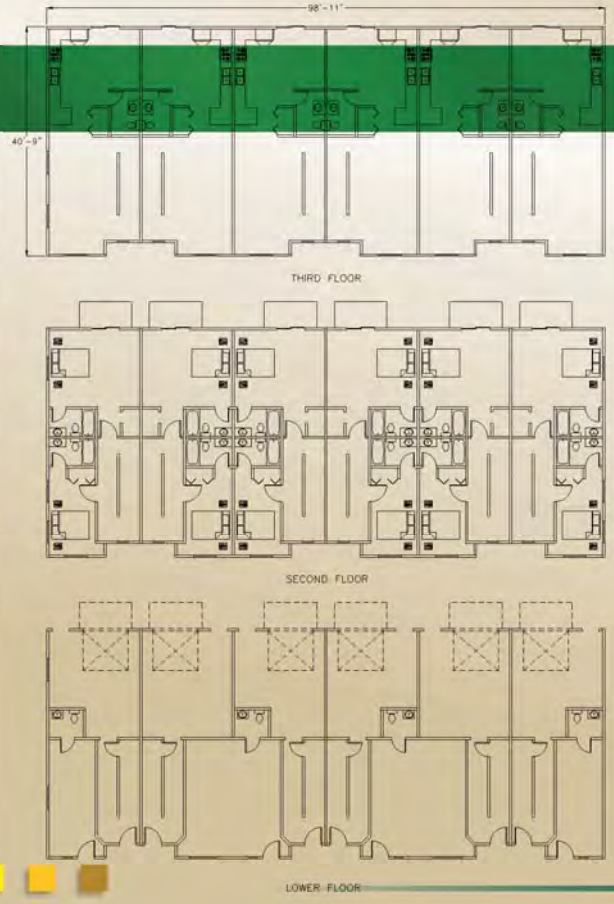
Type : Single Family
Index Bldg. 1

Colorado State University

Type : Multi-family
Index Bldg. 4
Stories:4, 6, 8



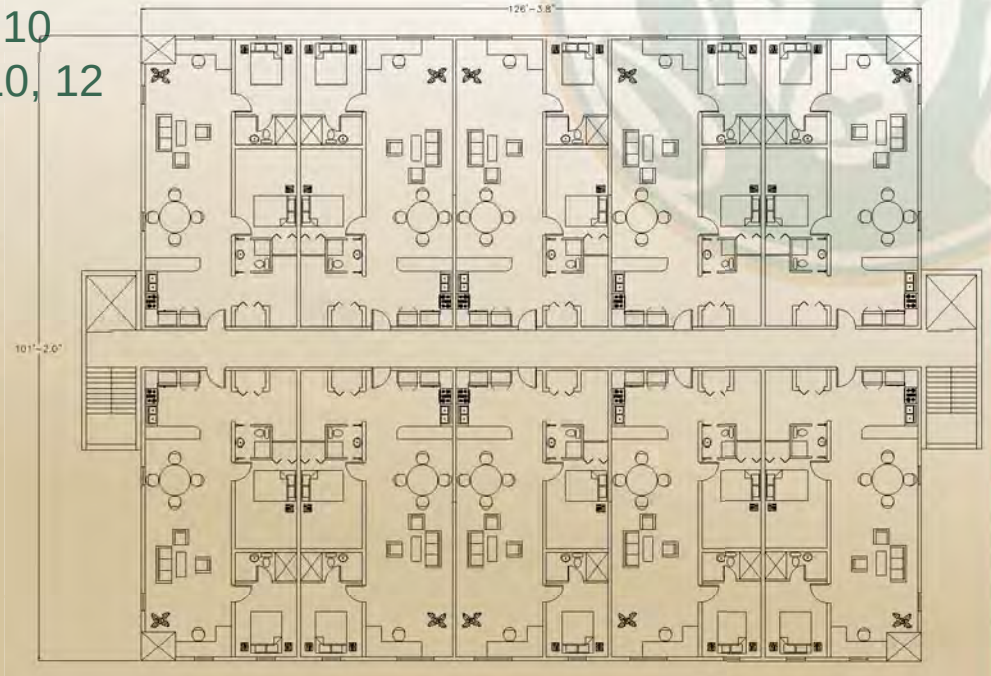
Colorado State University



Type : Multi-family
Index Bldg. 7
Stories: 3
Possibly mixed-use

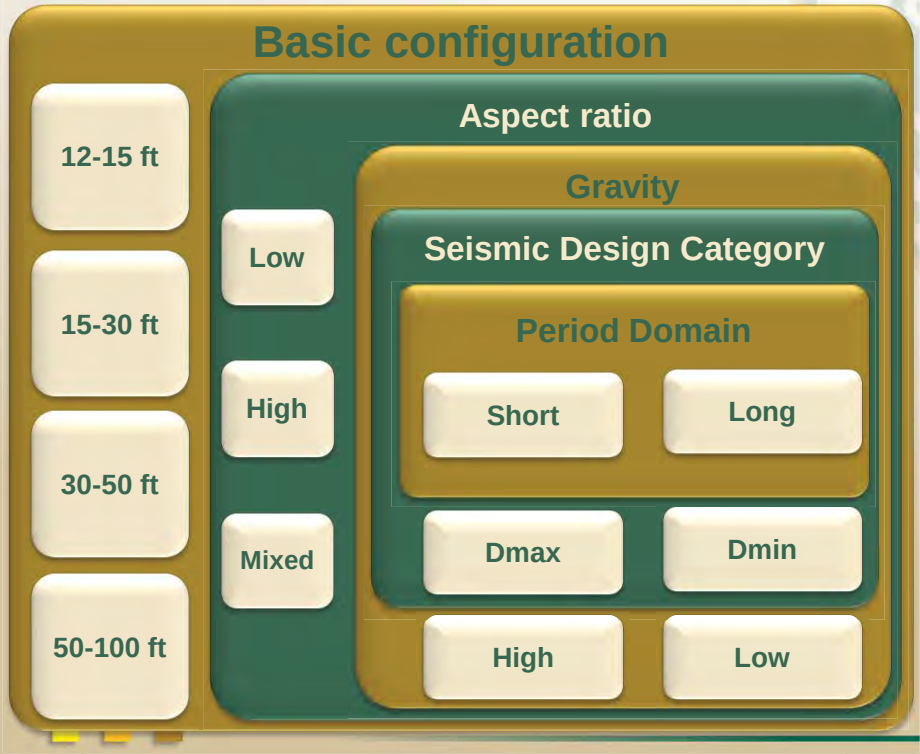
Colorado State University

Type : Multi-family
Index Bldg. 10
Stories: 8, 10, 12



Performance groups

Colorado State University



- Min. of 3 archetype per performance group
- Total= 96 performance group that is 288 archetypes

Performance groups

Colorado State University

Group No.	Grouping Criteria: Basic Config.		Design Load Level: Gravity	Design Load Level: Seismic	Period Domain	Archetype description
PG-65	30-50 ft wall	Mixed aspect ratio panels	High	SDC Dmax	Short	Index building 1, 3 stories
						Index building 4, 4 stories
						Index building 7, 3 stories
PG-66					Long	Index building 4, 6 stories
						Index building 4, 8 stories
						Index building 8, 8 stories
						Index building 9, 10 stories
PG-67				SDC Dmin	Short	Index building 1, 3 stories
						Index building 5, 2 stories
						Index building 7, 3 stories
PG-68					Long	Index building 4, 6 stories
						Index building 4, 8 stories
						Index building 8, 8 stories
						Index building 9, 10 stories
PG-69			Low	SDC Dmax	Short	Index building 1, 3 stories
						Index building 4, 4 stories
						Index building 7, 3 stories
PG-70					Long	Index building 4, 8 stories
						Index building 4, 6 stories
						Index building 8, 8 stories
						Index building 9, 10 stories
PG-71				SDC Dmin	Short	Index building 1, 3 stories
						Index building 5, 2 stories
						Index building 7, 3 stories
PG-72					Long	Index building 4, 6 stories
						Index building 4, 8 stories
						Index building 8, 8 stories
						Index building 9, 10 stories

Reducing Archetypes

Colorado State University

- SDC Dmax only
- Based on the testing Low aspect ratio vs. High aspect ratio vs. Mixed aspect ratio critical case will be determined
- Calculating exact gravity loads based on architectural plans is deemed sufficient by the peer panel and there is no need to specifically consider low vs. high gravity
- Visual Inspection of some of the archetypes
- Only 8 performance groups are expected to be analyzed

Performance groups

Colorado State University

Grouping Criteria						
Group No.	Basic Config.		Design Load Level		Period Domain	Archetype description
			Gravity	Seismic		
PG-65	Example				Short	Index building 1, 3 stories Index building 4, 4 stories Index building 7, 3 stories
PG-66	30-50 ft wall Reduced	Critical aspect ratio	Calculated	SDC Dmax	Long	Index building 4, 6 stories Index building 4, 8 stories Index building 8, 8 stories Index building 9, 10 stories
PG-67	30-50 ft wall	Mixed aspect ratio panels	High	SDC Dmin	Short	Index building 1, 3 stories Index building 5, 2 stories Index building 7, 3 stories
PG-68					Long	Index building 4, 6 stories Index building 4, 8 stories Index building 8, 8 stories Index building 9, 10 stories
PG-69			Low	SDC Dmax	Short	Index building 1, 3 stories Index building 4, 4 stories Index building 7, 3 stories
PG-70					Long	Index building 4, 8 stories Index building 4, 6 stories Index building 8, 8 stories Index building 9, 10 stories
PG-71				SDC Dmin	Short	Index building 1, 3 stories Index building 5, 2 stories Index building 7, 3 stories
PG-72					Long	Index building 4, 6 stories Index building 4, 8 stories Index building 8, 8 stories Index building 9, 10 stories

Testing Program

Colorado State University

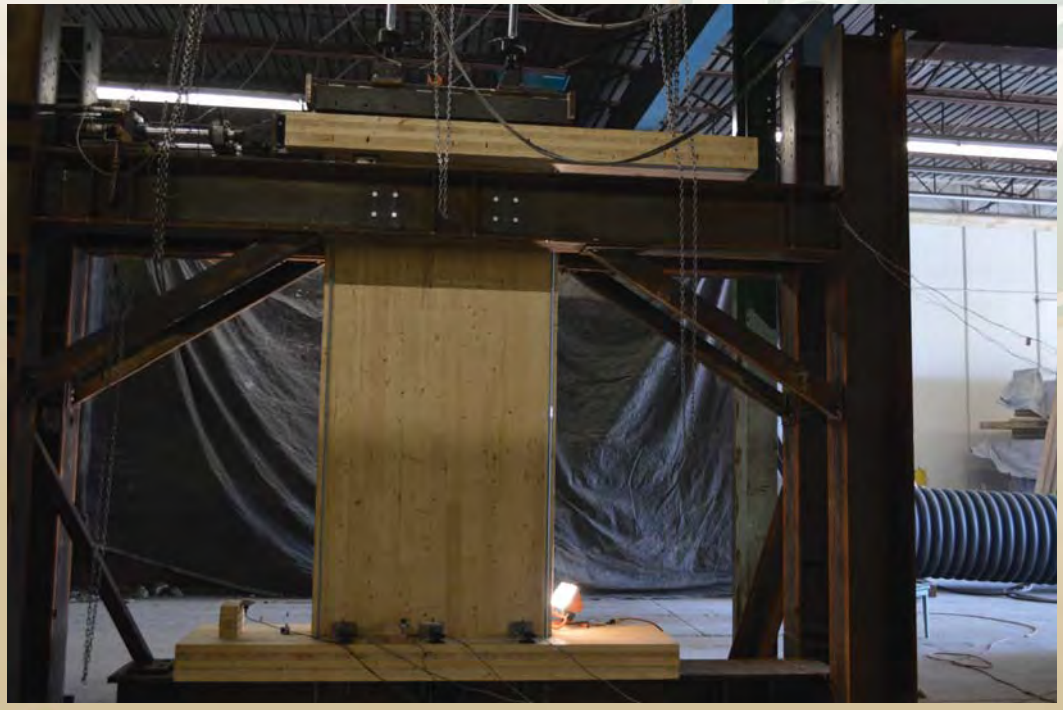
Test Type	Objective	
Connector tests	• Behavior under cyclic loading • Interpanel connector behavior	
Isolated Wall Tests	• Boundary condition • Gravity loading • Connector thicknesses • Connector type • CLT panel thickness • Connector thickness • CLT panel aspect ratio • Inter-panel connector (vertical joint) • CLT grade	
Box type configuration	• Effect of diaphragm on wall behavior • Diaphragm behavior • Effect of out-of-plane loading on the connector • Effect of bi-directional loading • Holddowns in the corners • Stability of the walls	
Box type configuration with multiple panel walls	• Effect of out-of-plane loading on the connector • Effect of bi-directional loading • Holddowns in the corners • Stability of the walls • Vertical joints between perpendicular walls will also be investigated	
3-sided wall with a diaphragm	• Effect of diaphragm rotation • Combined loading on the connectors	

Testing Program

Colorado State University

Testing Program

Colorado State University



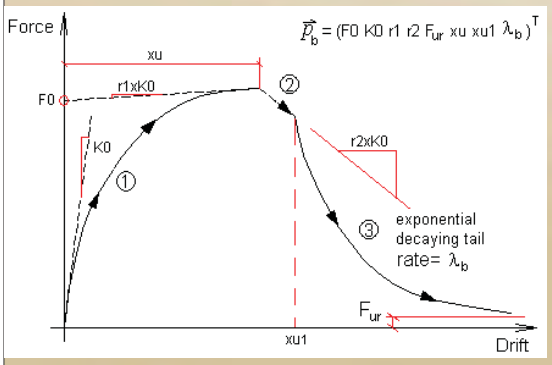
Testing Program

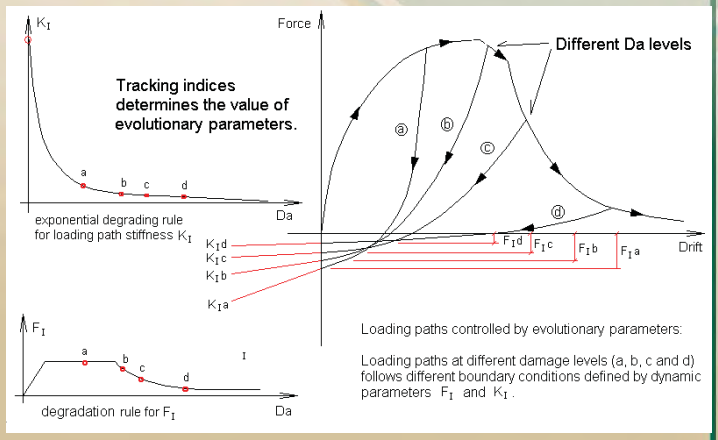
Colorado State University

Modeling

Colorado State University

- 16-parameter hysteretic model
- Developed at CSU and TAMU
- It allows more adaptive modeling of the degradation behavior of the wood shearwall components





Backbone curve for EPHM hysteresis

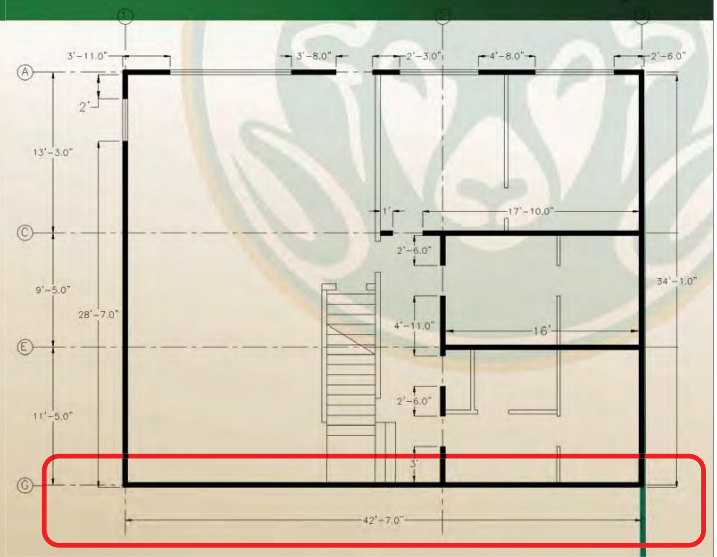
Degradation of loading paths

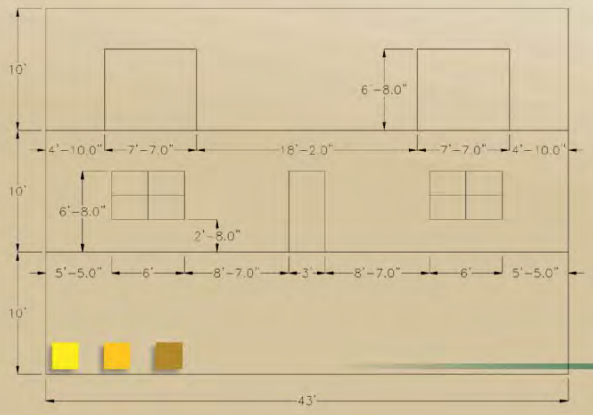
(Pang et al, 2007; Pei and van de Lindt, 2009)

Illustrative example

Colorado State University

Extraction of
archetypes for PG 65

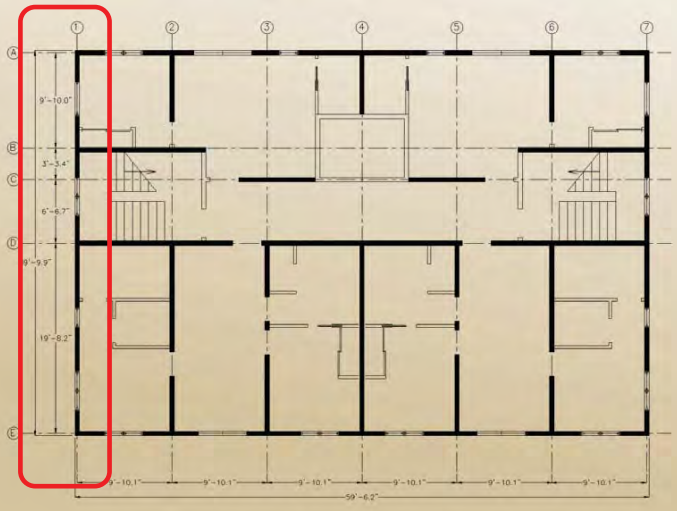


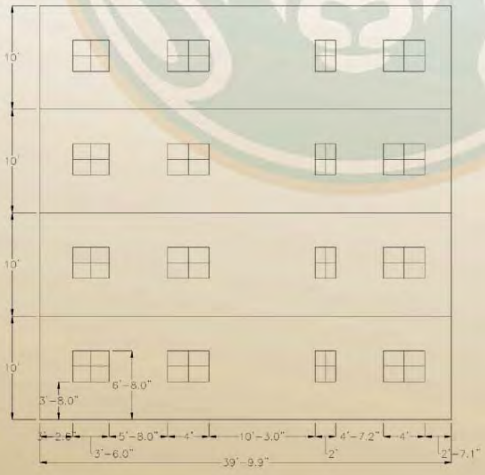


Archetype 65-1

Illustrative example

Colorado State University

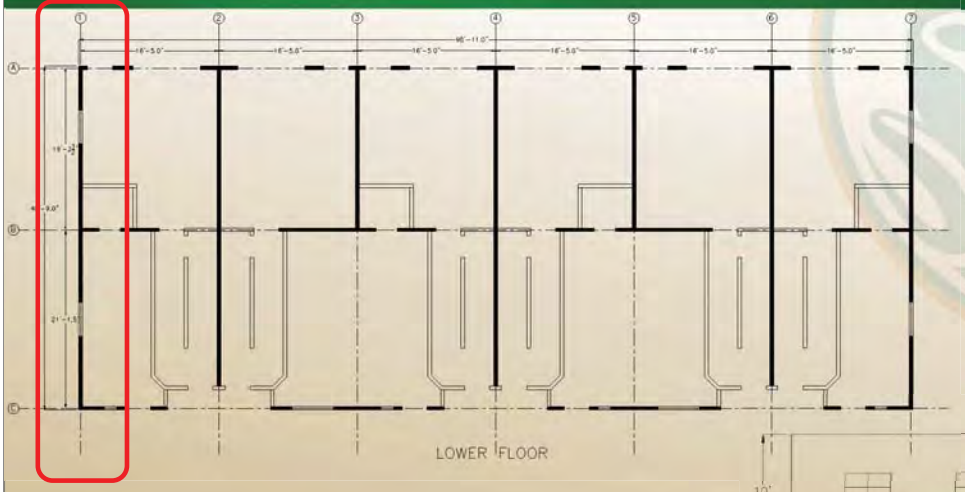


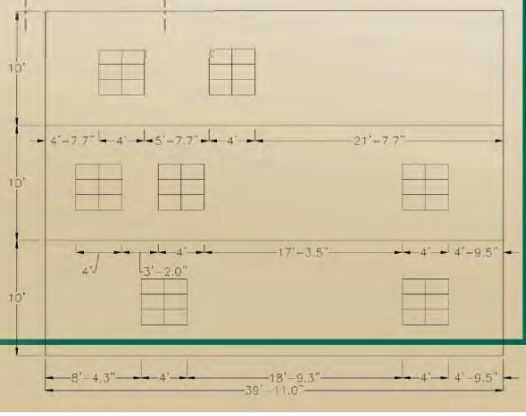


Archetype 65-2

Illustrative example

Colorado State University

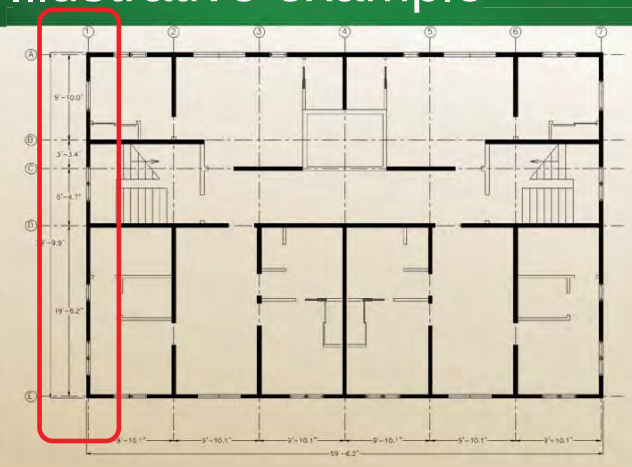


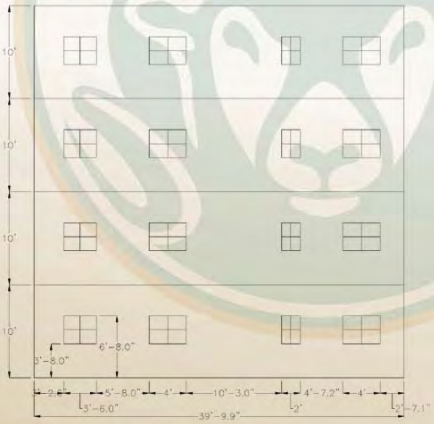


Archetype 65-3

Illustrative example

Colorado State University





ELF

Obtain shear forces for the archetype model

Design Methodology

Design the archetype model using the design methodology

Modeling

Obtain parameters for the walls and model the building using SAPWood

Nonlinear Analysis

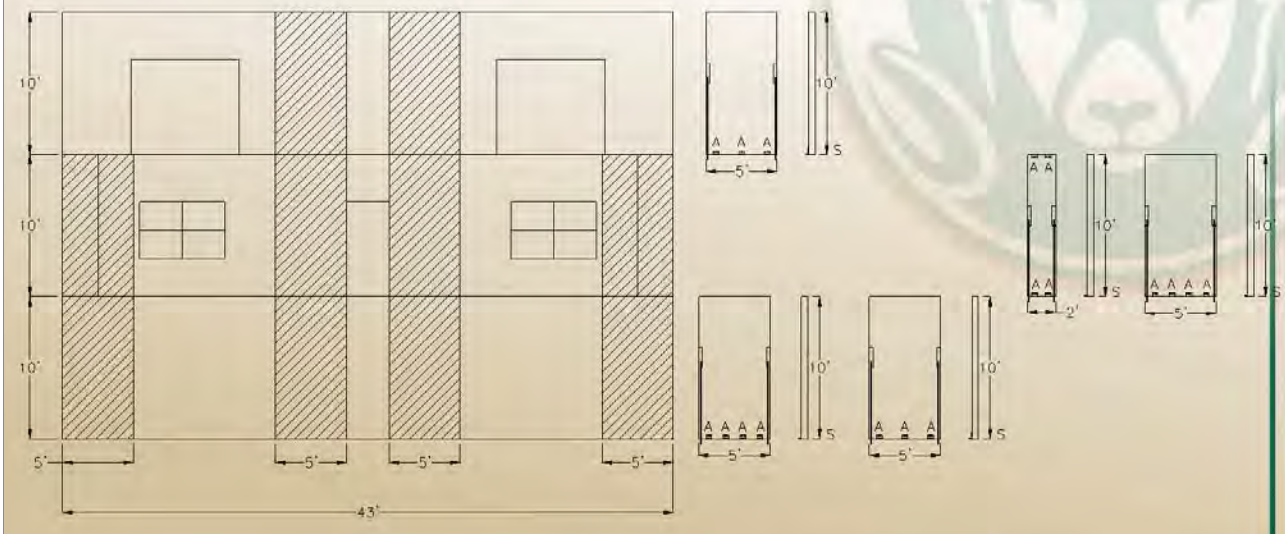
Static pushover and dynamic analysis

Performance evaluation

CMR and ACMR

Illustrative example

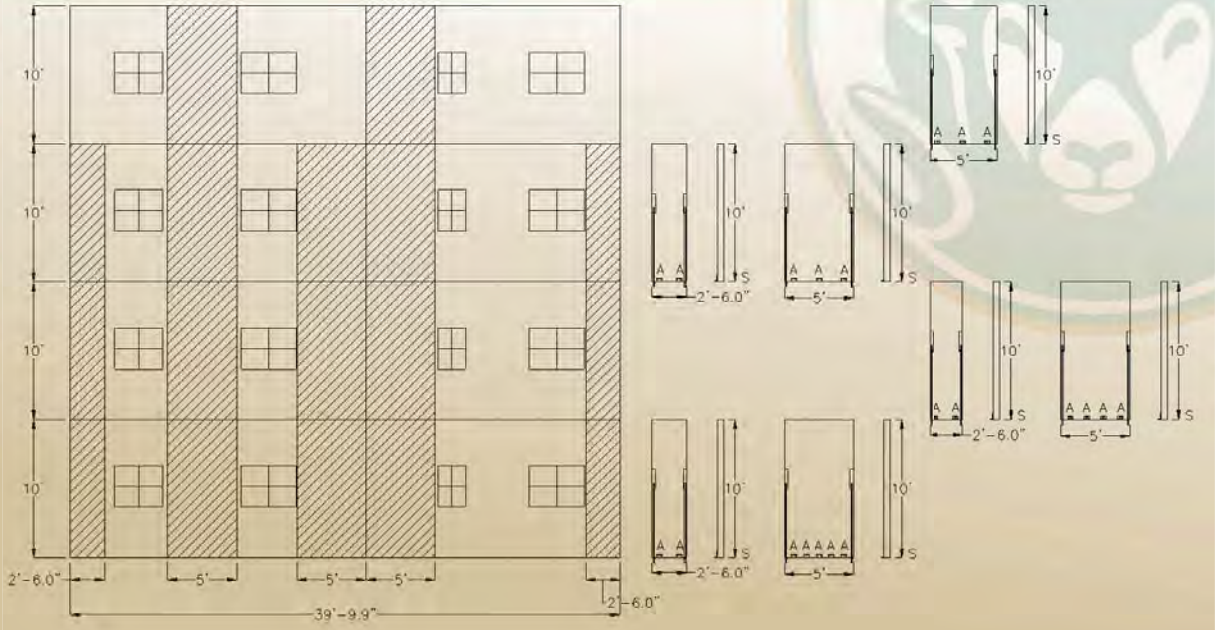
Colorado State University



Archetype 65-1

Illustrative example

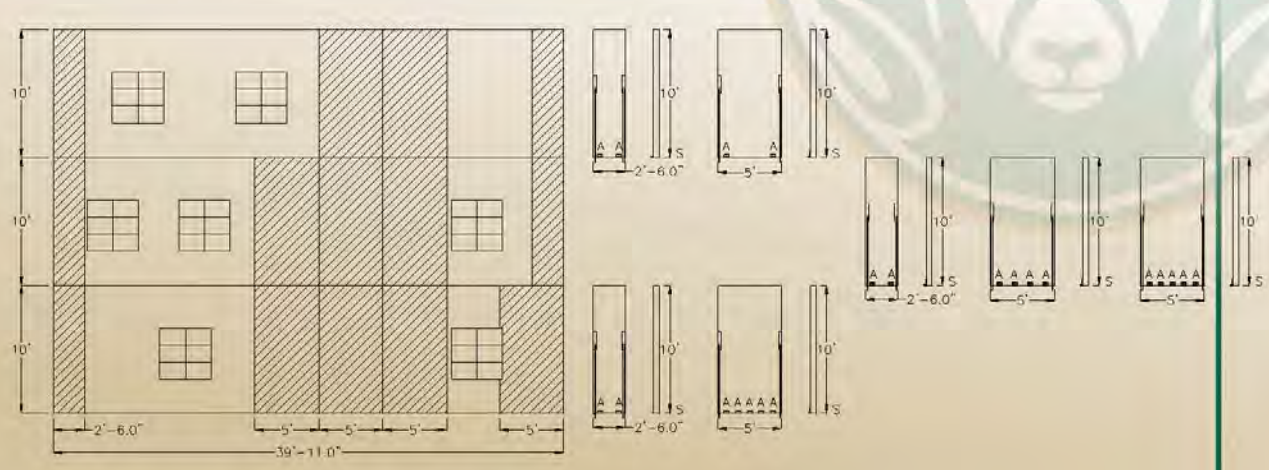
Colorado State University



Archetype 65-2

Illustrative example

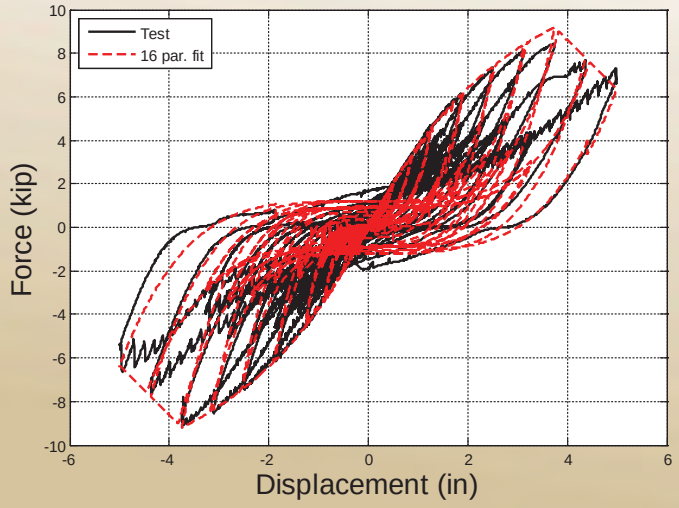
Colorado State University



Archetype 65-3

Illustrative example

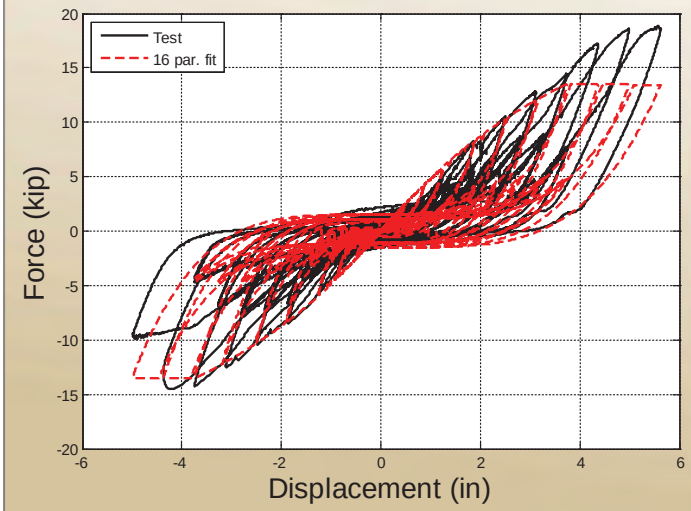
Colorado State University

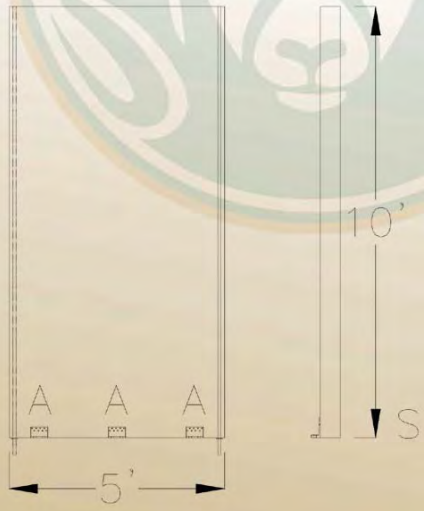


Note: Scaled results

Illustrative example

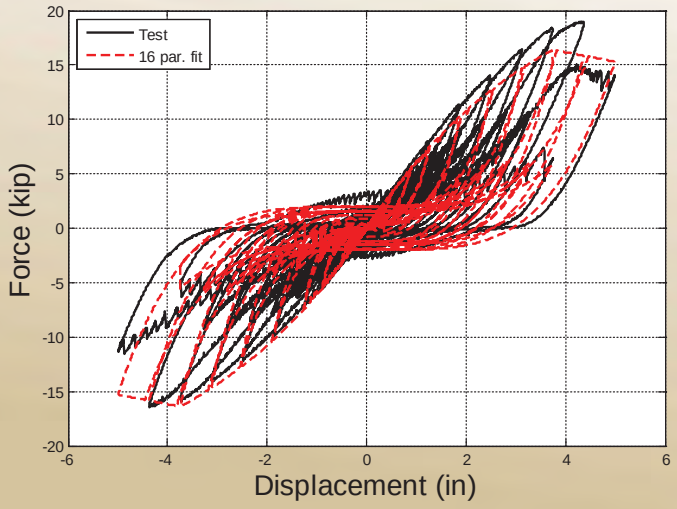
Colorado State University

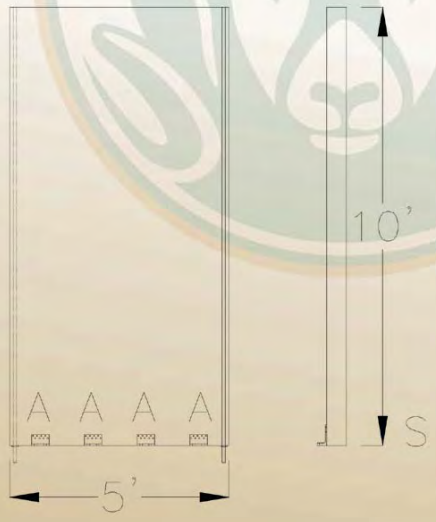




Illustrative example

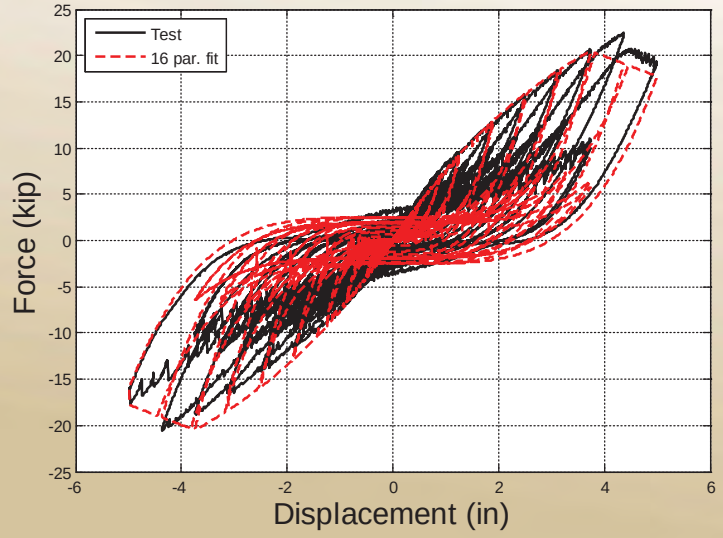
Colorado State University

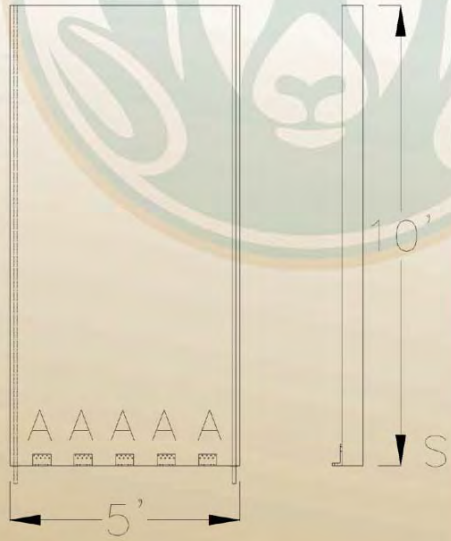




Illustrative example

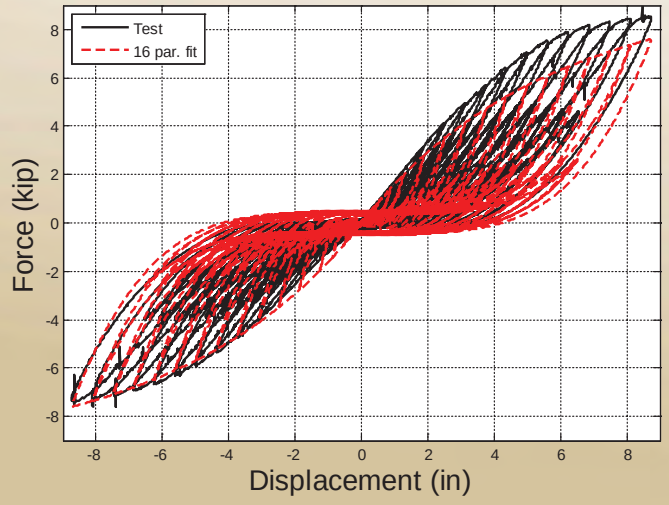
Colorado State University





Illustrative example

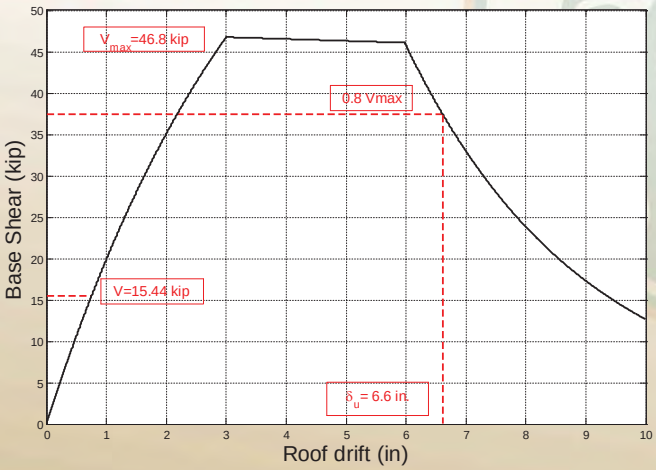
Colorado State University



Illustrative example

Colorado State University

Archetype 65-1



$$\Omega = \frac{V_{max}}{V} = 3.03$$

$$\delta_{y,eff} = C_o \frac{V_{max}}{W}\left(\frac{g}{4\pi^2}\right) * (\max(\mathrm{T}, T_1))^2 = 4.42\ in.$$

$$C_o = \phi_{1,r} \frac{\sum_1^N m_x \phi_{1,x}}{\sum_1^N m_x\, \phi_{1,x}^2}$$

$$\mu_T = \frac{6.6\ in.}{4.42\ in.} = 1.5$$

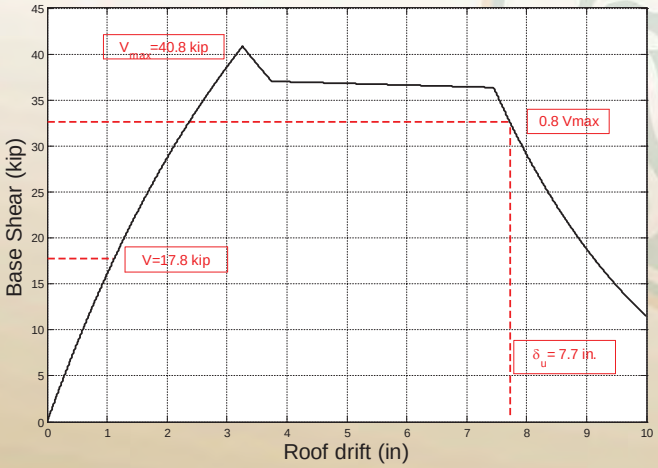
$$\mathrm{T} = 0.36\ sec$$

$$T_1 = 0.66\ sec$$

Illustrative example

Colorado State University

Archetype 65-2



$$\Omega = \frac{V_{max}}{V} = 2.29$$

$$\delta_{y,eff} = C_o \frac{V_{max}}{W}\left(\frac{g}{4\pi^2}\right) * (\max(\mathrm{T}, T_1))^2 = 4.21\ in.$$

$$C_o = \phi_{1,r} \frac{\sum_1^N m_x \phi_{1,x}}{\sum_1^N m_x\, \phi_{1,x}^2}$$

$$\mu_T = \frac{7.7\ in.}{4.21\ in.} = 1.83$$

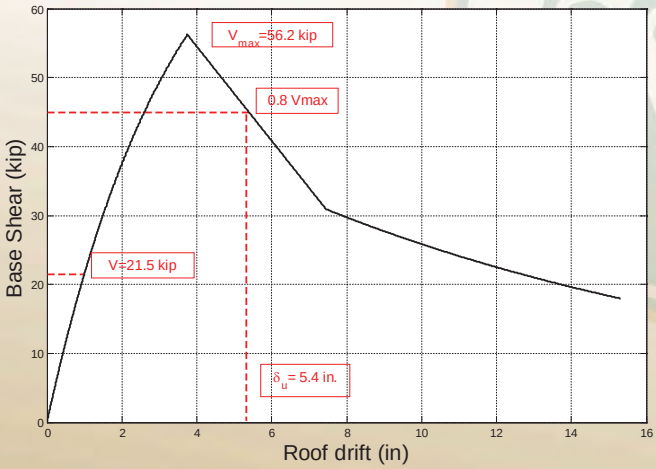
$$\mathrm{T} = 0.44\ sec$$

$$T_1 = 0.74\ sec$$

Illustrative example

Colorado State University

Archetype 65-3



$$\Omega = \frac{V_{max}}{V} = 2.61$$

$$\delta_{y,eff} = C_o \frac{V_{max}}{W}\left(\frac{g}{4\pi^2}\right) * (\max(\mathrm{T}, T_1))^2 = 3.49$$

$$C_o = \phi_{1,r} \frac{\sum_1^N m_x \phi_{1,x}}{\sum_1^N m_x\, \phi_{1,x}^2}$$

$$\mu_T = \frac{5.4\ in.}{3.49\ in.} = 1.55$$

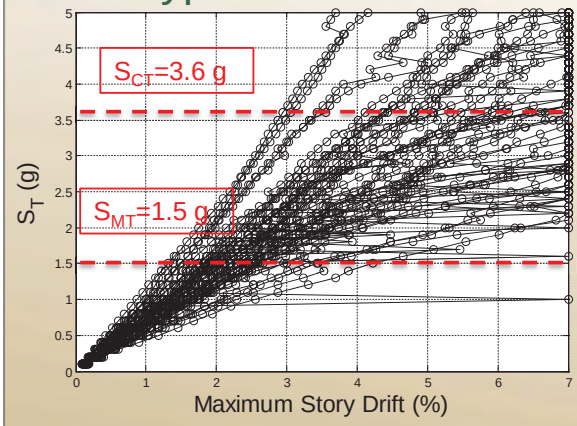
$$T = 0.36\ sec$$

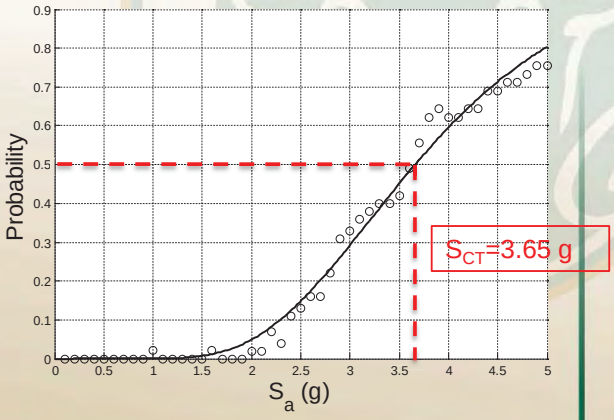
$$T_1 = 0.67\ sec$$

Illustrative example

Colorado State University

Archetype 65-1





$$CMR = \frac{S_{CT}}{S_{MT}} = \frac{3.65g}{1.5g} = 2.4$$

$$ACMR = SSF * CMR = 1.1 * 2.4 = 2.64$$

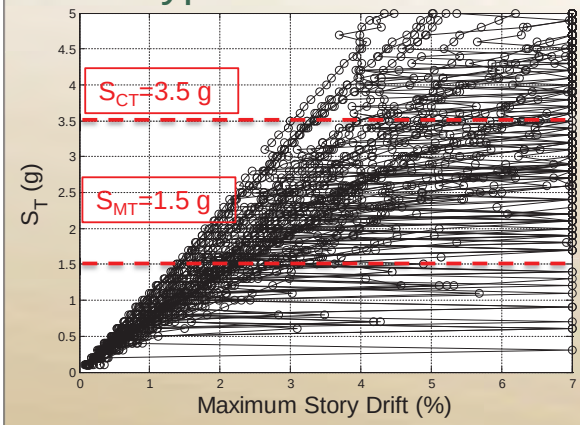
Table 7-1b Spectral Shape Factor (*SSF*) for Archetypes Designed using SDC D_{max}

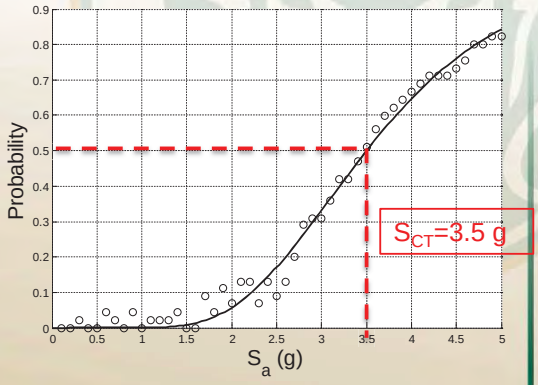
T (sec.)	Period-Based Ductility, μ_T							
	1.0	1.1	1.5	2	3	4	6	≥ 8
≤ 0.5	1.00	1.05	1.1	1.13	1.18	1.22	1.28	1.33
0.6	1.00	1.05	1.11	1.14	1.2	1.24	1.3	1.36
0.7	1.00	1.06	1.11	1.15	1.21	1.25	1.32	1.38
0.8	1.00	1.06	1.12	1.16	1.22	1.27	1.35	1.41
0.9	1.00	1.06	1.13	1.17	1.24	1.29	1.37	1.44
1.0	1.00	1.07	1.13	1.18	1.25	1.31	1.39	1.46
1.1	1.00	1.07	1.14	1.19	1.27	1.32	1.41	1.49
1.2	1.00	1.07	1.15	1.2	1.28	1.34	1.44	1.52
1.3	1.00	1.08	1.16	1.21	1.29	1.36	1.46	1.55
1.4	1.00	1.08	1.16	1.22	1.31	1.38	1.49	1.58
≥ 1.5	1.00	1.08	1.17	1.23	1.32	1.4	1.51	1.61

Illustrative example

Colorado State University

Archetype 65-2





$$CMR = \frac{S_{CT}}{S_{MT}} = \frac{3.5g}{1.5g} = 2.33$$

$$ACMR = SSF * CMR = 1.1 * 2.33 = 2.57$$

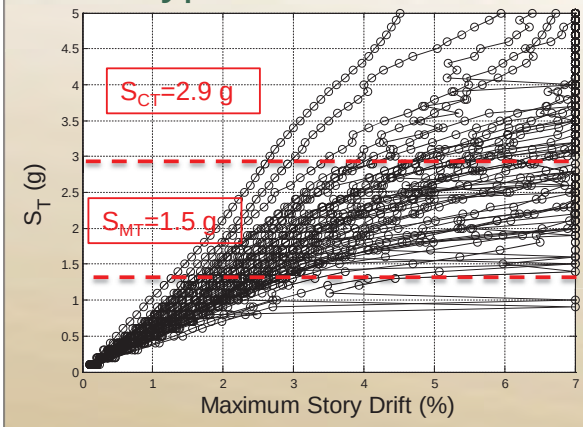
Table 7-1b Spectral Shape Factor (*SSF*) for Archetypes Designed using SDC D_{max}

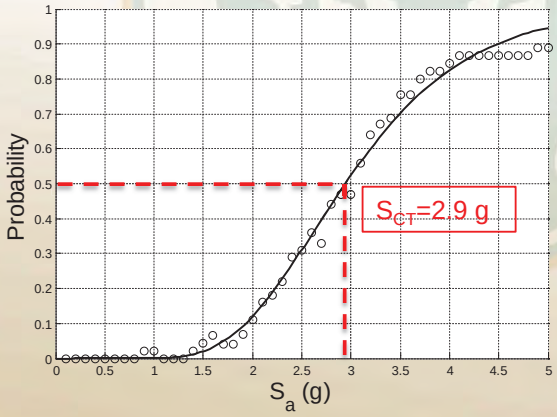
T (sec.)	Period-Based Ductility, μ_T							
	1.0	1.1	1.5	2	3	4	6	≥ 8
≤ 0.5	1.00	1.05	1.1	1.13	1.18	1.22	1.28	1.33
0.6	1.00	1.05	1.11	1.14	1.2	1.24	1.3	1.36
0.7	1.00	1.06	1.11	1.15	1.21	1.25	1.32	1.38
0.8	1.00	1.06	1.12	1.16	1.22	1.27	1.35	1.41
0.9	1.00	1.06	1.13	1.17	1.24	1.29	1.37	1.44
1.0	1.00	1.07	1.13	1.18	1.25	1.31	1.39	1.46
1.1	1.00	1.07	1.14	1.19	1.27	1.32	1.41	1.49
1.2	1.00	1.07	1.15	1.2	1.28	1.34	1.44	1.52
1.3	1.00	1.08	1.16	1.21	1.29	1.36	1.46	1.55
1.4	1.00	1.08	1.16	1.22	1.31	1.38	1.49	1.58
≥ 1.5	1.00	1.08	1.17	1.23	1.32	1.4	1.51	1.61

Illustrative example

Colorado State University

Archetype 65-3





$$CMR = \frac{S_{CT}}{S_{MT}} = \frac{2.9g}{1.5g} = 1.93$$

$$ACMR = SSF * CMR = 1.1 * 1.93 = 2.12$$

Table 7-1b Spectral Shape Factor (*SSF*) for Archetypes Designed using SDC D_{max}

T (sec.)	Period-Based Ductility, μ_T							
	1.0	1.1	1.5	2	3	4	6	≥ 8
≤ 0.5	1.00	1.05	1.1	1.13	1.18	1.22	1.28	1.33
0.6	1.00	1.05	1.11	1.14	1.2	1.24	1.3	1.36
0.7	1.00	1.06	1.11	1.15	1.21	1.25	1.32	1.38
0.8	1.00	1.06	1.12	1.16	1.22	1.27	1.35	1.41
0.9	1.00	1.06	1.13	1.17	1.24	1.29	1.37	1.44
1.0	1.00	1.07	1.13	1.18	1.25	1.31	1.39	1.46
1.1	1.00	1.07	1.14	1.19	1.27	1.32	1.41	1.49
1.2	1.00	1.07	1.15	1.2	1.28	1.34	1.44	1.52
1.3	1.00	1.08	1.16	1.21	1.29	1.36	1.46	1.55
1.4	1.00	1.08	1.16	1.22	1.31	1.38	1.49	1.58
≥ 1.5	1.00	1.08	1.17	1.23	1.32	1.4	1.51	1.61

Illustrative example

Colorado State University

Completeness and Robustness	Confidence in Basis of Design Requirements		
	High	Medium	Low
High. Extensive safeguards against unanticipated failure modes. All important design and quality assurance issues are addressed.	(A) Superior $\beta_{TD} = 0.10$	(B) Good $\beta_{TD} = 0.20$	(C) Fair $\beta_{TD} = 0.35$
Medium. Reasonable safeguards against unanticipated failure modes. Most of the important design and quality assurance issues are addressed.	(B) Good $\beta_{TD} = 0.20$	(C) Fair $\beta_{TD} = 0.35$	(D) Poor $\beta_{TD} = 0.50$
Low. Questionable safeguards against unanticipated failure modes. Many important design and quality assurance issues are not addressed.	(C) Fair $\beta_{TD} = 0.35$	(D) Poor $\beta_{TD} = 0.50$	—

Representation of Collapse Characteristics	Accuracy and Robustness of Models		
	High	Medium	Low
High. Index models capture the full range of the archetype design space and structural behavioral effects that contribute to collapse.	(A) Superior $\beta_{MDL} = 0.10$	(B) Good $\beta_{MDL} = 0.20$	(C) Fair $\beta_{MDL} = 0.35$
Medium. Index models are generally comprehensive and representative of the design space and behavioral effects that contribute to collapse.	(B) Good $\beta_{MDL} = 0.20$	(C) Fair $\beta_{MDL} = 0.35$	(D) Poor $\beta_{MDL} = 0.50$
Low. Significant aspects of the design space and/or collapse behavior are not captured in the index models.	(C) Fair $\beta_{MDL} = 0.35$	(D) Poor $\beta_{MDL} = 0.50$	—

Completeness and Robustness	Confidence in Test Results		
	High	Medium	Low
High. Material, component, connection, assembly, and system behavior well understood and accounted for. All, or nearly all, important testing issues addressed.	(A) Superior $\beta_{TD} = 0.10$	(B) Good $\beta_{TD} = 0.20$	(C) Fair $\beta_{TD} = 0.35$
Medium. Material, component, connection, assembly, and system behavior generally understood and accounted for. Most important testing issues addressed.	(B) Good $\beta_{TD} = 0.20$	(C) Fair $\beta_{TD} = 0.35$	(D) Poor $\beta_{TD} = 0.50$
Low. Material, component, connection, assembly, and system behavior fairly understood and accounted for. Several important testing issues not addressed.	(C) Fair $\beta_{TD} = 0.35$	(D) Poor $\beta_{TD} = 0.50$	—

$$\beta_{RTR} = 0.1 + 0.1 * \mu_T \leq 0.4$$

$$\beta_{RTR} = 0.1 + 0.1 * 1.6 = 0.26$$

$$\beta_{TOT} = \sqrt{\beta_{RTR}^2 + \beta_{DR}^2 + \beta_{TD}^2 + \beta_{MDL}^2} = 0.66$$

$$Avg.ACMR = 2.44 > 2.38 \Rightarrow Pass$$

Table 7-3 Acceptable Values of Adjusted Collapse Margin Ratio ($ACMR_{10\%}$ and $ACMR_{20\%}$)

Total System Collapse Uncertainty	Collapse Probability				
	5%	10% ($ACMR_{10\%}$)	15%	20% ($ACMR_{20\%}$)	25%
0.275	1.57	1.42	1.33	1.26	1.20
0.600	2.68	2.16	1.86	1.66	1.50
0.625	2.80	2.23	1.91	1.69	1.52
0.650	2.91	2.30	1.96	1.73	1.55
0.675	3.04	2.38	2.01	1.76	1.58
0.700	3.16	2.45	2.07	1.80	1.60
0.725	3.30	2.53	2.12	1.84	1.63

On average for performance group

For any one archetype

Illustrative example

Colorado State University

Overstrength Factor

The value of the system overstrength factor, Ωo, for use in design should not be taken as less than the largest average value of calculated archetype overstrength, Ω, from any performance group

Deflection Amplification Factor

Inherent damping may be assumed to be 5 percent of critical, and a corresponding value of the damping coefficient, $B_I = 1.0$

$$C_d = \frac{R}{B_I}$$

Table 18.6-1 Damping Coefficient, B_{V+I}, B_{1D}, B_R, B_{1M}, B_{mD}, B_{mM} (Where Period of the Structure ≥ T_0)

Effective Damping, β (percentage of critical)	B_{v+I}, B_{1D}, B_R, B_{1M}, B_{mD}, B_{mM} (where period of the structure ≥ T_0)
≤2	0.8
5	1.0
10	1.2
20	1.5
30	1.8
40	2.1
50	2.4
60	2.7
70	3.0
80	3.3
90	3.6
≥100	4.0

Next Steps

Colorado State University

- Wall assembly with a diaphragm
  - Low aspect ratio panels
  - High aspect ratio panels
  - 3 sided with an opening on one side

- Finalizing analyses
- Report submittal to the peer panel

Acknowledgements

Colorado State University

This study is funded by a joint venture agreement between the United States Department of Agriculture Forest Products Laboratory (FPL) and Colorado State University. That support is gratefully acknowledged.

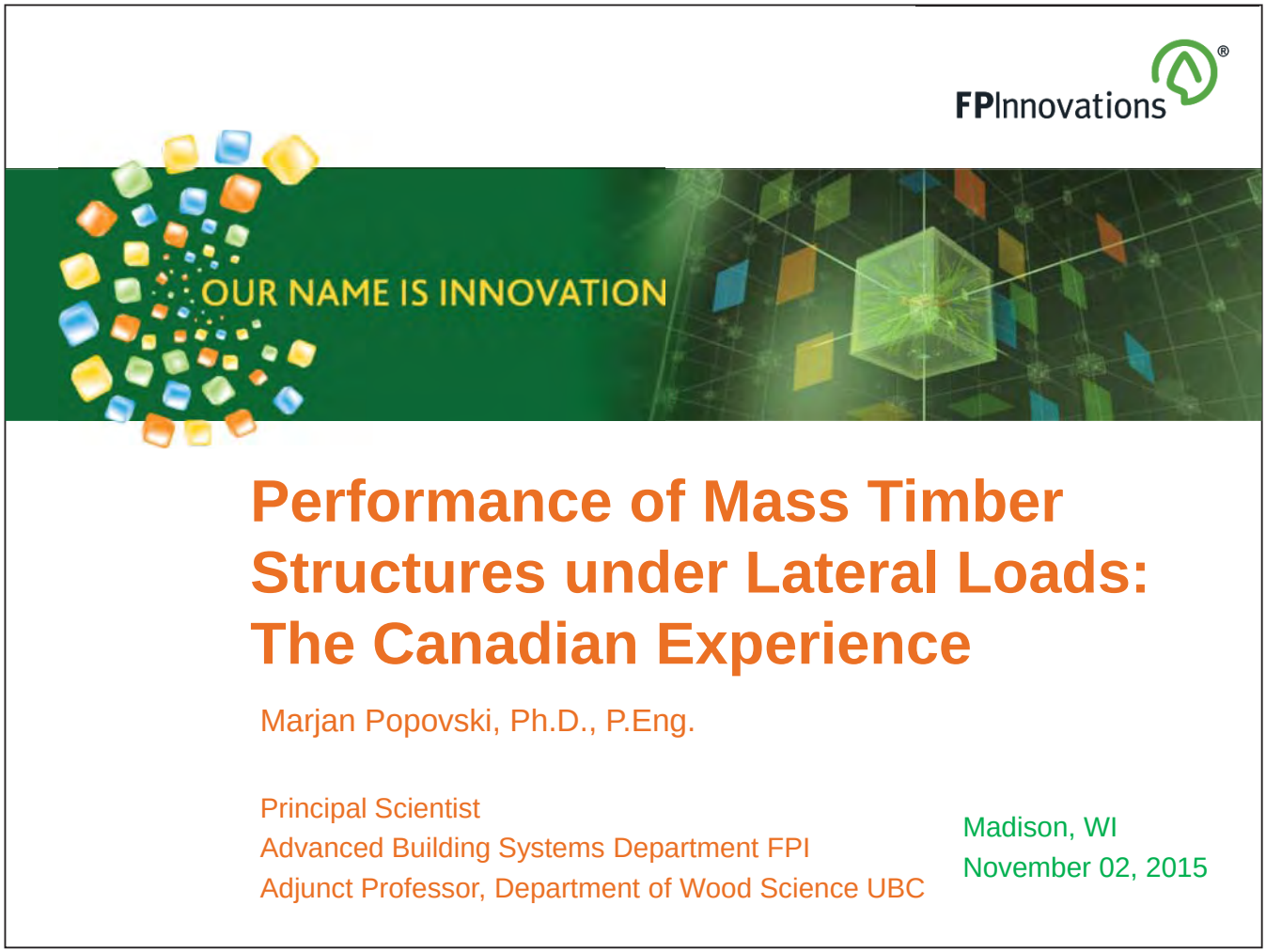
Colorado State University

Thank you!

Performance of Mass Timber Structures under Lateral Loads: The Canadian Experience

Marjan Popovski, Principal Scientist
FPInnovations, Vancouver, British Columbia, Canada

In the past 20 years, mass timber (MT) products have emerged as cost competitive, carbon efficient, sustainable, and reliable structural components for use in residential and nonresidential applications. They can complement existing light-frame and heavy-timber systems or can be used in new innovative construction applications that are currently dominated by concrete, masonry, and steel. MT has also given the opportunity to wood as a structural material to be used in tall buildings once again. To use these new MT-based structural systems in regions with high wind and seismic loads, a comprehensive investigation of their performance under lateral loads is needed. This presentation will summarize some of the research activities and findings related to the performance of MT-based structural systems under lateral loads in Canada.



Introduction

- Mass Timber Construction (MTC) offers a wide range of advantages compared to other types of construction
- Possibility for use of MT products in Lateral Load Resisting Systems (LLRS) with adequate response to earthquakes or high winds
- Presentation will cover some of the research activities in Canada on this topic
- CLT was by far most used MT product in the research projects

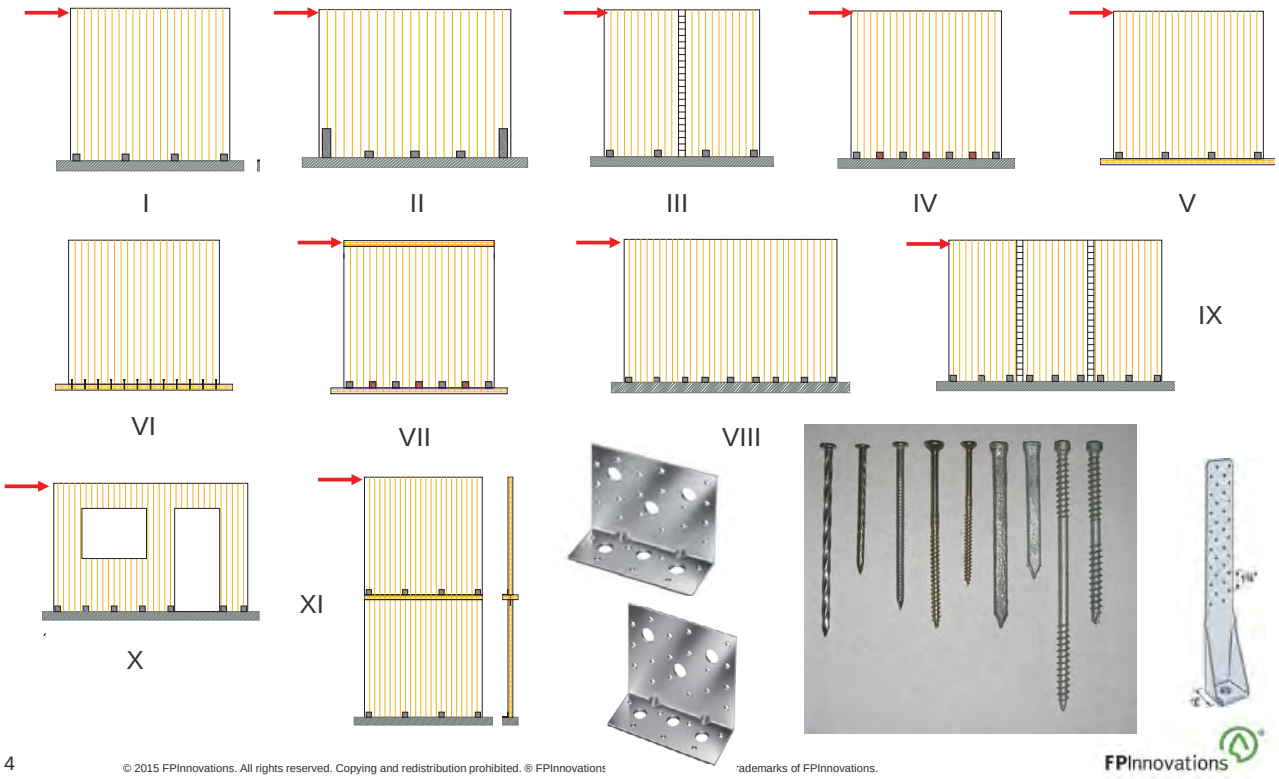
© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

The Research on MT as LLRS in Canada

- In 2007/08, FPI launched its first research program on CLT, part of it related to performance of CLT as LLRS
- In 2010, the NSERC, FPI and NRCan have partnered to create the NEWBuildS, a multi-disciplinary strategic research **N**etwork for **E**ngineered **W**ood-based **Build**ing **S**ystems
  - 23 Professors and 17 Researchers from FPI, NRC and CWC
  - 60 graduate students and PDFs from 11 Canadian universities
  - 2 out of 4 themes of the network dealt with MT
    - CLT and second
    - Hybrid Systems

© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

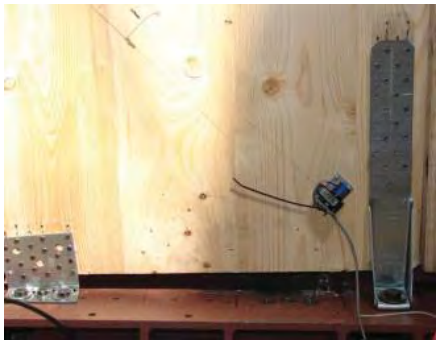
CLT Walls as LLRS: Configurations Tested

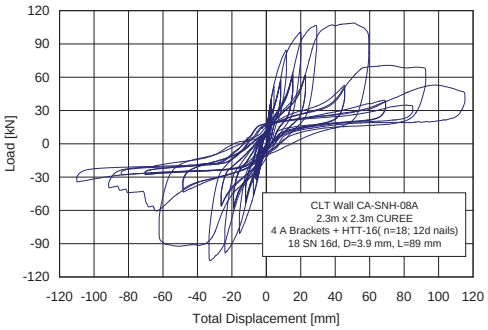


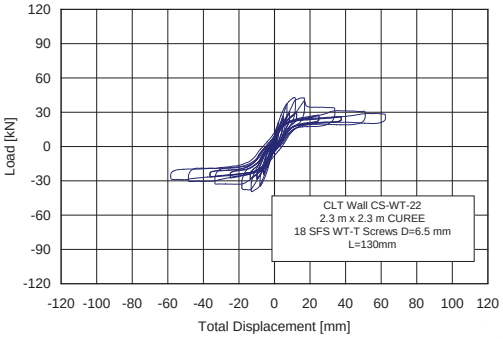
© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations
ademarks of FPInnovations.

FPInnovations

Examples of Test Results



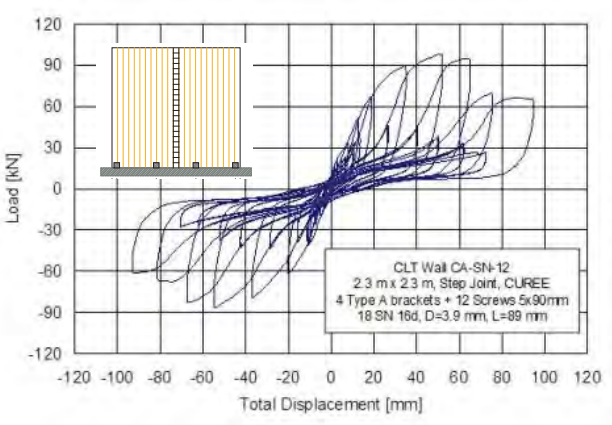


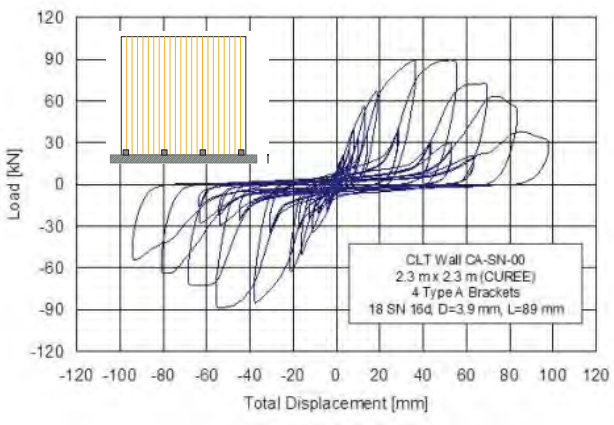


© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

FPInnovations

Examples of Test Results



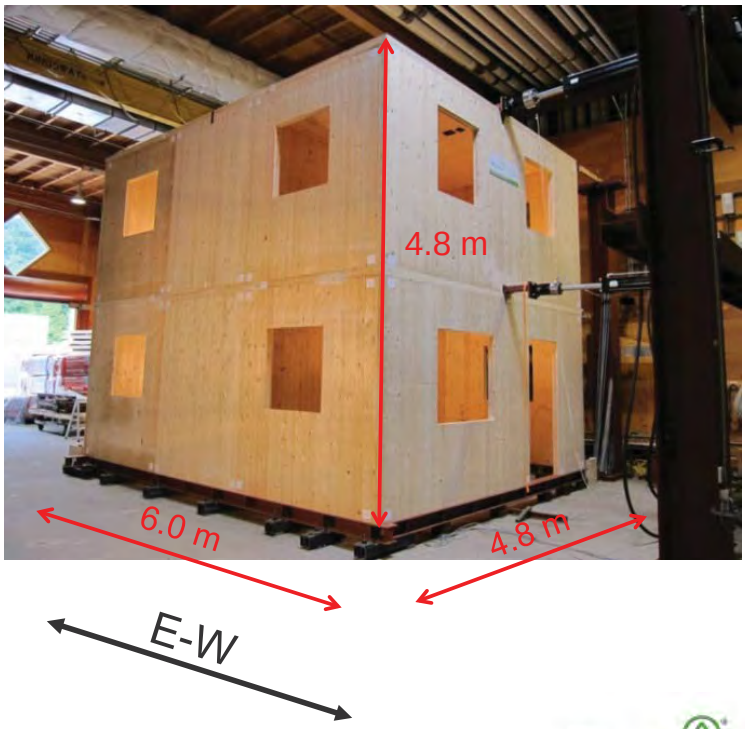


© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

FPInnovations

Tested CLT House

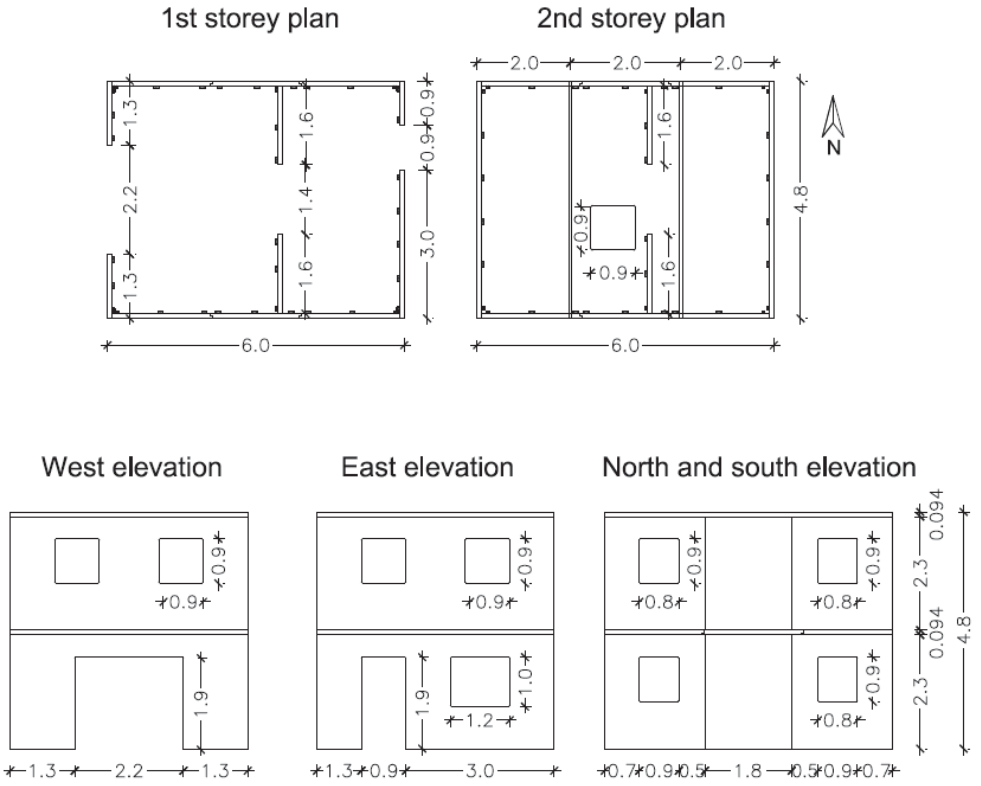
- 6.0 m x 4.8 m in plan
- H = 4.8 m
- Platform construction with 94mm thick panels
- Symmetric in E-W direction
- Non-symmetric in N-S
- 13.6 kN dead load/level
- Seismic design according to NBCC for Vancouver, BC (R_d = 2.0; R_0 = 1.5)



© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

FPInnovations

Plan and Elevation



© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

FPInnovations

Objectives

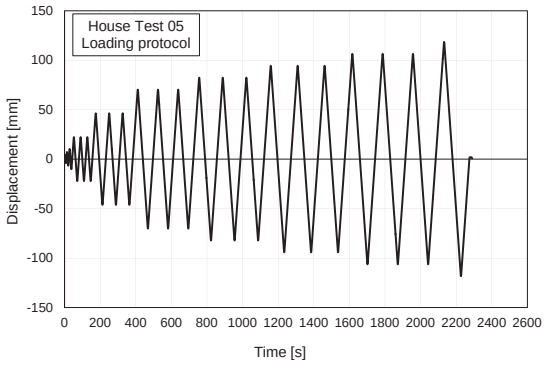
- Deformability of the 3-D CLT structure
- Storey drifts that can be sustained
- Failure mechanisms
- Effects of wall openings on the response
- Performance of diaphragms
- Effects of perpendicular walls and hold-downs on resistance and deformability

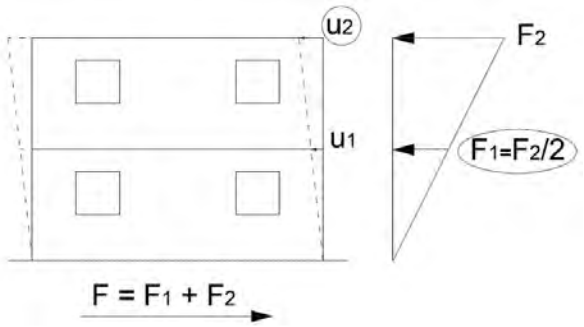
© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

FPInnovations

Lateral Loading and Protocols

- Loads applied on each storey, one direction at a time
- ISO 16670 cyclic loading protocol





© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

Testing Program

Test	Type	Direction	Loading Rate	Changes in the Specimen
01	Monotonic	E-W (L)	5.1 mm/min until 72 mm (1.5% of total house height H)	
02	Cyclic	E-W (L)	2.5 mm/s to 60mm (1.25% H)	
03	Cyclic	E-W (L)	2.5 mm/s to 84 mm (1.75% H)	Additional Hold-Downs
04	Cyclic	N-S	2.5 mm/s until 108 mm (2.25% H)	With Additional H-D
05	Cyclic	N-S	2.5 mm/s until 108 mm (2.25% H)	64% less wall-to wall screws

© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

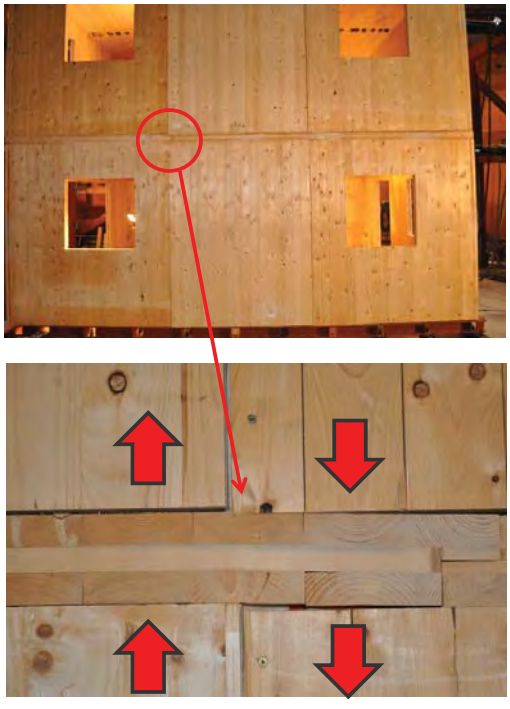
Global Response

- Combination of sliding and uplift deformations
- Walls with openings had higher in-plane deformation (some torsion in Tests 04 and 05 N-S)
- More deformation in the first storey (max drift 3.2%)
- Structural integrity was not compromised at failure

© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

Diaphragm Behaviour

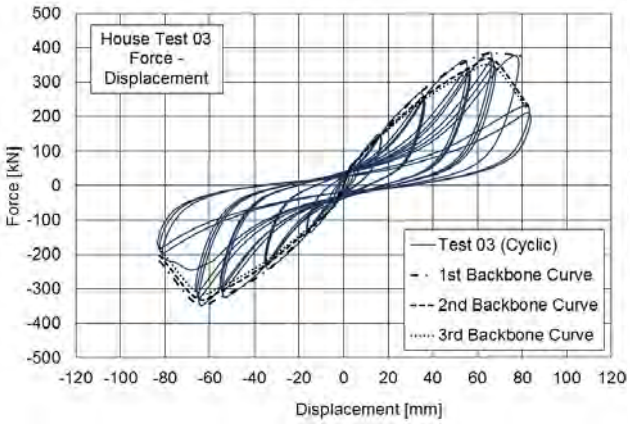
- Negligible slip between diaphragm panels (max 1.7 mm)
- Rigid diaphragm behaviour (mid-span deflection only 14% of that of the walls below)
- Out-of-plane bending helped the wall rocking at lap-joints

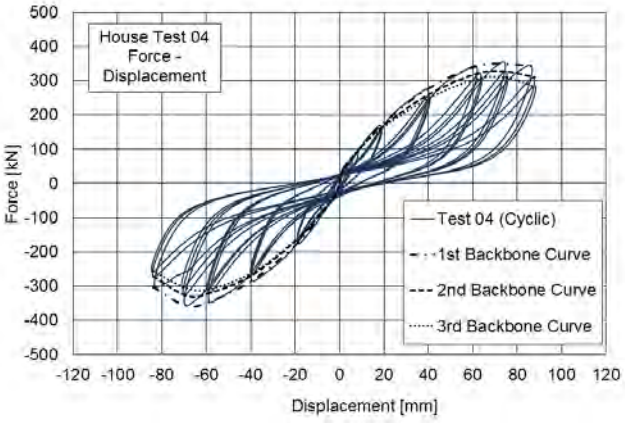


© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

E-W vs N-S Performance (Test 03 vs Test 04)

- Only 2.5% difference in resistance
- Higher deformability in N-S (2.2% vs 1.8% storey drift) due to:
  - Wall openings
  - Higher building aspect ratio (rocking component)

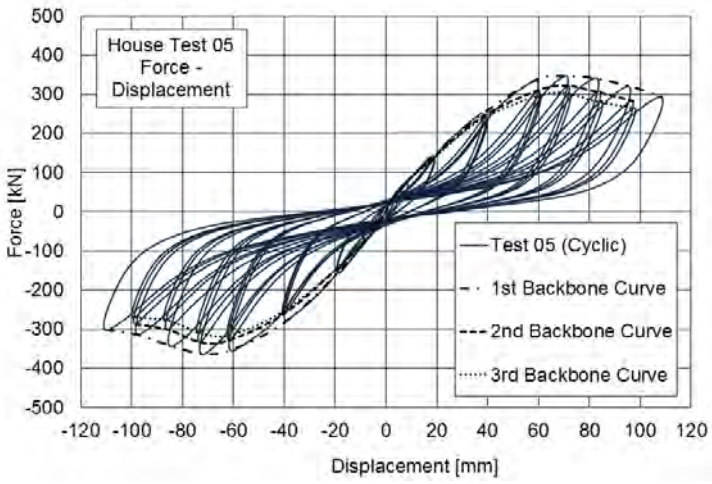




© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

Less screws in Perpendicular Walls (Test 05)

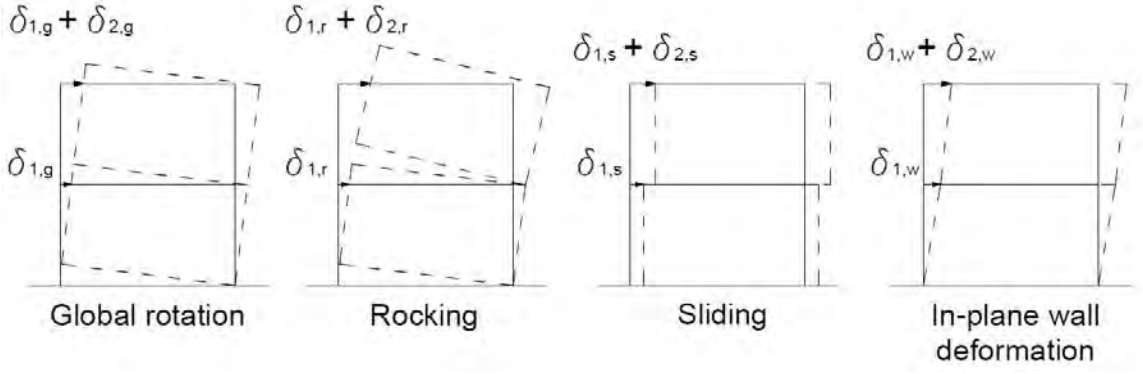
- Did not reduce the resistance
- Increased the slip between walls (max. 6.2 mm)
- Increased the house flexibility (3.2% vs 2.3% drift)



© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

Deformability Components

- Total storey deformation $\delta_{i,tot} = \delta_{i,g} + \delta_{i,r} + \delta_{i,s} + \delta_{i,w}$

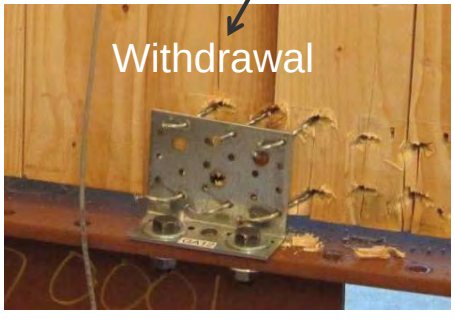


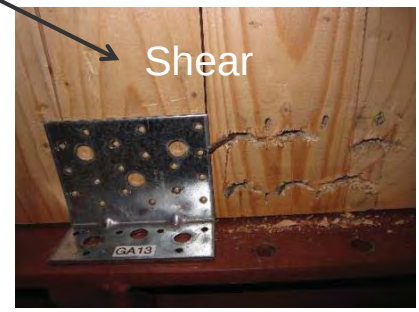
Test No.	1st Storey			2nd Storey			Total Deflection δ_{tot} [mm]
	Rocking $\delta_{1,r}$ [%]	Sliding $\delta_{1,s}$ [%]	In-plane $\delta_{1,w}$ [%]	Rocking $\delta_{2,r}$ [%]	Sliding $\delta_{2,s}$ [%]	In-plane $\delta_{2,w}$ [%]	
03	16.0	39.5	6.9	6.3	9.9	5.4	73.7
04	26.6	21.4	14.9	2.7	5.4	2.4	86.2
05	26.8	28.3	10.8	2.2	3.3	1.8	109.6

© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

Failure Mechanisms

- Almost all damage at the bottom storey
- Yielding of screws in step-joints
- Nail withdrawal in the hold-downs
- Shear and withdrawal failure of nails in the brackets

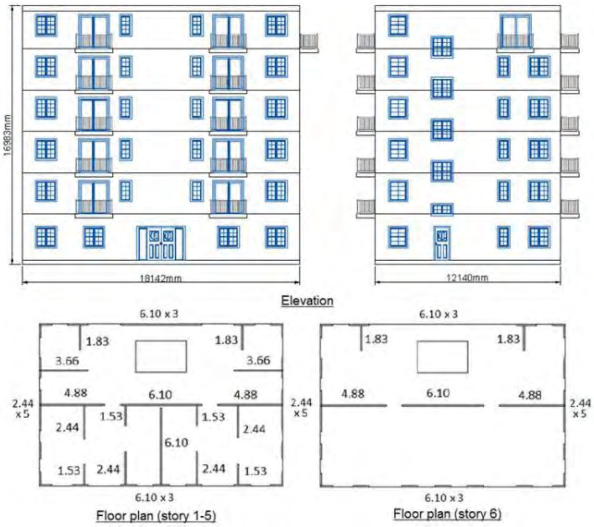




© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

Preliminary Force Modification Factors (Rd-factors)

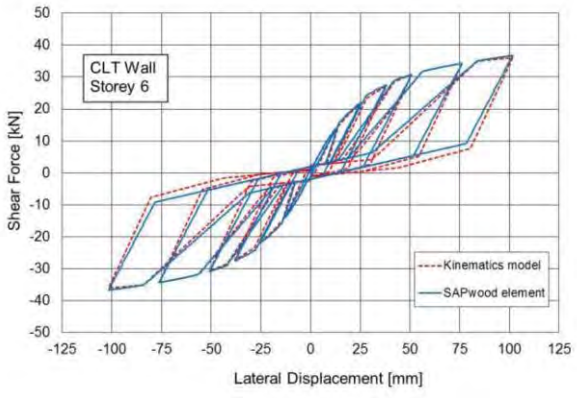
- 2015 NBCC has two R-factors
  - Ro-factor, over-strength
  - Rd-factor, ductility
- Analytical study was done with CSU and CSM to quantify preliminary Rd-factors for symmetrical platform type CLT structures



© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

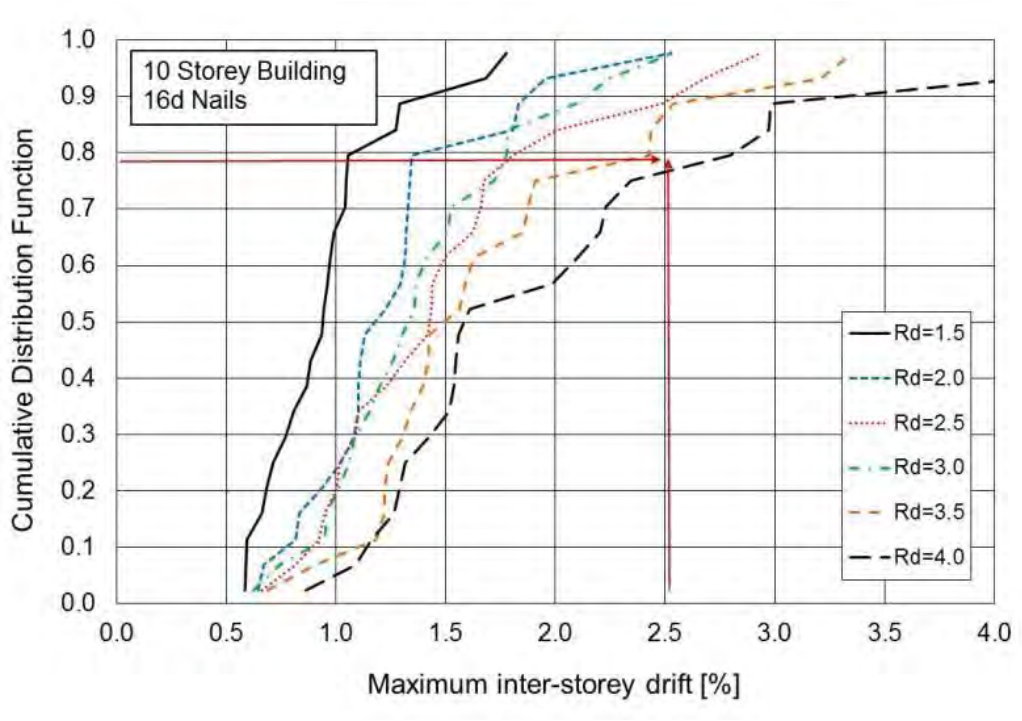
Analysed Building Models

- Buildings with 3 heights
  - 6 storey
  - 10 storey
  - 15 storey
- Designed according to NBCC 2010 ESF Procedure
  - Vancouver, BC with Sa =0.743g
  - R_o = 1.5
- R_d from 1.5 to 4.0 (to 6.0 for 6 storey)
- 48 six-storey CLT buildings
- Six 10-storey and 15-storey buildings
- Total of 60 buildings analyzed with SAPWood



© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

CDF for 10 storey CLT Building



© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

Rd-factors for Different Buildings and Performance Targets

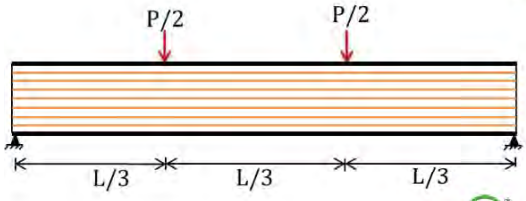
- Minimum R_d factor is 2.0

Performance Targets Storey Drift [%] with PNE [%]	6 Storey	10 Storey	15 Storey
1.5% with 50% PNE	2.5	3.5	4.0
2.0% with 80% PNE	2.0	3.0	4.0
2.5% with 80% PNE	2.5	3.5	4.0
4.0% with 80% PNE	2.5	4.0	4.0

© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

In-plane Stiffness of CLT Panels: Experimental Programme

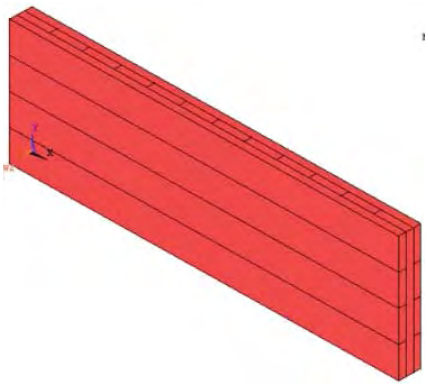
- CLT Panels Tested at FPInnovations, Quebec
- CLT beams were 1.2m high and 5-ply (175mm) thick
- 6 panels from each length of 3.6m (12'), 6.1m (20'), and 8.5m (28') were tested

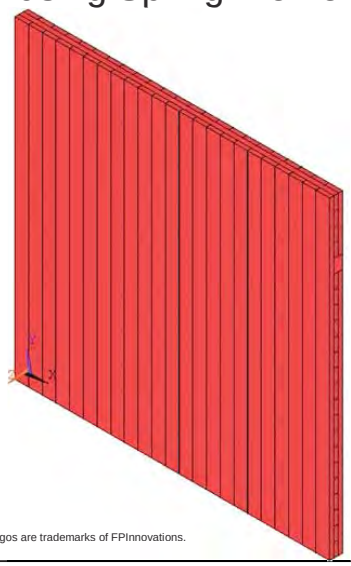


© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

Finite Element Analyses

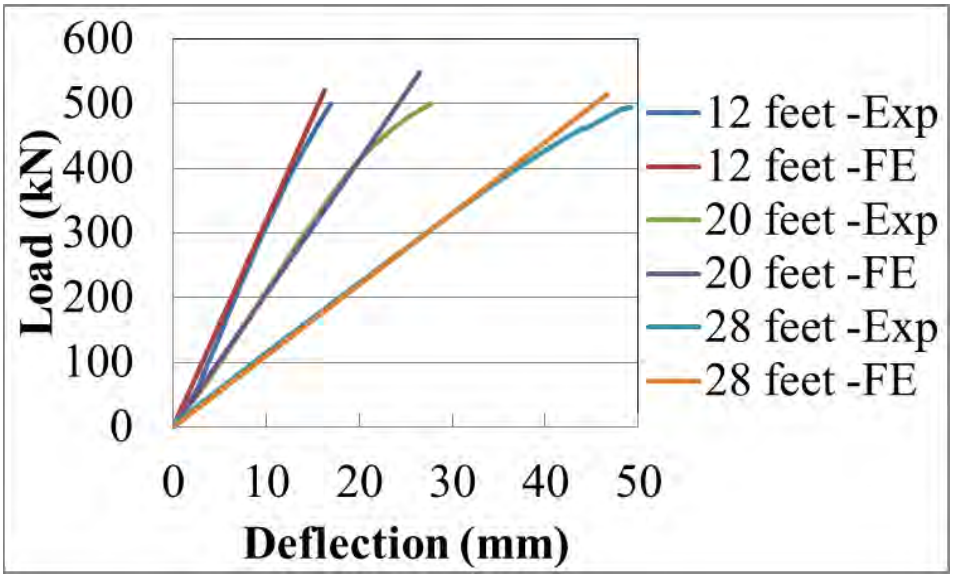
- FE models of CLT panels and walls were developed in ANSYS
- UBC + FPI (Shahnewaz Md, T. Tannert, M. Popovski)
  - CLT panels modelled using Solid Elements
  - Glue line between lamellas modelled using Contact Elements
  - Connections in CLT walls modelled using Spring Elements





© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

Comparison of Experimental vs Analytical Results



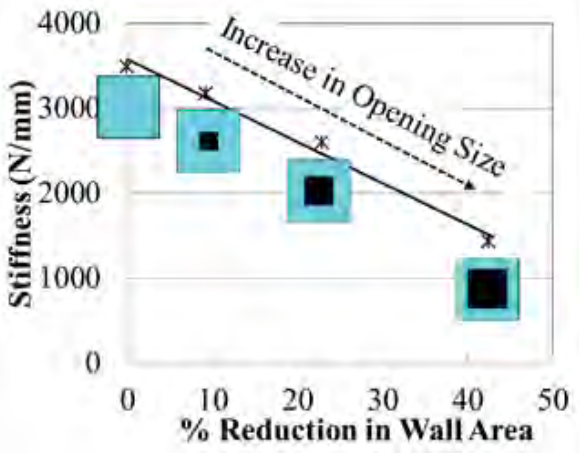
© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

Walls With Openings

- Stiffness decreased linearly with an increase in opening area
- Analytical model to calculate the in-plane stiffness of CLT walls with opening was proposed

$$k_O = k_P \left[1 - \frac{(A_O / A_P)}{1.15 - (A_O / A_P)} \right]$$

k_O & k_P wall stiffness with and without opening
A_O & A_P area of walls with and without opening



© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

Helping FFTT Concept Become Reality

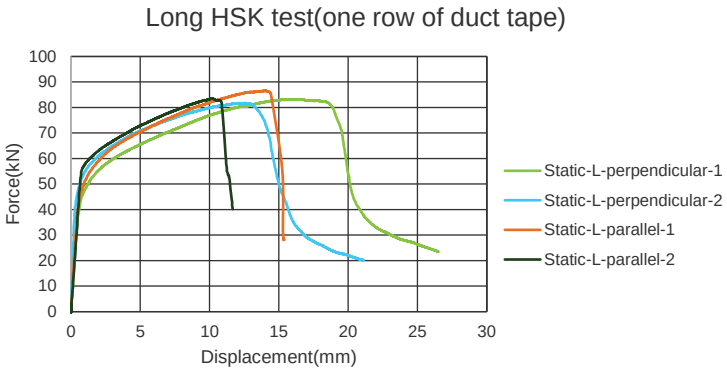
- Experimental and analytical work to quantify performance of FFTT under lateral loads (UBC + FPI)
  (X. Zhang, M. Popovski, T. Tannert)

© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

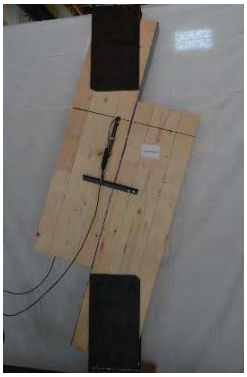
FPInnovations

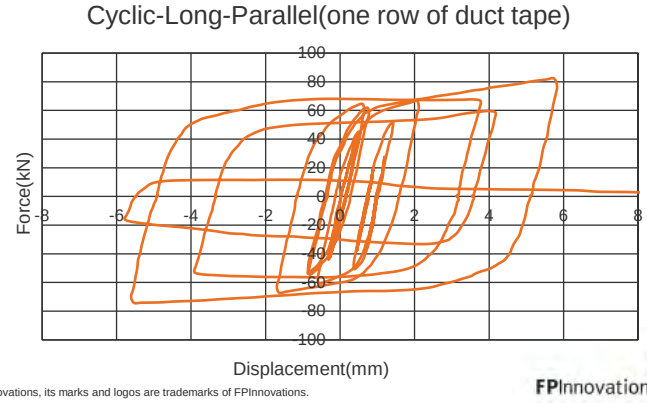
Tests on Novel HSK Hold-downs

- Static Test



- Cyclic Test



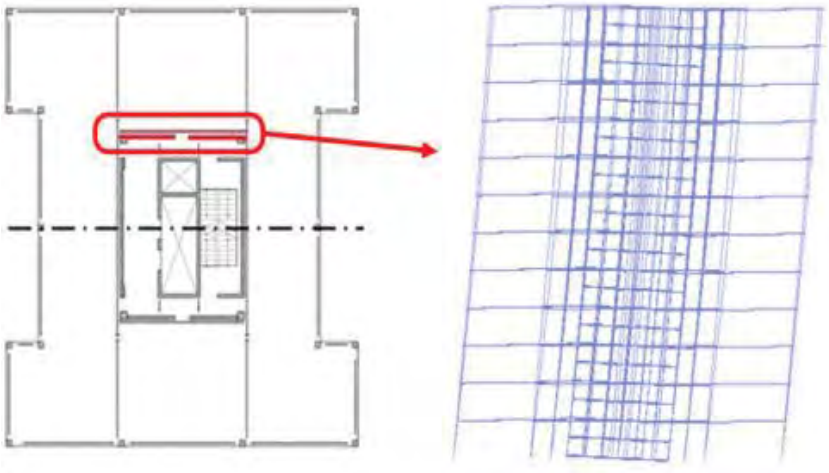


© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

FPInnovations

R-factors for FFTT

- Buildings Considered with 3 , 6 , 9, 12 storeys
- Ro=1.5; Rd=1.5 to 6.0

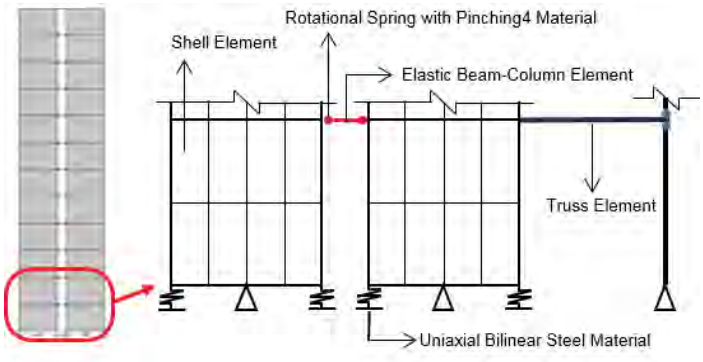


Layout and first mode shape for FFTT System Option-1

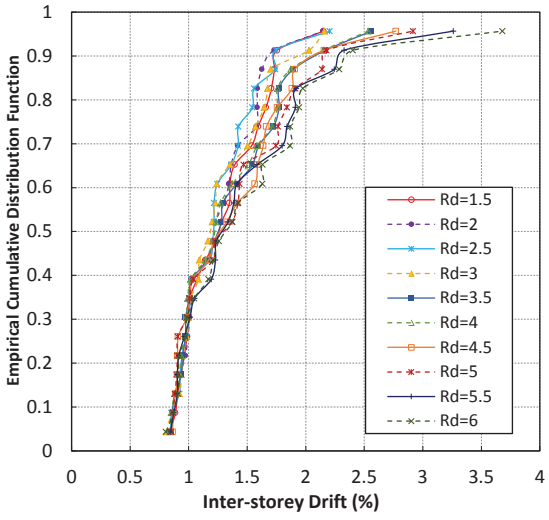
© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

FPInnovations

Model and Preliminary Results



OpenSeas Model

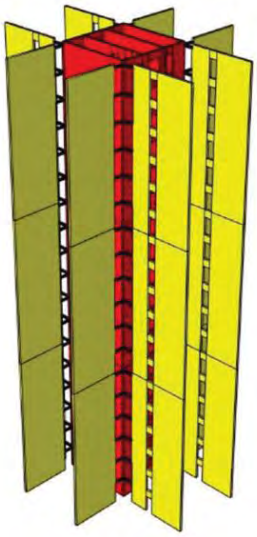


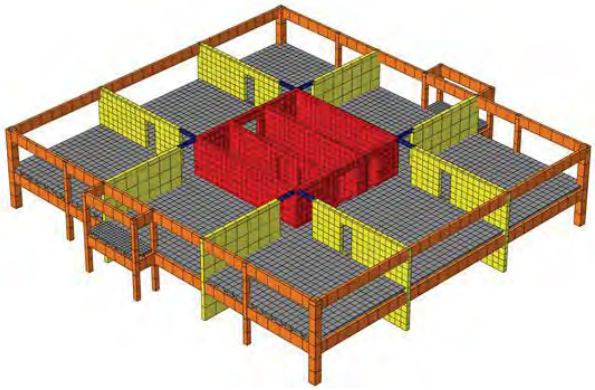
© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

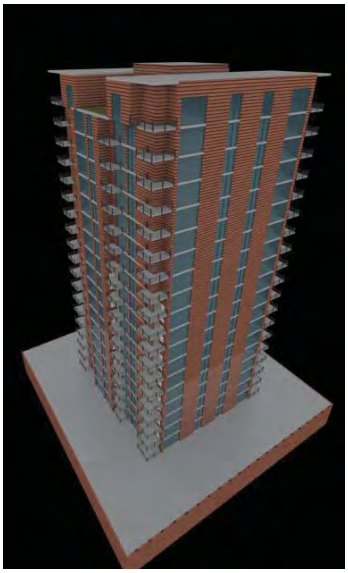
FPInnovations

NEWBuildS Tall Wood Design Project

- Goal: To execute the design process of a 20-storey tall hybrid mass timber building located in North Vancouver, BC
- Chapter 3 Lateral Load Design
  (Z. Chen, Y. Chui, M. Popovski)



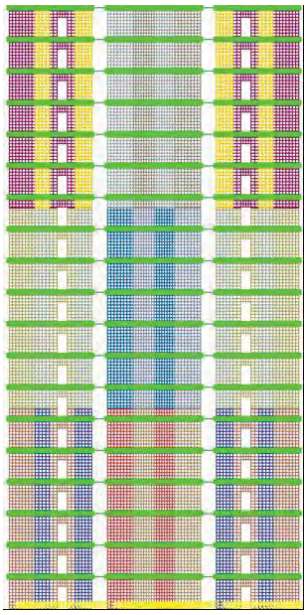




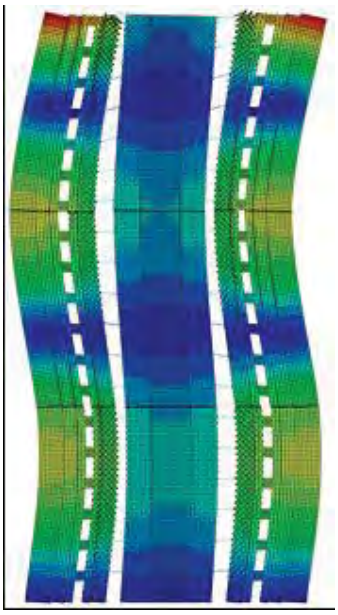
© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

FPInnovations

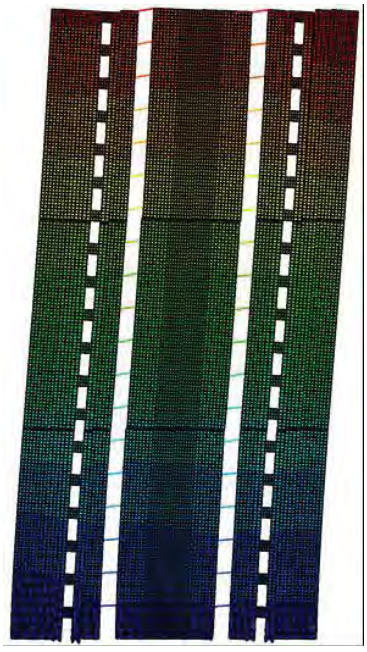
Model and Analyses



Model in Abacus



3rd Mode Shape

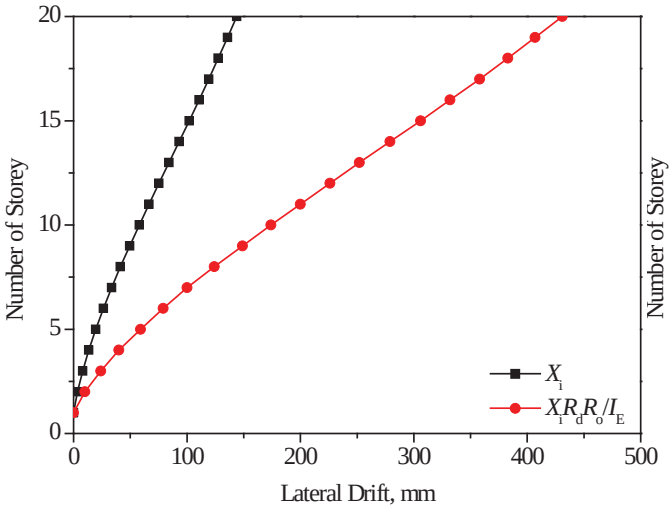


Pushover Analysis

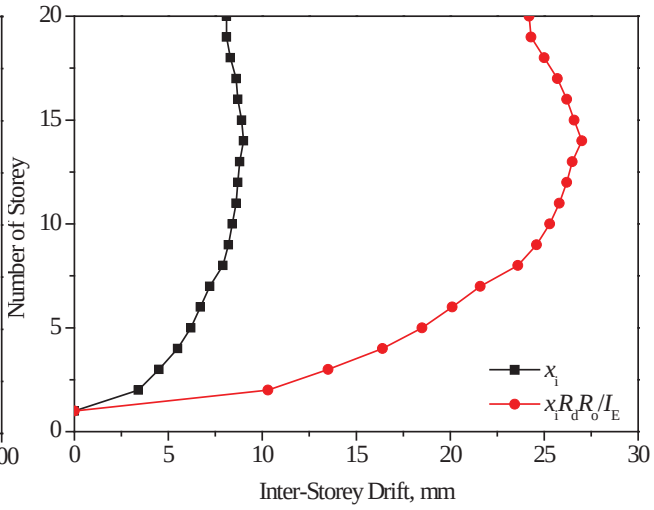
© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

FPInnovations

Example of LDA Results



Elastic and Non-Linear Deflection

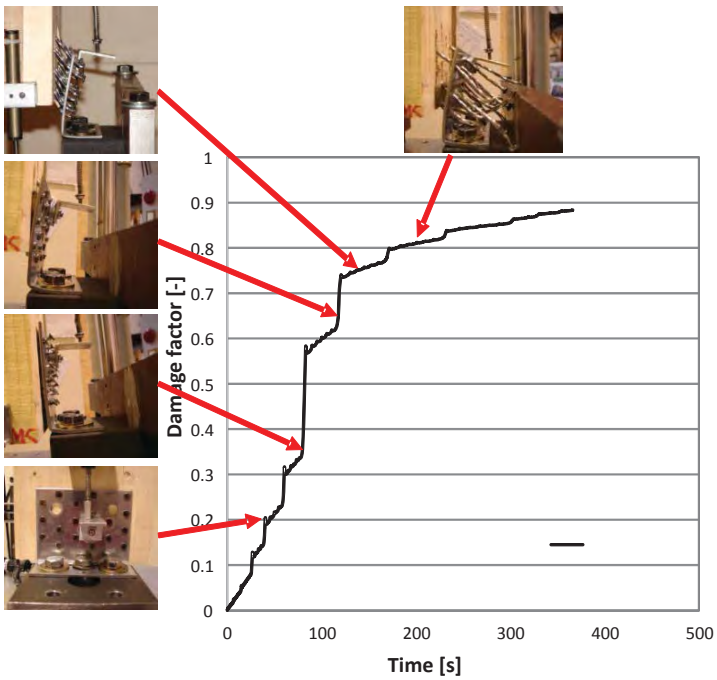


Elastic and Non-Linear Storey Drifts

© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

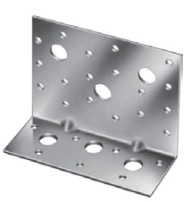
Damage Accumulation of CLT Structures

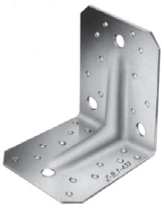
- UBC + FPI (J. Schneider, S. Tesfamariam, M. Popovski)



© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

Comparison of the Connection Tests

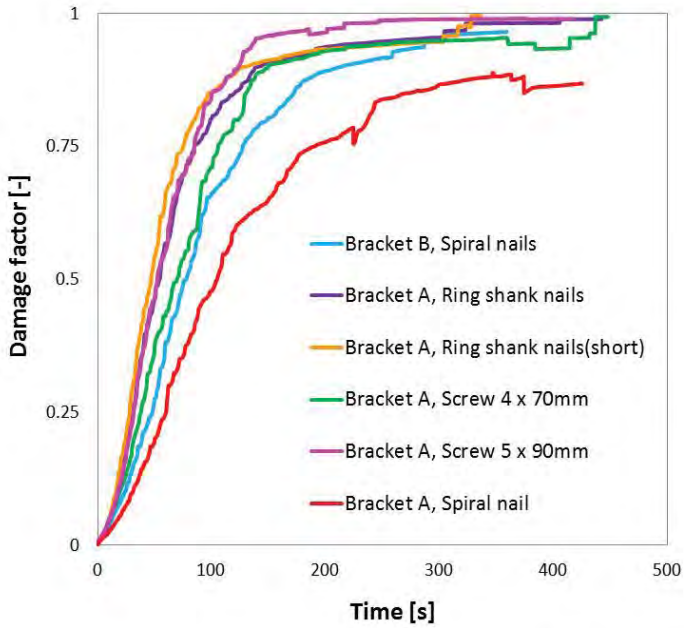




Bracket A

Bracket B

a) Spiral Nail 3.8 x 89 mm
b) Ring Shank Nail 3.4 x 76 mm
c) Ring Shank Nail 3.8 x 60 mm
d) Self tapping Screw 5 x 90 mm
e) Self tapping Screw 4 x 70 mm

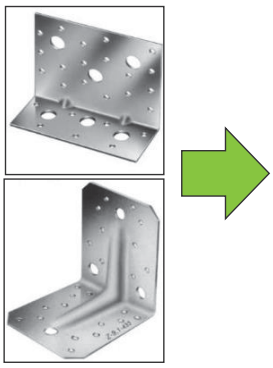


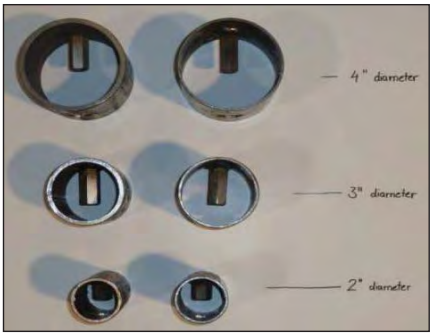
© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

FPInnovations

Use of Innovative Connectors in CLT

- Collaboration UBC Okanagan + FPI
- (J. Schneider, S. Tesfamariam, M. Popovski)



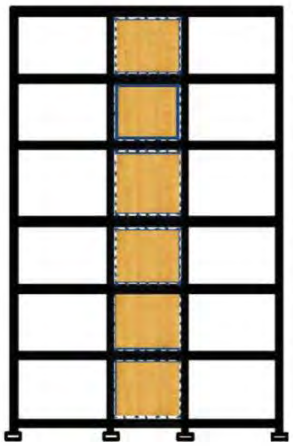


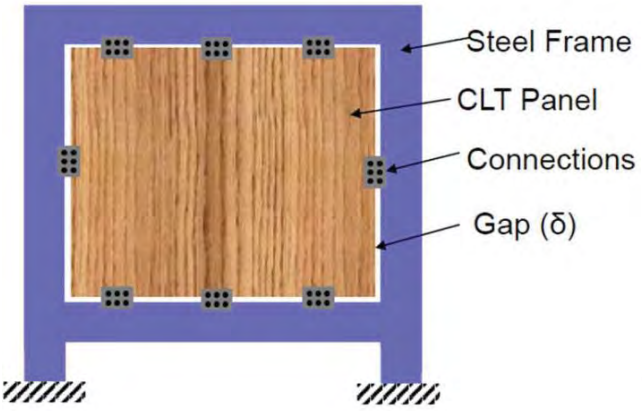
© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

FPInnovations

Steel Frame-CLT Hybrid System

- Combination of steel moment frame and infill CLT panels connected with brackets to the frame
- Optimize the system performance, determine the R-factors for such systems, produce design guidelines
- UBC Okanagan + FPI (M. Bezabeh, S. Tesfamariam, M. Popovski)





© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

Concluding Remarks

- Mass Timber Structures in platform-type or balloon construction can achieve limited damage under strong earthquake when properly designed
- The type of fasteners and connections used, selection of "dissipative zones", aspect ratios of CLT walls and wall segments among others influence the performance under seismic loads
- Further research in the area is needed and will be discussed during the Workshop

© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

FPInnovations

Thank you

For more information contact:

marjan.popovski@fpinnovations.ca

Follow us on

www.fpinnovations.ca

Natural Resources Canada / Ressources naturelles Canada

Canada

FPI Members

Forestry Innovation Investment

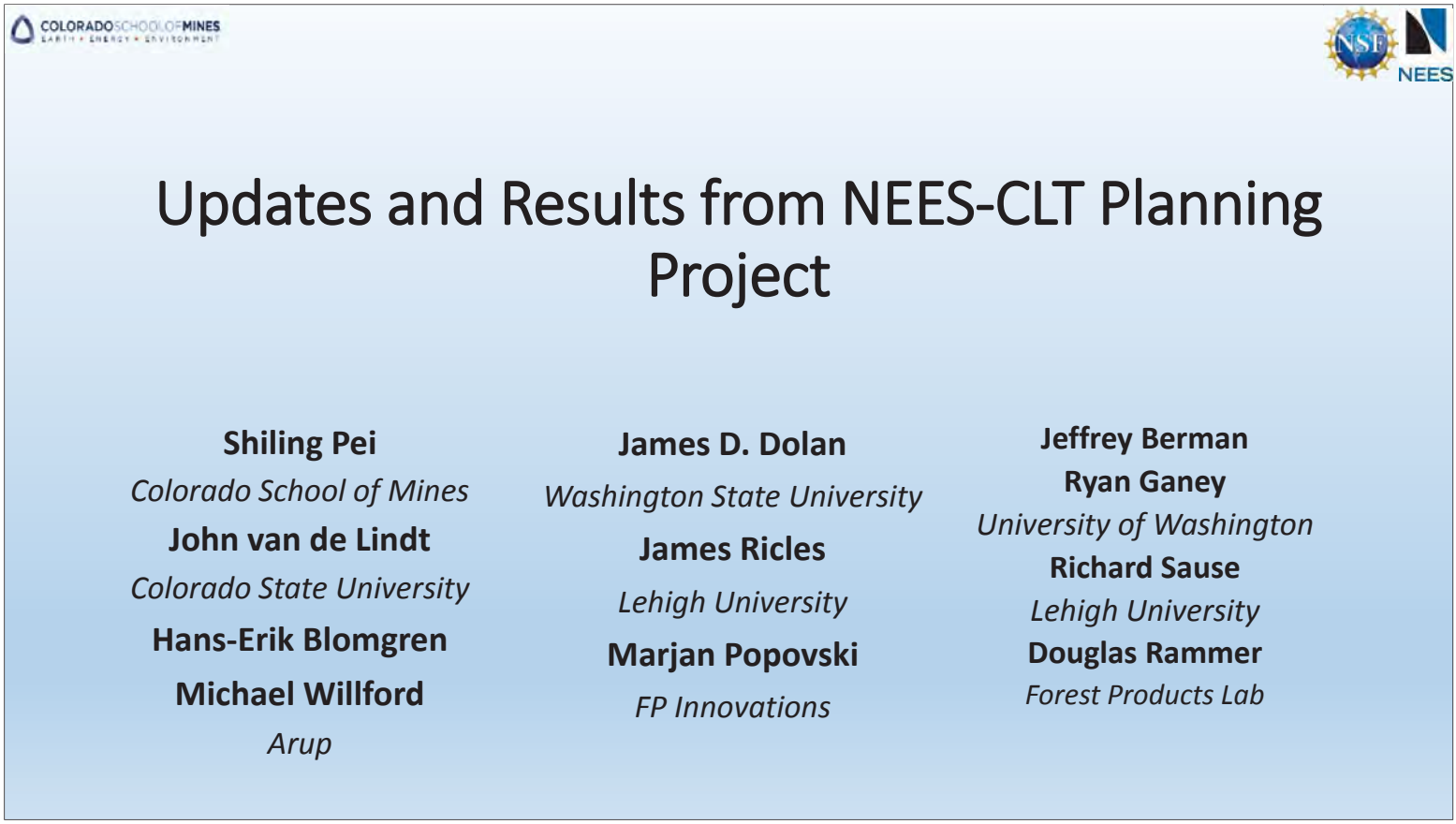
SLB SOFTWOOD LUMBER BOARD

© 2013 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

Updates and Results from NEES–CLT Planning Project

Shiling Pei, Assistant Professor
Colorado School of Mines, Golden, Colorado

As urban densification occurs in regions of high seismicity, there is a demand for tall buildings that are seismically resilient, economically viable, and have less negative environmental impact. In urban regions on the west coast of the United States, specifically the Pacific Northwest, there is significant interest in utilizing cross laminated timber (CLT) in 8- to 20-story residential and commercial buildings using locally sourced, sustainable, and economically competitive building material. This presentation will introduce preliminary results from the NEES-CLT Planning Project that concludes September 2015, which is aimed at developing and testing CLT lateral systems that may be implemented in future tall CLT buildings in regions with large lateral loading. A series of tests, including two types of CLT lateral systems, were performed at Washington State University's Composite Materials and Engineering Laboratory, including a self-centering rocking wall system and a deformable floor diaphragm system. Numerical models for both systems were also developed to study the sensitivity of system performance to design parameters. The project team is in process of refining the analysis and the design approach and is proposing full-scale experimental validation of the tall resilient timber building concept in high seismic regions.



NEES-CLT Planning Project

- Objective: Conduct technical preparation for enabling design and testing of 8-20 story resilient CLT buildings
- Website: NEESCLT.mines.edu

Shiling Pei

Dan Dolan

James Ricles

Richard Sauce

Jeffrey Berman

John van de Lindt

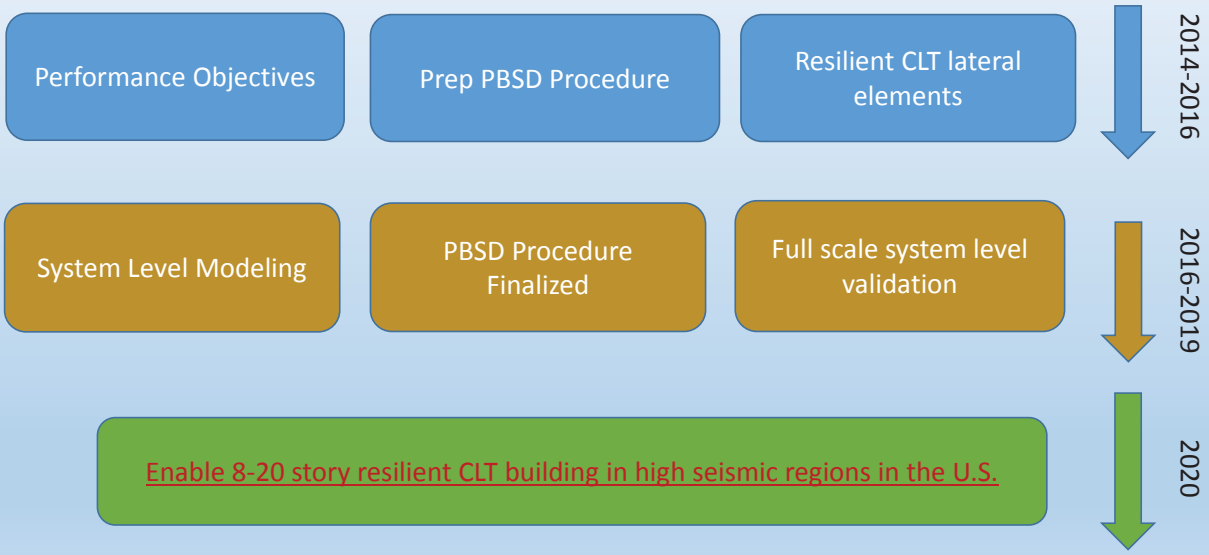
Marjan Popovski

Michael Willford

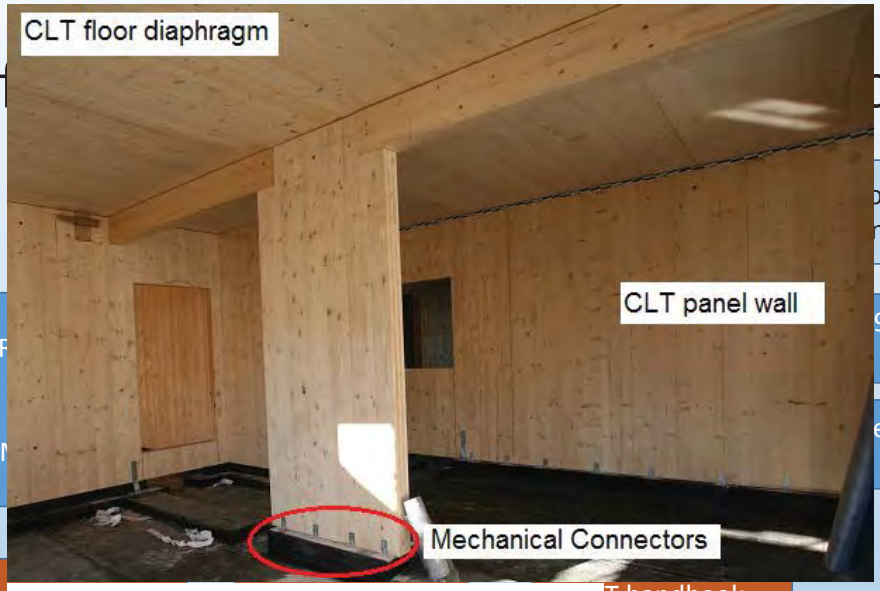
Hans-Erik Blomgren

Douglas Rammer

Plan and Vision



A Brief ... ch



So far, for CLT system similar to this!

CLT Invented in early 1990's

...f R factor for ...nd ASCE7

CLT Building tests in Japan

...95 on CLT shear wall

...eismic Retrofit (NEESSoft)

...T handbook

NEES CLT Planning

Shake table test of wall assembly

Shake table tests at NIED 3-story, 7-story

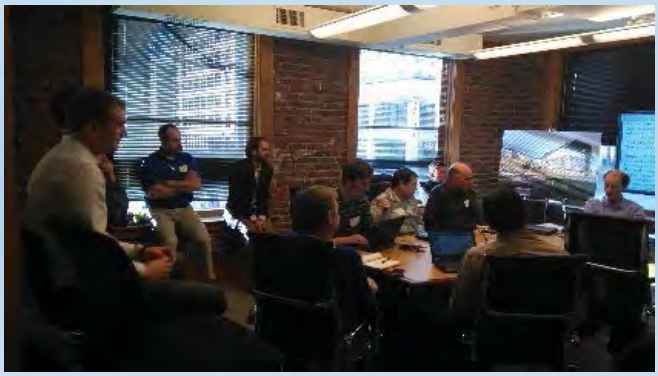
Resilient Timber systems in NZ

Resilient CLT systems

Tall CLT Building Workshop

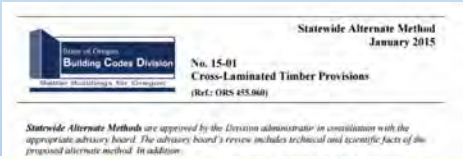
- January 2014, Seattle: Learn from practitioner and end-user communities
  - About 60 Participants
  - Agenda: Societal needs, Performance expectations, Engineering challenges
- All workshop documents available at NEESCLT website
  - White paper
  - All presentations
  - Research progresses

NEESCLT.mines.edu



Challenges for CLT in U.S.

- First-cost still dominates decision making for adopting CLT
  - Other traits (energy, carbon sequestration) adds to value but not as decisive
  - Not cost competitive (first cost) at lower height
- Other Challenges:
  - Fire related code provisions
  - Lack of experience in construction and design
  - Local jurisdiction buy-in



Statewide Alternate Method
January 2015

Building Codes Division

No. 15-01
Cross-Laminated Timber Provisions
(Ref.: ORS 455.060)

Statewide Alternate Methods are approved by the Division administrator in consultation with the appropriate advisory board. The advisory board's review includes technical and scientific facts of the proposed alternate method. In addition:

U.S. TALL WOOD BUILDING PRIZE COMPETITION

SLB SOFTWOOD LUMBER BOARD

USDA

BSLC Binational Softwood Lumber Council

Performance Expectations

- Not necessarily the higher the better. Balance of performance and cost
- A three-tiered performance expectations for tall CLT buildings

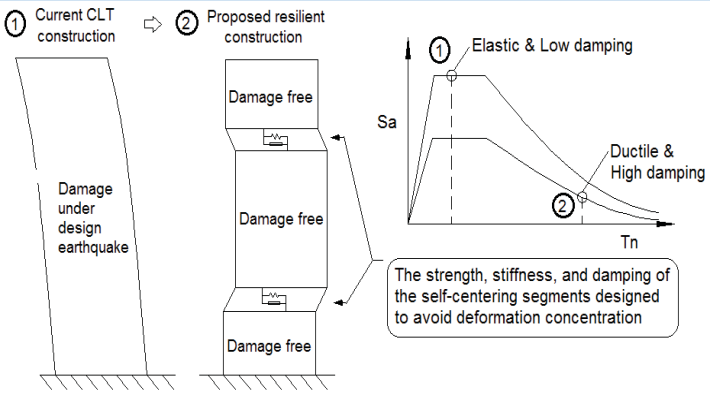
Seismic Hazard Levels (POE[1])	System performance	Structural components	Non-structural components	Estimated Repair Time[4]
Tier 1: Code Minimum (Optimizing current system and detailing, force-based design)				
Service Level Earthquake (50% in 50 yrs.)	Immediate Occupancy:	Remain Elastic	Minor damage, repairable	1~7 days
Tier 2: Code Plus (Innovative detailing or advanced protection systems, PBSD)				
Service Level Earthquake (50% in 50 yrs.)	Immediate Occupancy	Elastic	Minor damage, repairable	1~7 days
Tier 3: Resilience (Resilient structural systems implemented, PBSD)				
Service Level Earthquake (50% in 30 yrs.)	Continuous Operation	Elastic/Resilient system operational	No damage	0~30 min
Design Basis Earthquake (10% in 50 yrs.)	Immediate Occupancy	Resilient system operational	Minor contents damage	1~7 days
Maximum Considered Earthquake (2% in 50 yrs.)	Planned Damage[3]	Resilient system repair needed at planned locations	Moderate damage	1~2 months
Near Fault Ground Motions	Limited Damage Probability of Collapse negligible	Damage extended to unplanned locations, repair may be costly	Moderate damage	2~6 months

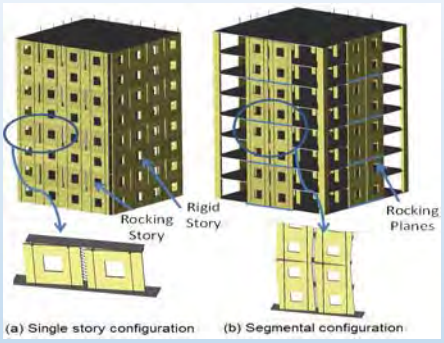
COLORADO SCHOOL OF MINES

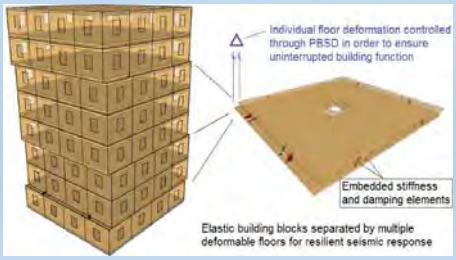
NSF NEES

Try Two Resilient Systems

- Adding ductility and energy dissipation
- Remain damage free at large deformation







UNIVERSITY of WASHINGTON

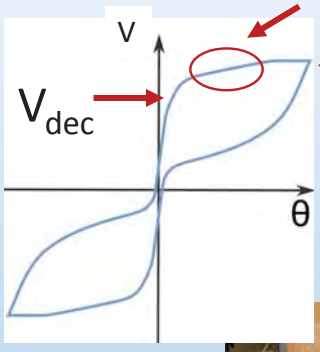
WASHINGTON STATE UNIVERSITY

NSF NEES

CLT Rocking Wall Tests at WSU

- Goal: Understand the behavior of rocking CLT walls

- Wall Parameters of Interest:
  - PT bar area
  - PT bar initial stress
  - Rocking base type
  - CLT panel type
  - Single vs. coupled panel

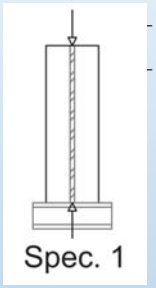
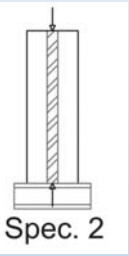
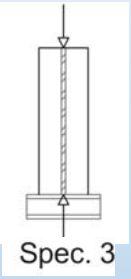
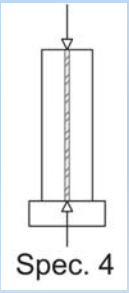
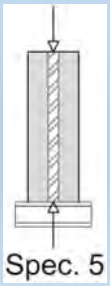
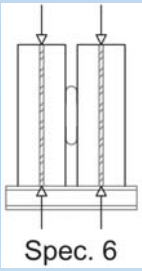


5 PLY CLT PANEL

CLT PANEL WITH SCL CORE

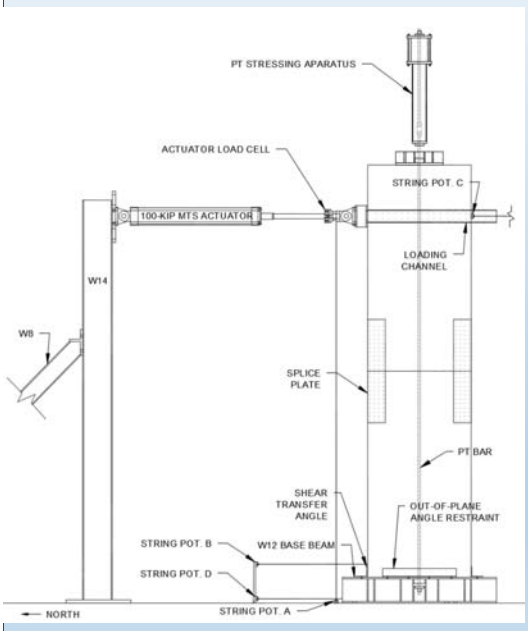
UNIVERSITY of WASHINGTON WASHINGTON STATE UNIVERSITY NSF NEES

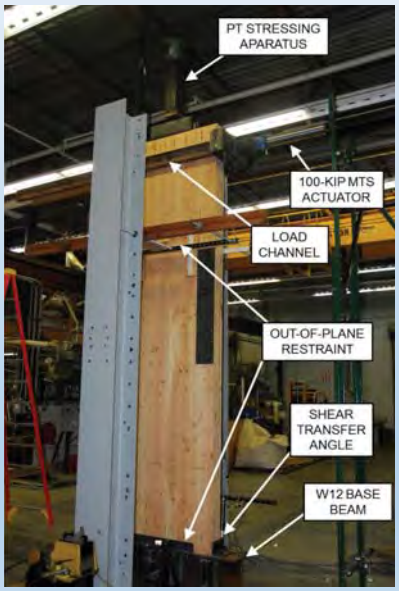
The Test Matrix

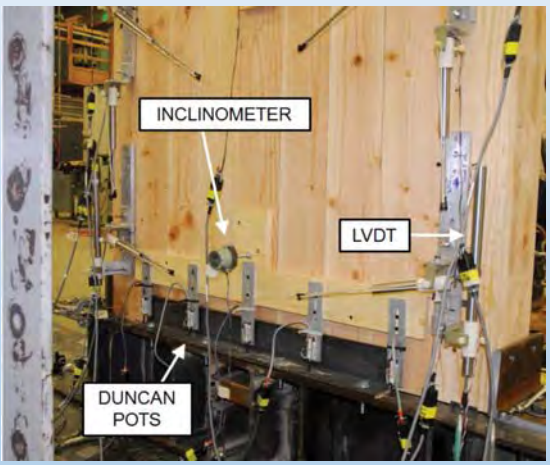
 Spec. 1 - Low V_{dec} - Low K_{dec} 0.85 sq in 0.2 Fpu	 Spec. 2 - Low V_{dec} - High K_{dec} - High V_{max} 1.58 sq in 0.1 Fpu	 Spec. 3 - High V_{dec} - Low K_{dec} 1.25 sq in 0.4 Fpu
 Spec. 4 - CLT Base - Same PT bar properties as Specimen 3	 Spec. 5 - CLT panel with SCL core - High V_{max} - Same initial stress as Specimen 3	 Spec. 6 - Coupled wall with UFPs - Same PT bar properties as Specimen 3

UNIVERSITY of WASHINGTON WASHINGTON STATE UNIVERSITY NSF NEES

Test Setup

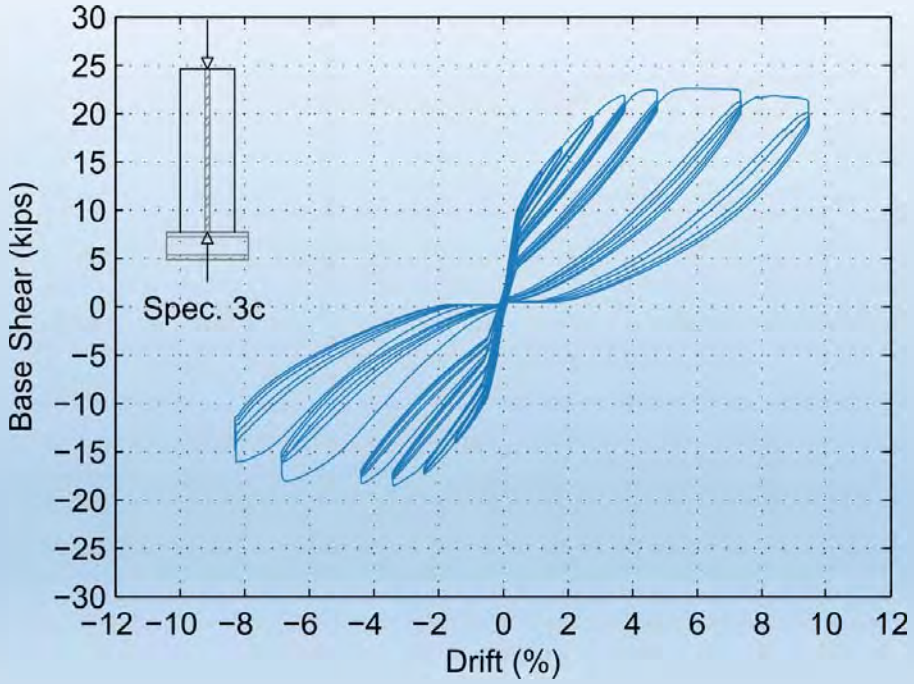






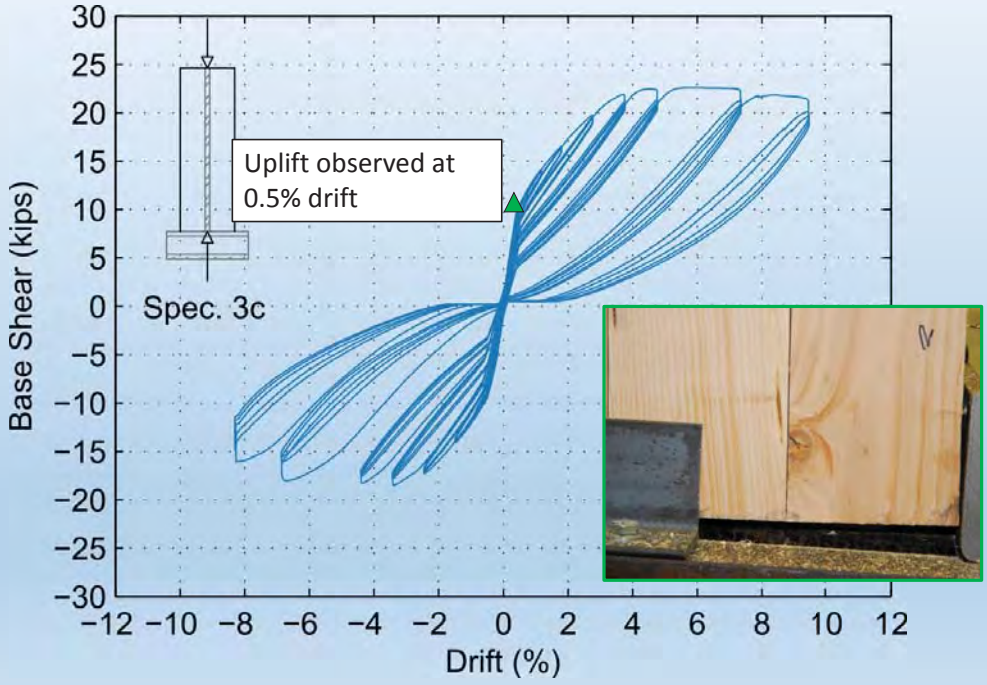
UNIVERSITY of WASHINGTON WASHINGTON STATE UNIVERSITY NSF NEES

Specimen 3 - High V_{dec} and Low K_{dec}



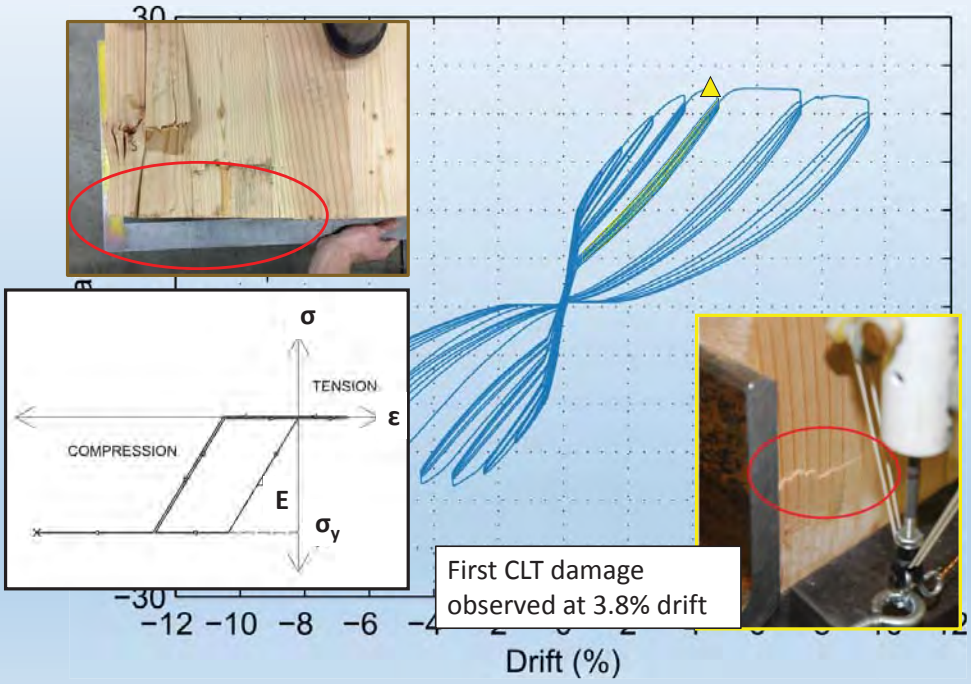
UNIVERSITY of WASHINGTON WASHINGTON STATE UNIVERSITY NSF NEES

Specimen 3 - High V_{dec} and Low K_{dec}



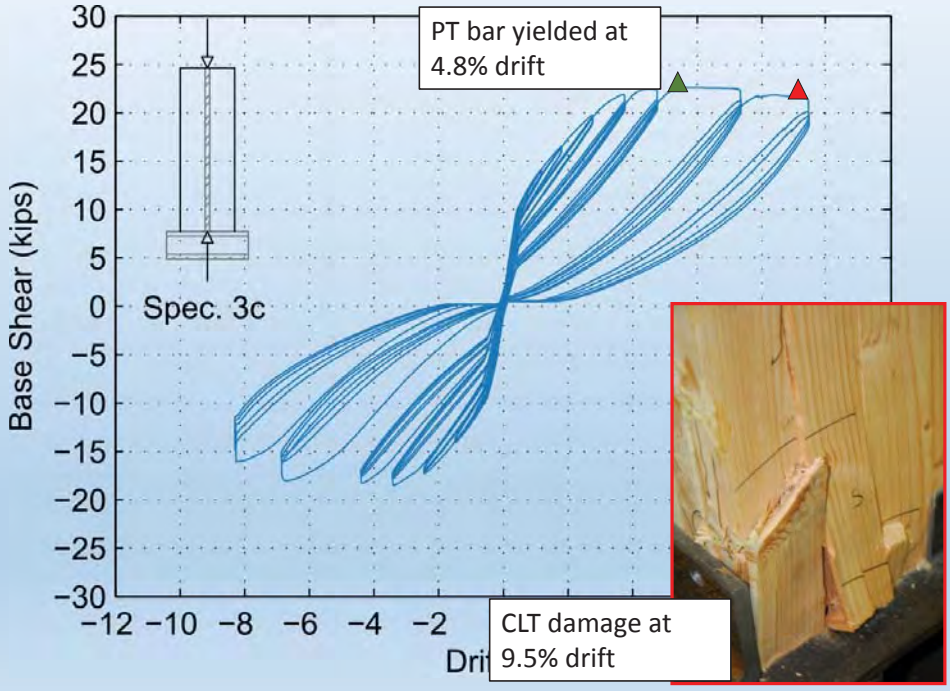
UNIVERSITY of WASHINGTON WASHINGTON STATE UNIVERSITY NSF NEES

Specimen 3 - High V_{dec} and Low K_{dec}



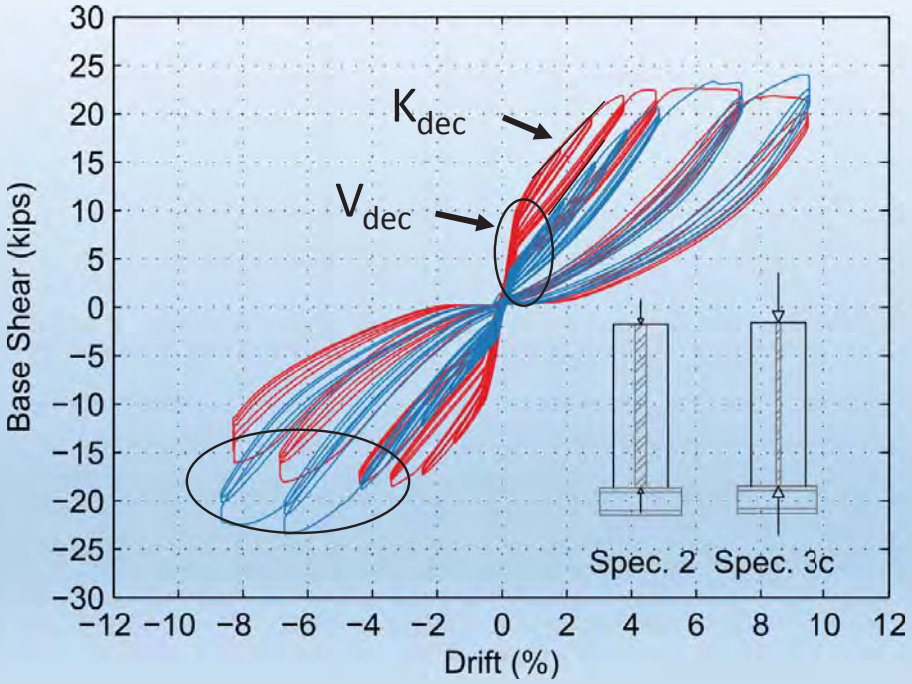
UNIVERSITY of WASHINGTON WASHINGTON STATE UNIVERSITY NSF NEES

Specimen 3 - High V_{dec} and Low K_{dec}



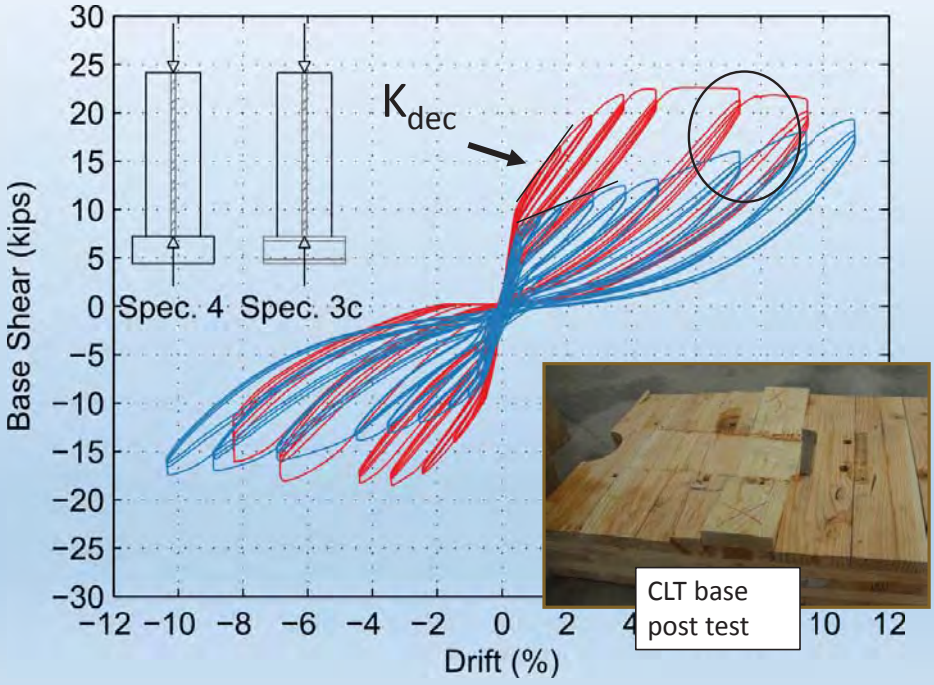
UNIVERSITY of WASHINGTON WASHINGTON STATE UNIVERSITY NSF NEES

Spec. 2/Spec. 3 Comparison



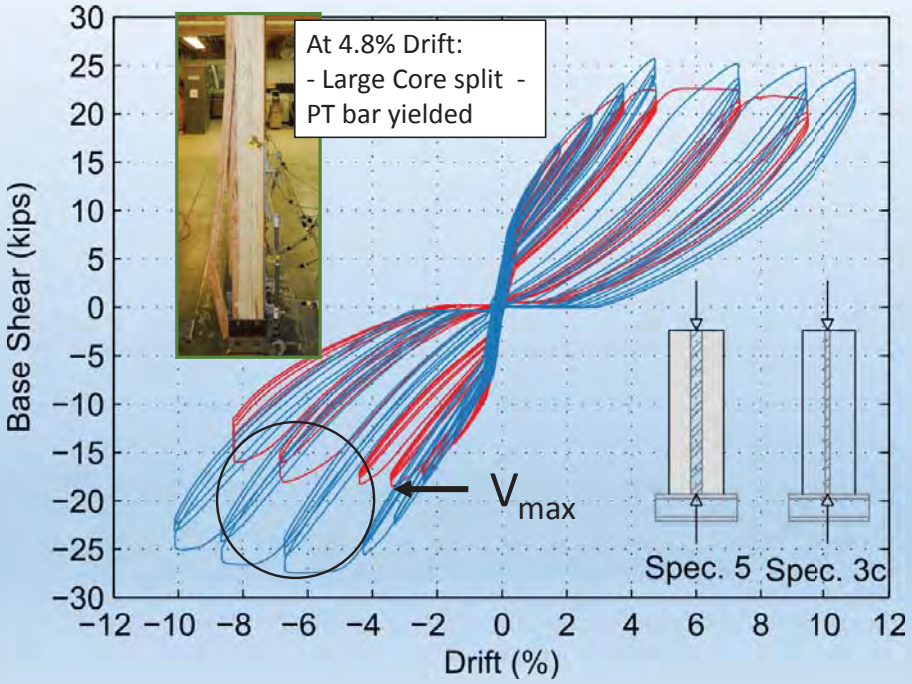
UNIVERSITY of WASHINGTON WASHINGTON STATE UNIVERSITY NSF NEES

Spec. 3/Spec. 4 Comparison



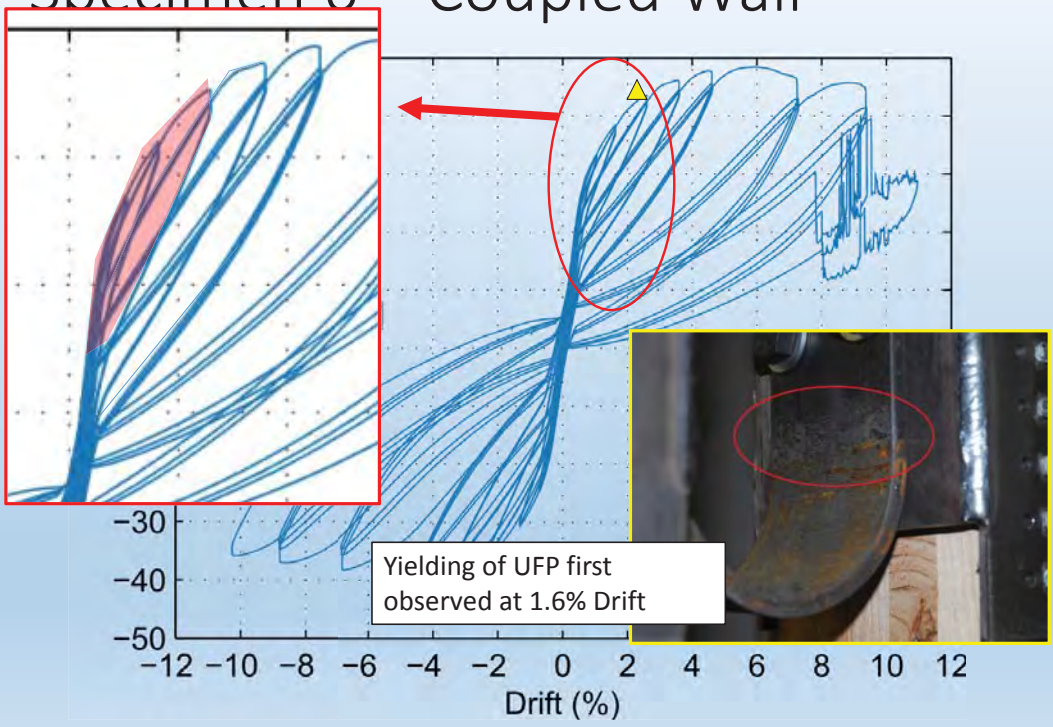
UNIVERSITY of WASHINGTON WASHINGTON STATE UNIVERSITY NSF NEES

Spec. 3/Spec. 5 Comparison

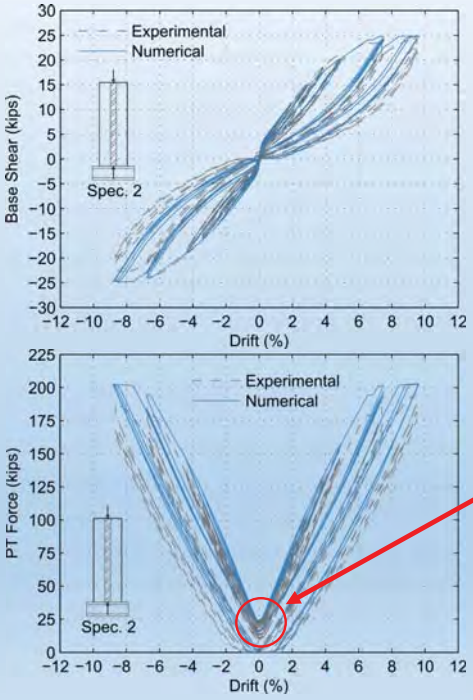


UNIVERSITY of WASHINGTON WASHINGTON STATE UNIVERSITY NSF NEES

Specimen 6 – Coupled Wall



Experimental-Numerical Comparison



- Predicts strength and stiffness well
- Fairly good at predicting CLT damage
- Does not capture PT losses due to seating at top of wall

What did we learn from rocking wall tests

- CLT Rocking Wall Design Procedure
  - The proposed seismic design procedure for tall timber buildings resulted in CLT walls with adequate performance
- Experimental Program
  - Rocking CLT panels have good ductility
  - A hierarchy of desirable limit states was identified (UFP yielding, CLT crushing, PT yielding)
  - Variability in CLT materials is a concern for design
- Numerical Model
  - Relatively simple nonlinear model was able to represent the test data
  - Implementation of the model for tall CLT buildings showed the design procedure can meet the performance objectives
- More research needs to be conducted for the system to be implemented

Inter-story Isolation

- Test on-going at WSU

Summary

- Current way of CLT construction: Great for life-safety, will see expensive damage during major earthquakes
- A road map proposed for Tall CLT in U.S. seismic region by 2020
- Two types of resilient CLT component tested during NEES-CLT Planning, showing great potentials.
- Research Team planning for full scale system level validation of resilient CLT design.

What's Next?

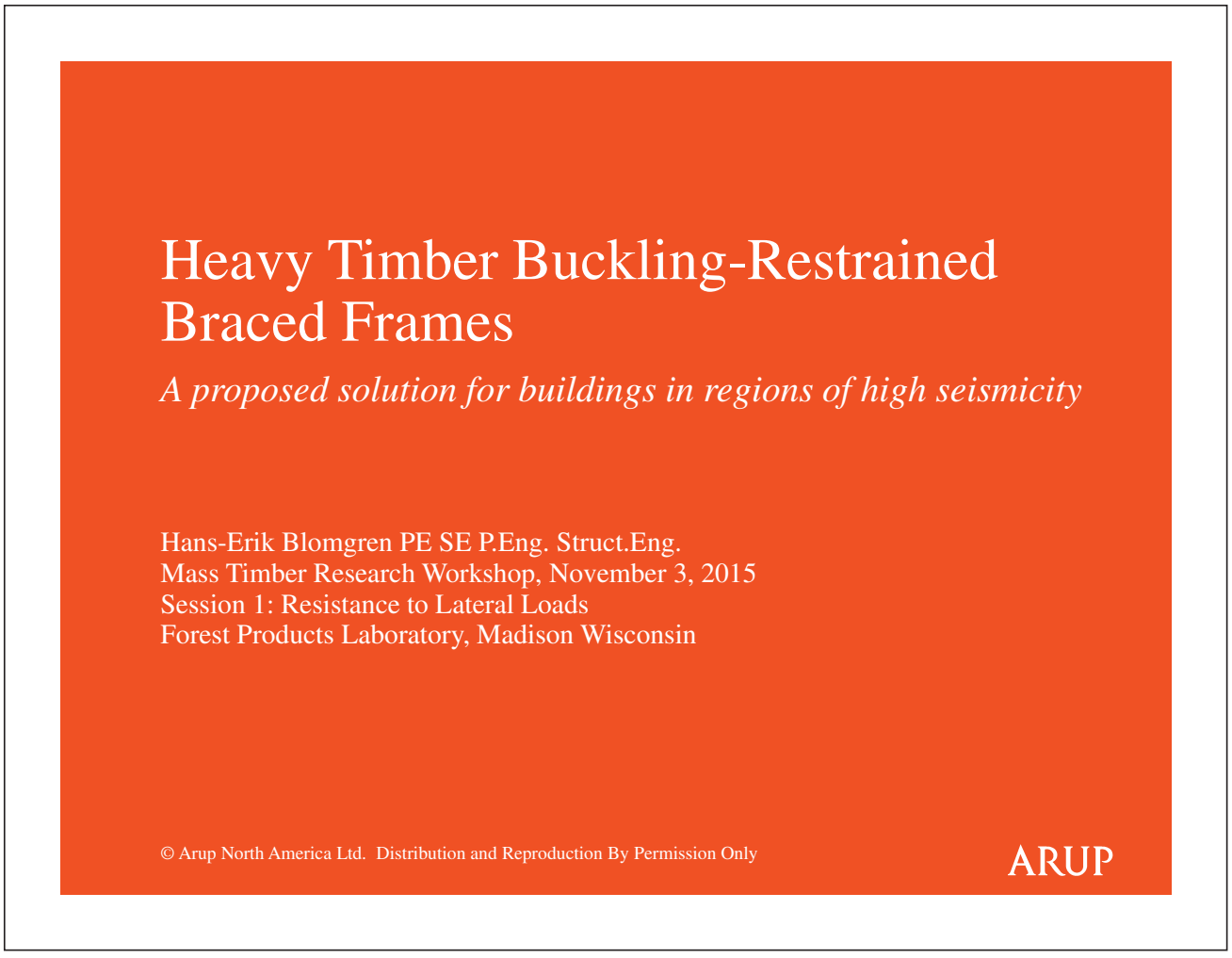
Testing a Full-scale Ten-story CLT Building on UCSD Shake Table (working on it)

Shiling Pei spei@mines.edu
Jeffrey W Berman jwberman@myuw.net
Dan Dolan jddolan@wsu.edu

The Heavy Timber Buckling Restrained Braced Frame System as a Solution for Commercial Construction in Regions of High Seismicity

Hans-Erik Blomgren, Structural Engineer/Associate
Jan-Peter Koppitz, Associate
Abel Díaz Valdés, Senior Structural Analyst
ARUP, Seattle, Washington

Wood construction has been traditionally utilized to reduce inertial demands in high seismic regions. However, applications are often limited to low-rise buildings of light-wood construction. Recent advancements in timber technologies are pushing mass timber systems into larger commercial scale markets where steel and concrete systems currently dominate the landscape. In high seismic regions, however, timber buildings currently lack code-defined lateral force resisting systems. This paper presents a new concept of a seismic force resisting system known as the Heavy Timber Buckling Restrained Braced Frame. The system is intended, although not limited, for application for tall building timber construction and is inspired by the unbonded brace technology today widely spread throughout Japan and the United States. To prequalify the system for future implementation in building codes, this paper first addresses component testing of a brace consisting of a steel core and a mechanically laminated glulam assembly acting as the buckling restraint mechanism. Test results are discussed, and implementation at the system level in an archetype building is addressed, in order to assess overall system performance, constructability, and detailing.



Outline

Heavy Timber Braced Frames

- Current code
- System attributes
- Precedents

The Heavy Timber BRBF concept

- BRBF primer
- Component testing
- System level evaluation

Conclusion

© Arup North America Ltd. Distribution and Reproduction By Permission Only

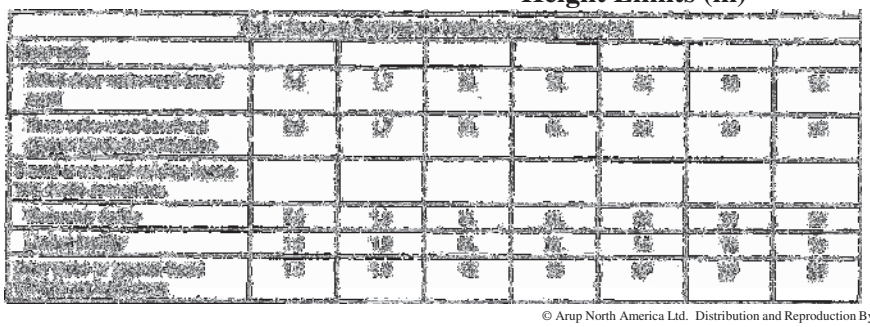
Current Code Definitions

IBC 2012 (ASCE 7-10)

		R	Ωo	Cd	Height Limits (ft)				
15. Light-frame (wood) walls sheathed with wood structural panels rated for shear resistance or steel sheets	14.1 and 14.5	6½	3	4	NL	NL	65	65	65
6. Timber frames	14.5	1½	1½	1½	35	35	35	NP	NP

BCBC 2012

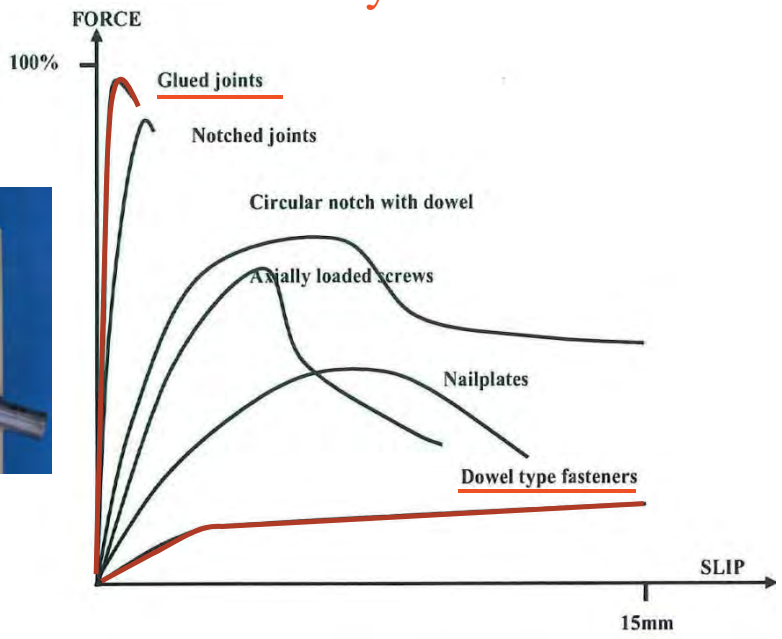
	Rd	Ro	Height Limits (m)				



© Arup North America Ltd. Distribution and Reproduction By Permission Only

Attributes of Wood in Seismic Systems

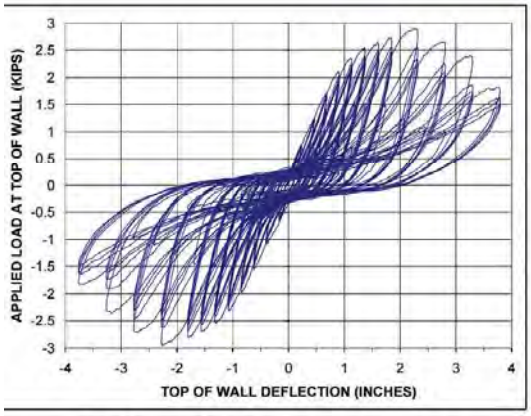
Dowel type fastener



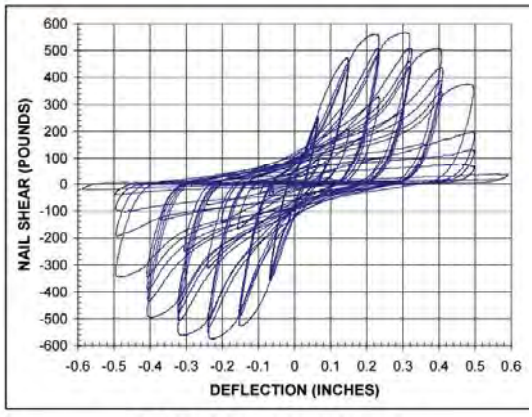
© Arup North America Ltd. Distribution and Reproduction By Permission Only

Attributes of Wood in Seismic Systems

Sources of Ductility and Energy Dissipation in Wood Structures



Full-scale shear wall test



Individual nail test

© Arup North America Ltd. Distribution and Reproduction By Permission Only

Attributes of Wood in Seismic Systems

Advantages

- High strength/weight ratio (low mass)
- High short term load strength

Disadvantages

- Brittle failure modes exist
- Localized damage at post-yield (pinched hysteresis)
- Concentrated locations of limited ductility (fasteners)
- Ductile connections = low stiffness

© Arup North America Ltd. Distribution and Reproduction By Permission Only

Heavy Timber Braced Frame Precedents

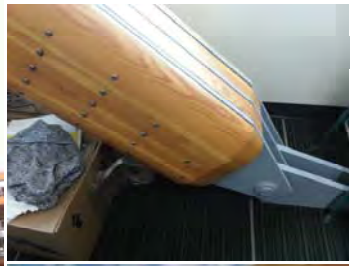
Heavy Timber Braced Frame Precedents

© Arup North America Ltd. Distribution and Reproduction By Permission Only

Braced Frames – Side Plates & Bolts (Source: Cal Poly)

ARUP

Heavy Timber Braced Frame Precedents

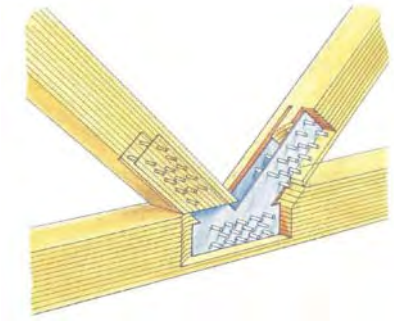


© Arup North America Ltd. Distribution and Reproduction By Permission Only

Braced Frames – Dowel and Flitch Plates (Source: Structurlam)

ARUP

Heavy Timber Braced Frame Precedents



© Arup North America Ltd. Distribution and Reproduction By Permission Only

Braced Frames – Dowel & Flitch Plates (Source: Sweco)

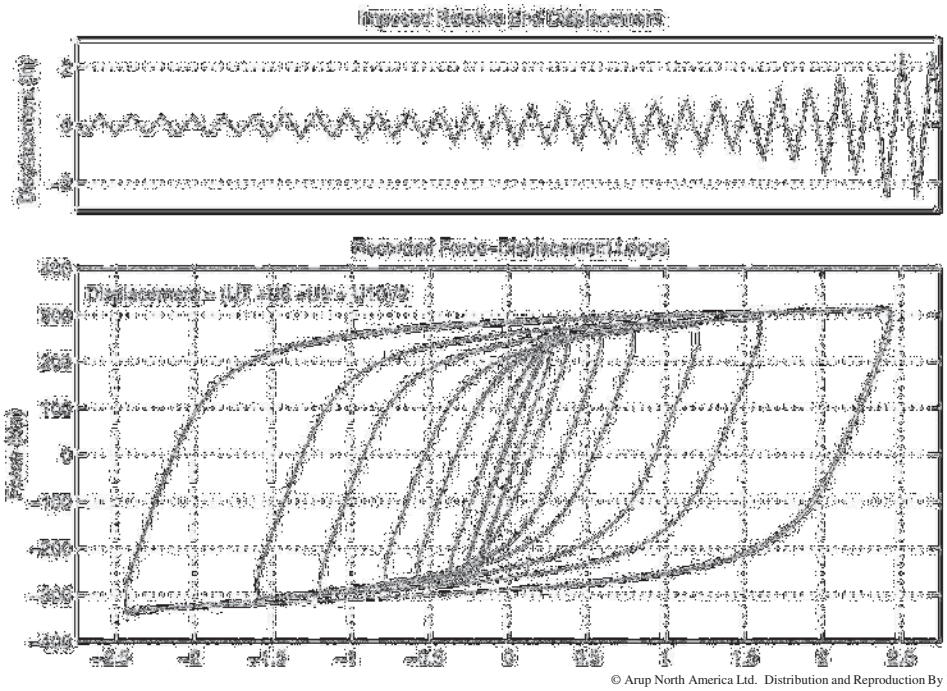
ARUP

The BRB - Primer

Buckling-Restrained Braced Frame Primer

© Arup North America Ltd. Distribution and Reproduction By Permission Only

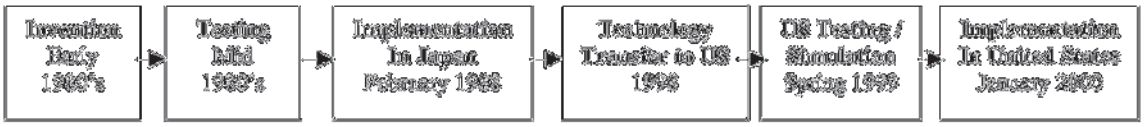
Buckling-Restrained Braced Frame Primer



© Arup North America Ltd. Distribution and Reproduction By Permission Only

Buckling-Restrained Braced Frame Primer

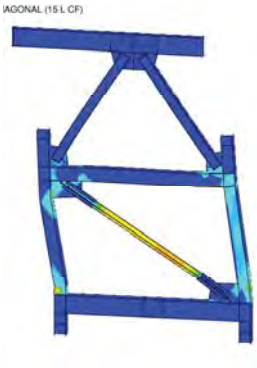
Timeline



Current Code:

		R	Ω_o	C_d					
25. Steel buckling-restrained braced frames	14.1	8	2½	5	NL	NL	160	160	100

- AISC 341-10
  - Section F4 – Design Provisions
    - Capacity based philosophy
  - Section K3 – Testing Qualifications
    - Component
    - Subassembly



© Arup North America Ltd. Distribution and Reproduction By Permission Only

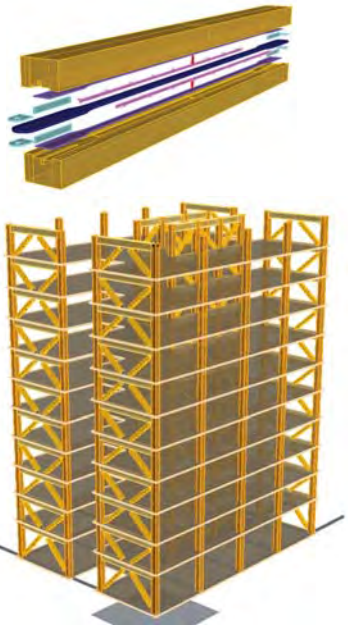
The HTBRB

Heavy Timber Buckling-Restrained Brace

ARUP

StarSeismic®

S|L|B SOFTWOOD LUMBER BOARD



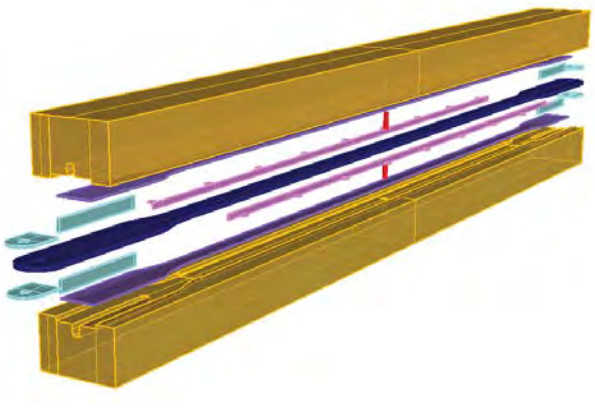
INVEST IN ARUP | Apply | Projects | Finance | Hans-Erik Blomgren

12661 Heavy Timber Buckling Restrained Braced Frame (HT-BRBF) - System-level development

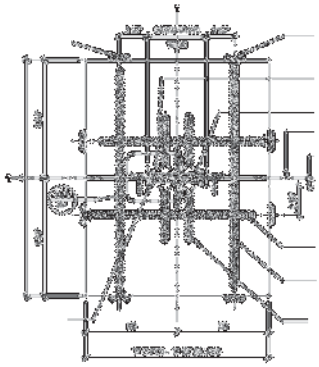
© Arup North America Ltd. Distribution and Reproduction By Permission Only

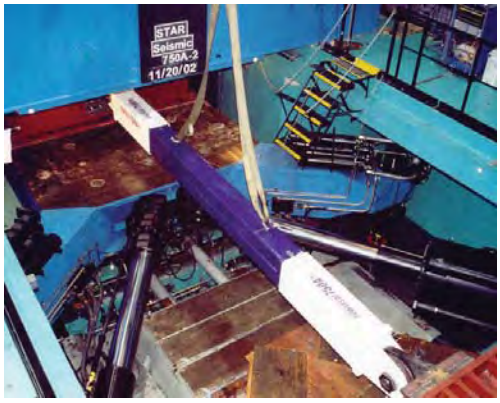
ARUP

HTBRB Construction



BRB Specimen Capacity = 100k





© Arup North America Ltd. Distribution and Reproduction By Permission Only

ARUP

HTBRB Component Level Test Requirements

1 THE SPECIMENS SHALL BE TESTED TO THE AISC 341-10 SECTION K3 "REQUIREMENTS FOR QUALIFYING CYCLIC TESTS OF INDIVIDUAL BUCKLING-RESTRAINED BRACE TEST SPECIMENS".

2. THE AXIAL DEFORMATION Δ_{bm} AS DEFINED BY AISC 341-10 OF THE SPECIMEN SHALL BE 2.2 INCHES.

3. ACCEPTANCE CRITERIA:

   A. THE HYSTERETIC BEHAVIOR SHALL DISPLAY NO POST-YIELD LOSS OF STRENGTH, DEGRADATION, OR PINCHING.

   B. FRACTURE OF ANY PORTION OF THE BRB SHALL NOT OCCUR.

   C. A CUMULATIVE INELASTIC DUCTILITY VALUE OF 200 SHALL BE ATTAINED.

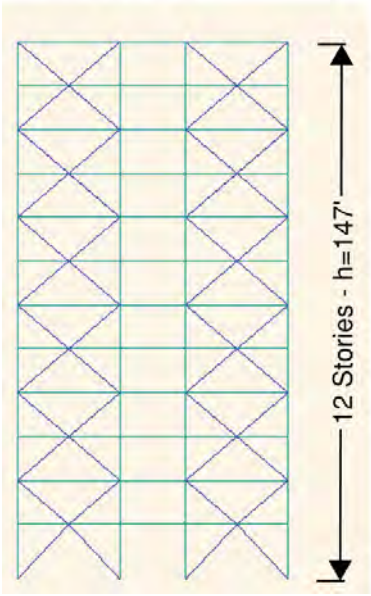
   D. THE COMPRESSION STRENGTH ADJUSTMENT FACTOR AT β SHALL BE NO GREATER THAN 1.15.

© Arup North America Ltd. Distribution and Reproduction By Permission Only

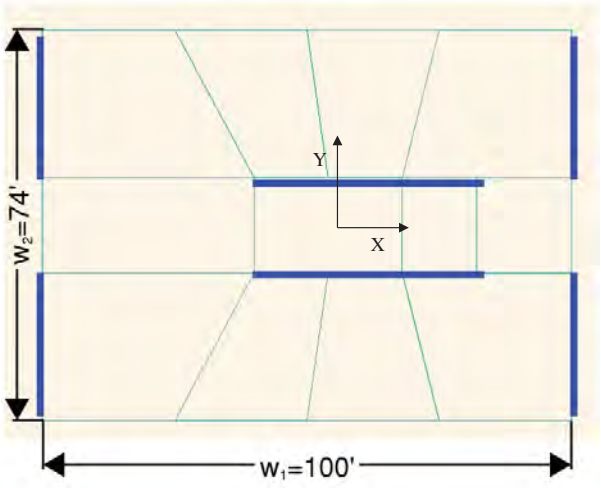
HTBRBF System Level Evaluation

HTBRBF System Level Study

ELEVATION

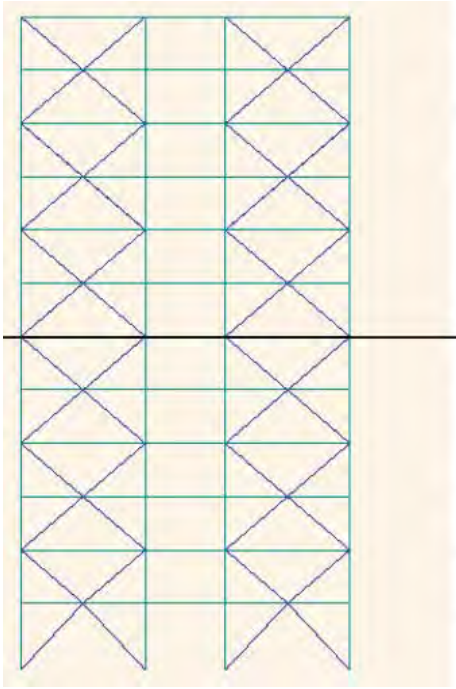


PLAN VIEW



© Arup North America Ltd. Distribution and Reproduction By Permission Only

HTBRBF System Level Study



Levels 7-12

Typical BRB column size = 16"x16"

Typical gravity column size = 12"x12"

Column sizes vary

Levels 1-6

Typical BRB column size = 24"x24"

Typical gravity column size = 18"x18"

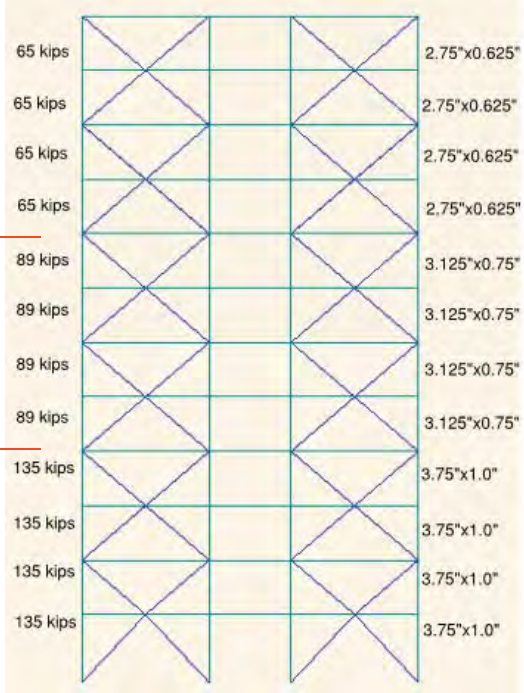
© Arup North America Ltd. Distribution and Reproduction By Permission Only

HTBRBF System Level Study

65kip

89kip

135kip



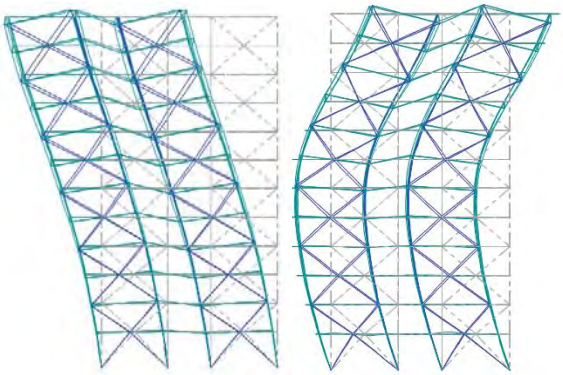
BRB Sizes

BRB Core Areas (Fy = 42ksi)

© Arup North America Ltd. Distribution and Reproduction By Permission Only

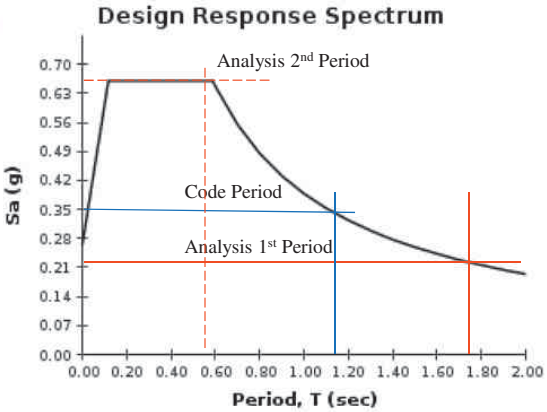
HTBRBF System Level Study

Site Class	*C*	**I_e**	*1.0*	**R**	*6*	**W**	*6,247k*
S_{ds}	*0.66*	**SDC**	*D*	**C_d**	*5*	**Cs**	*0.055*
S_1	*0.39*	**β**	*5%*	**Ωo**	*2.5*	**V**	*290k*



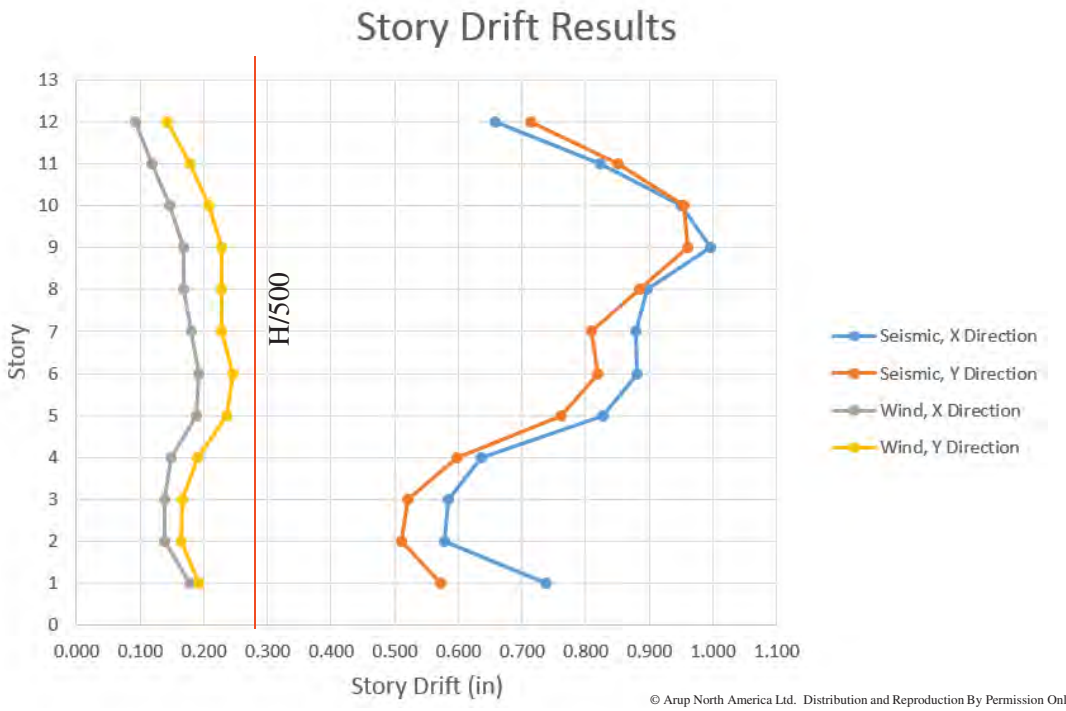
1st Mode = 1.77s
Mass Part. = 73%

2nd Mode = 0.57s
Mass Part. = 18%



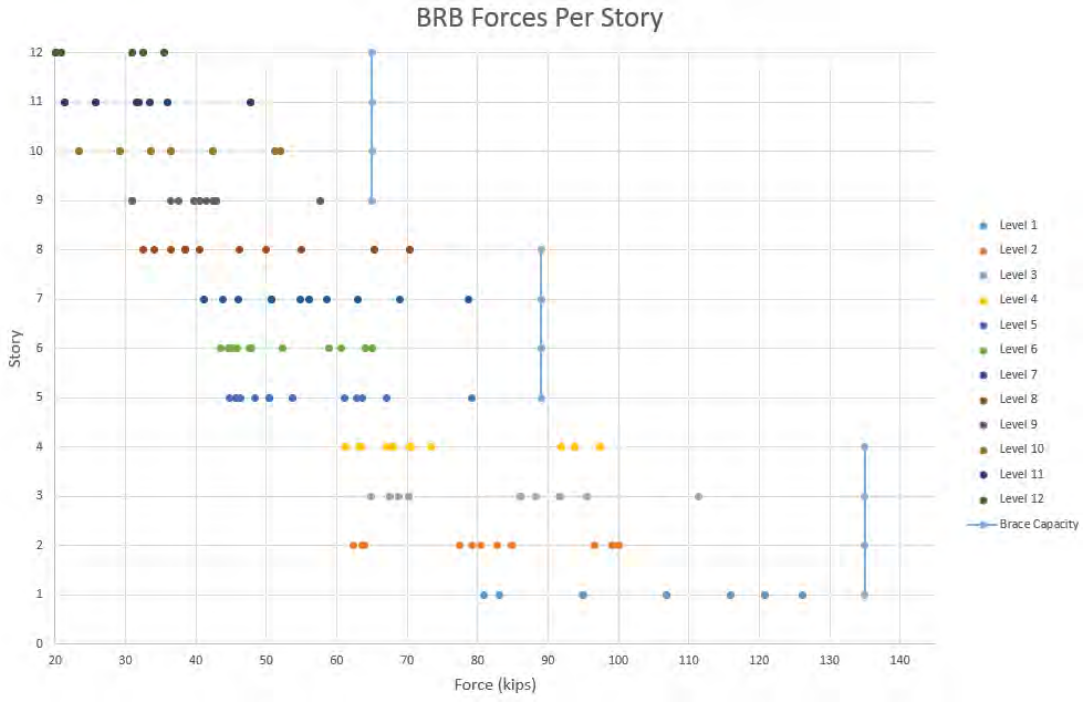
© Arup North America Ltd. Distribution and Reproduction By Permission Only

HTBRBF System Level Study



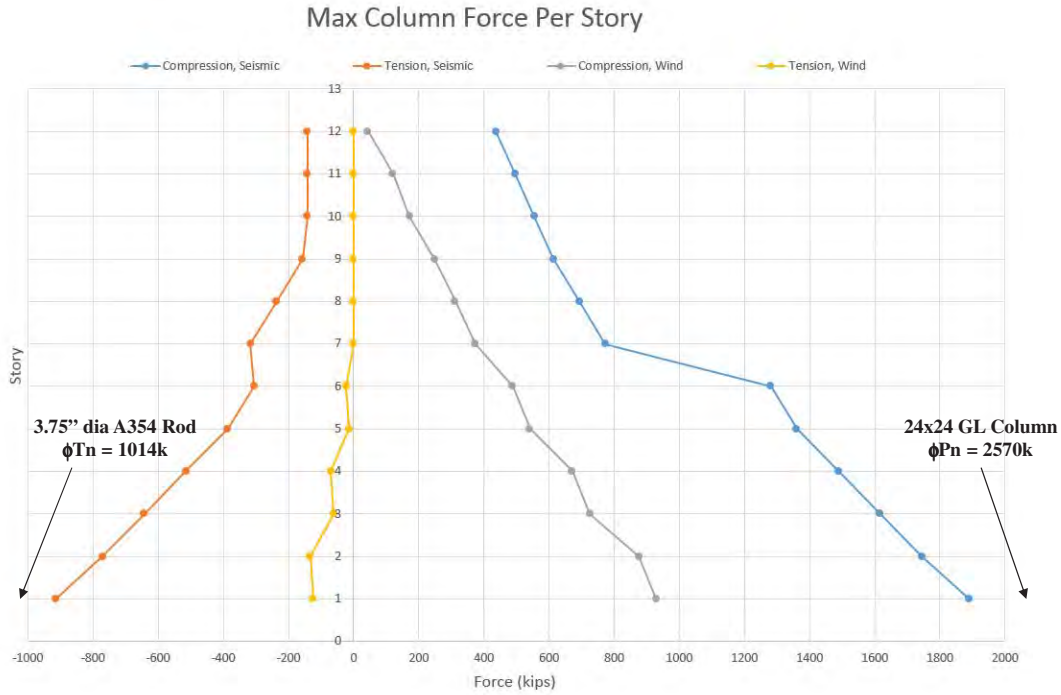
© Arup North America Ltd. Distribution and Reproduction By Permission Only

HTBRBF System Level Study



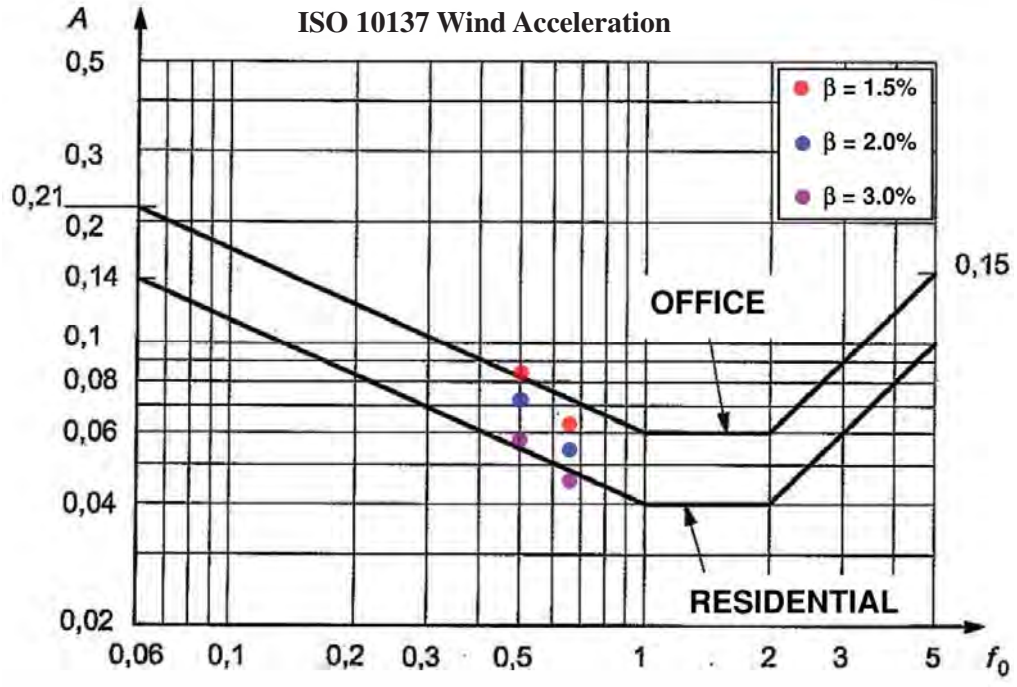
© Arup North America Ltd. Distribution and Reproduction By Permission Only

HTBRBF System Level Study



© Arup North America Ltd. Distribution and Reproduction By Permission Only

HTBRBF System Level Study



© Arup North America Ltd. Distribution and Reproduction By Permission Only

Conclusion

- There is a need for code-defined heavy timber seismic systems
- The HTBRBF is a possible solution b/c:
  - An extension of codified AISC 341 steel BRBF system
  - Easy to analyze
  - High strength, stiffness, & ductility (win-win-win)
  - Limited irrecoverable timber damage
  - Potential for rapid application near-term (PBD – ASCE 41-13)
- Sub-assembly test needed
- Economic/constructible frame details needed
- Start USA code definition
  - P-695

© Arup North America Ltd. Distribution and Reproduction By Permission Only

CLT Diaphragm Research and Design in North America

Scott Breneman, Senior Technical Director
WoodWorks, Deer Park, Washington

This presentation will discuss the state of knowledge for cross laminated timber diaphragms for the U.S. project design environment. Emphasis will be given to the importance of diaphragm deflections linked to North American research, testing planned, and in progress.

WoodWorks

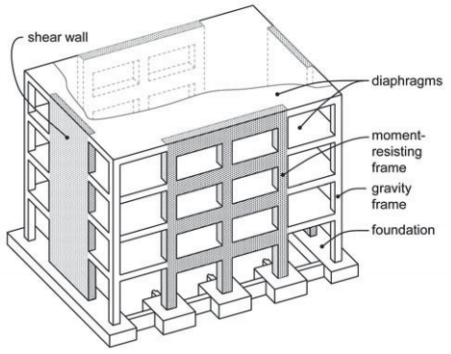
CLT Diaphragm Research and Design in North America

USDA Forest Products Lab
Mass Timber Workshop
November 3rd, 2015

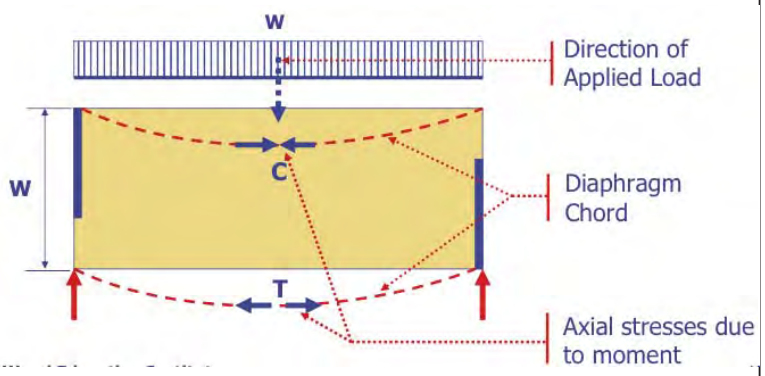
Scott E. Breneman, PhD, PE, SE
Senior Technical Director
WoodWorks – Wood Products Council

Diaphragm Design

- Diaphragm: Roof, floor transferring lateral forces to the vertical resisting elements
- Diaphragm loads are generally uniform loads, resisted by the diaphragm in bending, similar to a horizontal deep beam
- Diaphragm bending results in tension/compression in chords perpendicular to load



NIST NEHRP



Wood Education Institute

CLT in NDS 2015 – Panel Strength

New **Chapter 10** covering Adjustment Factors for CLT

Formatting Similar to Wood Structural Panels

Table 10.3.1 Applicability of Adjustment Factors for Cross-Laminated Timber

		ASD only	ASD and LRFD					LRFD only		
		Load Duration Factor	Wet Service Factor	Temperature Factor	Beam Stability Factor	Column Stability Factor	Bearing Area Factor	Format Conversion Factor	Resistance Factor	Time Effect Factor
$F_b(S_{eff})' = F_b(S_{eff})$	x	C_D	C_M	C_t	C_L	-	-	2.54	0.85	λ
$F_t(A_{parallel})' = F_t(A_{parallel})$	x	C_D	C_M	C_t	-	-	-	2.70	0.80	λ
$F_v(t_v)' = F_v(t_v)$	x	C_D	C_M	C_t	-	-	-	2.88	0.75	λ
$F_s(Ib/Q)_{eff}' = F_s(Ib/Q)_{eff}$	x	-	C_M	C_t	-	-	-	2.88	0.75	-
$F_c(A_{parallel})' = F_c(A_{parallel})$	x	C_D	C_M	C_t	-	C_P	-	2.40	0.90	λ
$F_{c\perp}(A)' = F_{c\perp}(A)$	x	-	C_M	C_t	-	-	C_b	1.67	0.90	-
$(EI)_{app}' = (EI)_{app}$	x	-	C_M	C_t	-	-	-	-	-	-
$(EI)_{app\text{-}min}' = (EI)_{app\text{-}min}$	x	-	C_M	C_t	-	-	-	1.76	0.85	-

ANSI/APA PRG 320 Product Reports

Table 1. Allowable Design Properties[a] for Nordic X-Lam (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)
E1	1,950	1.7	1,375	1,800	135	45	500	1.2	250	650	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 size adjustment 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 Table 2).

Table 2. The Allowable Bending Capacities[a] for Nordic X-Lam Listed in Table 1 (for use in the U.S.)

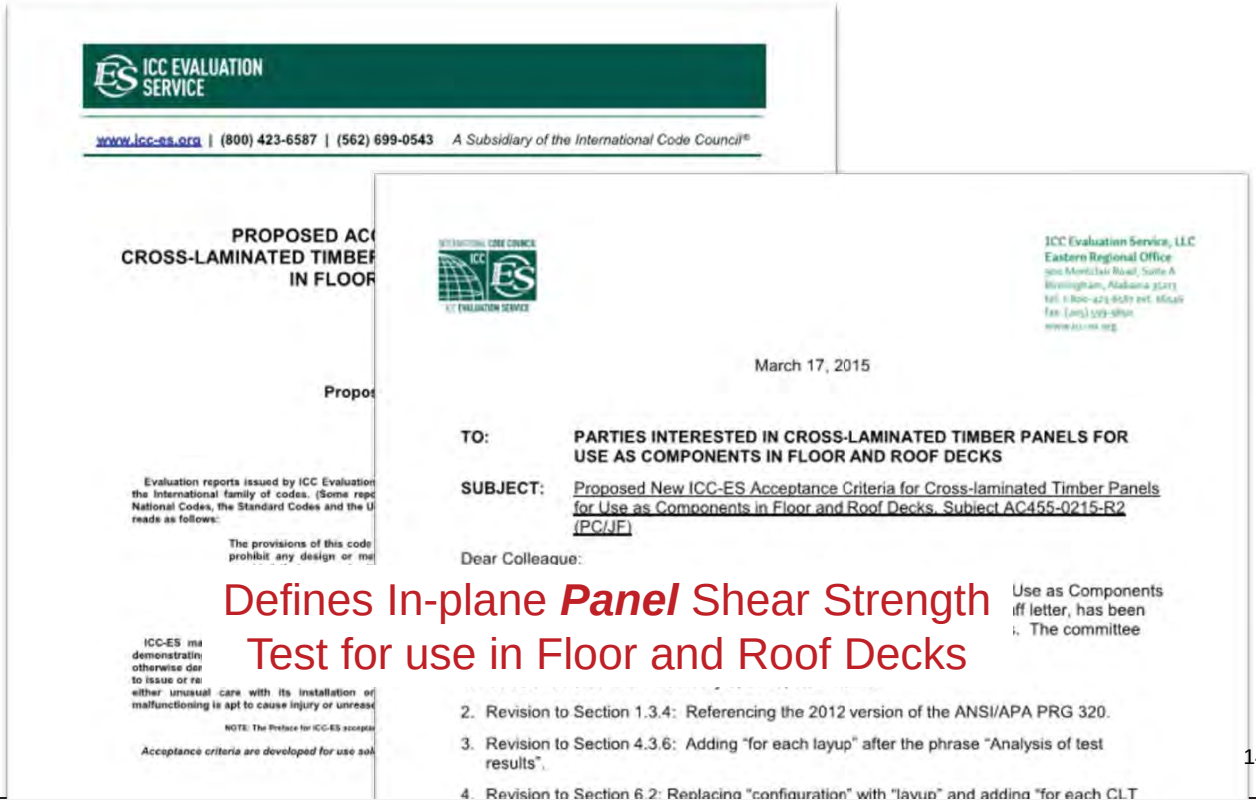
CLT Grade[b]	Layup #[c]	Thick-ness (in.)	Lamination Thickness (in.) in CLT Layup							Major Strength Direction				Minor Strength Direction			
			=	⊥	=	⊥	=	⊥	=	$F_bS_{eff,0}$ (lbf-ft/ft)	$EI_{eff,0}$ (10^6 lbf-in.²/ft)	$GA_{eff,0}$ (10^6 lbf/ft)	$V_{r,0}$ (lbf/ft)	$F_bS_{eff,90}$ (lbf-ft/ft)	$EI_{eff,90}$ (10^6 lbf-in.²/ft)	$GA_{eff,90}$ (10^6 lbf/ft)	$V_{r,90}$ (lbf/ft)
E1	78-3s	3 1/8	1 1/64	1 1/16	1 1/64					2,525	48	0.34	1,070	95	1.4	0.47	380
	105-3s	4 1/8	1 3/8	1 3/8	1 3/8					4,525	115	0.46	1,430	160	3.1	0.61	495
	131-5s	5 1/8	1 1/64	1 1/16	1 1/64	1 1/16	1 1/64			5,800	184	0.69	1,470	785	35	0.94	1,090
	175-5s	6 7/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8			10,400	440	0.92	1,970	1,370	81	1.2	1,430
	220-7s	8 1/4	1 3/8	1 1/16	1 3/8	1 1/16	1 3/8	1 1/16	1 3/8	15,975	853	1.4	2,400	2,160	184	1.5	1,580
	244-7l	9 5/8	1 3/8x2	1 3/8	1 3/8	1 3/8	1 3/8x2			23,700	1,404	2.0	3,200	1,370	81	1.9	1,430
	314-9l	12 3/8	1 3/8x2	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8x2	36,700	2,794	2.4	3,875	3,125	309	2.5	1,960

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

[a] Tabulated values are allowable design values and not permitted to be increased for the lumber size adjustment factor in accordance with the NDS.
[b] The CLT grades are developed based on ANSI/APA PRG 320, as permitted by the standard.
[c] The layup designation refers to the panel thickness (in mm), the number of layers, and the layup combination ("s" for standard perpendicular layers, and "l" for doubled outermost parallel layers).

Does not include In-plane ***Panel*** Shear Strength

ICC-ES Acceptance Criteria AC 455



ICC EVALUATION SERVICE

www.icc-es.org | (800) 423-6587 | (562) 699-0543 *A Subsidiary of the International Code Council®*

PROPOSED AC
CROSS-LAMINATED TIMBE
IN FLOOR

Propos

Evaluation reports issued by ICC Evaluation
the International family of codes. (Some repo
National Codes, the Standard Codes and the U
reads as follows:

The provisions of this code
prohibit any design or me

ICC-ES ma
demonstratin
otherwise der
to issue or re
either unusual care with its installation or
malfunctioning is apt to cause injury or unreas

NOTE: The Preface for ICC-ES accepta

Acceptance criteria are developed for use sol

ICC Evaluation Service, LLC
Eastern Regional Office

March 17, 2015

TO: **PARTIES INTERESTED IN CROSS-LAMINATED TIMBER PANELS FOR USE AS COMPONENTS IN FLOOR AND ROOF DECKS**

SUBJECT: Proposed New ICC-ES Acceptance Criteria for Cross-laminated Timber Panels for Use as Components in Floor and Roof Decks, Subject AC455-0215-R2 (PC/JF)

Dear Colleague:

Use as Components
iff letter, has been
. The committee

2. Revision to Section 1.3.4: Referencing the 2012 version of the ANSI/APA PRG 320.
3. Revision to Section 4.3.6: Adding "for each layup" after the phrase "Analysis of test results".
4. Revision to Section 6.2: Replacing "configuration" with "layup" and adding "for each CLT

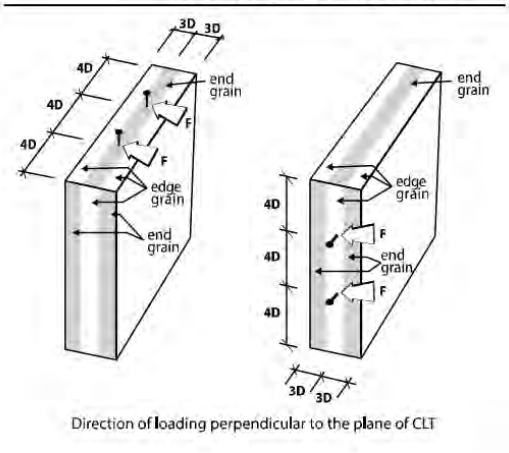
Defines In-plane ***Panel*** Shear Strength
Test for use in Floor and Roof Decks

CLT in NDS 2015 - Connectors

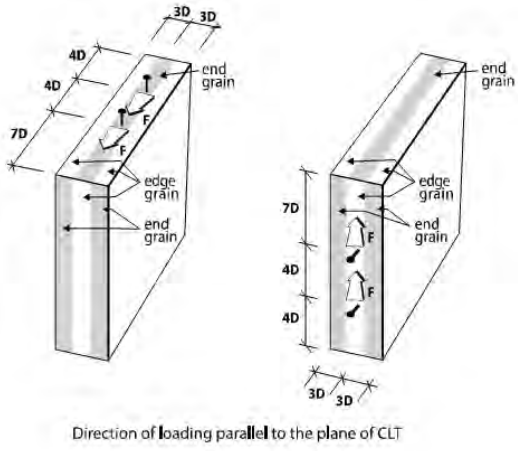
Connectors for CLT in NDS 2015:

Dowel Type Fasteners, e.g. Lag Screws, Bolts and Nails

Figure 12I **End Distance, Edge Distance and Fastener Spacing Requirements in Narrow Edge of Cross-Laminated Timber**



Direction of loading perpendicular to the plane of CLT



Direction of loading parallel to the plane of CLT

Panel + Connection = Diaphragm ?

- WSP Diaphragms based on ***system testing***
- WSP Diaphragms capacities listed in AWC's Special Design Provisions for Wind and Seismic

Need for System Level Diaphragm Strength Verification

Table 4.2A Nominal Unit Shear Capacities for Wood-Frame Diaphragms

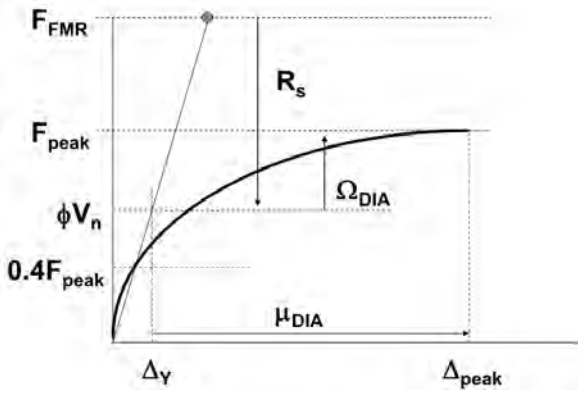
Blocked Wood Structural Panel Diaphragms[1,2,3,4]

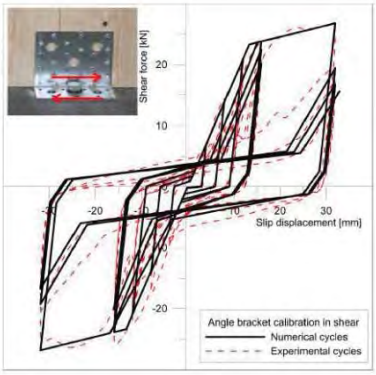
Sheathing Grade	Common Nail Size	Minimum Fastener Penetration in Framing Member or Blocking (in.)	Minimum Nominal Panel Thickness (in.)	Minimum Nominal Width of Nailed Face at Adjoining Panel Edges and Boundaries (in.)	A SEISMIC: Nail Spacing (in.) at diaphragm boundaries (all cases), at continuous panel edges parallel to load (Cases 3 & 4), and at all panel edges (Cases 5 & 6)												B WIND: Nail Spacing (in.) at diaphragm boundaries (all cases), at continuous panel edges parallel to load (Cases 3 & 4), and at all panel edges (Cases 5 & 6)			
					6			4			2-1/2			2			6	4	2-1/2	2
					Nail Spacing (in.) at other panel edges (Cases 1, 2, 3, & 4)												Nail Spacing (in.) at other panel edges (Cases 1, 2, 3, & 4)			
					6			6			4			3			6	6	4	3
					v_s (plf)	G_a (kips/in.)		v_s (plf)	G_a (kips/in.)		v_s (plf)	G_a (kips/in.)		v_s (plf)	G_a (kips/in.)		v_w (plf)	v_w (plf)	v_w (plf)	v_w (plf)
						OSB	PLY		OSB	PLY		OSB	PLY		OSB	PLY				
Structural I	6d	1-1/4	5/16	2	370	15	12	500	8.5	7.5	750	12	10	840	20	15	520	700	1050	1175
				3	420	12	9.5	560	7.0	6.0	840	9.5	8.5	950	17	13	590	785	1175	1330
	8d	1-3/8	3/8	2	540	14	11	720	9.0	7.5	1060	13	10	1200	21	15	755	1010	1485	1680
				3	600	12	10	800	7.5	6.5	1200	10	9.0	1350	18	13	840	1120	1680	1895
	10d	1-1/2	15/32	2	640	24	17	850	15	12	1280	20	15	1460	31	21	895	1190	1790	2045
				3	720	20	15	960	12	9.5	1440	16	13	1640	26	18	1010	1345	2015	2295

CLT Diaphragms for Seismic

Seismic behavior is not simple question of *force* demands and capacity.

Seismic design uses force as a proxy for EQ behavior





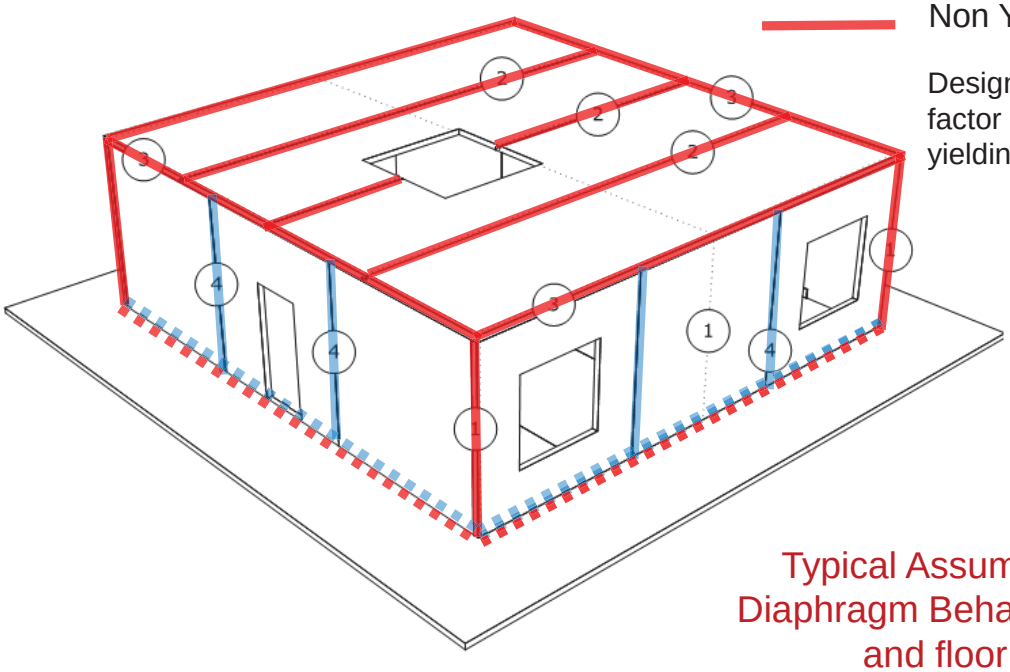
An European Approach

Fragiacomo, Vasallo et al.

Yielding Connections

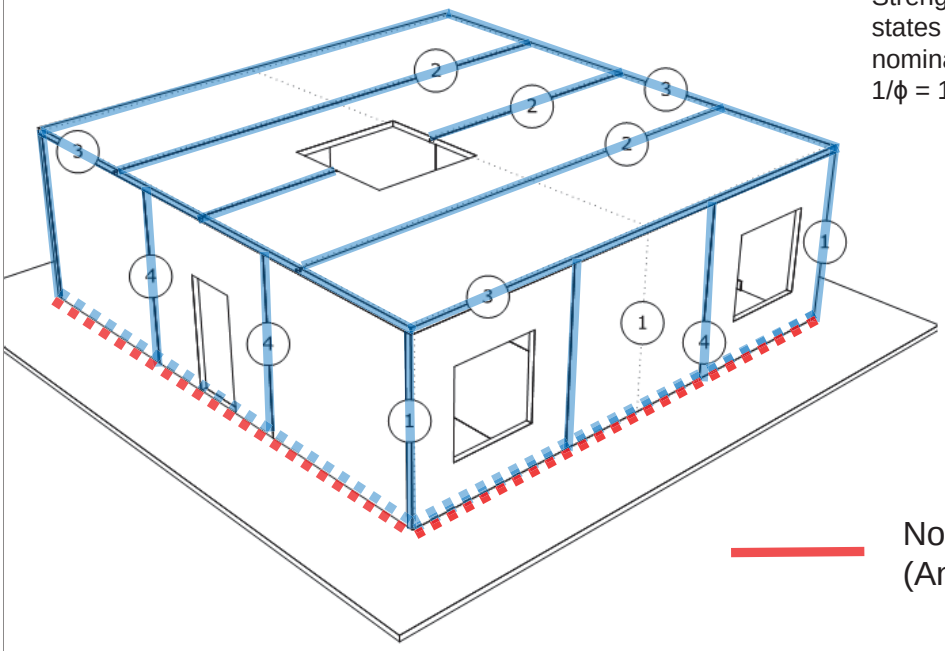
Non Yielding Connections

Designed to Overstrength factor of 1.3 to 1.6 of yielding connection strength



Typical Assumption of Rigid Diaphragm Behavior for CLT wall and floor systems

US CLT Handbook Approach



Yielding Connections

- NDS Yield Modes III and IV govern.
- Strength of other (non-yielding) limit states at connection designed to nominal yielding connection capacity. $1/\phi = 1/0.65 = 1.54$ overstrength factor

Non Yielding Connections (Anchorage to Support)

Design Example White Paper

CROSS LAMINATED TIMBER

Horizontal Diaphragm Design Example

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

CLT HORIZONTAL DIAPHRAGM DESIGN

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

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

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

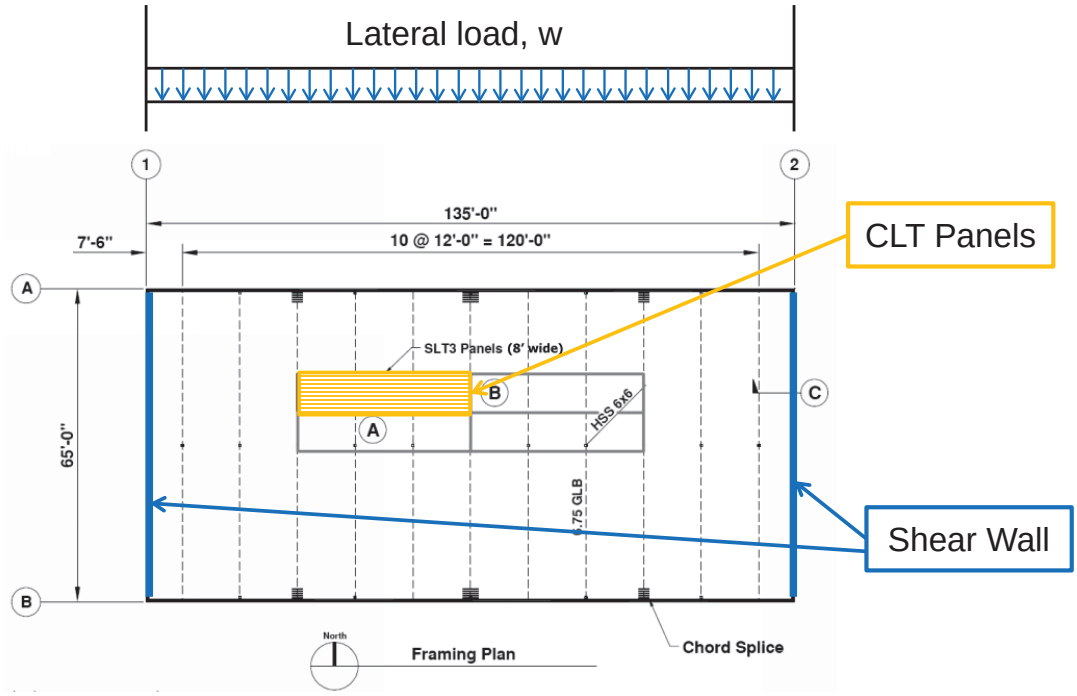
Kris Sprickler P.E.
Heavy Timber Group
Structurlam Products LP
Penticton, BC
ksprickler@structurlam.com
www.structurlam.com

Max Closen
Dipl.-Ing (FH), MaSc
MyTi Con Timber
Connectors Inc.
Surrey, BC
max@my-ti-con.com
www.my-ti-con.com

Philip Line, P.E.
American Wood Council
Leesburg, VA
pline@awc.org
www.awc.org

Martin Pohll P.E., S.E.
Martin Pohll Structural
Engineering
Rancho Murieta, CA
mpohll@ranchomurieta.org

Diaphragm Design Example



Design Example White Paper

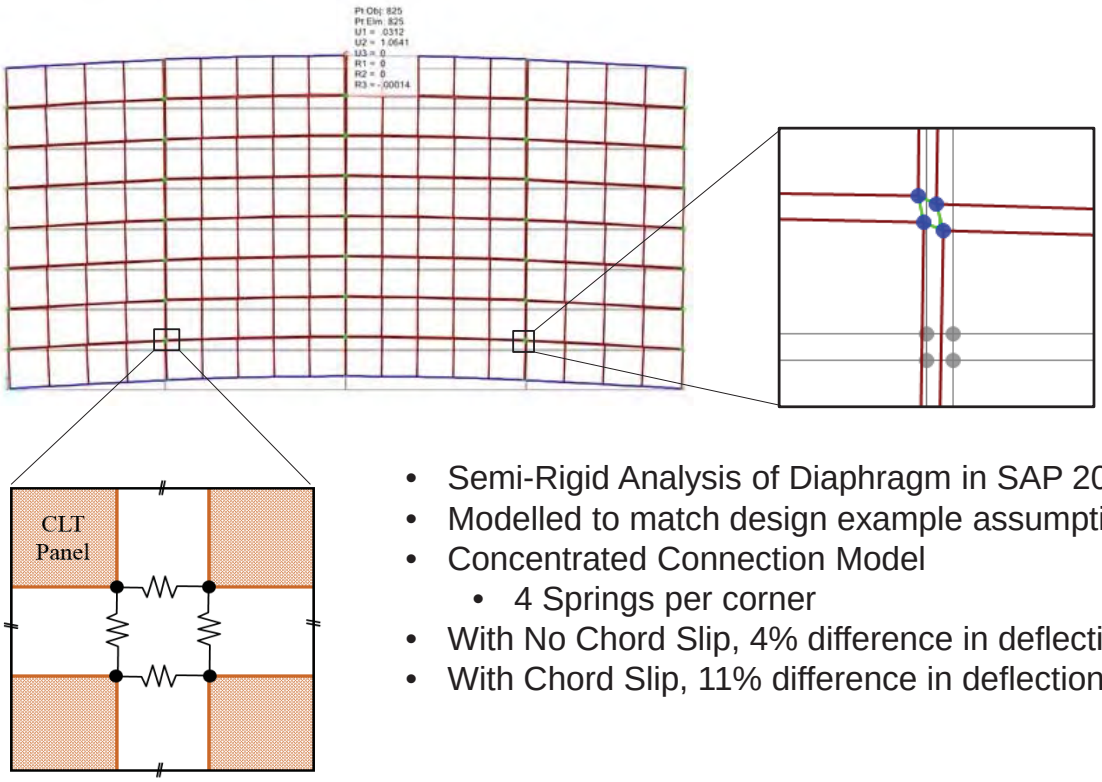
- Shows calculations for simple diaphragm following US CLT Handbook Recommendations with many limit states.
- Presented modification of WSP diaphragm deflection calculation for large Panels

$$\delta_{dia} = \frac{5vL^3}{8EAW} + \frac{vL}{4G_v t_v} + CLe_n + \frac{\sum(x\Delta_c)}{2W}$$

$$C = \frac{1}{2}\left(\frac{1}{P_L} + \frac{1}{P_W}\right)$$

P_L is panel length
P_W is panel width

FEM Modeling for Design Work

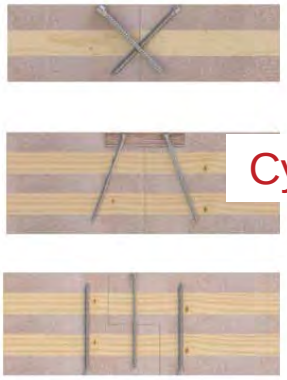


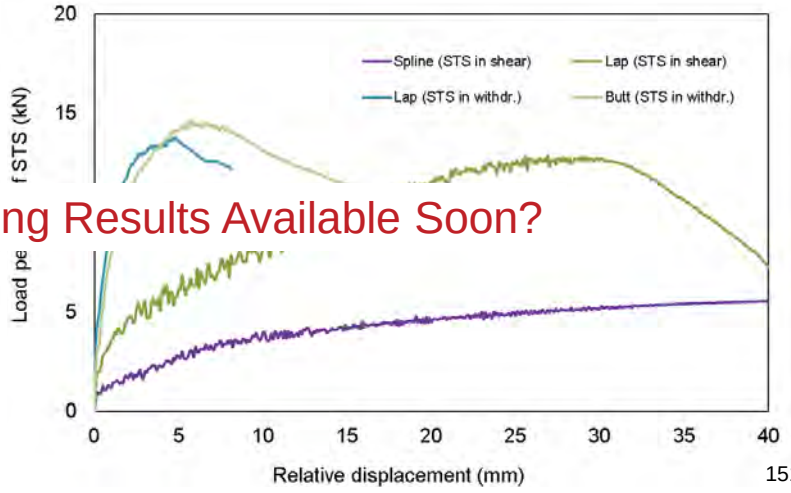
- Semi-Rigid Analysis of Diaphragm in SAP 2000
- Modelled to match design example assumptions
- Concentrated Connection Model
  - 4 Springs per corner
- With No Chord Slip, 4% difference in deflections
- With Chord Slip, 11% difference in deflections

Research In Progress

University of British Columbia:

- Prof. Thomas Tannert
- Afrin Hossain, PhD Candidate



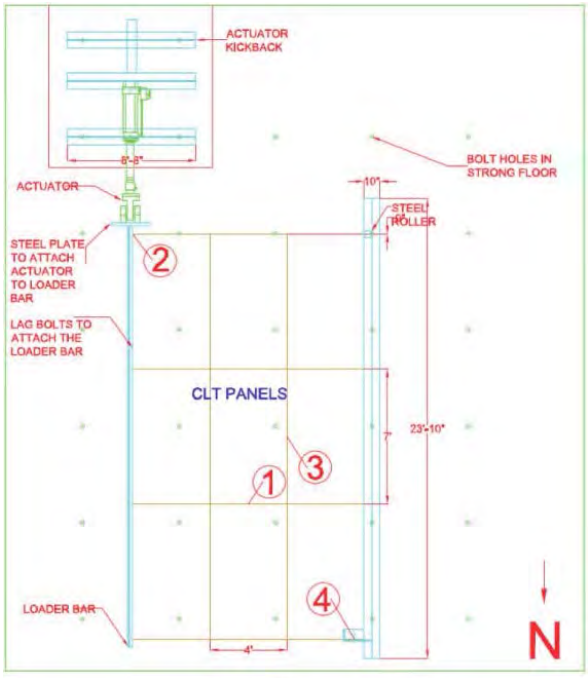


Cyclic Testing Results Available Soon?

Research In Progress

Colorado State University

- John van de Lindt
- Planning small full-scale diaphragm test



Research in Progress

Oregon State University:

- Rakesh Gupta, Lech Muszinsky, Andre Barbosa. CLT connections, etc.

University of British Columbia, Vancouver

- Terje Haukaas, Frank Lam. CLT connections, CLT Diaphragm Modelling.

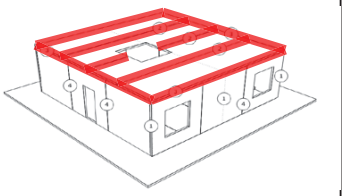
And More?

Ideas for Design Standardization

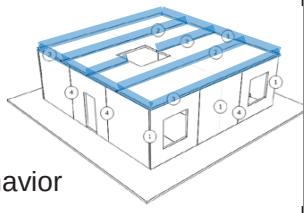
- Testing, Testing, Testing:
  - Continue connection level testing
  - Cyclical Testing of Proprietary connectors
  - Diaphragm Testing paired with Analytical Studies
  - Chord Design and Detailing.
- Refinement of Engineering Design Approach
  - Collaboration of researchers, industry, and practitioners
- Standardization of Developed of Design Method
  - Code referenceable engineered design standards for capacity design method
  - Possibly new testing protocols for panel and connection behavior
- Education of designers for proliferation of use.

Ideas for Near Term Seismic Projects

- Possible routes for near term ***seismic*** project designs under Alternative Means and Methods include

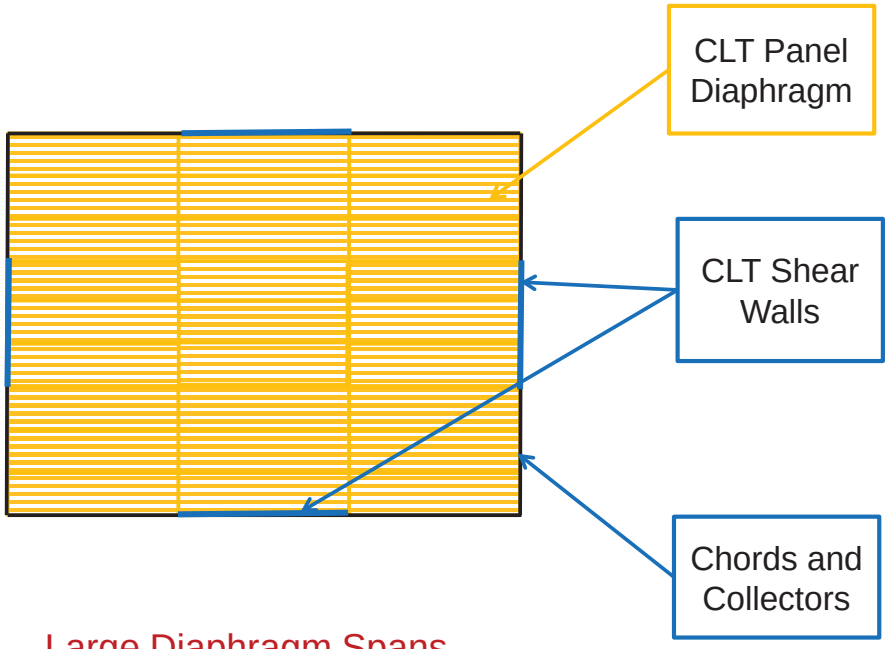


1) Elastic Design Method
   - Based on lower-bound strength of components
   - Following new ASCE 7-16 alternative diaphragm method to determine elastic seismic diaphragm force demands



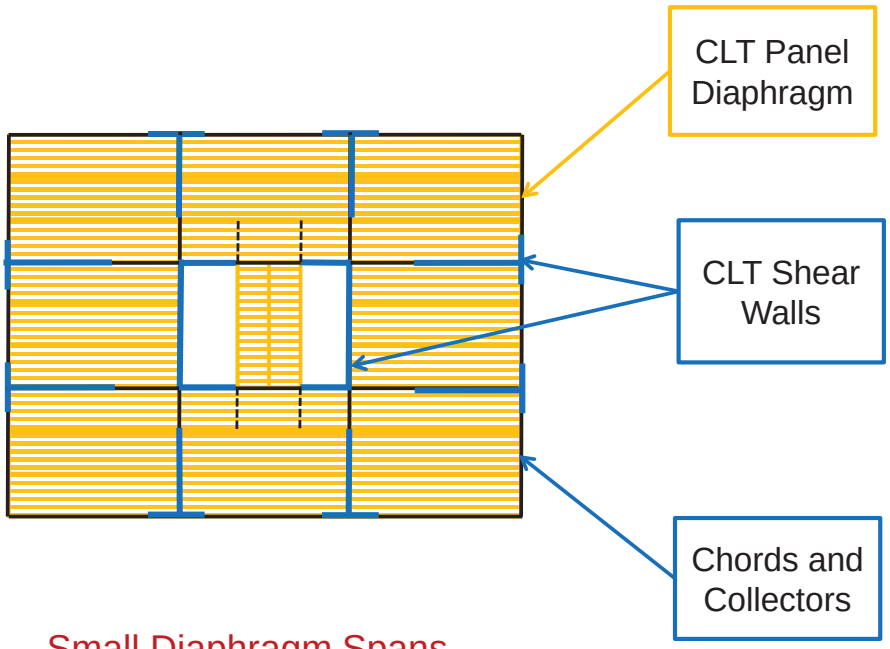
2) Capacity-Based Design Method
   - Using designated yielding connections with overstrength design of non-desirable limit states.
   - Based on yielding connection technologies of proven cyclic behavior
     - Relatively equivalent to Wood Structural Panel diaphragm behavior OR
     - Advanced Engineering with supporting testing to justify design

CLT Diaphragm Scenarios



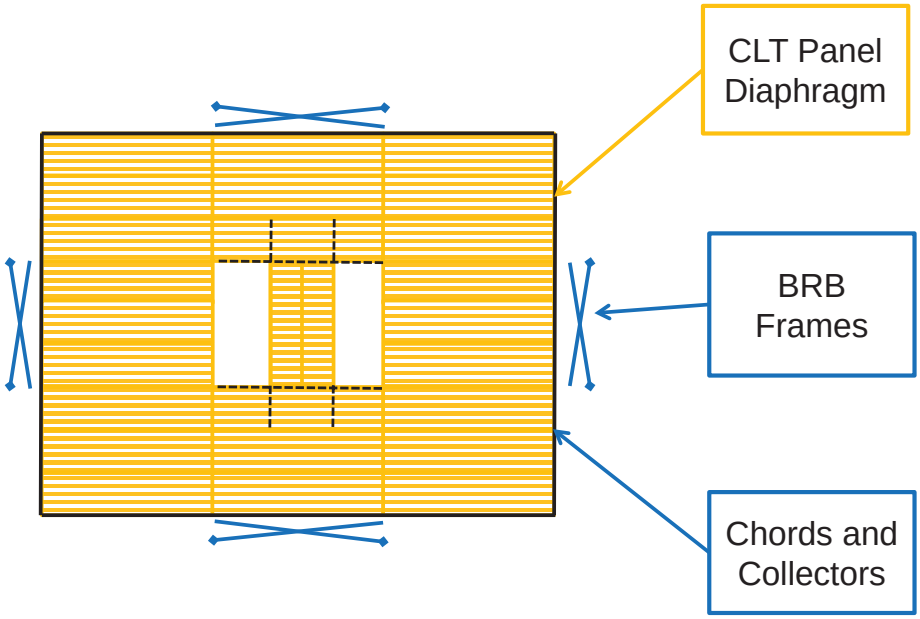
Large Diaphragm Spans…
With multiple panels per span

CLT Diaphragm Scenarios



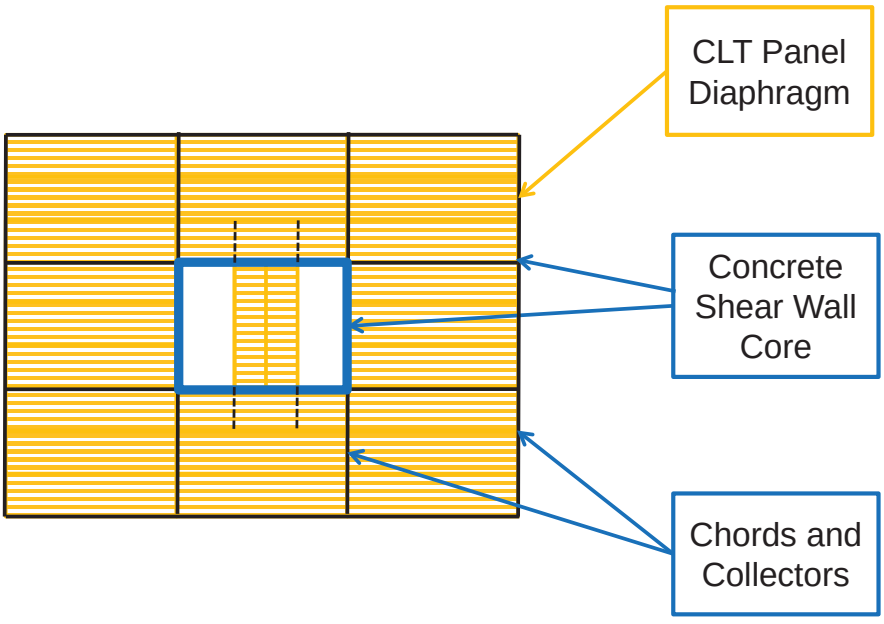
Small Diaphragm Spans…
With full diaphragm-width panels

CLT Diaphragm Scenarios



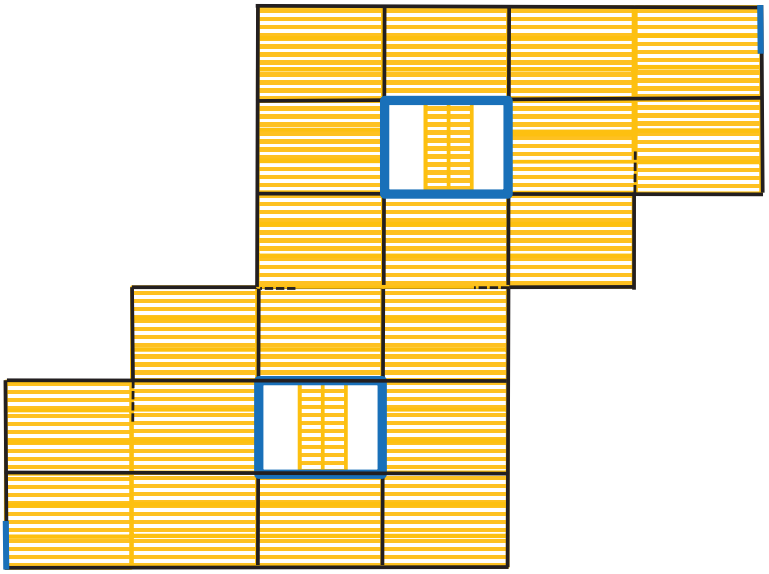
Diaphragm spanning between Soft Braces

CLT Diaphragm Scenarios



Diaphragm cantilevering off Stiff Core

CLT Diaphragm Scenarios



Real buildings are not all rectangles

Session 2—Building Performance: Durability, Sound, Vibration and Life Cycle Analysis

CLT Systems: Acoustic, Vibration, and Creep Performance

Ciprian Pirvu, Senior Scientist
FPInnovations, Vancouver, British Columbia, Canada

This presentation will focus on serviceability performance of cross laminated timber systems. Acceptable sound insulation performance of walls and floors in buildings, as well as adequate vibration and time-dependent deflection (creep) of floors, are mandatory requirements specified in building codes. It is critical that these performance attributes are taken into account in the design to ensure that required safety and comfort levels of occupants are maintained during the specified service life of the structure. Building code requirements, research results, and practical construction solutions will be presented.

Serviceability of CLT Systems

- Acoustic performance
- Vibration performance
- Creep performance

© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

Acoustic Performance of CLT Assemblies

- Airborne and structure-borne sound
- Noise control requirements in building codes
- Strategies for noise control
- Examples of practical solutions

© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

Airborne Sound

- Sound wave propagating through air
- Sound Transmission Class (STC)
  - Single number rating
  - Classifies airborne sound insulation of a building element
  - Laboratory measurements (ASTM E90) → airborne sound transmission loss through a wall/floor-ceiling assembly

    → STC rating

    (based on ASTM E413)

Noise Source & Human Perception	STC
Loud speech or music audible, bass notes particularly strong	45
Loud speech faintly audible / Loud music barely audible, but bass notes quite noticeable	50
Loud music not generally audible, but bass notes still heard	55
Loud music inaudible except for very strong bass notes	60

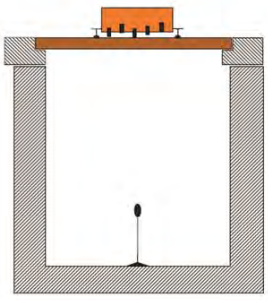
Source Table: NRC Canada

© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

Structure-Born Sound (Impact Sound)

- Sound wave propagating through a solid structure
- Impact Insulation Class (IIC)
  - Single number rating
  - Classifies impact sound insulation of a floor-ceiling assembly
  - Acoustical chamber without flanking (laboratory) measurements (ASTM E492, tapping machine) → impact sound transmission

    → IIC rating (based on ASTM E989)



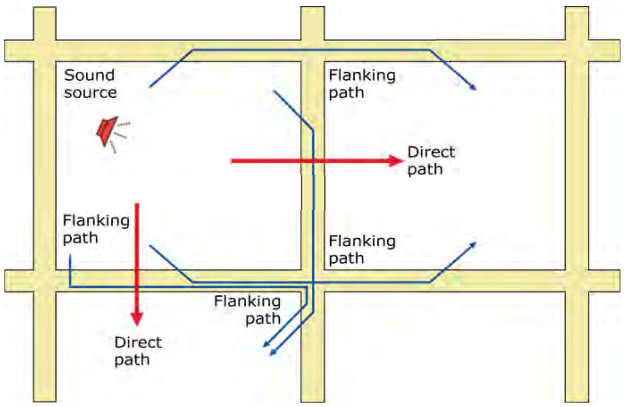
© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

Sound Transmission Paths

- Direct Path (via partition)
  - Assessed in acoustical chambers (labs) without flanking
- Flanking Paths (via junction)
  - Suppressed in lab tests for STC/IIC measurements

EXAMPLES FLANKING PATHS:

- Windows and doors;
- Continuous (shared) floors/walls;
- Wall and floor/ceiling junctions;
- Plumbing chases



Source Figure: NRC Canada

© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

Field Sound Transmission Classes

- FSTC / ASTC
  - Field Sound Transmission Class (FSTC)
  - Accounts for direct airborne sound and flanking transmission
  - Field measurements (ASTM E336) → direct sound transmission loss and flanking transmission loss
    → FSTC rating (based on ASTM E413)
  - Same as Apparent Sound Transmission Class (ASTC)
- FIIC
  - Field Impact Insulation Class (FIIC)
  - Accounts for direct impact sound and flanking transmission
  - Field measurements (ASTM E1007) → impact sound transmission and flanking transmission
    → FIIC rating (based on ASTM E989)

FSTC < STC

FIIC < IIC

© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

Noise Control Requirements (IBC)

- Minimum requirements for demising walls and floor-ceiling assemblies

Assembly	Airborne Sound		Impact Sound	
Wall	STC	50	N/A	
	FSTC	45 [1]		
Floor	STC	50	IIC	50
	FSTC	45 [1]	FIIC	45 [2]

[1] When tested in accordance with ASTM E336 for FSTC and ASTM E90 for STC

[2] When tested in accordance with ASTM E1007 for FIIC and ASTM E492 for IIC

Source Table: 2009 IBC

© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

FPInnovations

Acoustical Performance Recommendations (ICC)

- Acceptable & preferred grades (field tests)

Field Sound Rating	Acceptable Performance (Grade B)	Preferred Performance (Grade A)
Airborne Noise (NNIC[1])	52	57
Impact Noise (NISR[2])	52	57

[1] Normalized Noise Isolation Class: When tested according to ASTM E336

[2] Normalized Impact Sound Rating: When tested according to ASTM E1007

- Acceptable & preferred grades (lab tests)

Laboratory Sound Rating	Acceptable Performance (Grade B)	Preferred Performance (Grade A)
Airborne Noise (STC[1])	55	60
Impact Noise (IIC[2])	55	60

[1] Sound Transmission Class: When tested in accordance with ASTM E90

[2] Impact Insulation Class: When tested in accordance with ASTM E492

Source Tables: 2010 ICC G2

© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

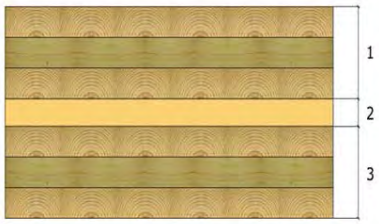
FPInnovations

Three Defence Approach for Noise Control

1. Control noise at the source
   - Contain airborne noise in source room (use low porosity materials)
   - Use resilient layer under flooring to absorb footstep impact and reduce (floor) vibration
2. Control vibrations with mass and stiffness
   - The greater the weight, the better the sound insulation
   - The stiffer the assembly, the better the sound insulation
3. Control vibrations by decupling elements
   - Prevent transmission of wall/floor vibration to adjacent element
   - Use multiple layers with an air space between elements

© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

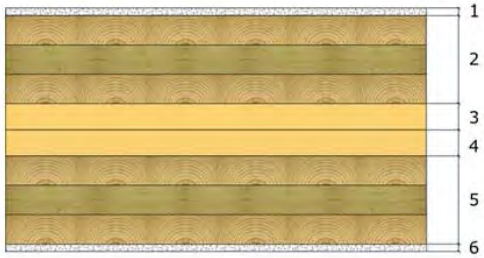
CLT Wall Design Example (STC 32 – 55)

Cross Section	Details	STC
	3-layer CLT (3 ¾ - 4 ½ in)	32 - 34
	1. 5/8 in gypsum board (directly attached to CLT on 1 side) 2. 3-layer CLT (3 ¾ - 4 ½ in)	36 - 38
	1. & 3. 3-layer CLT (3 ¾ - 4 ½ in) 2. Sound insulation material (mineral wool) about 1.2 in	50
	With 5/8 in gypsum board (both sides)	55

Source: CLT Handbook, US Ed.

© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

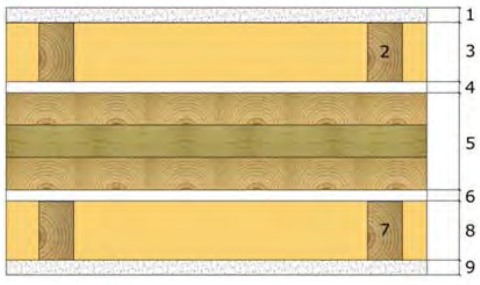
CLT Wall Design Example (STC 55 & up)

Cross Section	Details
	1. 5/8 in gypsum board 2. 3-layer CLT (3 ¾ - 4 ½ in) 3. Sound insulation material (mineral wool) about 1.2 in 4. Sound insulation material (mineral wool) about 1.2 in 5. 3-layer CLT (3 ¾ - 4 ½ in) 6. 5/8 in gypsum board

Source: CLT Handbook, Canadian Ed.

© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

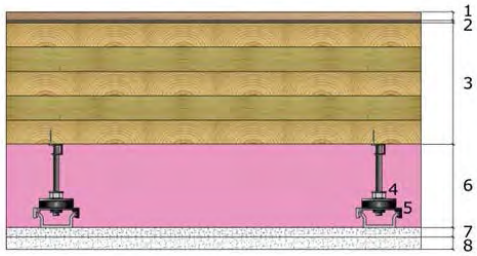
CLT Wall Design Example (FSTC 50)

Cross Section	Details
	1. 5/8 in gypsum board 2. 2x3 wood studs at 16 in o.c. 3. 2 ½ in mineral wool in the wall cavity 4. ½ in air gap 5. 3-layer CLT (4 ½ in) 6. ½ in air gap 7. 2x3 wood studs at 16 in o.c. 8. 2 ½ in mineral wool in the wall cavity 9. 5/8 in gypsum board

Source: CLT Handbook, US Ed.

© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

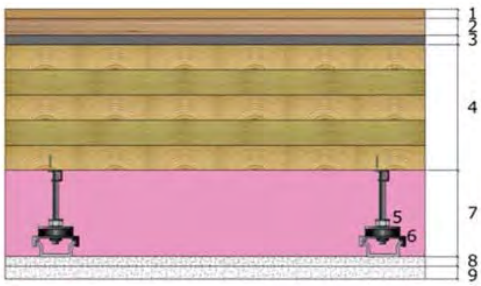
CLT Floor-Ceiling Assembly (FSTC >50, FIIC >50)

Cross Section	Details
	1. 2/5 laminated or engineered wood flooring 2. 1/8 in resilient underlayment (0.16 to 0.37 lb/ft^2) 3. 5-layer CLT (6 7/8 in) 4. Sound Isolation Clip (4 in high) 5. Metal hat channel at 16 in o.c. 6. Sound absorption materials (e.g. glass fibre) (4 in) 7. ½ in gypsum board 8. 5/8 in gypsum board

Source: CLT Handbook, US Ed.

© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

CLT Floor-Ceiling Assembly (FSTC >53, FIIC >53)

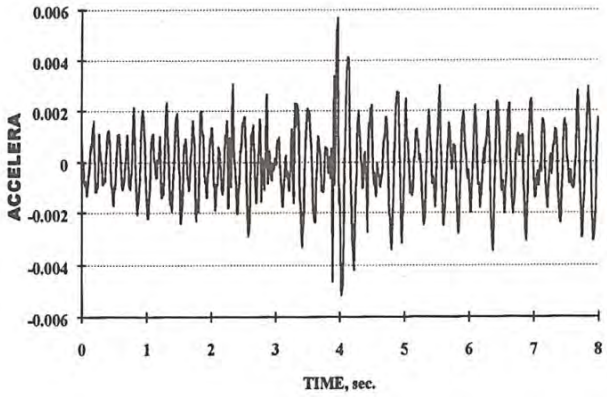
Cross Section	Details
	1. Hardwood flooring attached to plywood 2. ¾ in plywood 3. 2/5 in resilient underlayment (0.16 to 0.37 lb/ft^2) 4. 5-layer CLT (6 7/8 in) 5. Sound isolation clips (4 in high) 6. Metal hat channel 7. Sound insulation material (e.g. glass fibre) (4 in) 8. ½ in gypsum board 9. 5/8 in gypsum board

Source: CLT Handbook, US Ed.

© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

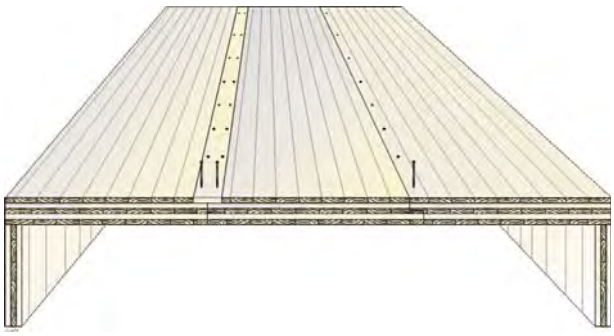
Vibration Performance of CLT Floors

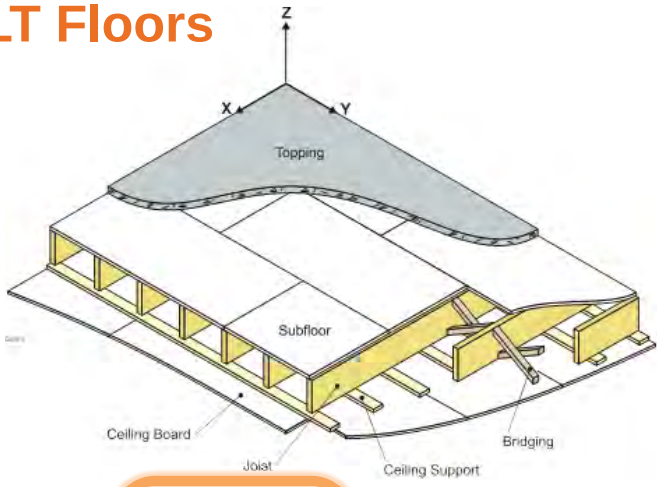
- Particular features of CLT floors
- Proposed Canadian design method for controlling floor vibration (FPI)



© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

Dynamic Properties of CLT Floors





Property	Wood Fram	CLT	Concrete
Area Mass, lb/ft^2 (kg/m^2)	4-23[1] (20-110	10-30 (50-150)	> 40 (> 200)
Damping (%)	3	1	2[2] - 8[3]
Fundamental Natural Frequency (Hz)	10[1] - 15	> 9	< 8

Note: [1] Conventional wood joisted floors with concrete topping
[2] Bare concrete floors (Allen D.E. and Murray T.M, 1993)
[3] Full height partitions (Allen D.E. and Murray T.M, 1993)

© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

Design Methods for Floor Vibration

Design Method	2010 NBCC[1]	Not Addressed	Steel-Concrete (Steel Design Guide[2])
Floor Construction	lightweight joisted floor without topping	joisted floors with concrete topping **CLT floors**	steel joists concrete slab
Area Mass, lb/ft^2 (kg/m^2)	3-6 (15-30)	6-30 (30-150)	> 30 (150)
Fundamental Natural Frequency (Hz)	> 15	9-15	< 9

Note: [1] NBCC recommends limits for static deflection of wood frame joisted floors under concentrated loads of 225 lb (1 kN) at floor centre

[2] Murray et al, 1997. Method limits peak acceleration of a floor to control vibration.

→ Existing design methods do not cover CLT floors!

© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

Proposed Canadian Design Method for Controlling CLT Floor Vibration

- Design criterion for CLT floors
  - Applies to:
    - Floors with or without topping
    - Simple or continuous multi-span system
    - Vibrations induced by walking
    - Well-supported floors
    - Well-connected CLT panels

$$\frac{f}{d^{0.7}} \geq 125.1$$

f, fundamental natural frequency (Hz) of a 1 ft wide CLT panel simply supported at both ends

d, point load static deflection at mid-span of a simple beam (in)

© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

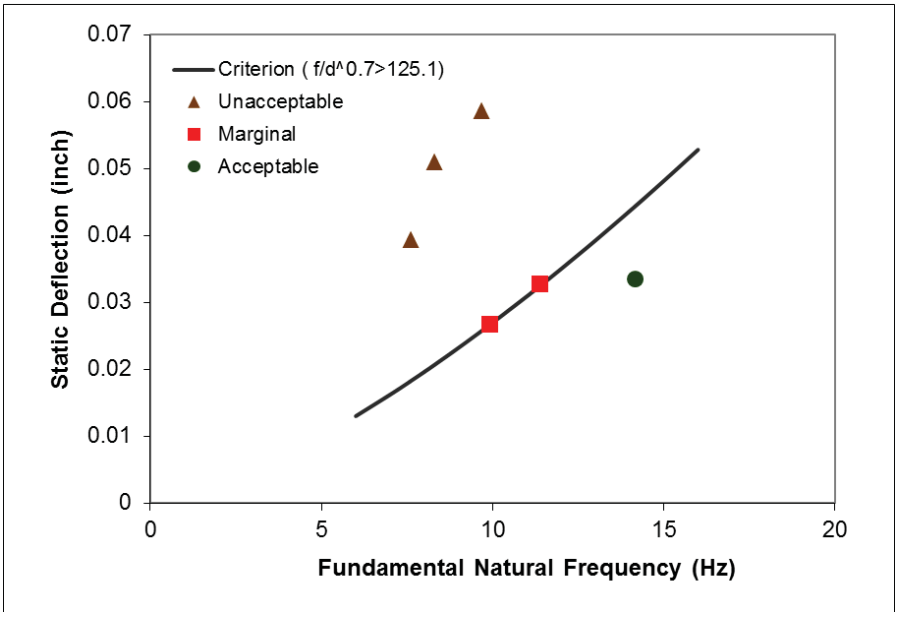
Verification of Proposed Method

- Vibration tests on 5-ply and 7-ply CLT floors
  - Calculation of criterion parameters to predict floor vibration
    - FUNDAMENTAL NATURAL FREQUENCY (*f*)
    - POINT LOAD STATIC DEFLECTION (d)
  - Subjective evaluation of floor movement (ratings given by evaluators)

© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

FPInnovations

Results of Subjective Evaluations



→ Agreement between predicted floor vibration performance and actual floor vibration rated by evaluators.

© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

FPInnovations

Comparative Verification of Proposed Method

CLT thickness (in.)	Proposed design method span (ft. – in.)	CLTdesigner span for 1% damping and no topping floors (ft.- in.) (Schickhofer and Thiel 2010)
3 15/16	11-9	11-7
4 3/4	12-4	12-4
5 3/4	14-9	14-6
6 5/16	15-9	15-7
7 1/8	16-11	16-10
7 7/8	18-7	18-7
8 11/16	19-1	19-4
9 7/16	20-0	20-3

CLTdesigner Software, Graz University of Technology, Austria.

© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

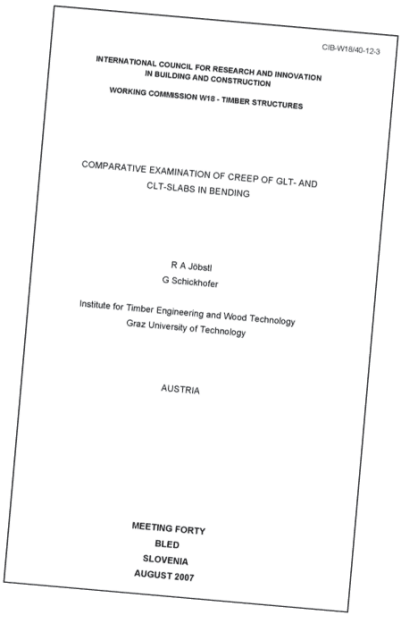
Creep Performance of CLT

- Earlier study (Austria)
- Exploratory study on creep of Canadian CLT (FPInnovations)
- Design considerations – creep factor

© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

Earlier Study on Creep of CLT

- Long-term behaviour of CLT comparable to that of plywood (TU Graz, Austria)
- Creep of CLT is 30-40% larger than that of glulam (TU Graz)



CIB-W18/40-12-3

INTERNATIONAL COUNCIL FOR RESEARCH AND INNOVATION IN BUILDING AND CONSTRUCTION

WORKING COMMISSION W18 - TIMBER STRUCTURES

COMPARATIVE EXAMINATION OF CREEP OF GLT- AND CLT-SLABS IN BENDING

R A Jöbstl
G Schickhofer

Institute for Timber Engineering and Wood Technology
Graz University of Technology

AUSTRIA

MEETING FORTY
BLED
SLOVENIA
AUGUST 2007

© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

Study on Creep of CLT at FPInnovations: Samples

- Lumber: 2x SPF (B.C. & Quebec), Hem-Fir (N)
- CLT panel manufacture:
  - 5-ply CLT – 9 CLT panels – size: 13x4 ft
  - 3 CLT qualities based on E-rates (MOE)

	SPF (W)	SPF (E)	Hem-Fir (N)
CLT Quality 1 (Highest)	CLT 1	CLT 4	CLT 7
CLT Quality 2 (High)	CLT 2	CLT 5	CLT 8
CLT Quality 3 (Lower)	CLT 3	CLT 6	CLT 9

- Press limitation: 54% lower vertical pressure than specified
- Sample Preparation: 3 billets/panel – 15 in wide

© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

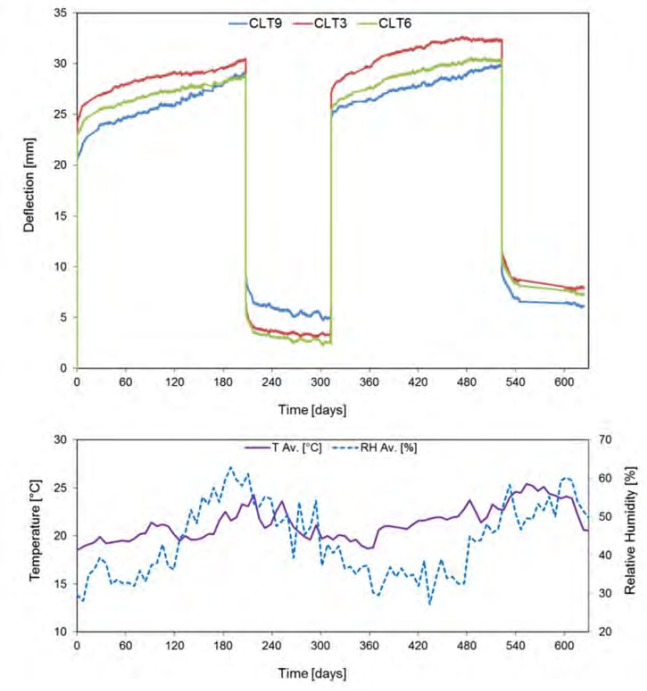
Study on Creep of CLT at FPInnovations: Tests

- 1-min ramp tests:
  - Bending tests
  - Third-point loading
  - Span 12 ft
  - Span-to-depth ratio 27:1
- Creep tests:
  - Constant loads allow max. deflection of L/180 (range 3100~4800 lb)
  - Test protocol (2 cycles):
    - Creep (~200 days)
    - Relaxation (~100 days)

© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

Study on Creep of CLT at FPInnovations: Results

- Decreasing creep rates after 90/120 days of loading
- Fractional deflections ≤ 1.43 after 90-day loading (≤ 2.0 in ASTM D6815)
  - LVL = 1.24-1.34
  - No. 2 Douglas fir = 1.63
  - Structural panels = 1.52
- Creep recovery ≥ 36% after 30 days of unloading (≥ 20% in ASTM D6815)



© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

Design Considerations for Creep of CLT

- Bending members (NDS® 2015, Eq. 3.5-1)

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

Δ_T: total deflection, in

K_{cr}: creep factor, K_{cr} = 2.0 for CLT (service MC<16%)

Δ_{LT}: deflection due to long-term component of design load, in

Δ_{ST}: deflection due to short-term component of design load, in

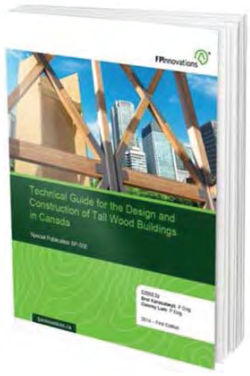
© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

Concluding Remarks

- Noise and vibration control are associated with the comfort level of occupants.
  - Subjective evaluation is important
  - Control flanking sound transmission (noise)
  - Control floor stiffness and mass (vibration)
  - In-situ measurements after the project is completed, and application of corrective measures prior to occupancy.
- Creep effects are of critical importance to timber engineering. A feasible test method for assessing creep effects of CLT is needed.

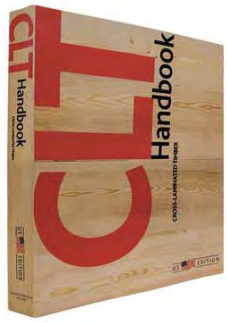
© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

Additional Technical Information on Acoustic, Vibration and Creep Performance of CLT



TG Design and Constructions of Tall Wood Buildings
https://fpinnovations.ca

CLT Handbook, Canada
https://fpinnovations.ca



CLT Handbook, US
http://www.masstimber.com

© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

Acknowledgements

- Natural Resources Canada (NRCan)
- Provincial governments in Canada
- FPInnovations' industry members
- Softwood Lumber Board
- National Research Council of Canada
- USDA Forest Products Laboratory

© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

FPInnovations

Thank you

Ciprian Pirvu, P.Eng, Ph.D.
FPInnovations, Wood Products Division
2665 East Mall, Vancouver BC V6T 1Z4
Phone: 1 (604) 224-3221
Email: ciprian.pirvu@fpinnovations.ca

Follow us on

www.fpinnovations.ca

© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

FPInnovates

November 25-26, 2015 | Montreal

INNOVATION & TECHNOLOGY CONFERENCE

By FPInnovations

REGISTER

at http://fpinnovates.com/

Hygrothermal Performance of Mass Timber Construction

Samuel V. Glass, Research Physical Scientist
USDA Forest Products Laboratory, Madison, Wisconsin

This presentation provides a brief overview of research at the Forest Products Laboratory on moisture and thermal performance of mass timber construction. The Building Enclosure Chapter of the *U.S. CLT Handbook* is summarized, with emphasis on strategies for managing water, air, vapor, and heat in wall and roof assemblies. Several projects are discussed, including laboratory research on interlocking CLT, field monitoring of in-service moisture and temperature conditions in CLT roof panels in a commercial building, and computer hygrothermal simulation of CLT exterior wall systems in different U.S. climates.

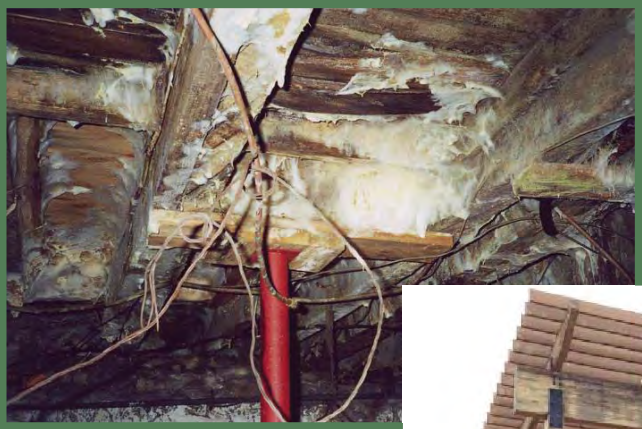
Mass Timber Research Workshop
November 3, 2015 – Madison, WI

Hygrothermal Performance of Mass Timber Construction

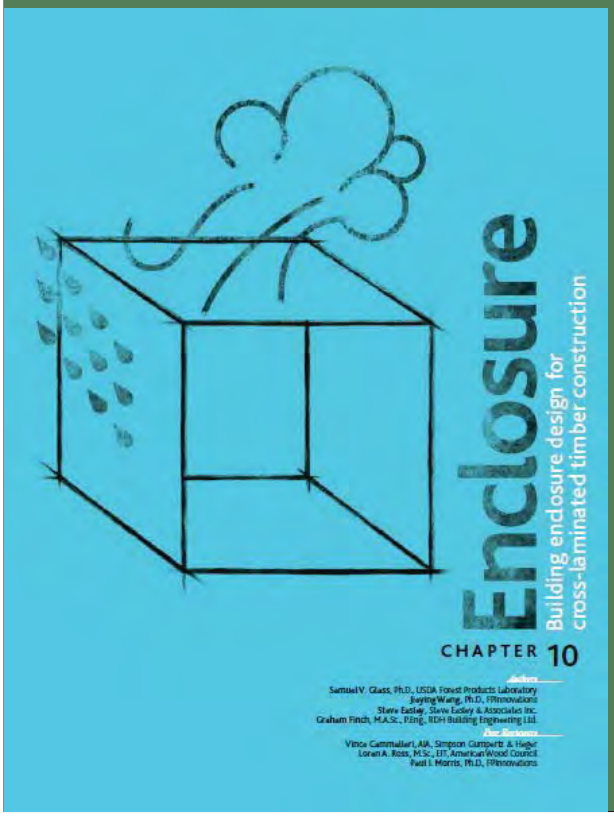
Samuel V. Glass, PhD
Building and Fire Sciences
Forest Products Laboratory

an ounce of prevention is worth a pound of cure

(Benjamin Franklin)



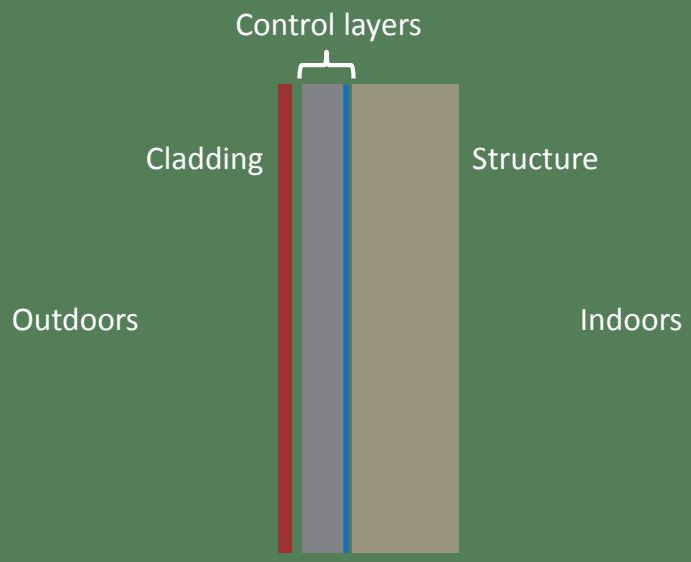
Building envelope is an environmental separator



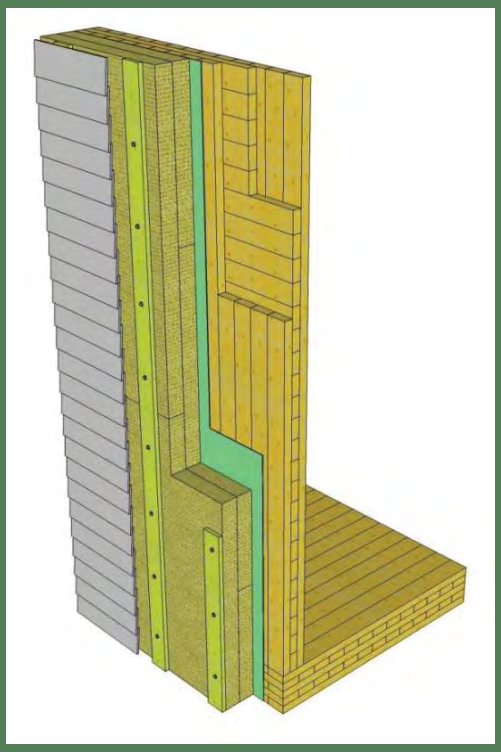
Critical functions:

1) Prevent water intrusion
2) Manage air flow
3) Manage vapor diffusion
4) Manage heat flow

“Perfect Wall” concept is apt for mass timber



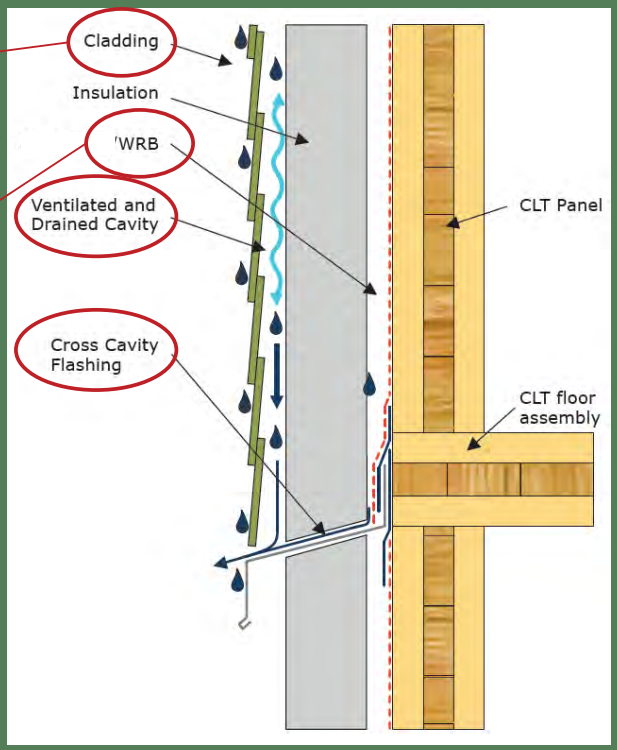
The Perfect Wall by J. Lstiburek
www.buildingscience.com



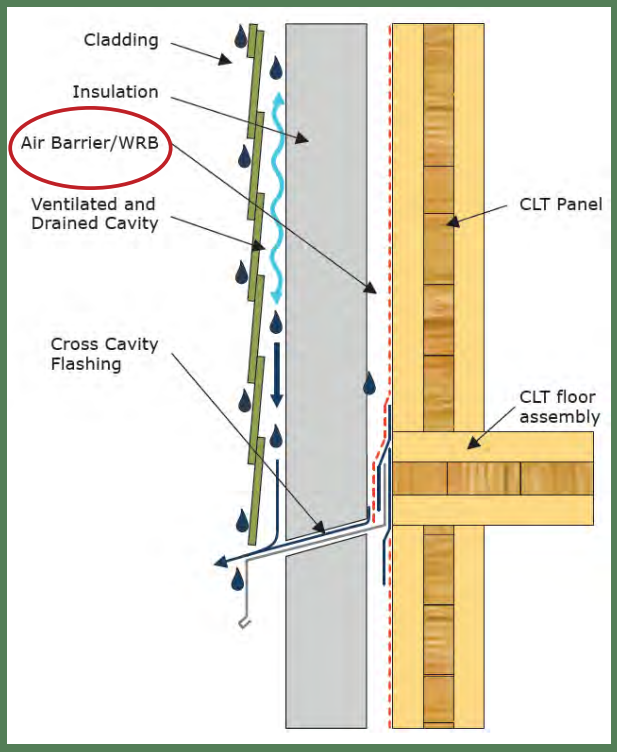
Water management is most important

Water-shedding surface

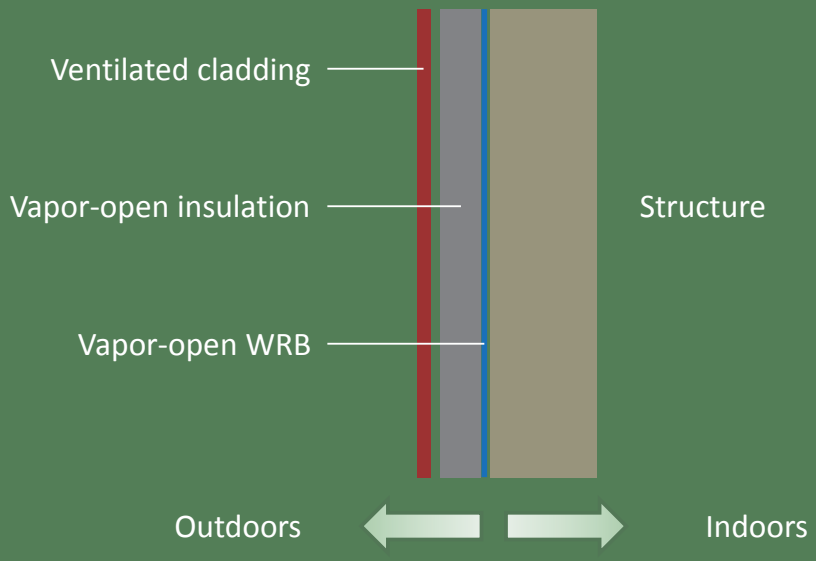
Water-resistive barrier (WRB)



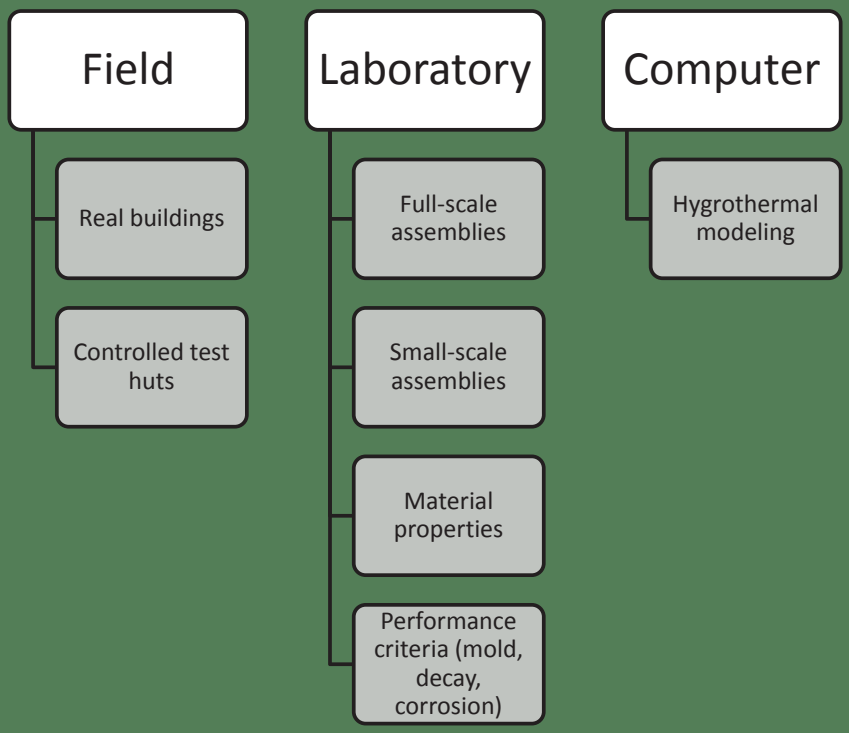
Water-resistive barrier doubles as air barrier



Vapor-open assemblies dry in both directions



Approaches to moisture performance research



FPL monitoring moisture in CLT roof

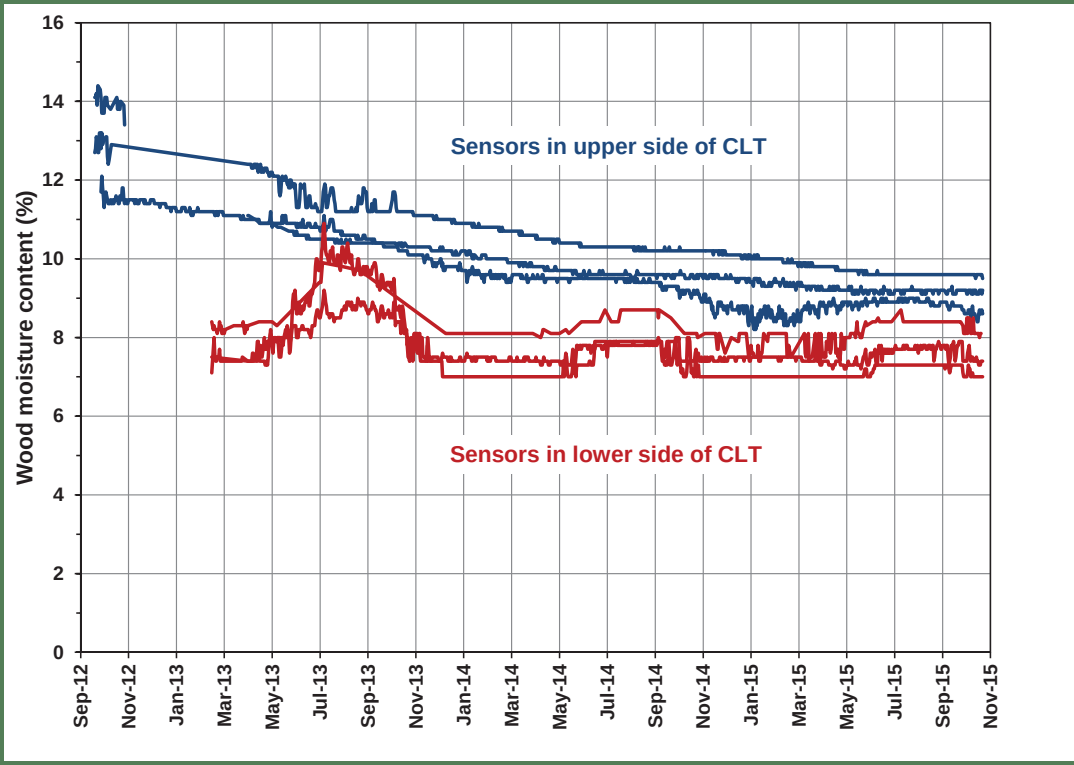
10

11

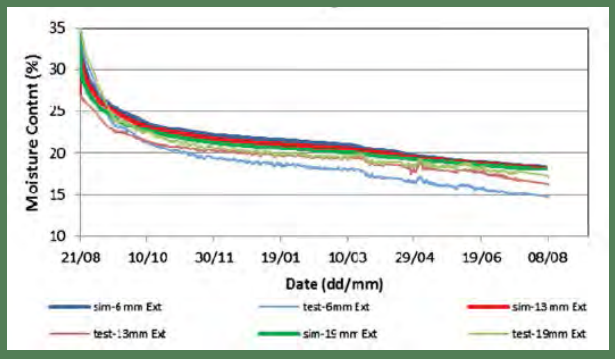
12

13

Monitoring demonstrates good moisture performance

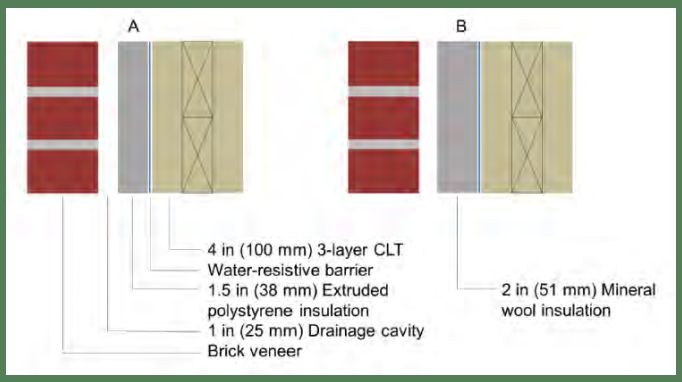


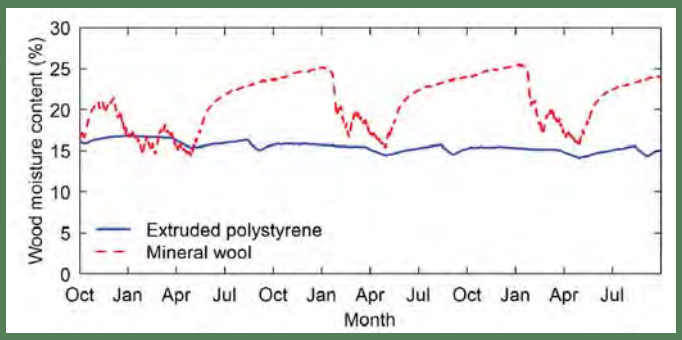
Test hut study shows CLT walls dry predictably



McClung, R.; Ge, H.; Straube, J.; Wang, J. 2014. Hygrothermal performance of cross-laminated timber wall assemblies with built-in moisture: field measurements and simulations. *Building and Environment* 71:95–110.

Hygrothermal modeling identifies potential risks





Glass, S.V.; TenWolde, A.; Zelinka, S.L. 2013. Hygrothermal simulation: a tool for building envelope design analysis. *Wood Design Focus* 23(3):18–25.

Interlocking CLT: low-rise buildings, dry climates

Rio Mesa Center Bath House

Cooperators:

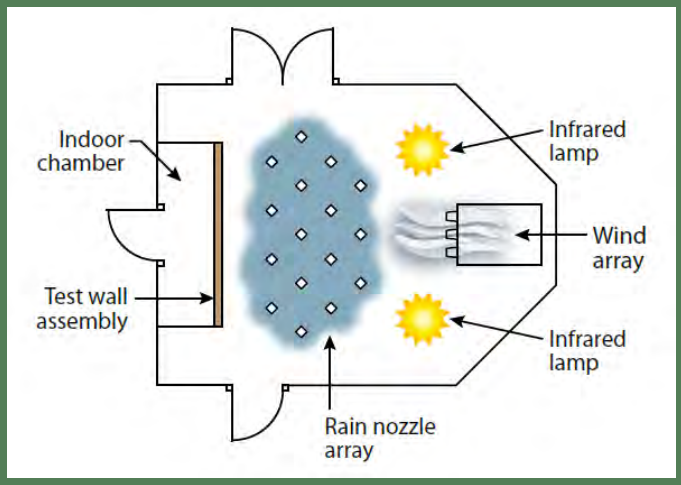
- University of Utah
- University of Idaho
- Brigham Young University
- Euclid Timber Frames

How will ICLT perform in other climates?

18

Chamber for **A**nalytic **R**esearch on **W**all **A**ssemblies exposed to **S**imulated weat**h**er (CARWASh)

19



Hygrothermal performance research needs

- Monitor in-service performance of real buildings
- Quantify wetting and drying during construction
- Gauge risk of solar-driven inward diffusion from absorptive claddings
- Measure variability in key material properties

Sam Glass | USDA FS Forest Products Laboratory | svglass@fs.fed.us

Acoustic Prediction Models Create Basis for Future Competitive Wooden Structures

Klas Hagberg, Head of Acoustics, Sweden
WSP, Malmö, Skåne, Sweden

The wood industry and its market shares are increasing. One important reason is raised requirements regarding sustainability in the building sector. However, long-term sustainability implies also that acoustic comfort mirrors the perception of the humans using the buildings, and in addition it requires that prediction models are available in order to anticipate the final acoustic and vibrational quality of buildings. That is not possible currently. To promote prediction model development for wooden construction, a new big project was started during Spring 2014 within the European WoodWisdom-Net+ programme. Results from the project should be integrated into the CEN and ISO standards in order to extend the use of these standard specifications to address wooden structures in the future. The models will be developed in a full frequency range (including low frequencies) adapted to future vibration criteria and sound insulation single numbers, developed to fit to human experience.

Introduction

→ **Some ”statements:**

→ **The acoustics decide the dimensions of a floor assembly**

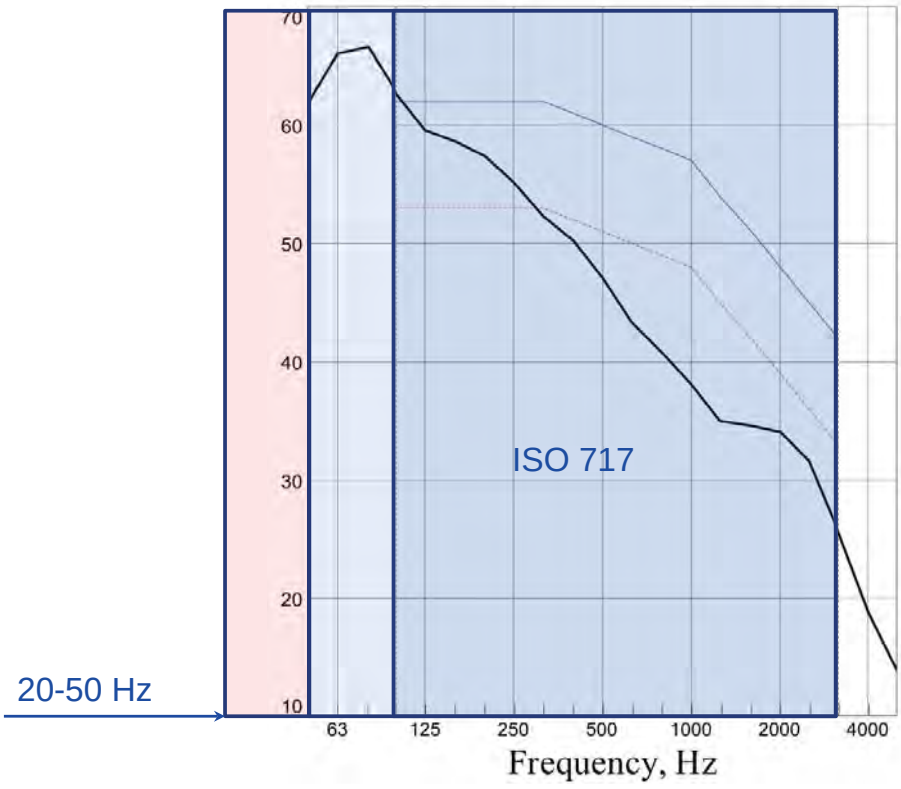
- Why is 250 mm concrete needed in a floor?
- Why is it needed 200 mm concrete in a wall?
- Why is it Hollow concrete 265 mm
- Etc etc

- Whith these dimensions, normally sound class B is fullfilled (in Sweden)

→ **Why is a wooden structure 500 mm thick?**

→ **It is always the acoustics that is the design paramater for the structure in a building**

Introduction - Where are we today?

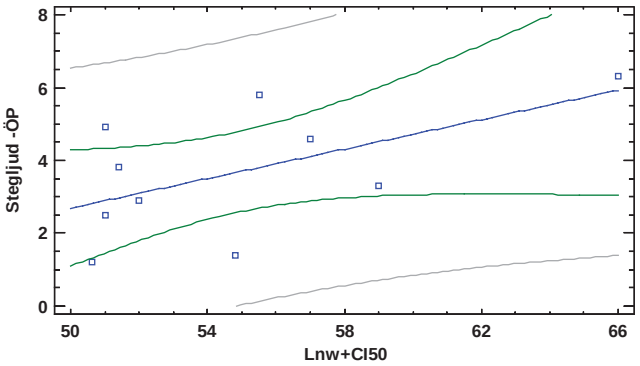


Introduction

→ **New research emphasizes the importance of introducing requirements in ”very low” frequency consideration in wooden structures (AkuLite and AcuWood). It might require new approaches in addition to traditional statistical methods**

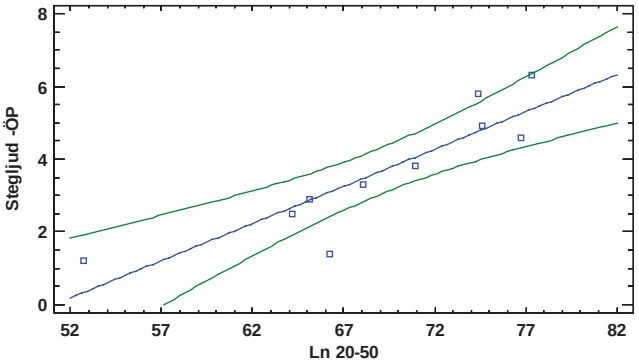
→ **Impact sound evaluation, correlation**

50 Hz -3150 Hz, ISO 717



R^2 = 32%

20-50 Hz only!



R^2 = 78%

WSP

Introduction

→ **At least one more project will continue after AkuLite and AcuWood to further develop the criteria for sound insulation, that is**

- “New improved building technique-neutral criteria for sound insulation evaluation” Luleå Technical University in Sweden, started spring 2014

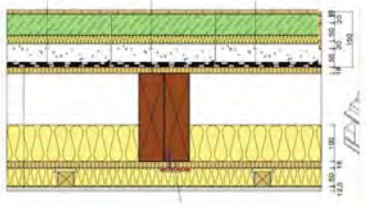
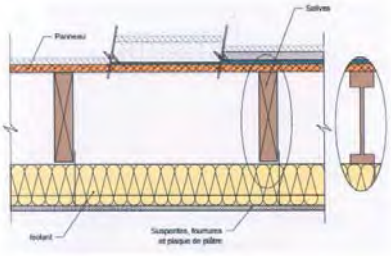
→ **But it is clear –**

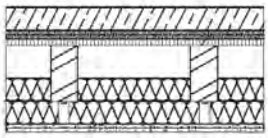
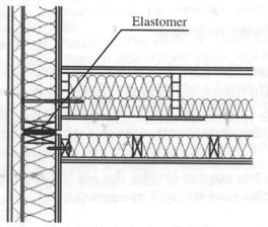
- in order to develop high rise wooden houses, low frequencies have to be considered in target values and also ….
- ..new prediction models.

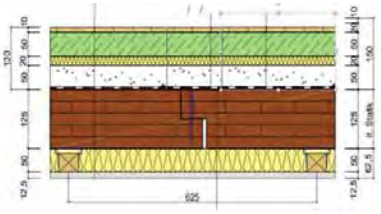
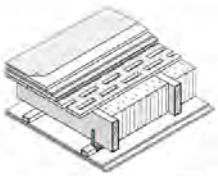
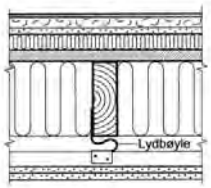
→ **The WWN+ project ”Silent Timber Build” will develop calculation models for wooden structures covering a ”full” frequency range**

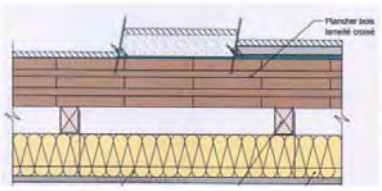
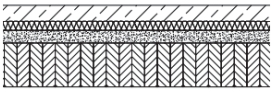
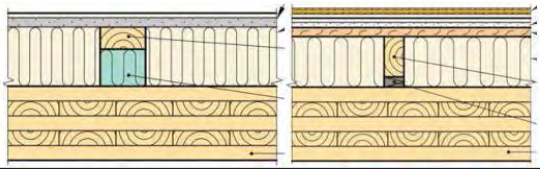
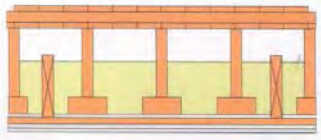
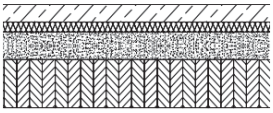
WSP

Material Charac-teristics is a challenge in order to deliver enough accuracy

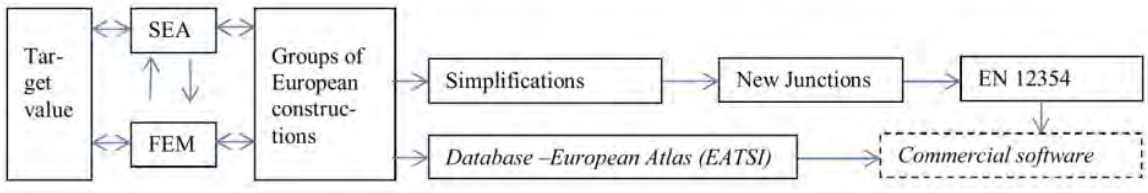



Silent Timber Build

→ **Idea is to use both FEM and SEA to cover a ”full” frequency range, 20-5000 Hz. New target values from recent research will be considered.**



→ **The work will be carried out in five Work Packages, three ”technical” WP:s (WP 1-3) and one WP (WP4) for dissemination and Exploitation and one WP (WP5) for Coordination**

Silent Timber Build

WP1: Prediction tools, low, medium and high frequencies

WP 1 – Prediction tools for low, medium and high frequencies
Initial work to state European target values from findings in ongoing and recently finished projects, "state of the art". From existing knowledge develop new prediction models using FEM, SEA and other approaches if necessary and to connect these methods depending on frequency range

WP2: Validation of prediction tools and constructions

WP 2 – Validation of prediction tools and constructions
This work package will validate the theoretical models developed in WP 1 by using already available and also new measurements from laboratory and field. Analysis will be made and optimized constructions will be used in validation procedure

WP3: European Timber Sound Insulation Atlas

WP 3 – European Timber Sound Insulation Atlas
Pioneer work made by Lignum will be used in order to apply the theories directly in an application for end users. Hence input from WP 1 and WP 2 will be applied in a web based interface for calculation of wooden structural systems

Silent Timber Build – expected results

- → **establishing basis for development of standardized engineering calculation methods applicable to lightweight structures**
- → **increased knowledge about calculation methods for multi storey wooden buildings**
- → **increased knowledge about building systems that can be predicted in terms of sound insulation considering future requirements**
- → **possibilities for future optimization of building systems by using prediction tools in the design stage in order to lower the costs and strengthen the competitiveness of the wooden building sector**

Silent Timber Build – expected results – long term

- **increased knowledge of sound and vibrations in the lightweight building industry, which is necessary for**
  - beneficial development of new acoustic solutions for the industry
  - innovative guidelines in the design stage

- **further improve the "sustainability" arguments for the wooden sector. Wooden constructions are fully "sustainable" when sound and vibration properties can be**
  - predicted according to modern design criteria, and then
  - as the final results in a building also correspond to the predicted values

Silent Timber Build - consortium

Research:

- **SP Wood Technology, Borås, Sweden (Project management, WP5, Klas Hagberg)**
- **Lund University, Lund, Sweden (WP leader WP1, Delphine Bard)**
- **Sintef, Trondheim, Norway (WP Leader WP2, Anders Homb)**
- **Lignum, Zürich, Switzerland (WP leader WP3, Olin Bartlomé)**
- **FCBA, Bordeaux, France (WP leader WP4, Jean-Luc Kouyoumji)**
- **CSTB, Grenoble, France (Catherine Guigou)**

Silent Timber Build - consortium

→ Research:

- → InterAC, France (Gerard Borello)
- → Fraunhofer Institut IBP, Stuttgart, Germany (Mortitz Spaeh)
- → TU Graz, Graz, Austria (Heinz Ferk)
- → Tecnalia, Spain, (Mariana Pérez Abendaño)

Silent Timber Build - consortium

→ Industry:

- → Building With Wood (CEI-Bois)
- → WSP Sweden
- → Simmons Acoustics and Development, Sweden
- → Fristad Bygg – Building contractor in Sweden
- → Norgeshus AS, Norway
- → Bauer Holzbau GmbH, Germany
- → Finland: Finish Wood Research Responsible person: Tomi Toratti, Confederation of Finish Construction Industries On behalf of FWR

Other cooperation

- → **Close cooperation with HCLTP (another WWN+ project)**
- → **Cooperation with ”Höga Trähus” in Sweden (new 2015)**
- → **Cooperation with one project in Luleå**
- → **US and Canada ➔ It has started ☺ - I hope for much more!**
- → **….. Industrial interest is big!**

Silent Timber Build

- → **Started in March 2014, however due to delayed financial decisions, it did not really start until August 2014**
- → **Expected to be finished in April 2017**
- → **Visit www.silent-timber-build.com**

SILENT TIMBER BUILD

Thanks for listening!

Klas Hagberg

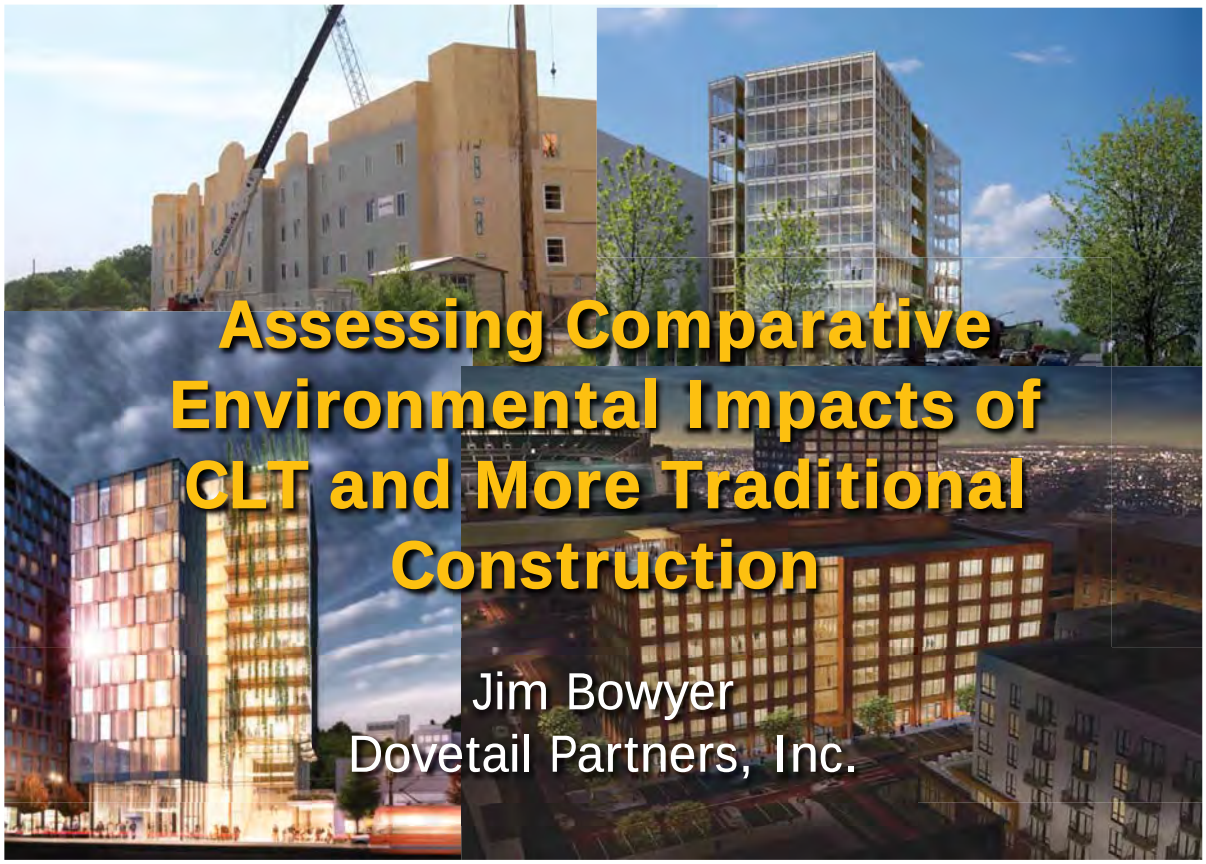
klas.hagberg@wspgroup.se
Klas.hagberg@sp.se
@klashagb

WSP

Comparative Life Cycle Assessment of a U.S. CLT Building: Planning and Challenges

Jim Bowyer, Director, Responsible Materials Program
Dovetail Partners, Minneapolis, Minnesota

As awareness of cross laminated timber (CLT) reaches the attention of more and more architects and engineers, additional information is needed regarding material properties and design limitations, environmental performance, and life cycle costs. With respect to the latter, definitive information is needed regarding environmental impact measures relative to typical concrete and steel construction, as well as projected comparative costs from construction through the life cycle of a building. This presentation will describe efforts to engage a U.S. partner in a comparative assessment and discuss challenges and issues encountered. The concept of a much more comprehensive (than initially envisioned) study will also be introduced.



Outline

- Identifying candidate projects for a comparative LCA - Procedure
- Observations regarding project selection
  - Completed projects vs. projects in planning
  - Vetting of project partners
- Conducting a comparative assessment
- Summary

Procedure

- Contacted architects and construction firms involved in some way in CLT building design and/or construction.
- Contacted manufacturers and distributors engaged in manufacturing and/or distributing CLT products.
- Contacted companies that represent over 90 percent of hotel construction in the U.S.
- Monitored new wood building announcements across the U.S. and Canada, and followed-up to contact principals involved.

Procedure

- Engaged in numerous conversations and meetings with key architectural firms regarding potential for collaboration in comparative LCA initiative.

Summary of Candidate Projects for Comparative LCA

U.S.		
Project	Description	Remarks
Timber loft, Hines, Minneapolis, Minnesota	7-story, mixed use commercial/ residential.	Final planning stage. CLT not selected for use in project.
Redstone hotel, Huntsville, Alabama	4-story CLT hotel with 93 keyed rooms.	Project completed 2014.
Beneficial State Bank Albina Building	11-story office building. Extent of CLT use not yet determined.	Proposed. Architect not yet revealed.
Carbon 12	8-story mixed use building. CLT proposed for use for both decking and shear walls.	Proposed. Developed by the Kaiser group and PATH Architecture.
Oregon Forest Science Complex	$60 million project in which a variety of engineered wood products, including CLT will be used. Nature and extent of CLT application not yet determined.	Proposed. Selection of architect and engineering firm underway. Building not viewed as replicable for comparative LCA.
Franklin School Project, Pendleton Country, West Virginia	1-story school building. All CLT.	No apparent interest in cooperating in LCA. Dropped from consideration.

Summary of Candidate Projects for Comparative LCA (Cont.)

Canada		
Project	Description	Remarks
Faction Projects, 3-story office building, Kelowna, B.C.	CLT construction.	Construction complete. Full set of information needed for comparative LCA has been provided by Faction Projects.
Gymnasium/sports facility, Calgary, Alberta	All above grade areas of a hybrid system of wood columns, glue-laminated beams and trusses, SIP wall panels, and CLT roof and floor plates.	Complete documentation developed for this structure and identical structure built entirely of concrete and steel.
Wood Innovation Design Centre, Prince George, B.C.	A 6-story 50,000 ft^2 building. The building structure consists of glulam columns and beams, CLT floor panels, and mass timber walls.	Completed 2014. Michael Green Architecture
Earth Systems Sciences Building, University of British Columbia, Vancouver, B.C.	A 5-story academic wing of this building is constructed of glue-laminated beams, timberstrand floor panels overlaid with concrete, and a 12,400 ft^2 CLT canopy that surrounds 3 sides of the building.	Completed in 2014. Perkins+Will Architects in conjunction with campus architect Gerry McGeough. This is an ideal candidate for a comparative LCA since a near-identical lab wing of the same building is steel reinforced concrete construction.

Summary of Candidate Projects for Comparative LCA (Cont.)

Canada		
Project	Description	Remarks
Bioenergy Research and Demonstration Facility, University of British Columbia, Vancouver, B.C.	4-story 6,200 ft^2 building constructed of glulam columns and beams and CLT. CLT panels make up the walls, roof deck, upper floor structure, and acoustic "gills".	Completed in 2014. Nextrerra Energy Corp. and McFarland Marceau Architect
Elkford Community Conference Centre, Elkford, B.C.	A 19,000 ft^2 building constructed of CLT walls and shear walls.	Completed in 2012. Douglas Sollows, Architect
North Shore Credit Union Environmental Learning Centre, North Vancouver, B.C.	This 11,000 ft^2 building features glulam beams supported by steel columns, and CLT floors overlaid with concrete.	Completed in 2012. McFarland Marceau Architects Ltd., Vancouver, BC. mchevalier@mmal.ca
Structurlam CLT Production Facility, Okanagan Falls, B.C.	A 10,000 ft^2 facility constructed of glulam and CLT. The roof is 5-ply CLT panels, the walls 3-ply CLT.	Completed in 2014.
Fort McMurray Airport Expansion, Fort McMurray, Alberta.	This 161,500 ft^2, 3-story project uses CLT for roof paneling and for infill between curved arches and rectangular boundaries.	Completed in 2014. MacFarlane Bigger Architects and Designers, Vancouver, B.C.

Summary of Candidate Projects for Comparative LCA (Cont.)

Canada		
Project	Description	Remarks
Wayne Gretzky Sport Centre, Brantford, Ontario.	This 3,000 ft^2 building incorporates 8" x 40" CLT panels into the roof structure which is supported by glulam beams and columns.	Completed in 2013. CS&P Architects, Toronto
Whistler, B.C. Fire Station.	The 5,000 ft^2 building incorporates glue laminated columns and beams and 5-ply CLT walls, 7-ply CLT floor panels, and 7-ply CLT roof panels.	Completed in 2014. Complete building plans, materials lists, and assembly details are available on-line.

Observations Regarding Project Selection

Redstone Arsenal, Huntsville, Alabama

Hines T-3 Project, Minneapolis, Minnesota

Beneficial State Bank Building, Portland, Oregon

Observations RE Project Selection

- Completed projects vs. projects in planning
  - Completed – no surprises
  - In Planning
    - Things can change (T-3)
    - Beware of code issues, redundancy (Redstone)
    - Designs can become proprietary (T-3)

Observations RE Project Selection

- Vetting of project partners
  - Important that developer fully understand what an LCA is (T-3, Redstone, Beneficial Bank)
  - Developer may seek control of environmental assessment, publicity (Redstone)

Observations RE Conducting the Assessment

- Plan for costs of developing alternative designs, material takeoffs.
- Individual comparisons of steel, concrete alternatives needed.
- Need to conduct parallel LCCA if at all possible.

Conclusions

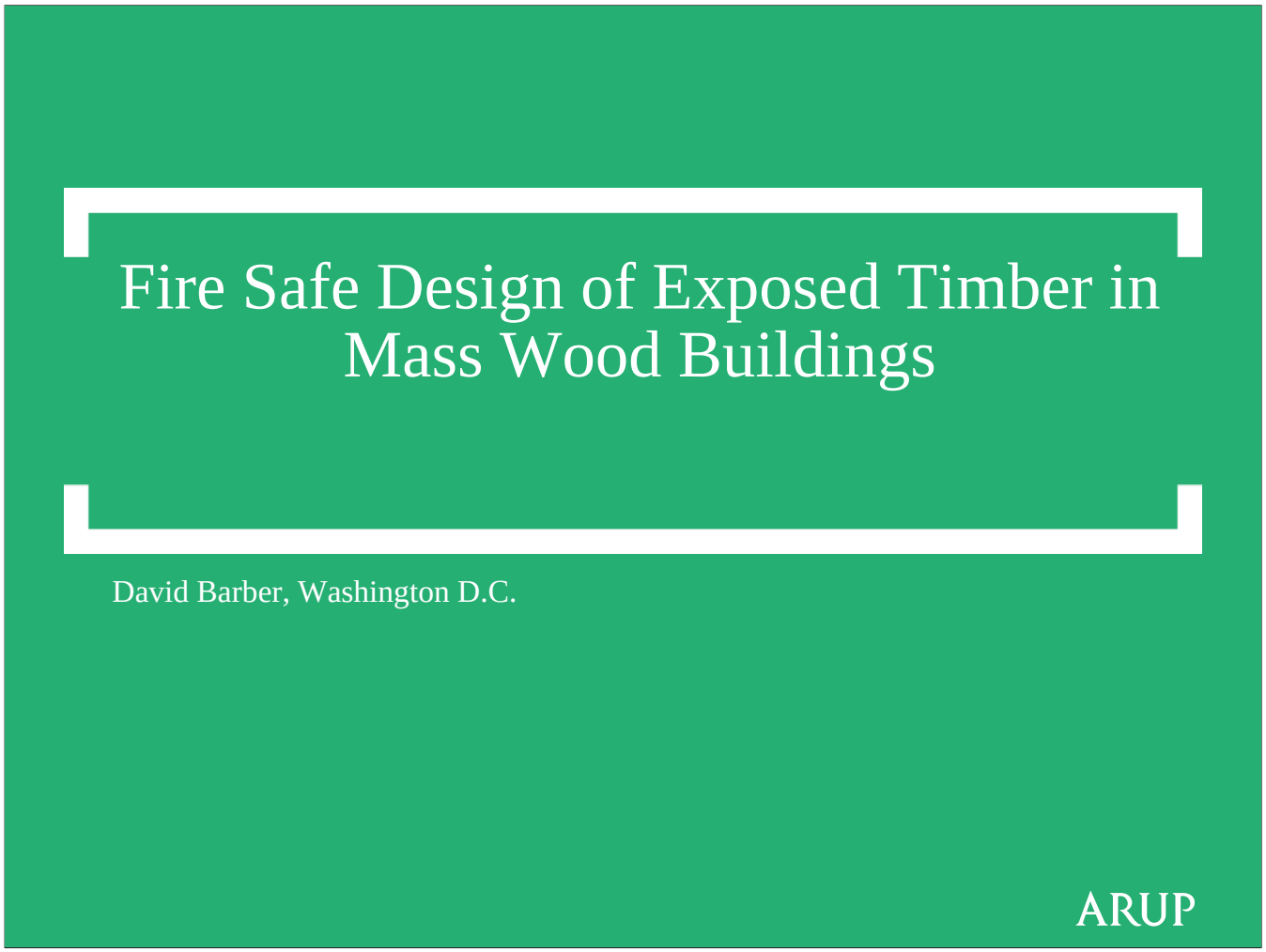
- Careful consideration is required in selecting a project and cooperators for a comparative LCA.
- There are advantages in selecting a completed construction project.
- All alternative designs should be assessed and reported individually.
- Need to conduct parallel LCCA if at all possible.

Session 3—Fire Safety

Fire Safe Design of Exposed Mass Timber in Buildings

David Barber, Principal
ARUP, Washington, D.C.

As timber buildings are constructed taller, architects and building owners are asking for more timber to be exposed within compartments and asking fire engineers to develop solutions to allow more timber to be seen. Addressing how the exposed timber impacts a fire over its full development through to self-extinguishment is a very current fire safety issue. There is limited research available on how exposed timber within a compartment impacts fire peak heat release rate, temperatures, and fire duration. This paper brings together the available research to understand similarities, parameters, and where results can be directly applied to buildings. Available fire testing would indicate that where an exposed timber wall is in the order of 20% or less, the compartment fire is minimally impacted. This paper will assist in developing engineering methodology to account for the change in compartment fire dynamics, better define fire extinguishment, and provide a clear understanding of the impact between differing areas of wall and ceiling exposed.

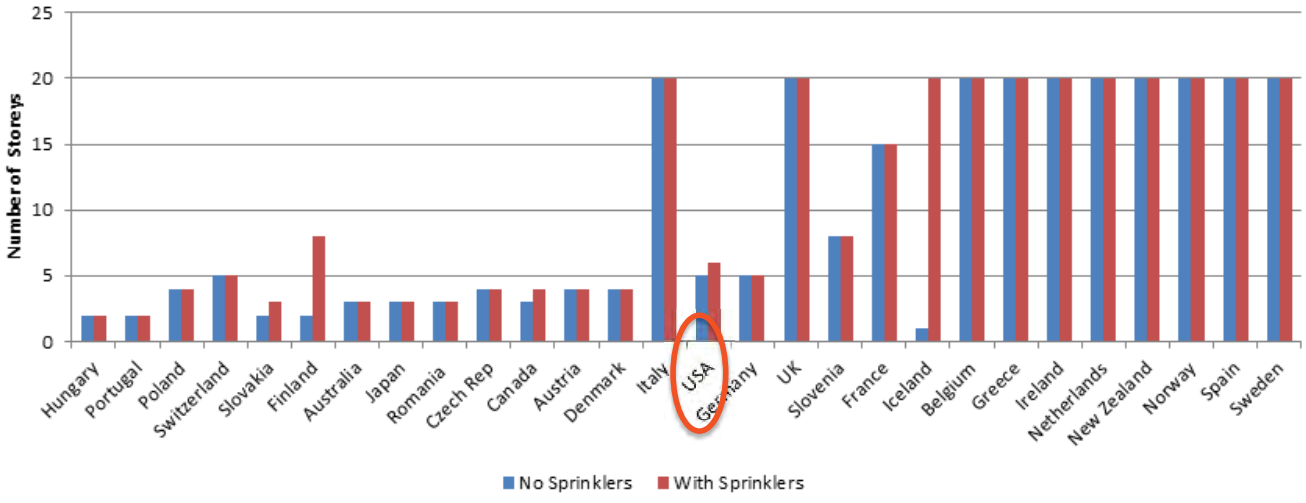


Wood Buildings

- Wood is new, again

Wood Buildings

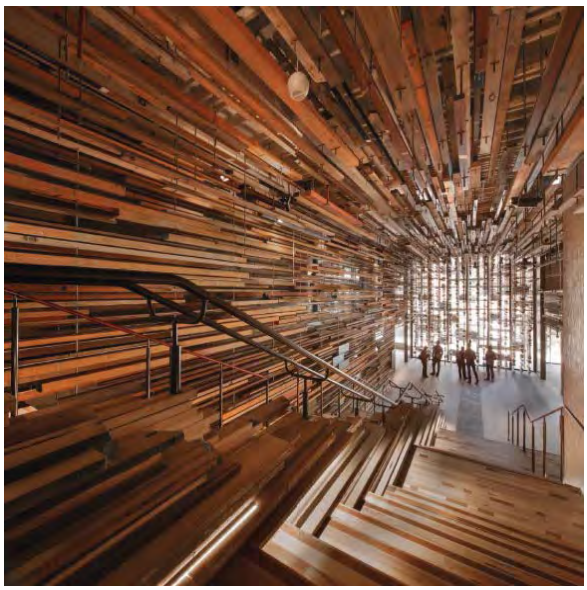
- Perception of risk in model buildings codes
  - Construction based on combustibility, not fire resistance
  - Height and area limits wood use



Exposed Wood – What Architects Want

- Architects want exposed wood within their buildings
- Don't we all !!!
- Limitations are based on fire safety, dealing with a new product (CLT) and general unfamiliarity with wood

Exposed Wood Fire Fundamentals



- Codes permit exposed wood as an interior finish
- Interior finish requirements are Class C to ASTM E84 (sprinkler protected building)
- Solid wood meets Class C (and some meets Class B)
- Exposed wood is not a new problem, it has just never been accounted for……

Exposed Wood Fire Fundamentals

- Exposed wood is now part of the load-bearing structure in mass wood buildings
- A new issue that needs to be addressed
- Exposed floors, columns, beams, walls:
  - Glulam is known, but not for high-rise
  - CLT is an unfamiliar product
- Fear of the unknown

Exposed Wood - Key Issues

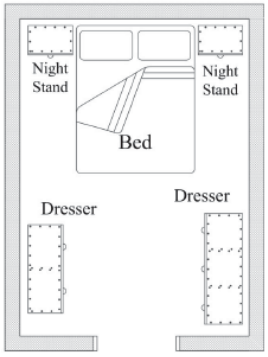
- How does the exposed wood change the fire dynamics ?
- Impacting on:
  - Fire duration ?
  - Size of the fire ? (heat release rate)
  - Fire temperature ?
- And hence, the fire resistance ratings required to allow the building to withstand a full burnout ?
- Interior wood finishes also impact on the above items…….
- Why aren't steel and concrete buildings assessed for full burn out ??

Exposed Wood Compartments – Recent Research

- Osborne and Dagenais “Preliminary CLT Fire Resistance Testing Report”, FPInnovations, 2012
- McGregor “Contribution of Cross Laminated Timber Panels to Room Fires”, Carleton University, 2013.
- Aguanno, “Fire Resistance Tests on Cross-Laminated Timber Floor Panels: An Experimental and Numerical Analysis”, Carleton University, 2013
- Medina Hevia “Fire Resistance Of Partially Protected Cross-Laminated Timber Rooms”, Carleton University, 2014
- Crielaard, “Self-Extinguishment of Cross-Laminated Timber”, Delft University of Technology, 2015.
- Li, “Modeling of Barrier Failure and Fire Spread in CUrisk”, Carleton University, 2015

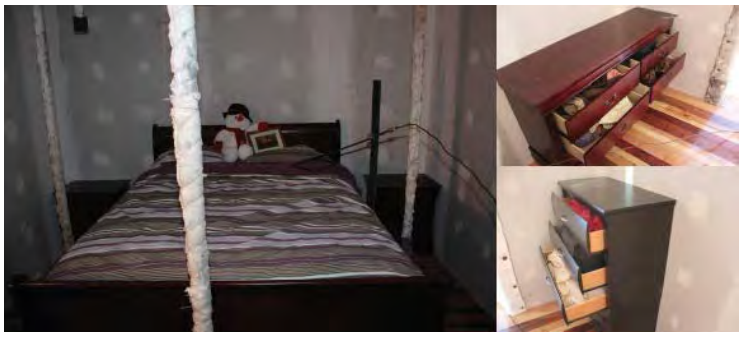
ARUP

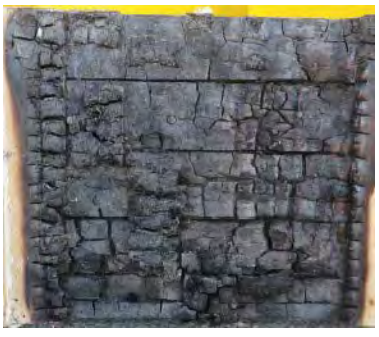
Exposed Wood Compartments– Recent Research



From Li, 2015

- Small ventilation controlled compartments, with real fuel loads (natural fires)
- Testing has ranged in type of exposed wood - walls, floors and ceilings
- Differing results provide difficulty in comparison, but trends are apparent

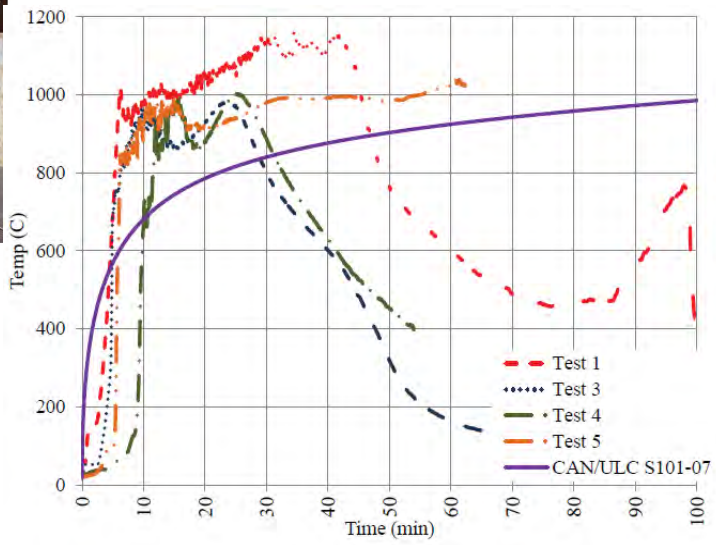




From Crielaard, 2015

ARUP

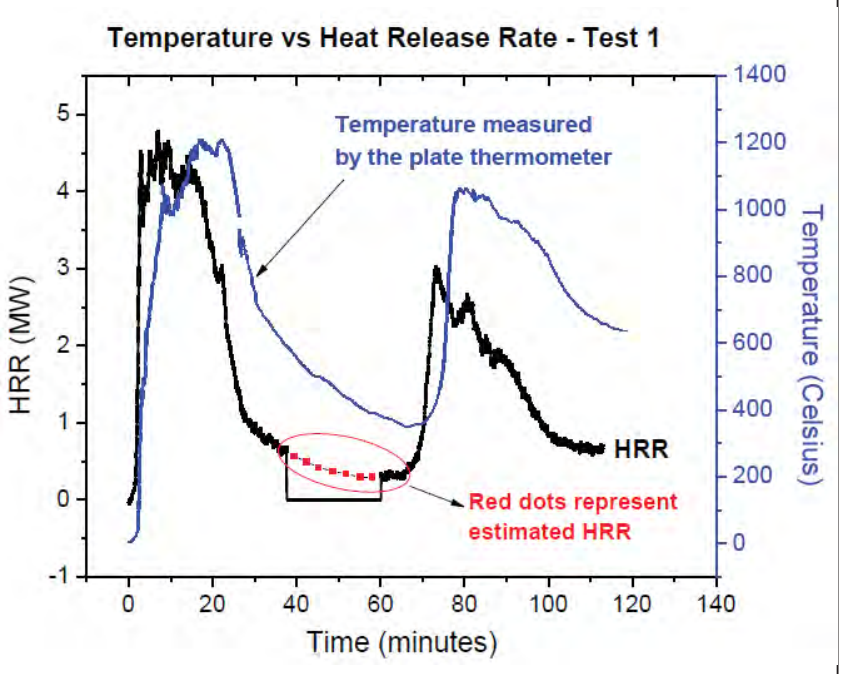
Exposed Wood - Temperatures



From McGregor, 2013

ARUP

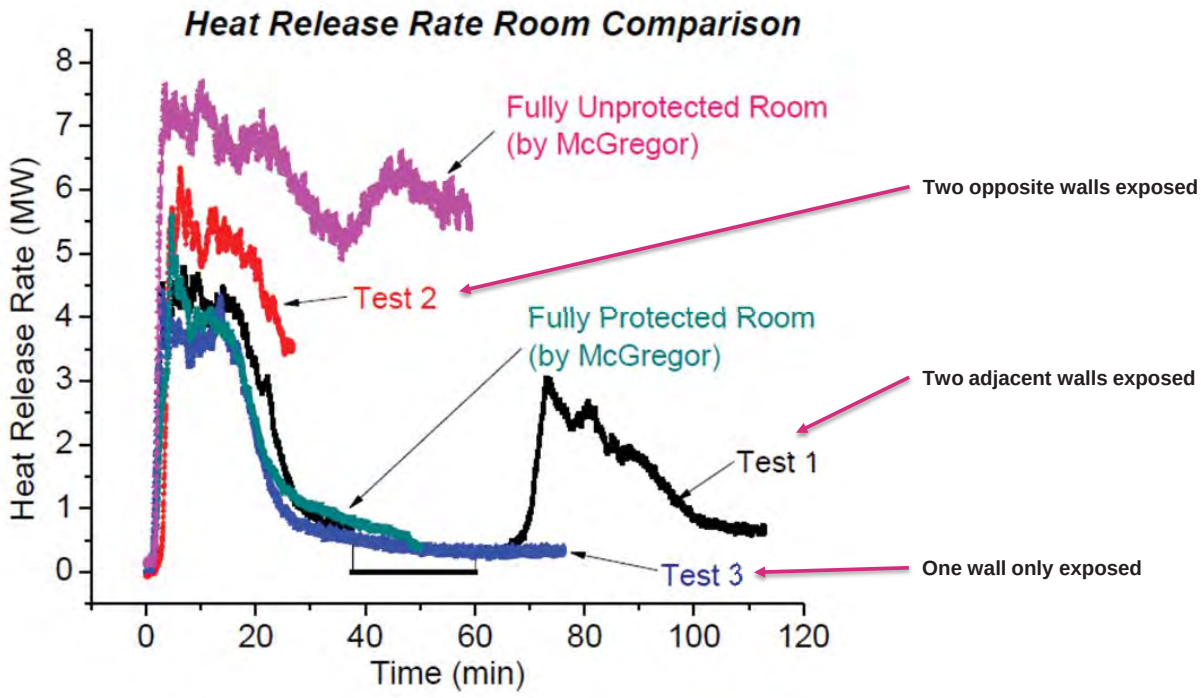
Exposed Wood – Fire Size (HRR)



From Medina-Hevia, 2014

ARUP

Exposed Wood – Fire Duration



From Medina-Hevia, 2014

ARUP

Exposed Wood Compartments – Solutions

- Failure of the CLT through delamination is an expected mode of failure
- Delamination should not be feared, but accepted and engineered
- Exposed wood increases the fuel load within the compartment – but can be accounted for

From Medina-Hevia, 2014

From Crielaard, 2015

ARUP

Exposed Wood Compartments – Solutions

- If multiple faces are exposed wood, re-radiation leads to continued burning after room combustibles have been consumed (so called “second flashover”)
- Exposed wood prolongs the fire duration – can be conservatively accounted for
- Direct impact on FRR
- How the compartment HRR decays is still yet to be fully determined when multiple faces are exposed
- More work is needed, but some reasonable correlations can be determined

Next Steps

- More testing is needed, especially with walls covered and ceiling exposed
- Fire Protection Research Foundation testing (2016 – 2017)
- Continued testing by research consortiums, University testing
- Medium term - correlations and basic design rules to be developed
- Longer term – detailed analytical models
- Wood buildings will continue to receive significant scrutiny

Summary – Tall Wood Building & Fire Issues

- Fire risks are misunderstood and often misrepresented
- There is not enough accredited third-party fire testing carried out in the US:
  - ASTM E119
  - ASTM E84
  - Glulam connections
- Suppliers need to invest more in fire testing
- The lack of evidential fire testing is a significant barrier to approval

ARUP

Performance of Mass Timber Construction in Fire

Christian Dagenais, Fire Scientist
FPInnovations, Quebec City, Quebec, Canada

Over the past 5 years, FPInnovations and National Research Council have been engaged in evaluating various aspects of the performance of cross laminated timber (CLT) assemblies in fire. A number of full-, intermediate-, and small-scale experiments have been conducted to understand the behavior of CLT assemblies in fire. This presentation will give some information about these experiments and will include fire-resistance tests, flame spread rating, service penetrations and fire stops, and large-scale compartment fires.

Outline

- Fire-Resistance
- Surface Flammability
- Fire Stops and Service Penetrations
- Compartment Fires
- Conclusion

© 2015 FPInnovations and NRC. All rights reserved. Copying and redistribution prohibited without written consent from both organizations.
® FPInnovations, its marks and logos are trademarks of FPInnovations.

Fire-Resistance of CLT

- Full-scale testing in accordance with ULC S101 / ASTM E119 (joint FPI/NRC Test Program)
  - Charring rate
  - Fire performance of adhesive (PUR)
  - Calculation procedure for US and Canadian standards
- Additional full-scale tests were also conducted with wood industry partners and CLT manufacturers

© 2015 FPInnovations and NRC. All rights reserved. Copying and redistribution prohibited without written consent from both organizations.
® FPInnovations, its marks and logos are trademarks of FPInnovations.

Fire-Resistance of CLT

Table 1 – Fire resistance test results (Dagenais 2014)

	# Plies	ANSI/APA PRG 320 Stress Grade	Thickness (in)	Gypsum Board Protection	Superimposed Load	Failure Time	Type of Failure
WALL	3	E2	4 1/2	2 x 1/2" Type X	22,818 lb/ft	1 h 46 min	R
	5	E1	6 7/8	Unprotected	22,818 lb/ft	1 h 53 min	E
	5	V2	4 1/8	Unprotected	4,934 lb/ft	57 min	R
	3 [1]	E1	4 1/8	Unprotected	20,214 lb/ft	32 min	R
	5 [2]	E1	6 7/8	1x 5/8" Type X (both sides)	8,702 lb/ft	3 h 06 min	R
	5 [3]	E1	6 7/8	2 x 5/8"	30,767 lb/ft	3 hr 39 min	R
FLOOR	3	E2	4 1/2	2 x 1/2" Type X	56 psf	1 h 17 min	[4]
	5	E1	6 7/8	Unprotected	246 psf	1 h 36 min	E
	3	V2	4 1/8	1 x 5/8" Type X	50 psf	1 h 26 min	R
	5	V2	6 7/8	1 x 5/8" Type X	169 psf	2 h 04 min	E
	7	V2	9 3/8	Unprotected	305 psf	2 h 58 min	R
	5 [3]	E1	6 7/8	3 1/2" Glass Fiber Insulation 5/8" Resilient Channels 1 x 5/8" Type X	196 psf	2 h 08 min	R

*R—Structural Failure, E—Integrity Failure

[1] in Collaboration with CWC, [2] In Collaboration with AWC, [3] (Osborne 2014), [4] Test Was Stopped Prematurely Due to Equipment Safety Concerns

Source: Dagenais C. & Osborne L. (2015) "*Recent Advances in Fire Performance of Cross-Laminated Timber*". Wood Design Focus Journal, V. 25, N. 3, pp.21-26.

© 2015 FPInnovations and NRC. All rights reserved. Copying and redistribution prohibited without written consent from both organizations.
® FPInnovations, its marks and logos are trademarks of FPInnovations.

FPInnovations

Fire-Resistance of CLT

- Timber-Concrete Composite Floors

FRR > 3½ hrs

© 2015 FPInnovations and NRC. All rights reserved. Copying and redistribution prohibited without written consent from both organizations.
® FPInnovations, its marks and logos are trademarks of FPInnovations.

FPInnovations

Fire-Resistance of CLT

- CLT can exhibit **significant fire-resistance**
- Charring rate similar to mass timber, but…
  - 0.65 mm/min (one-dimensional)
  - Stepped charring model (i.e. not constant throughout)
  - Influenced by the adhesive and thickness of laminates
    - More studies are required on adhesives exposed to fire
- Failure modes are different from walls to floors
  - Buckling (P-Δ effects) vs. Integrity between panels
    - Fire integrity can easily be resolved using flooring/topping

© 2015 FPInnovations and NRC. All rights reserved. Copying and redistribution prohibited without written consent from both organizations.
® FPInnovations, its marks and logos are trademarks of FPInnovations.

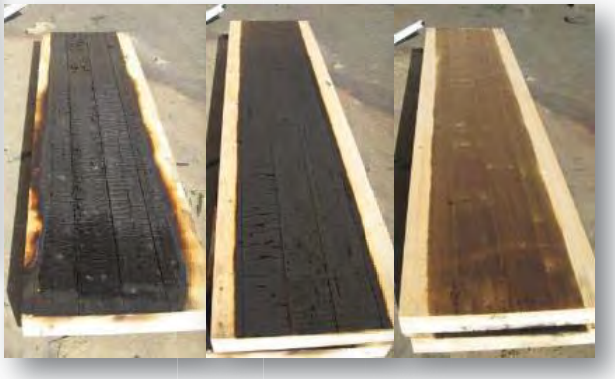
Surface Flammability

- Full-scale testing in accordance with ULC S102 and ASTM E84
  - Tests conducted with AWC and CLT/SCL manufacturers
- Mass timber behaves as thermally-thick solids (vs. thermally-thin)
- Exhibit lower FSI when compared to traditional interior wood finish materials

© 2015 FPInnovations and NRC. All rights reserved. Copying and redistribution prohibited without written consent from both organizations.
® FPInnovations, its marks and logos are trademarks of FPInnovations.

Surface Flammability

1st Panel 2nd Panel 3rd Panel



© 2015 FPInnovations and NRC. All rights reserved. Copying and redistribution prohibited without written consent from both organizations.
® FPInnovations, its marks and logos are trademarks of FPInnovations.

FPInnovations

Surface Flammability

Wood and Wood-Based Products		Flame Spread Rating	Smoke Developped Classification
Lumber, not less than 19 mm (¾") in thickness			
Oak	Red White	100	100
Spruce	White Sitka Western	65 74 100	n.d. 74 n.d.
Structural Composite Lumber (SCL)			
PSL	Min. 89 mm (3½") on flat	35	25
LVL	Min. 140 mm (5½") on edge	35	30
LSL	Min. 89 mm (3½") on flat	70	85
Cross-Laminated Timber (CLT)			
CLT	E1 Stress Grade (min. 105 mm)	35	40
	V2 Stress Grade (min. 99 mm)	40	30

© 2015 FPInnovations and NRC. All rights reserved. Copying and redistribution prohibited without written consent from both organizations.
® FPInnovations, its marks and logos are trademarks of FPInnovations.

FPInnovations

Fire Stops and Service Penetrations

- **INTEGRITY** and **CONTINUITY** of fire separations are fundamental for achieving/providing the expected level of compartmentation
  - Penetrations and junctions are to be firestopped (tested per CAN/ULC S115 / ASTM E814)

© 2015 FPInnovations and NRC. All rights reserved. Copying and redistribution prohibited without written consent from both organizations.
® FPInnovations, its marks and logos are trademarks of FPInnovations.

FPInnovations

Fire Stops and Service Penetrations

- Junctions evaluated per CAN/ULC S115
  - Floor-to-wall (sealant on unexposed side)
  - Floor-to-wall (sealant on exposed side)
  - Wall-to-Floor (sealant on both sides)
  - Floor-to-Floor
  - Stair landings

→ FT-rating of 1 to 2 hours

© 2015 FPInnovations and NRC. All rights reserved. Copying and redistribution prohibited without written consent from both organizations.
® FPInnovations, its marks and logos are trademarks of FPInnovations.

FPInnovations

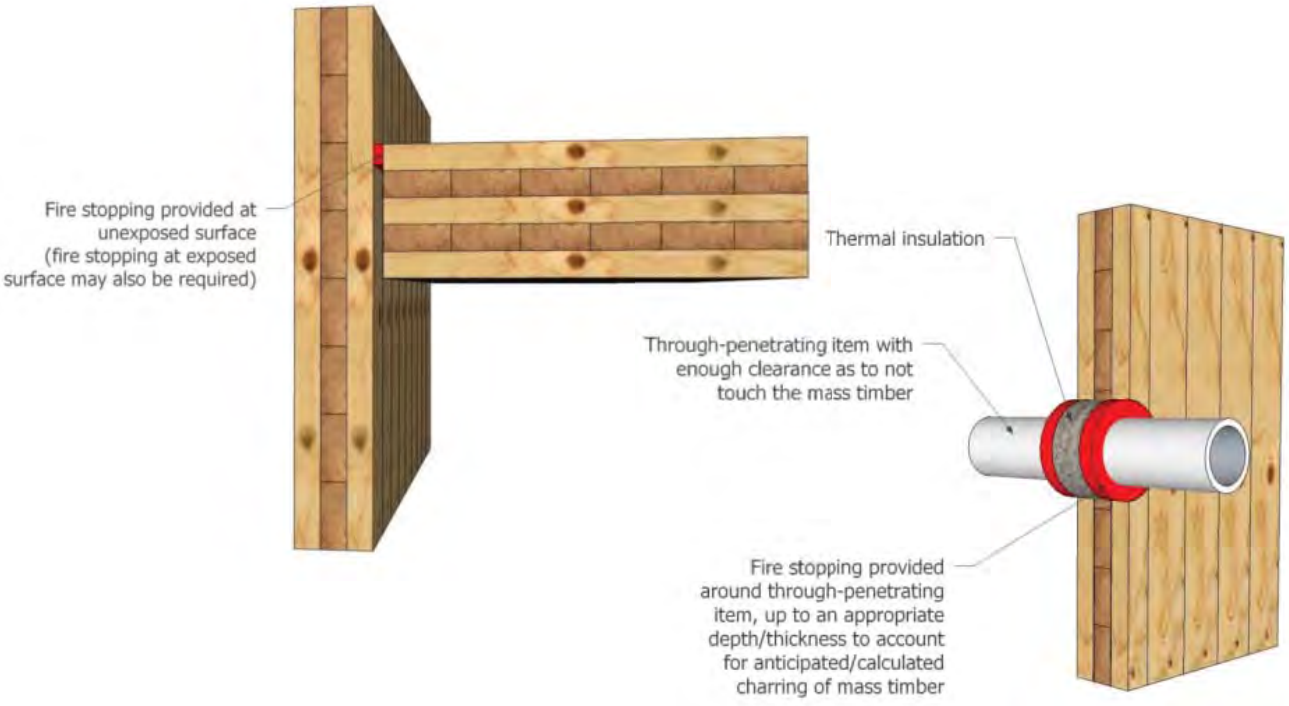
Fire Stops and Service Penetrations

- 6 penetrations tested per CAN/ULC S115
  → F-rating of 1½ hrs.

© 2015 FPInnovations and NRC. All rights reserved. Copying and redistribution prohibited without written consent from both organizations.
® FPInnovations, its marks and logos are trademarks of FPInnovations.

FPInnovations

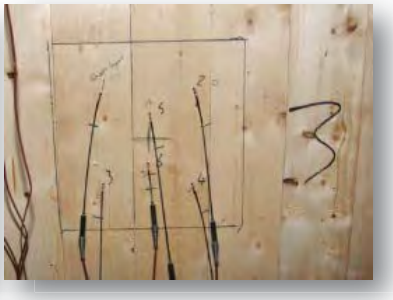
Fire Stops and Service Penetrations



© 2015 FPInnovations and NRC. All rights reserved. Copying and redistribution prohibited without written consent from both organizations.
® FPInnovations, its marks and logos are trademarks of FPInnovations.

FPInnovations

Compartment Fires

- Compartment fire tests from 2011-2014

© 2015 FPInnovations and NRC. All rights reserved. Copying and redistribution prohibited without written consent from both organizations.
® FPInnovations, its marks and logos are trademarks of FPInnovations.

Compartment Fires

- Compartment fire tests from 2011-2014
  - Scenarios where CLT is 100% exposed
    - Contribution to fire growth
  - Scenarios where CLT is partially-exposed
    - Burnout of fuel content, depending on exposed face configurations
  - Scenarios where CLT is fully protected
    - Burnout of fuel content

Source: McGregor C., "*Contribution of Cross-Laminated Timber Panels to Room Fires - Thesis*", Carleton University, 2013.

© 2015 FPInnovations and NRC. All rights reserved. Copying and redistribution prohibited without written consent from both organizations.
® FPInnovations, its marks and logos are trademarks of FPInnovations.

Compartment Fires

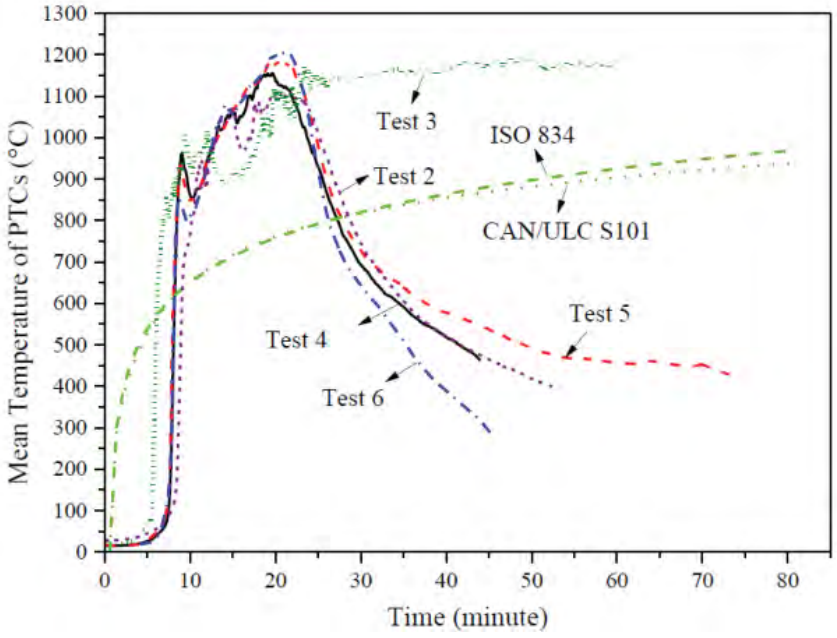
- Compartment fire tests from 2011-2014
  - Evaluation of combustible and noncombustible construction subjected to natural fires
    1. CLT: 2 x Type C (½ in.)
    2. CLT: 2 x Type C (½ in.)
    3. CLT: fully exposed
    4. Wood-Frame: 1 x Type C (½ in.)
    5. Wood-Frame: 2 x Type C (½ in.)
    6. Cold-Formed Steel Frame: 1 x Type C (½ in.)

Source: Li X., Zhang X., Hadjisophocleous G., McGregor C. (2015) "*Experimental study of combustible and non-combustible construction in a natural fire*", Fire Technology Journal, Vol. 51 (6), pp. 1447-1474.

© 2015 FPInnovations and NRC. All rights reserved. Copying and redistribution prohibited without written consent from both organizations.
® FPInnovations, its marks and logos are trademarks of FPInnovations.

Compartment Fires

- Compartment fire tests from 2011-2014



© 2015 FPInnovations and NRC. All rights reserved. Copying and redistribution prohibited without written consent from both organizations.
® FPInnovations, its marks and logos are trademarks of FPInnovations.

Compartment Fires

- Mid-Rise Research Consortium (NRCC/CWC/FPI)
  - 3-Storey Apartment Unit, no sprinklers

© 2015 FPInnovations and NRC. All rights reserved. Copying and redistribution prohibited without written consent from both organizations.
® FPInnovations, its marks and logos are trademarks of FPInnovations.

Compartment Fires

- Mid-Rise Research Consortium (NRCC/CWC/FPI)
  - Duration: 185 min.
  - No structural failure
  - No fire spread beyond compartment boundaries
  - Fire dynamics similar to that of a compartment of noncombustible construction

  - CLT performed better than CFS apartment test

© 2015 FPInnovations and NRC. All rights reserved. Copying and redistribution prohibited without written consent from both organizations.
® FPInnovations, its marks and logos are trademarks of FPInnovations.

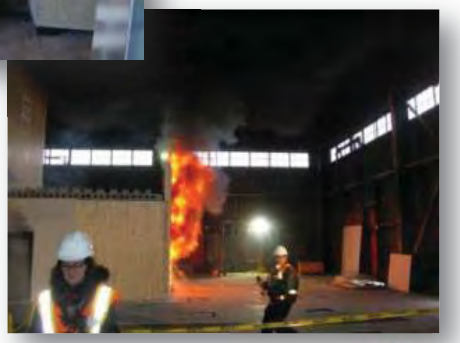
Compartment Fires

- Fire tests in support of a TWB in Quebec City
  - Exposed CLT in vertical shaft
  - Encapsulated CLT in room of fire origin
  - Gypsum board around fire-rated door
  - 45-min fire-rated door (vs. 20 min.)
  - Tested at NRCC laboratory
  - Funded by Quebec Government (MFFP)

© 2015 FPInnovations and NRC. All rights reserved. Copying and redistribution prohibited without written consent from both organizations.
® FPInnovations, its marks and logos are trademarks of FPInnovations.

Compartment Fires

- Fire tests in support of a TWB in Quebec City



© 2015 FPInnovations and NRC. All rights reserved. Copying and redistribution prohibited without written consent from both organizations.
® FPInnovations, its marks and logos are trademarks of FPInnovations.

Compartment Fires

- Fire tests in support of a TWB in Quebec City
  - Test conducted for 2 hours
    - Per NBCC for noncombustible construction
  - No fire penetration through walls/floor/ceiling
  - Very little charring on exposed CLT shaft wall
  - No charring/smoke inside CLT shaft
  - Reports (French/English) and video (French) available at:
    http://www.mffp.gouv.qc.ca/forets/entreprises/entreprises-transformation-resistance-feu.jsp

© 2015 FPInnovations and NRC. All rights reserved. Copying and redistribution prohibited without written consent from both organizations.
® FPInnovations, its marks and logos are trademarks of FPInnovations.

Conclusion

- CLT detailing can provide for highly fire-resistance rated compartmentation in buildings
- Test results showed the effectiveness of the encapsulation approach in delaying contribution of wood structural members to fires
- Inherent fire performance of CLT makes it suitable for sound alternative solutions
- Design methods and guides are readily available

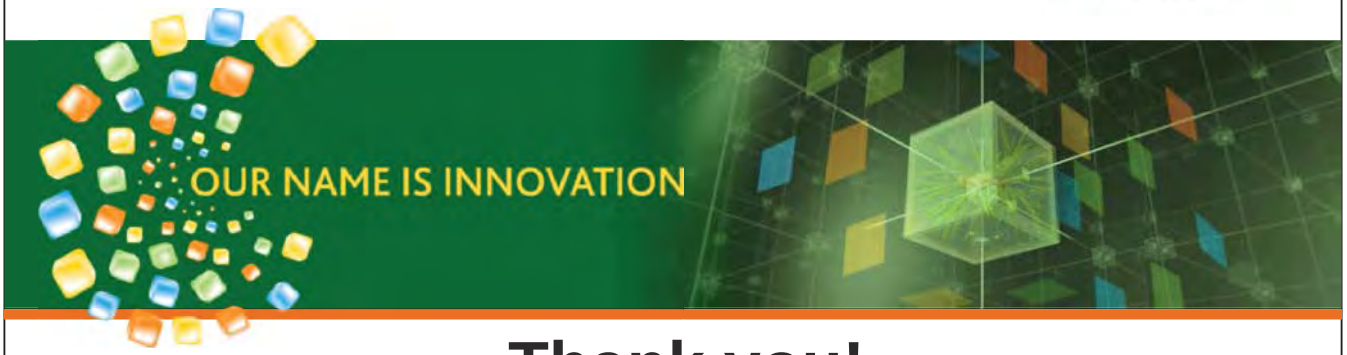
© 2015 FPInnovations and NRC. All rights reserved. Copying and redistribution prohibited without written consent from both organizations.
® FPInnovations, its marks and logos are trademarks of FPInnovations.

Acknowledgements

- Natural Resources Canada (NRCan)
- Provincial governments, namely RBQ, MFFP, OMMAH and BC FII
- Softwood Lumber Board
- FPInnovations' industry members
- FPInnovations, NRC and USDA FPL staff

© 2015 FPInnovations and NRC. All rights reserved. Copying and redistribution prohibited without written consent from both organizations.
® FPInnovations, its marks and logos are trademarks of FPInnovations.

FPInnovations



Thank you!

Christian Dagenais, Eng., M.Sc.
Scientist – Serviceability & Fire Performance
Advanced Building Systems
christian.dagenais@fpinnovations.ca

Follow us on

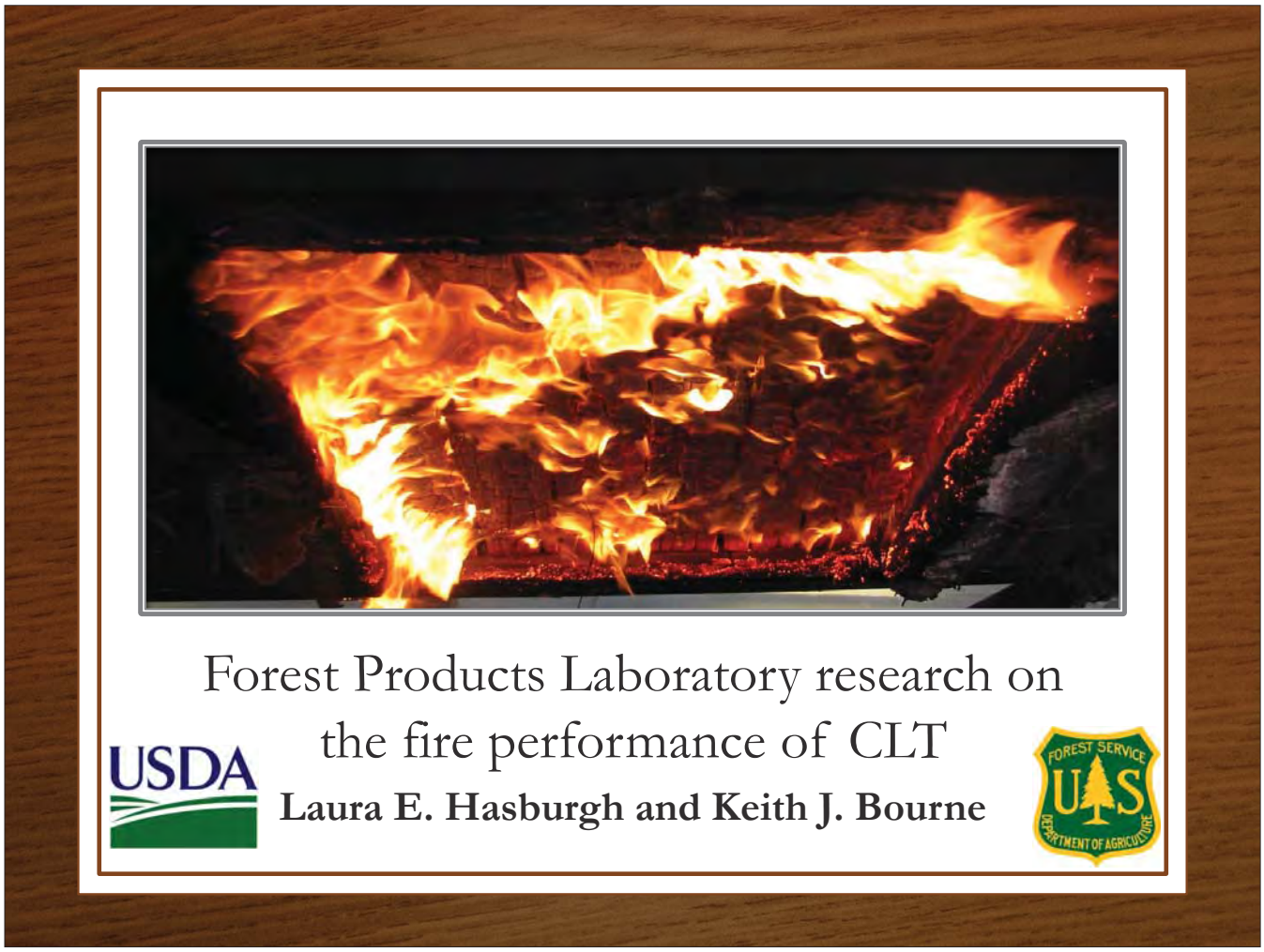
www.fpinnovations.ca

© 2015 FPInnovations. All rights reserved. Copying and redistribution prohibited. ® FPInnovations, its marks and logos are trademarks of FPInnovations.

Forest Products Laboratory Research on the Fire Performance of Cross Laminated Timber

Laura E. Hasburgh, Fire Protection Engineer
Keith J. Bourne, Mechanical Engineer
USDA Forest Products Laboratory, Madison, Wisconsin

Wood has been employed as a building material for thousands of years because it is readily available and easy to work with. Due to a recent push for sustainable construction, the use of mass timber elements, such as cross laminated timber (CLT), is increasing. The Fire Research Team at the USDA Forest Products Laboratory have developed collaborations with universities and other institutions to study the fire resistance properties of CLT and improve its marketability for mid- to high-rise construction. The goal is to find a design that maximizes the hourly fire rating so that the structural panels can be used in a larger variety of situations. This presentation summarizes ongoing research that has investigated how features such as the grade of wood, configuration of plies, adhesive types, and protective membranes can be optimized to reduce the charring rate and increase the hourly rating of the panel.



Overall Goal

- Increase commercialization of CLT
- Demonstrating and increasing the hourly rating

The Library on The Dock; Photograph by Diana Snape

Collaborations

FPInnovations

CLEMSON UNIVERSITY

NORTH CAROLINA STATE UNIVERSITY

Total Specimens

- To date: 25
- By December 2015: 41

Variables

Machine Stress Rated - MSR

SPIB KD19HT 7
2400f MSR 2.0E

Visually Graded

AUDITED BY TP NO.1 KD HT
012 SYP

Variables

Melamine
Formaldehyde

Emulsion
Polymer
Isocyanate

Phenol
Resorcinol
Formaldehyde

Polyurethane

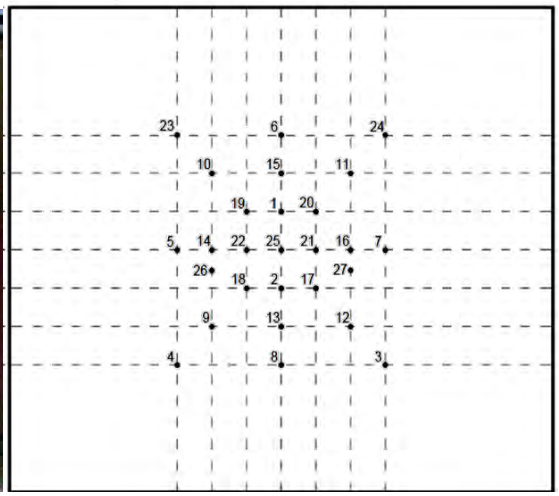
Variables

LCL

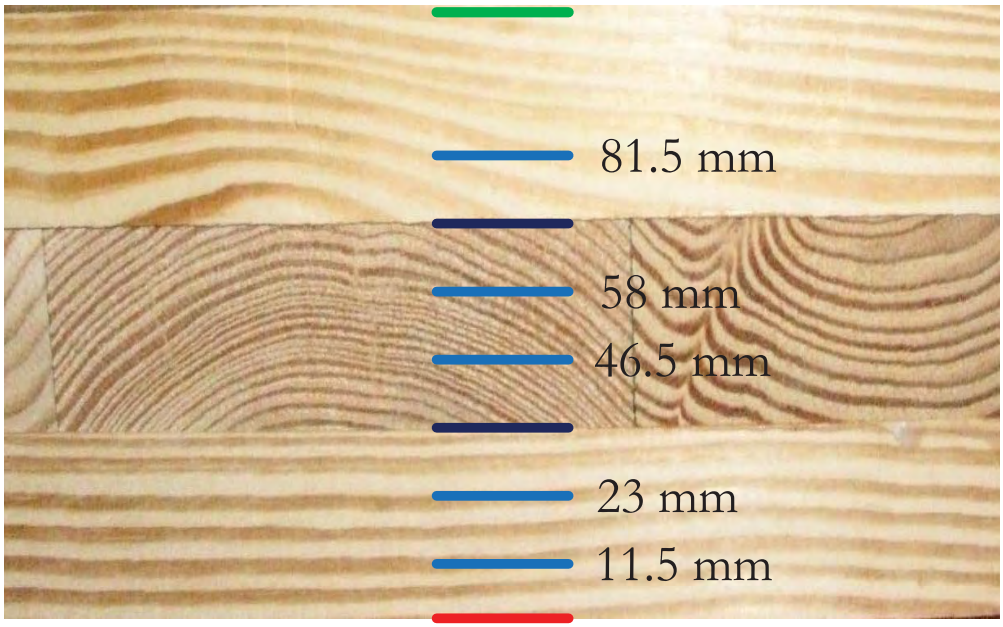
LLC

Variables

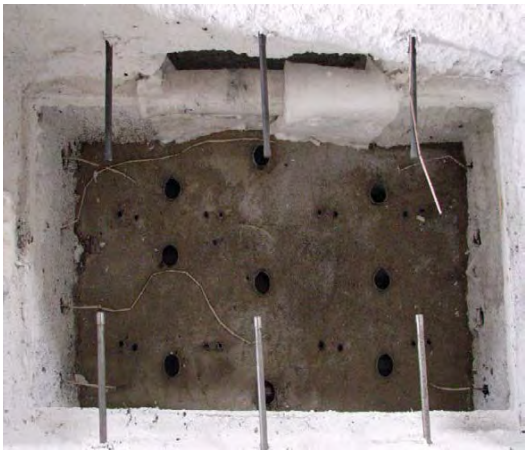
Methods



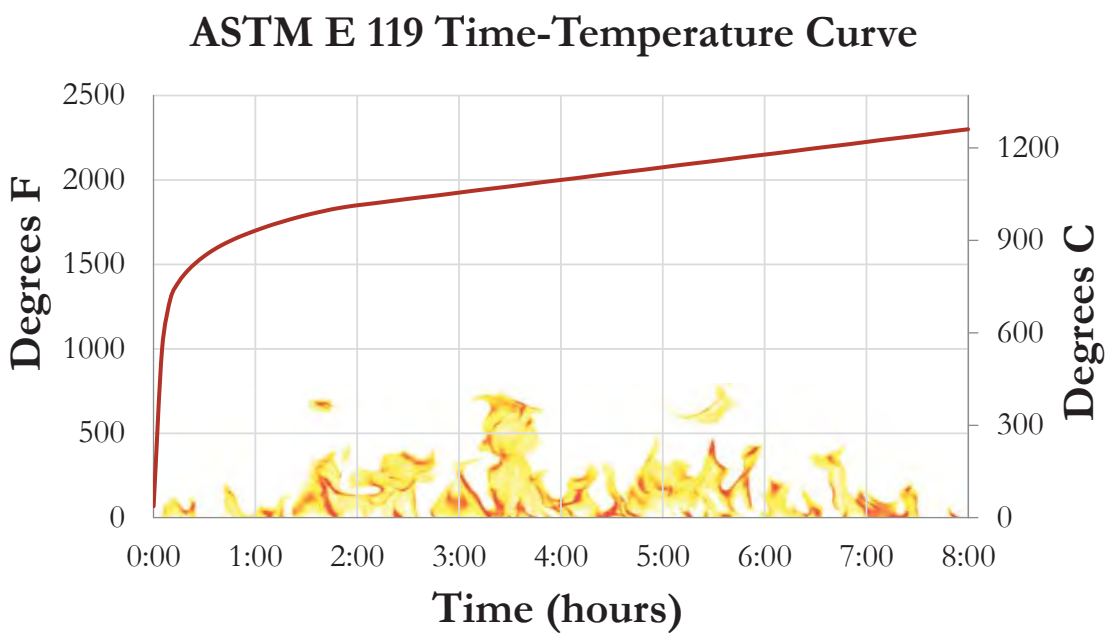
Methods



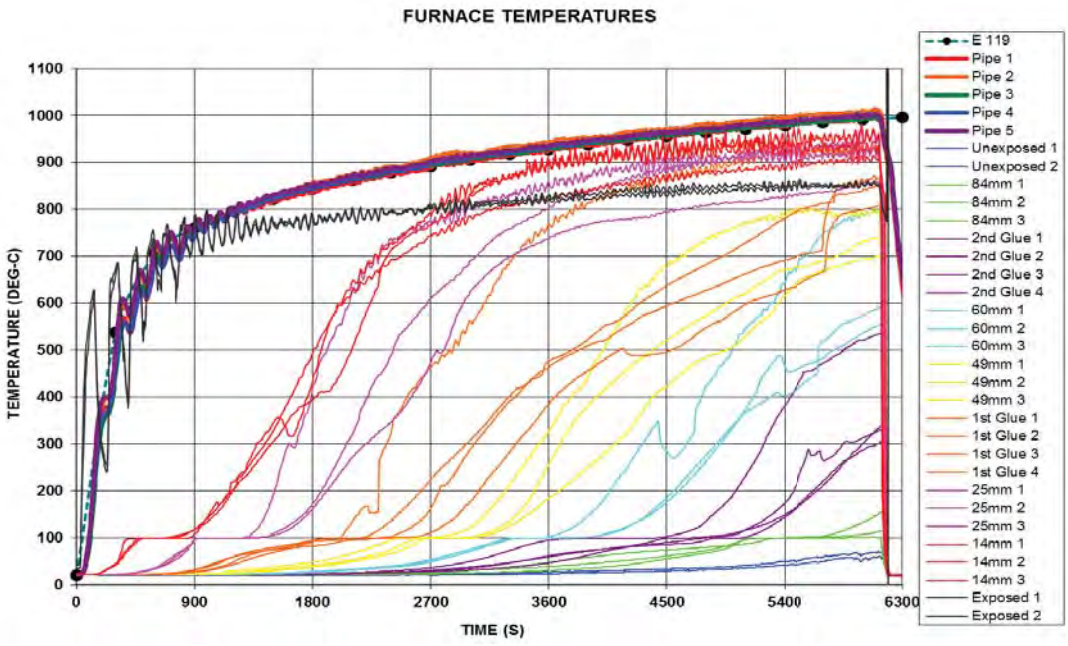
Methods



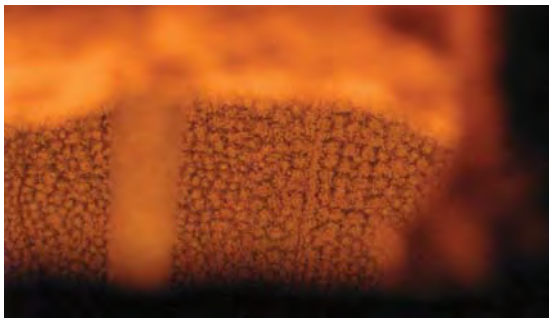
Methods

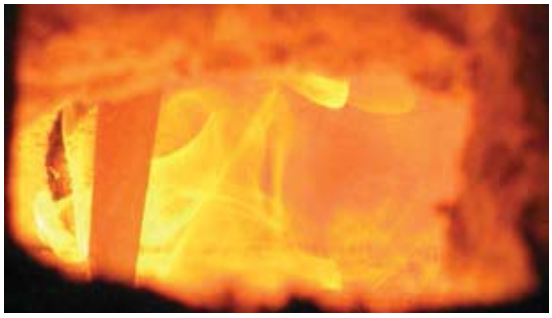


Methods



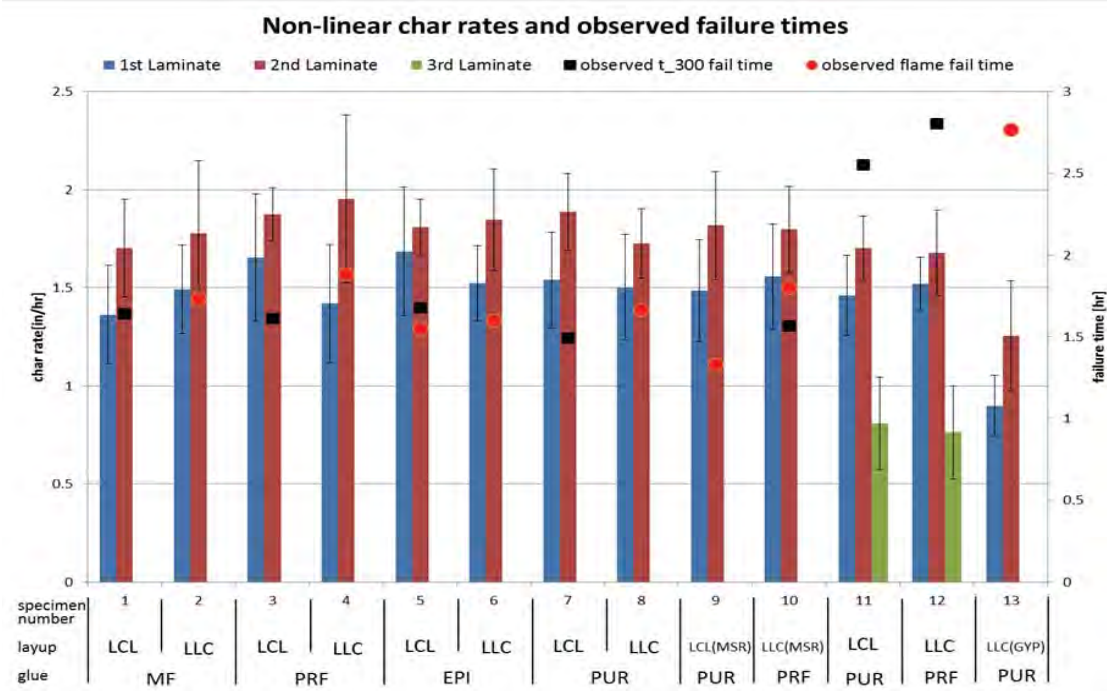
Methods



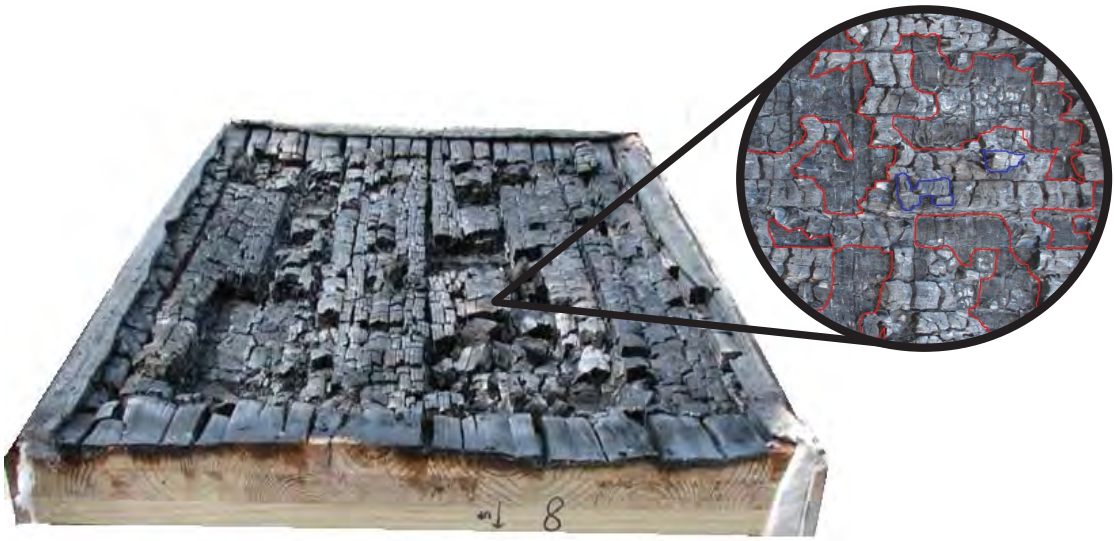


Methods

Results



Results



Results

Questions?

Fire Safety of Tall Wood Buildings—Property Protection View

Kuma Sumathipala, Director, Fire Technology
American Wood Council, Leesburg, Virginia

The Unites States is fortunate to have a vast supply of forest biomass suitable for manufacturing into products that can be used to build wood buildings greater than eight stories in height. To capture this opportunity, stakeholders in the building construction industry must be assured these buildings are safe for their occupants, as well as emergency responders, and do not present an unreasonable risk for loss of property. Current prescriptive building codes limit combustible construction to 85 feet in height and six stories. To expand the market for mass timber beyond these prescriptive limits, research and testing are needed to evaluate and quantify the contribution of mass timber elements to room/compartment fires with the types of structural systems that are expected to be found in tall wood buildings. Previous research has shown that unprotected timber elements can contribute to the fuel load and can aid the fire growth rate. Fuel contribution from structural elements can potentially overwhelm fire protection systems, designed to mitigate and extinguish fires in noncombustible construction. As such, a combustible structural element's contribution to compartment fires needs to be quantified and compared against noncombustible structural systems. A research program initiated by NFPA Fire Protection Research Foundation, and funded by Property Insurance Research Group and USDA Forest Service, expects to quantify the contribution of combustible structural elements to room/compartment fires for the full fire duration using metrics such as charring rate, visibility, temperature, etc. This will allow a designer to quantify the contribution, validate design equations, and develop suitable mitigating technologies. Findings will also provide data for the insurance industry to establish fire insurance premiums for this new type of construction. Additionally, test results could be used to develop and support new requirements for U.S. model building codes, so that these buildings can be constructed without undergoing time-consuming and expensive equivalency studies on a case-by-case basis.

American Wood Council

Fire Safety of Tall Wood Buildings
Property Underwriting
Madison, WI,
November 2015

Kuma Sumathipala

Copyright © 2015 American Wood Council

Tall Wood Building

- **U.S.**
- Code allow for 5/6-stories or 85’ (grade to-roof)
- Tall Wood
  - USDA/SLB Design competition for Tall Wood
    - Portland, OR. 12-story mixed: Retail/Residential
    - New York, NY. 10-Story:Residential

Copyright © 2015 American Wood Council

Property Underwriters

Property Underwrites Initiated a Research in 2013

- Characterize fire performance of tall wood
- Design to achieve a level of property protection equal to or above steel structures.
- Communicate results to serve as a guide for architects, engineers, and code officials.

Copyright © 2015 American Wood Council

Property Underwriters?

Property Insurance Research Group (PIRG)

- FM Global ($5B)
- CNA ($6B)
- Liberty Mutual ($30B)
- Tokio-Marine ($19B)
- Travelers ($22B)
- XL-Group ($6B)
- Zurich ($12B)
- AIG

Copyright © 2015 American Wood Council

Property Insurance Research

- Property Insurance Research Group (PIRG)
- Fire Research of Interest to underwriting
- $400K per Annum
- Secretariat is the Fire Protection Research Foundation

THE FIRE PROTECTION RESEARCH FOUNDATION

Copyright © 2015 American Wood Council

FPRF Overview

Role of the Foundation

- Plan, manage and communicate research in support of the NFPA mission
- Independent charitable organization
  - Formed by NFPA in 1982
  - Intended to provide data to support the needs of NFPA codes & standards
  - Research funds come primarily from:
    - Private and public sector consortia
    - Grants and government sources (e.g. DHS S&T, DOD, FEMA AFG, NIOSH, NIST, NSF, etc)
    - Multiple other sources (including NFPA, e.g., Code Fund)

NFPA | nfpa.org

Copyright © 2015 American Wood Council

FPRF Overview

Project participants… who are they?

- Funding (Sponsors): *Where does it come from?*
  - Manufacturers, trade associations, NFPA, federal agencies, research organizations, nowhere, etc…
- Contractors: *Who Does the Work?*
  - Consultants, research organizations, test labs, universities, NFPA Fire Analysis, volunteers
- Advisory Oversight: *Project Technical Panel*
  - Typically small (6 to 15)
  - Meet at important stages of project (start/end/other)

nfpa.org

Copyright © 2015 American Wood Council

FPRF Overview

Underlying benefits of Foundation projects

- Independence
- Collaboration
- Cost sharing
- Credibility
- Pipeline to implementation
- Communications network

"The whole is greater than the sum of its parts" - Aristotle

WWW.NFPA.ORG/FOUNDATION

nfpa.org

Copyright © 2015 American Wood Council

FPRF Phase 1 Research

❖Literature Survey and Gap Analysis

- Arup chosen from 16 responses to RFP
- Arup report available at NFPA website

Fire Safety Challenges of Tall Wood Buildings

Final Report

Prepared by:
Robert Gerard and David Barber
Arup North America Ltd
San Francisco, CA

Armin Wolski
San Francisco, CA

© December 2013 Fire Protection Research Foundation

THE FIRE PROTECTION RESEARCH FOUNDATION

FIRE RESEARCH

THE FIRE PROTECTION RESEARCH FOUNDATION
ONE BATTERYMARCH PARK
QUINCY, MASSACHUSETTS, U.S.A. 02169-7471
E-MAIL: Foundation@NFPA.org
WEB: www.nfpa.org/Foundation

Copyright © 2015 American Wood Council

FPRF Phase 1: Research

❖Identified Gaps

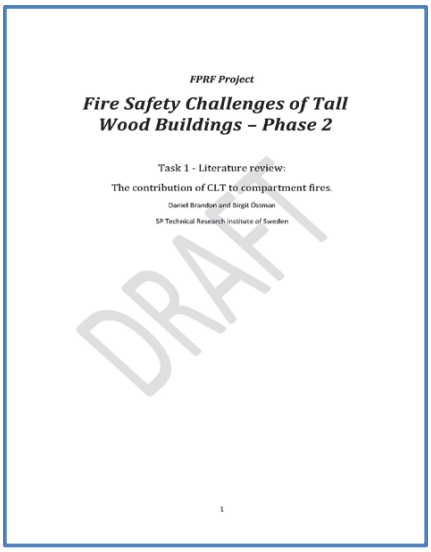
- Interaction of structural and non-structural components
  - Connections, Adhesives, Composites,, Penetrations, Facades & Claddings….
- **Compartment Fire Dynamics**
  - **Assume**
    - **Sprinklers do Not activate**
    - **Inadequate fire service response**
  - **Growth of Content Fire Comparison**
  - **Steel Vs. Wood Compartment**

Copyright © 2015 American Wood Council

Compartment Fire Dynamics

❖Compartment Fire Dynamics

- Contribution of structural wood to a content fire
- Literature Survey of wood compartment fires


FPRF Project

Fire Safety Challenges of Tall Wood Buildings – Phase 2

Task 1 - Literature review:

The contribution of CLT to compartment fires.

Daniel Brandon and Birgit Östman

SP Technical Research Institute of Sweden

DRAFT

1

Copyright © 2015 American Wood Council

Compartment Fire Tests

❖45 wood compartment fire tests 2000-2015

❖2008: Frangi

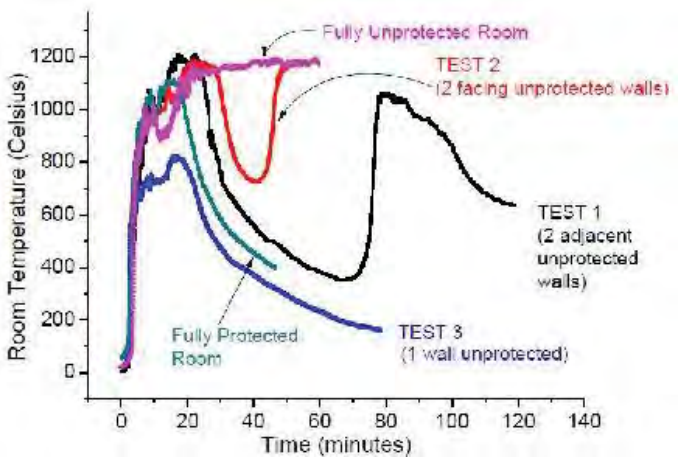
- 11’ x 11’ CLT room; window 3.3’ x 3.3’
- Hotel room contents in fire compartment
- Subject to shake table first
- Fire-rated & Regular gyp board
- Fire contained for 60 min
- Minimal damage to CLT

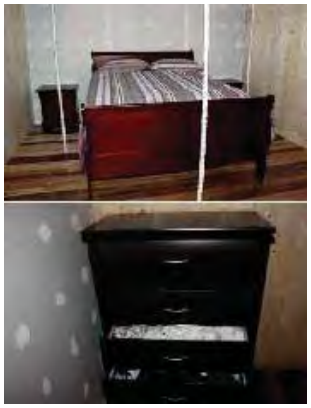
Copyright © 2015 American Wood Council

Compartment Fire Tests

❖Carleton University 2014

- 12’ x 8’ CLT room; door 6.5’ x 3.5’; 3-ply CLT
- Series of experiments with bedroom contents on fire





Copyright © 2015 American Wood Council

Compartment Fire Tests

❖National Research Council Canada 2013

- 27’ x 21’ CLT room; Two Windows 5-ply CLT
- Series of experiments with bedroom contents on fire

Copyright © 2015 American Wood Council

National Research Council Canada

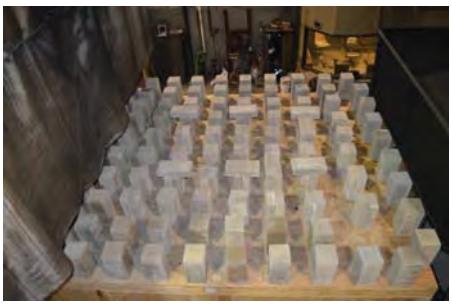
- Gypsum board protected CLT
- Fire burned out

Copyright © 2015 American Wood Council

Compartment Fire Tests

❖American Wood Council (2015)

- 16’ x 12’ CLT room; door 6.5’ x 3.5’; 5-ply CLT
- 2-layers of Type X Gypsum board



Copyright © 2015 American Wood Council

Compartment Fire Tests

3 min

5 min

6 min

60 min

Debris Cleared

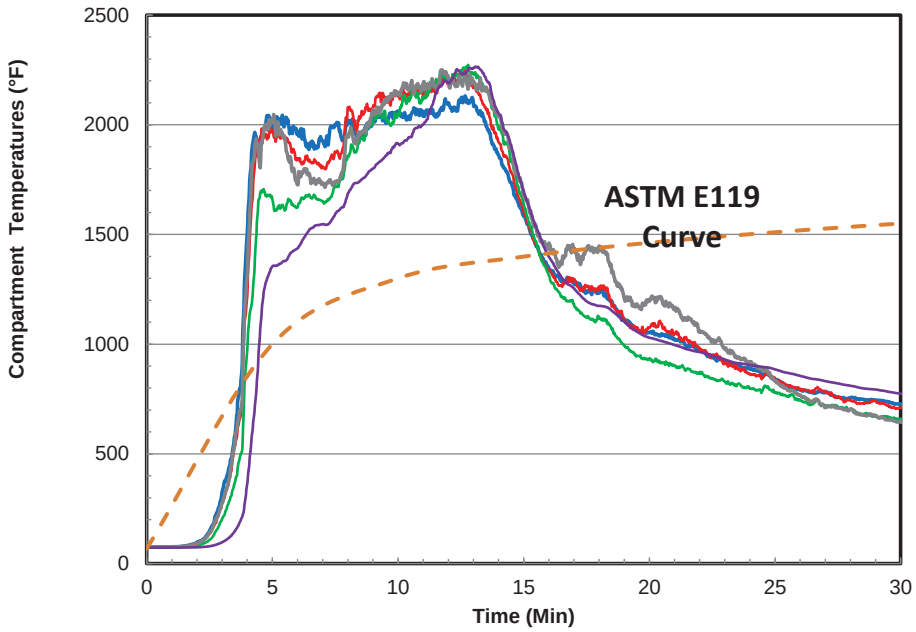
Copyright © 2015 American Wood Council

AWC Compartment Fire Tests

Post-Fire Compartment

Copyright © 2015 American Wood Council

AWC Compartment Fire Tests



Compartment Temperatures

Copyright © 2015 American Wood Council

Conclusions-Compartment Fires

- CLT protected by 2-layers of Type X Gypsum board perform similar to Steel
- One wall unprotected –acceptable performance
- Two walls unprotected - exhibit CLT delamination (40-80 mins)
- All walls unprotected – bad actor?

Copyright © 2015 American Wood Council

FPRF Compartment Fire Candidates

- **Compare steel compartment fire performance:**
  - Gypsum board protected CLT?
  - One-wall unprotected CLT?
  - Two-walls unprotected CLT?

Copyright © 2015 American Wood Council

Thank you!

Copyright © 2015 American Wood Council

Session 4—Material Resources and Other Topics

CLT Supply Chain from Forest to Market

Rusty Dramm, Forest Products Specialist
USDA Forest Products Laboratory, Madison, Wisconsin

The Forest Products Laboratory has entered into a cooperative agreement with Renewable Resource Solutions, LLC, to explore and assess the potential of using suitable USDA Forest Service timber resources and small-diameter trees as feedstock for potential siting of cross laminated timber (CLT) plants in the Pacific Northwest and Intermountain West. The CLT project will help provide preliminary due diligence for CLT and serve as a model for assessing other technologies in the future. Specific questions explored include (1) resource analysis—raw material characterization of CLT feedstock and availability of Federal timber and timber from stewardship contracting/agreements as sources of suitable wood supply; (2) CLT markets—CLT applications and uses—issues, barriers and opportunities considering both domestic and export markets; and (3) financial feasibility discussion for CLT plant siting.

CLT Supply Chain Project

Overview

- ✓ Explore potential sources of wood supply and markets for CLT manufacture
- ✓ Consider CLT markets – barriers and opportunities
- ✓ Provide ideas on preliminary siting a CLT plant in the PNW and Intermountain West

Western States included in the CLT Supply Chain Project

- ✓ FS Region 1
  - Northern Idaho
  - Montana
- ✓ FS Region 4
  - Southern Idaho
  - Nevada
  - Utah
- ✓ FS Region 6
  - Oregon
  - Washington

Planned Programming Approach

Consider the "forest to market" supply chain

Raw Material Resource Considerations for CLT

Resource Analysis

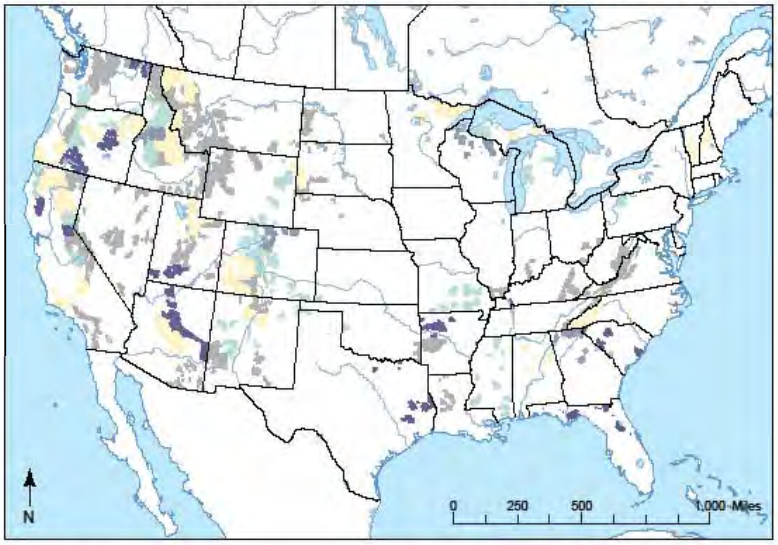
- ✓ Raw material characterization of CLT Feedstock
- ✓ Timber availability – FS timber sales and Stewardship Contracting as potential sources of suitable wood supply
  - Forest inventory analysis (FIA)
  - Timber product output (TPO)
  - Timber sales program
  - Stewardship contracting
  - Forestry operations capacity
  - Other non-Federal sources

Western Regions Timber Performance (FY 2014)

	R1	R4	R6
Timber Program Funding (all programs)	$29,900,000	$11,700,000	$54,500,000
Timber Target - million cunits	570 mccf	230 mccf	1,160 mccf
- million bd.ft. Scribner	285 mmbf	112 mmbf	603 mmbf
- million bd.ft. measure lumber tally equivalent	399 mmbf	161 mmbf	812 mmbf
Accomplished Percent (%)	99.4%	97.3%	98.6%

American Forest Resource Council
October 31, 2014

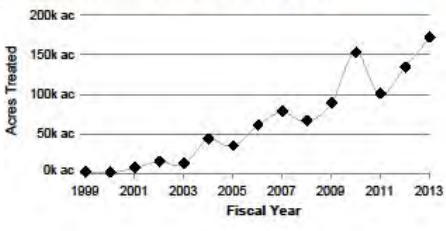
Acres Treated (2013) Forest Service Stewardship Contracts



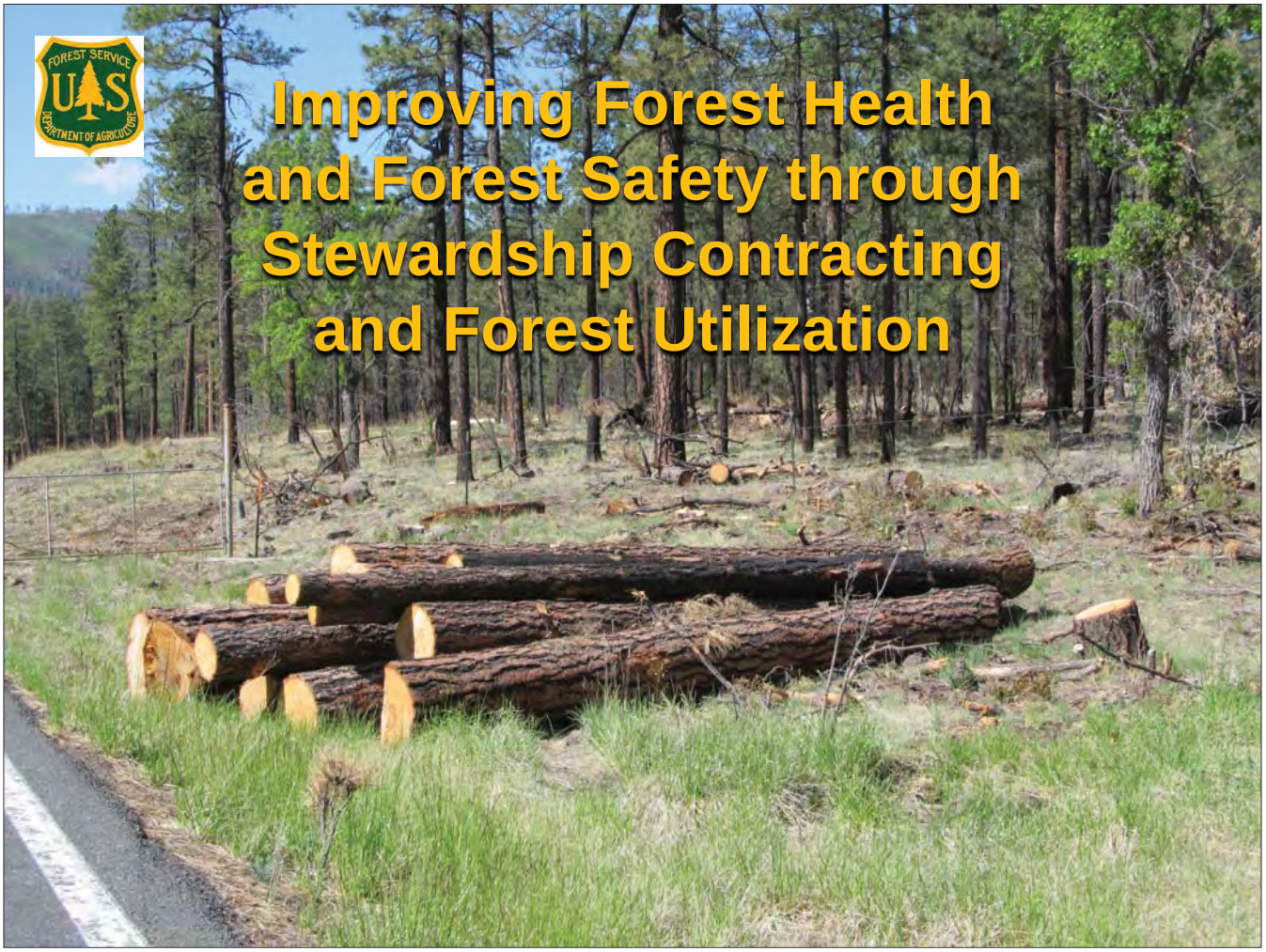
Acres treated in fiscal year 2013

- < 1000 ac
- 1000 - 2000 ac
- 2000 - 3000 ac
- > 3000 ac
- No treatment

Acres treated nationwide through stewardship contracts and agreements, fiscal years 1999 to 2013



Ecosystem Workforce Program, University of Oregon, 7/16/2014


Improving Forest Health
and Forest Safety through
Stewardship Contracting
and Forest Utilization

High-Speed Mobile Sawmilling

Market Considerations for CLT

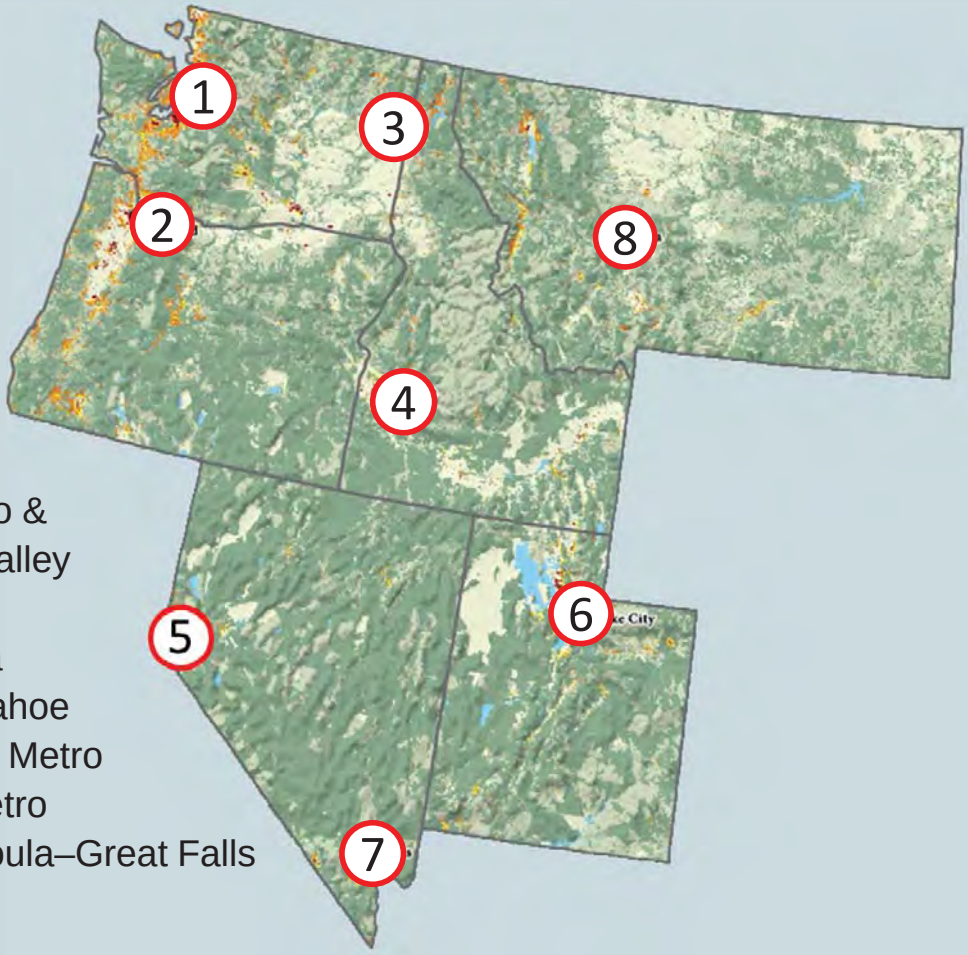
Markets – CLT applications and uses; issues, barriers and opportunities

- ✓ US Markets – structural and non-structural applications
  - Structural load bearing housing and commercial buildings (low-, mid-, and high-rise)
  - Non-load bearing (oil well mats) and industrial wood applications
- ✓ Export Markets – Canada, Europe, China

Construction Market Considerations for CLT

U.S. Markets – load bearing applications in low– and high–rise structures?

CLT Building Construction Markets

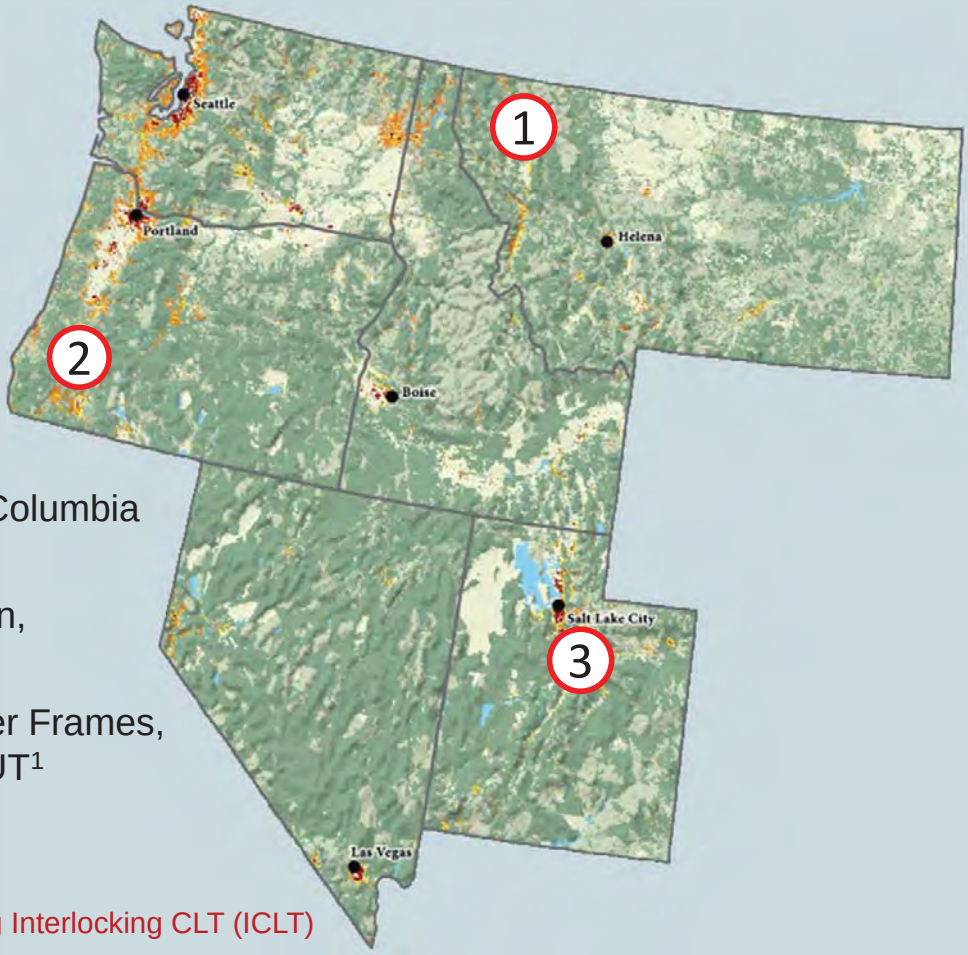


1. SeaTac Metro
2. Portland Metro & Willamette Valley
3. Inland Empire
4. Boise–Nampa
5. Reno–Lake Tahoe
6. Salt Lake City Metro
7. Las Vegas Metro
8. Helena–Missoula–Great Falls

CLT Plant Considerations

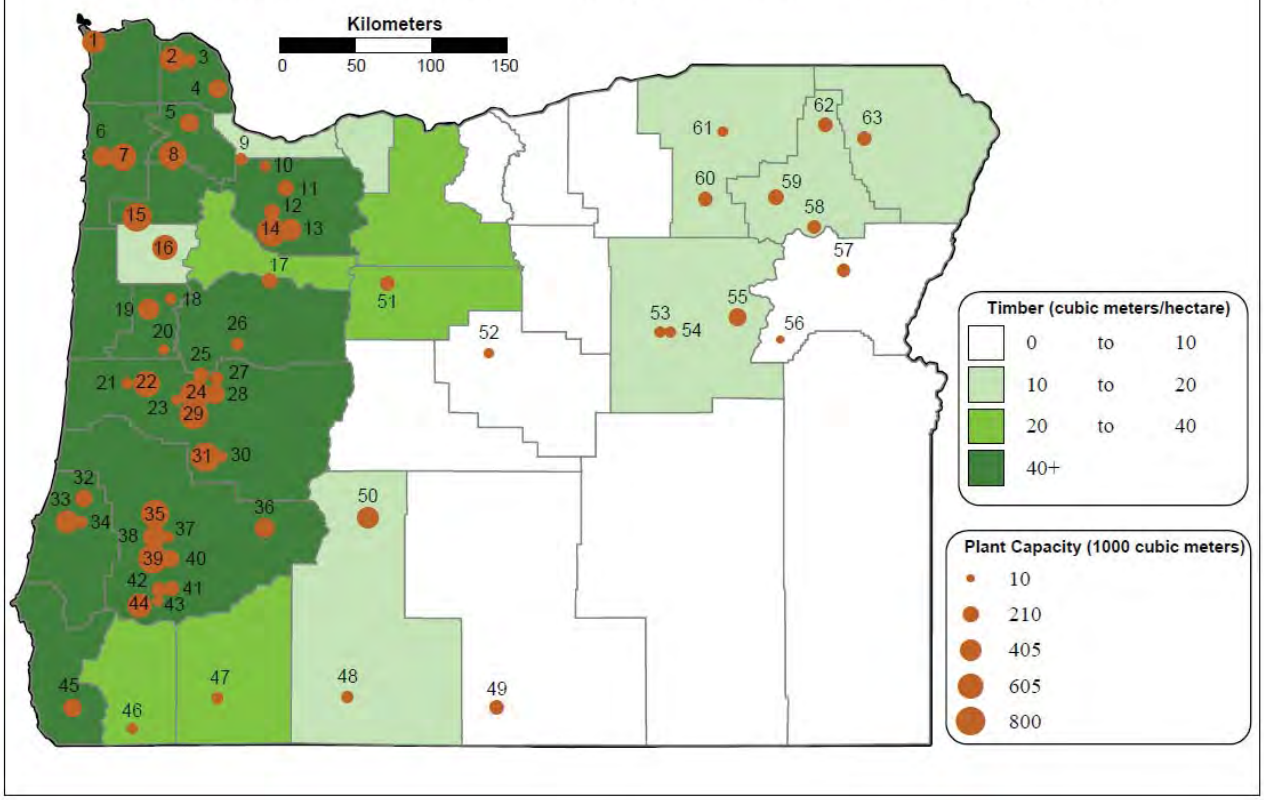
- ✓ CLT Supply Chain – resource, markets and manufacturing plant
- ✓ Logistical – location, personnel, procurement
- ✓ Design – site/plant layout, equipment
- ✓ Establishment – scheduling, management staffing, support services, recruiting
- ✓ Operations – operating plan, sales, QC program
- ✓ Maintenance – maintenance plan

Current U.S. CLT Plants



1. SmartLam, Columbia Falls, MT
2. D.R. Johnson, Riddle, OR
3. Euclid Timber Frames, LC, Heber, UT[1]

[1] Manufacturing Interlocking CLT (ICLT)



CLT Supply Chain Project Acknowledgements

Renewable Resource Solutions, LLC*

Don Peterson
Terry Mace
Heather Ross
Kari Divine

USDA FS – Forest Products Laboratory

Mike Ritter
Melody Jones
Doug Rammer
Dave Kretschmann
Brian Brashaw
Delton Alderman

* FPL Cooperative Agreement

Questions?

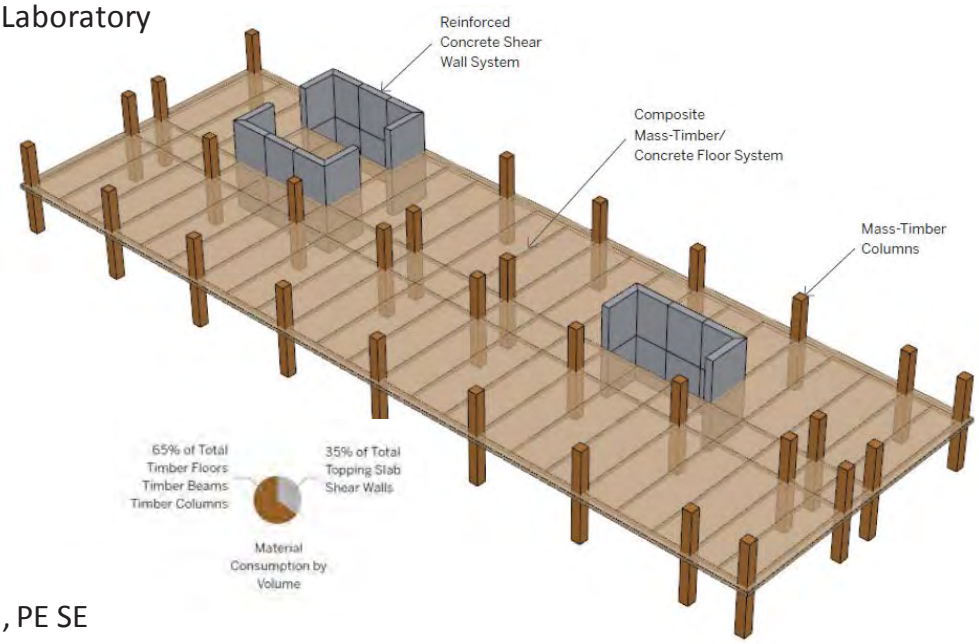
Timber–Concrete Composites

Benton Johnson, Associate
Skidmore, Owings & Merrill LLP, Chicago, Illinois

Composite construction combines different materials to satisfy the specific requirements of a given project. Common examples include composite metal deck slabs, composite steel beams with slabs, and mixed systems such as concrete cores with steel framing. This type of construction has steadily increased in popularity over the past decades. The rise in popularity stems from the economies gained by using different materials where they are most advantageous. The composite system approach can also be applied to mass timber structures to make them more economical and more competitive in the market. This presentation will discuss how composite timber–concrete systems can be used in a variety of building types. Current composite timber–concrete research will also be discussed as it relates to real building applications.

Timber-Concrete Composites

Mass Timber Research Workshop
November 3RD, 2015
Forest Products Laboratory



Presenter:
Benton Johnson, PE SE
Skidmore, Owings & Merrill LLP

Composite Elements

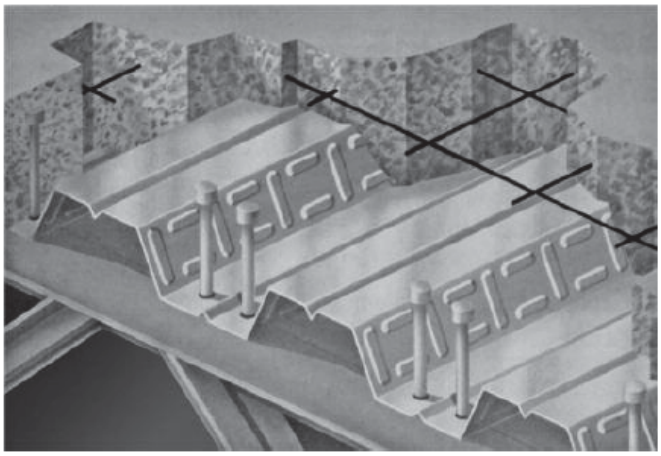
TIMBER

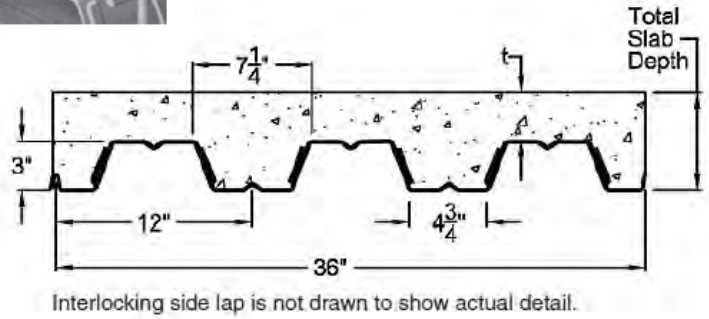
STEEL

CONCRETE

© 2015 Skidmore, Owings & Merrill LLP

Composite Elements



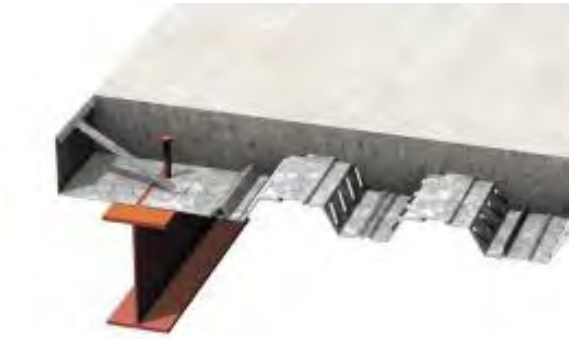


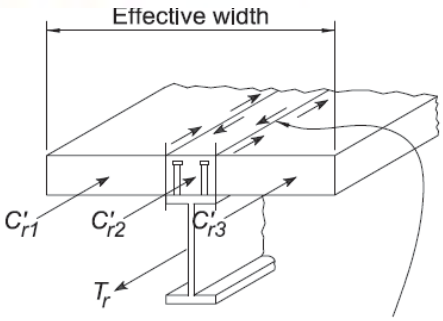
Interlocking side lap is not drawn to show actual detail.

Composite Metal Deck

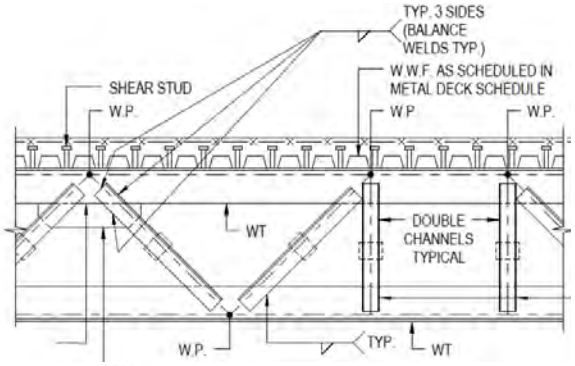
© 2015 Skidmore, Owings & Merrill LLP

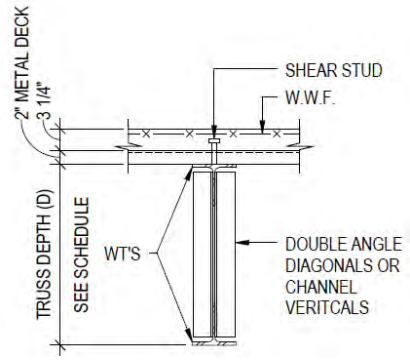
Composite Elements





Composite Steel Beams

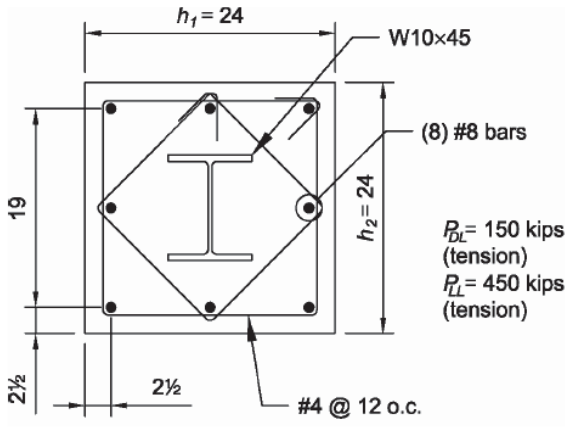




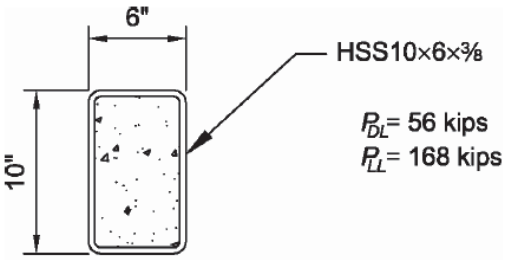
Composite Steel Trusses

© 2015 Skidmore, Owings & Merrill LLP

Composite Elements



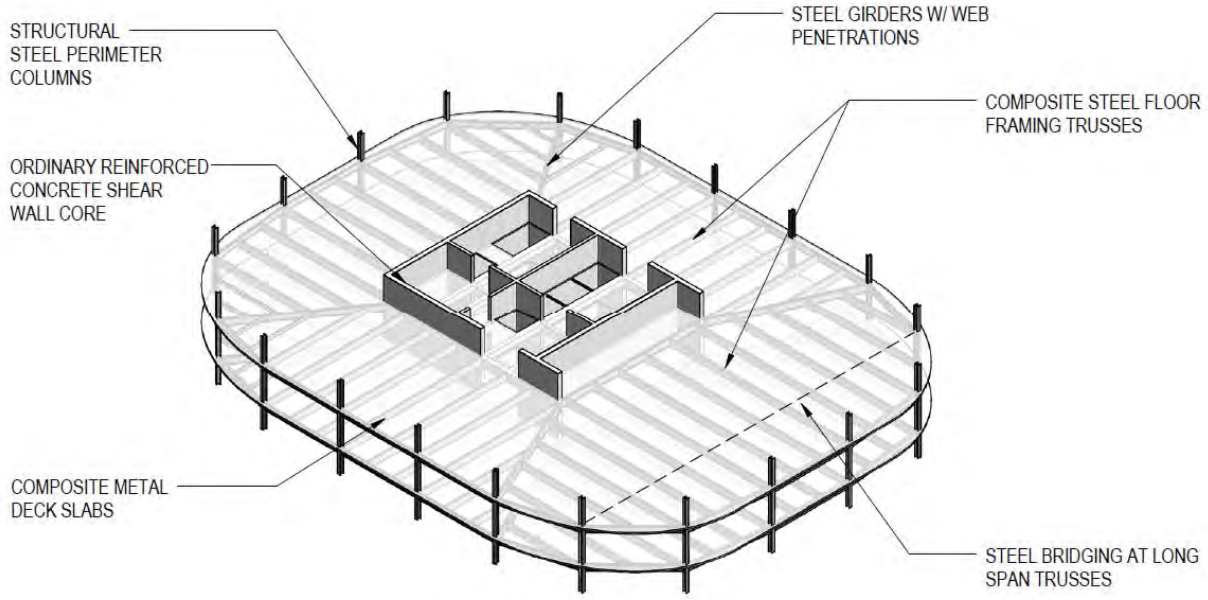
Concrete Encased Steel Column



Concrete Filled Steel Tube

© 2015 Skidmore, Owings & Merrill LLP

Composite Buildings



© 2015 Skidmore, Owings & Merrill LLP

Composite Buildings

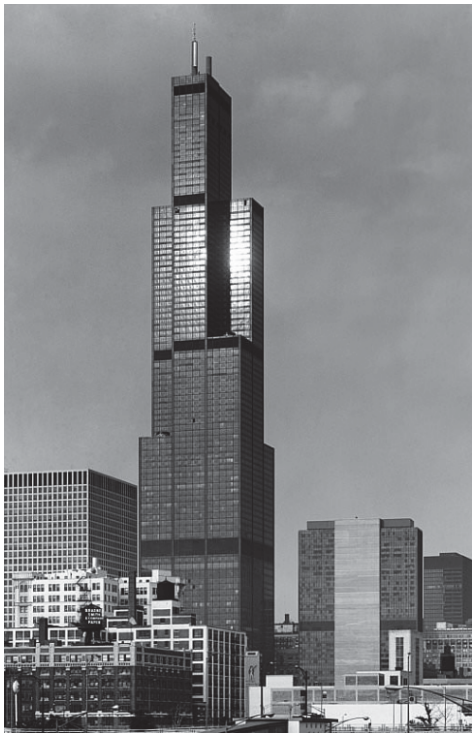


Photo © Ezra Stoller | Esto

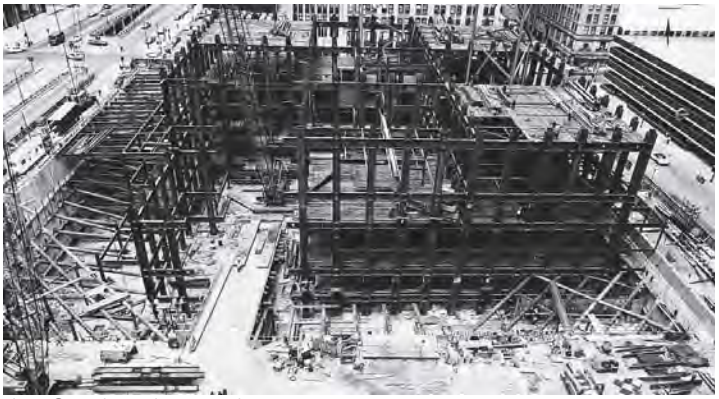


Photo © McShane Fleming Studios

#	Building Name	City	Height (ft)	Floors	Completed	Material
1	Willis Tower	Chicago (US)	1,451	108	1974	steel
2	Empire State Building	New York City (US)	1,250	102	1931	steel
3	Aon Center	Chicago (US)	1,136	83	1973	steel
4	The Center	Hong Kong (CN)	1,135	73	1998	steel
5	John Hancock Center	Chicago (US)	1,128	100	1969	steel
6	Minsheng Bank Building	Wuhan (CN)	1,086	68	2008	steel
7	Chrysler Building	New York City (US)	1,046	77	1930	steel

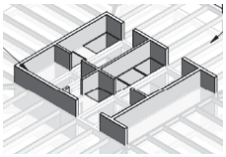
CTBUH Tallest Steel Building Rankings

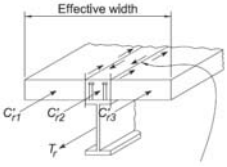
***Willis Tower consists of 75,000 tons of steel and 100,000 tons of concrete

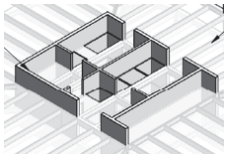
© 2015 Skidmore, Owings & Merrill LLP

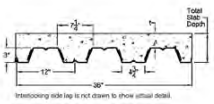
Why Composite?

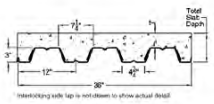
Strength | Stiffness | Mass | Acoustics | Fire

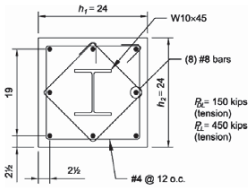


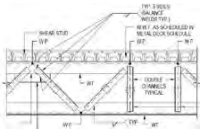


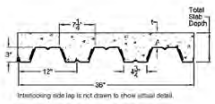


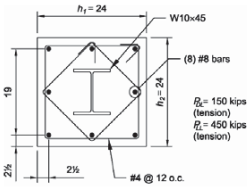








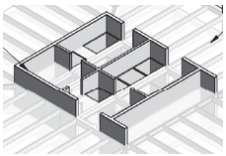


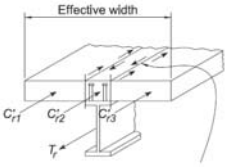


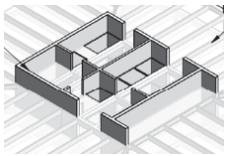
© 2015 Skidmore, Owings & Merrill LLP

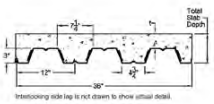
Why Composite?

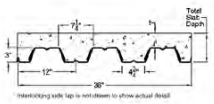
Strength | Stiffness | Mass | Acoustics | Fire

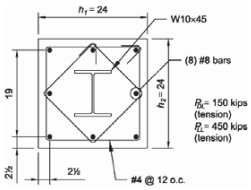


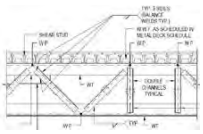


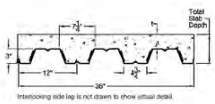


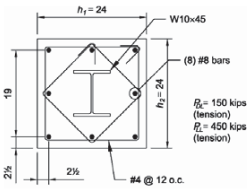










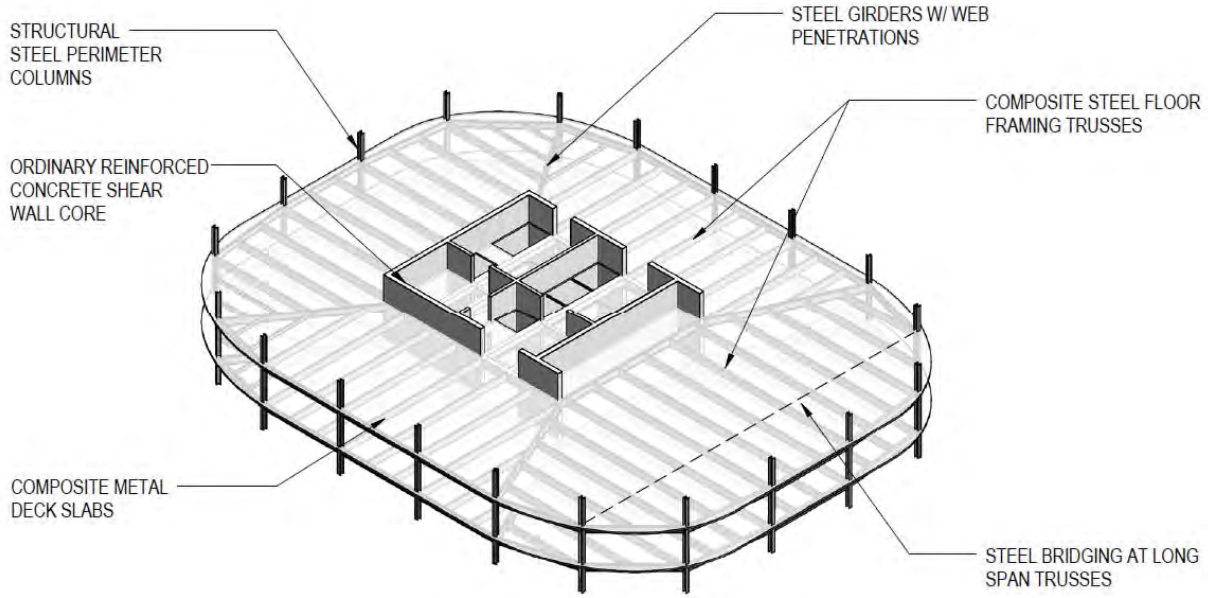


COST

Timber-Concrete Composites
November 3rd, 2015

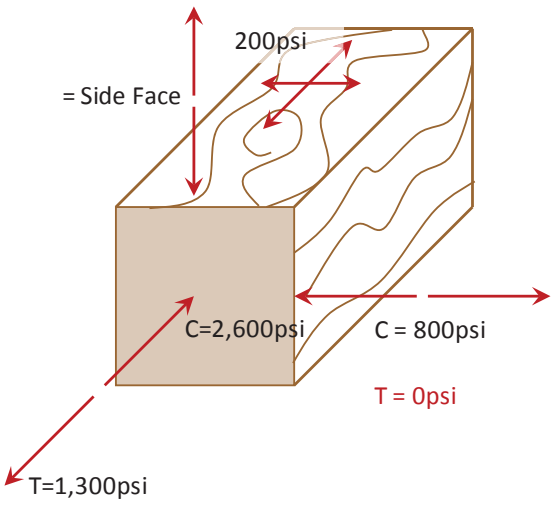
© 2015 Skidmore, Owings & Merrill LLP

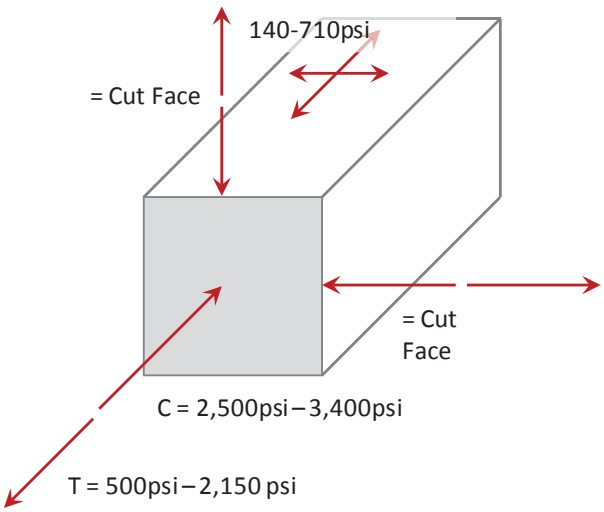
Learning from Other Industries



© 2015 Skidmore, Owings & Merrill LLP

Timber vs. Concrete





Select Structural SPF

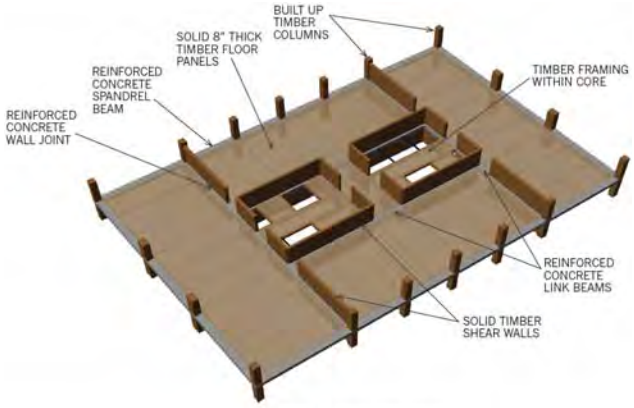
- Density = 30pcf +/-
- Combustible
- Shrink & swell
- Prefabricated
- Regular load paths

5,000 psi Concrete

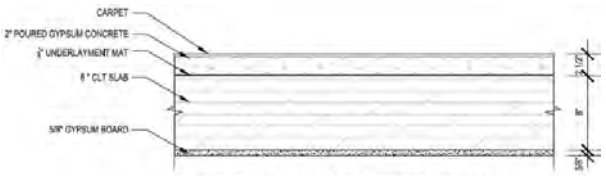
- Density = 145pcf +/-
- Non-combustible
- Shrink
- Cast-in-place
- Complex load paths

© 2015 Skidmore, Owings & Merrill LLP

SOM Research – Initial Project



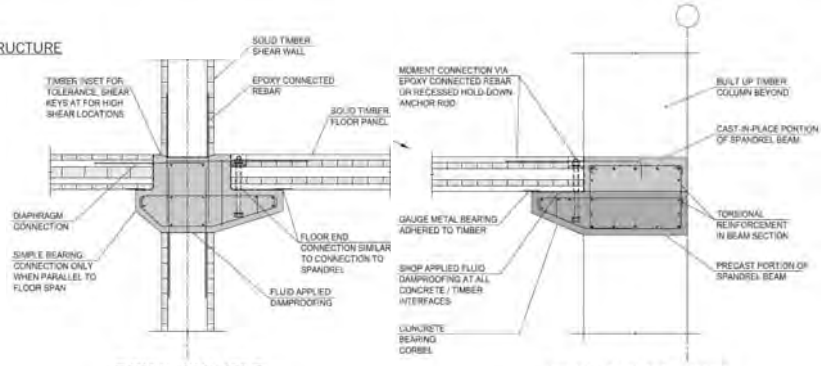
TYPICAL FLOOR STRUCTURE



ESTIMATED ACOUSTIC PERFORMANCE
RENTAL APARTMENTS
STC ≥ 55
IIC ≥ 60

COST

- Strength
- Stiffness
- Mass
- Acoustics
- Fire Resistance

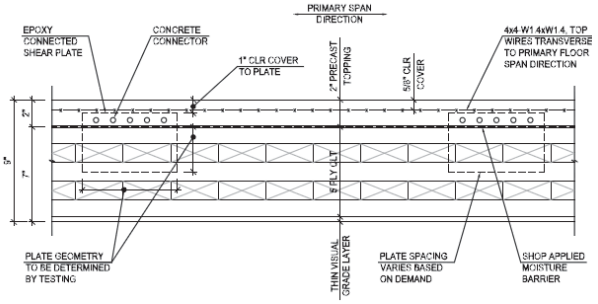


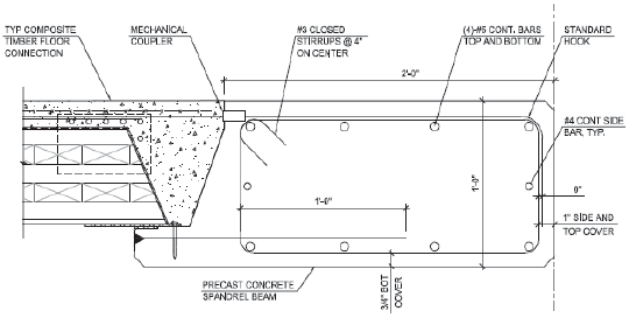
TYPICAL WALL JOINT

TYPICAL SPANDREL JOINT

© 2015 Skidmore, Owings & Merrill LLP

SOM Research – Gravity Framing Report





COST

- Strength
- Stiffness
- Mass
- Acoustics
- Fire Resistance

© 2015 Skidmore, Owings & Merrill LLP

Fire Resistance of Composite Timber Floors

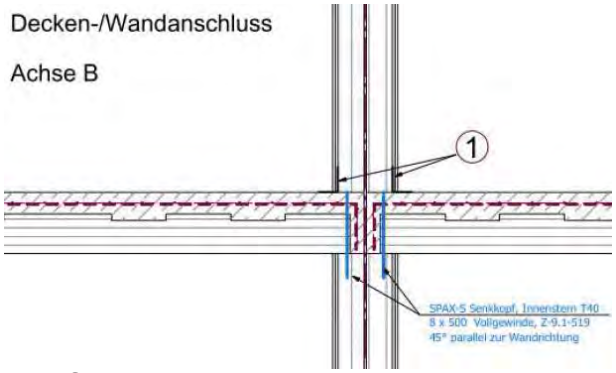
Table 7
Comparison between experiments and calculation methodology

	# of Plies	Experiments	Calculation Methodology		
		Failure Time (min)	Structural (min)	Integrity (min)	Assigned Fire Resistance (min)
Wall	3	106 (R)	63	102	63
	5	113 (R)	103	96	96
	5	57 (R)	53	57	53
Floor	3	77 (*)	81	102	81
	5	96 (E)	109	96	96
	3	86 (E)	59	87	59
	5	124 (E)	120	126	120
	7	178 (R)	107	135	107

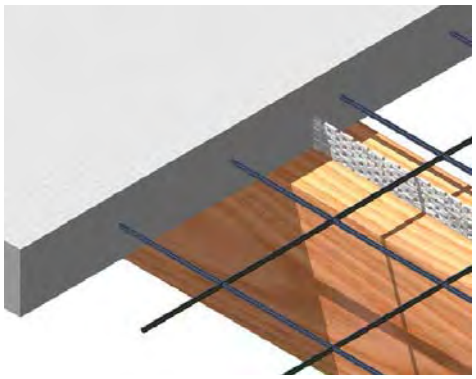
* Test was stopped due to equipment safety concerns. Failure was not reached.
R = Structural Failure, E = Integrity Failure

© 2015 Skidmore, Owings & Merrill LLP

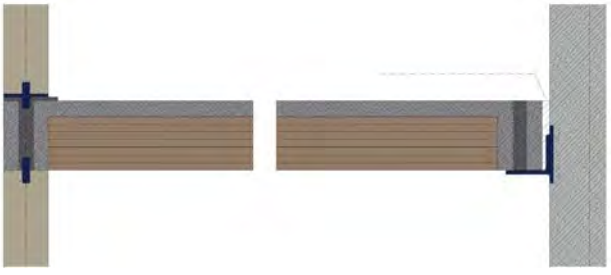
Composite Timber Floors



KLH System



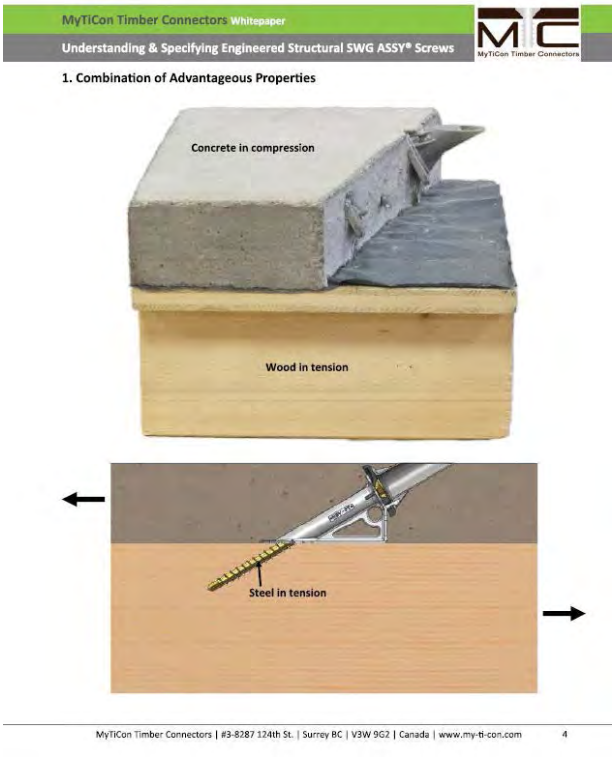
HSK / HBV Mesh Plates

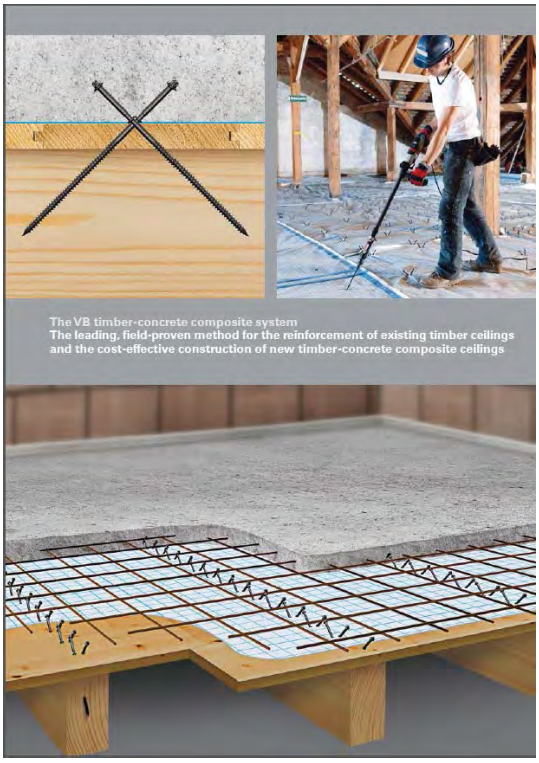


CREE System

© 2015 Skidmore, Owings & Merrill LLP

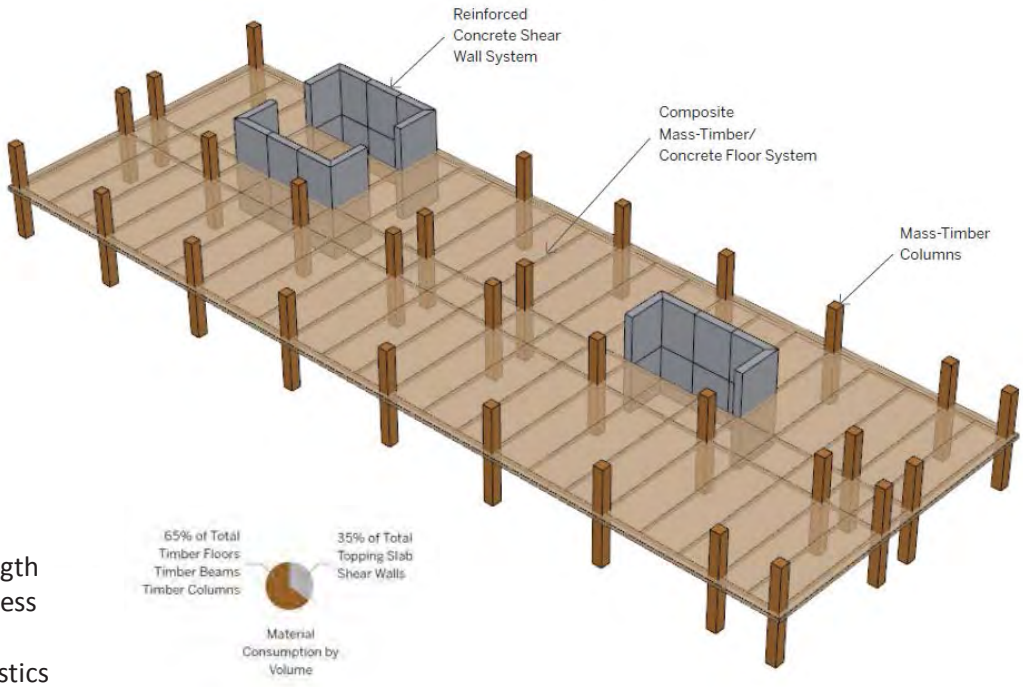
Composite Timber Floors





© 2015 Skidmore, Owings & Merrill LLP

Model Composite Timber Building



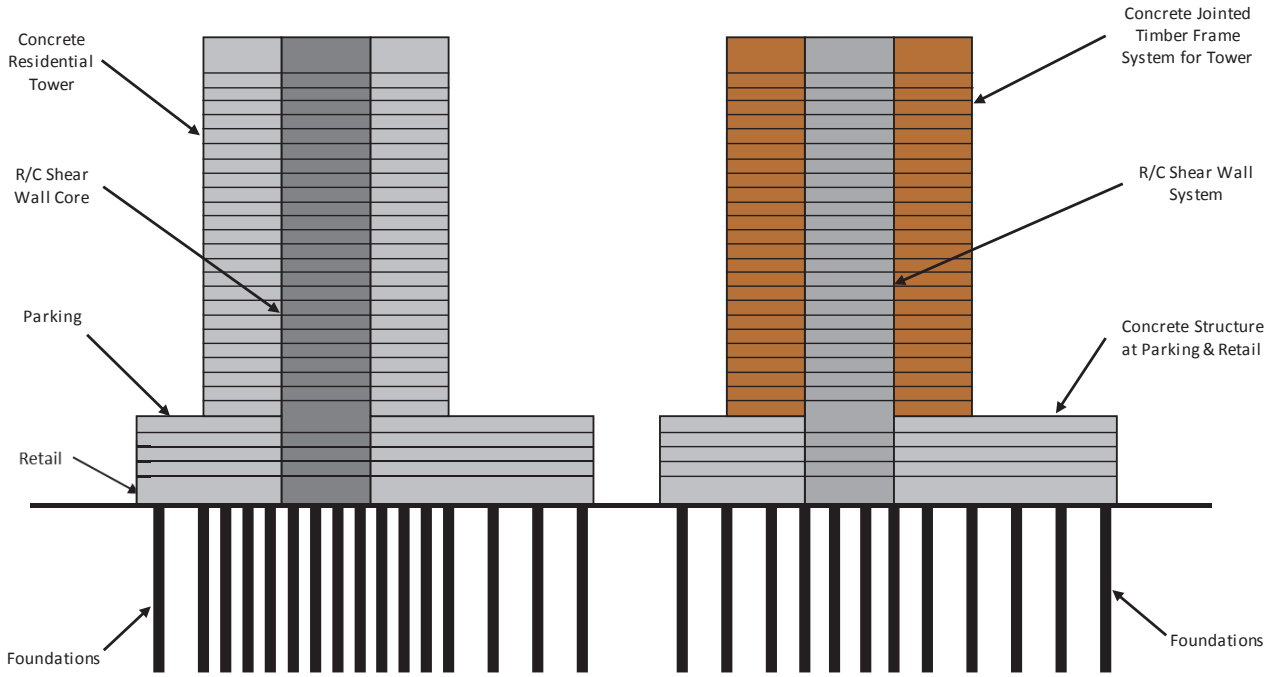
COST

- Strength
- Stiffness
- Mass
- Acoustics
- Fire Resistance

Model Building Diagram

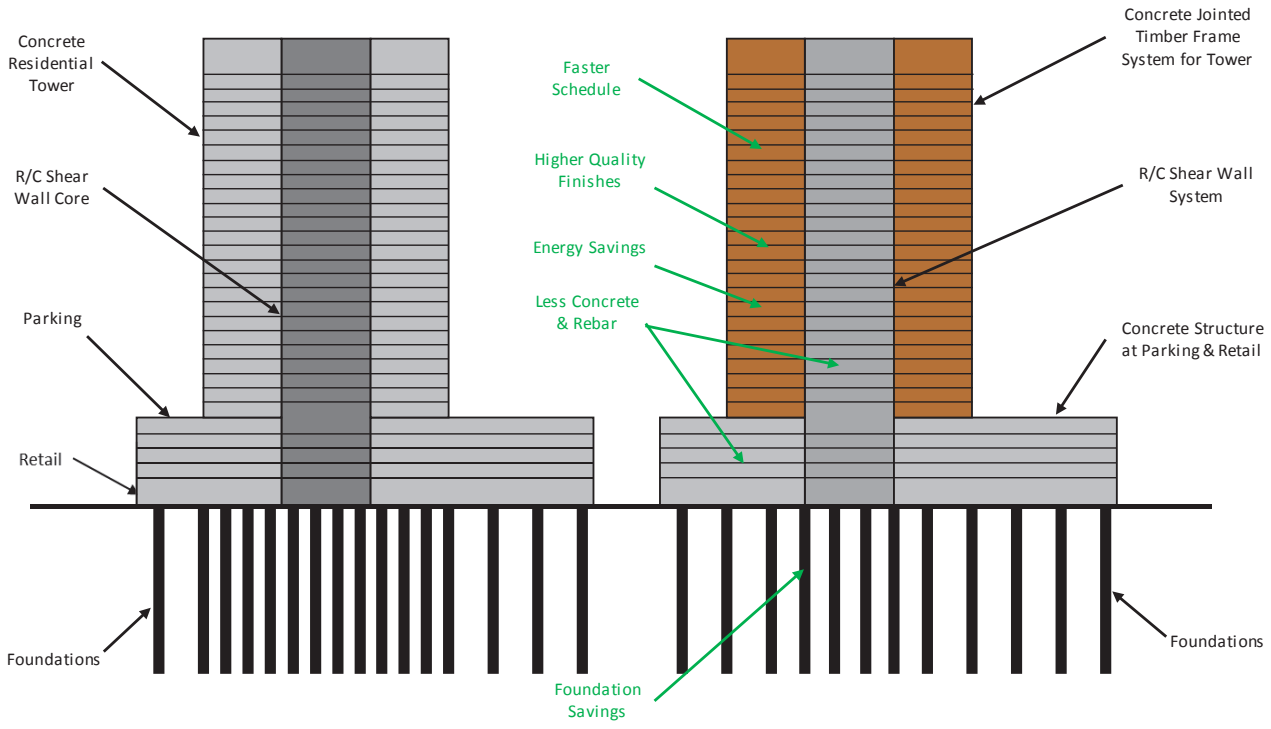
© 2015 Skidmore, Owings & Merrill LLP

Model Composite Timber Building



© 2015 Skidmore, Owings & Merrill LLP

Model Composite Timber Building



© 2015 Skidmore, Owings & Merrill LLP

Strategic Plan for ICC 2021

ICC Recognition of Composite Timber Floors / Structures

- Structural testing
- Acoustic testing
- Fire testing

TABLE 503—continued
ALLOWABLE BUILDING HEIGHTS AND AREAS[a, b]

GROUP		TYPE OF CONSTRUCTION								
		TYPE I		TYPE II		TYPE III		TYPE IV	TYPE V	
		A	B	A	B	A	B	HT	A	B
	HEIGHT (feet)	UL	160	65	55	65	55	65	50	40
		STORIES(S) AREA (A)								
R-1	S	UL	11	4	4	4	4	4	3	2
	A	UL	UL	24,000	16,000	24,000	16,000	20,500	12,000	7,000
R-2	S	UL	11	4	4	4	4	4	3	2
	A	UL	UL	24,000	16,000	24,000	16,000	20,500	12,000	7,000
R-3	S	UL	11	4	4	4	4	4	3	3
	A	UL	UL	UL	UL	UL	UL	UL	UL	UL
R-4	S	UL	11	4	4	4	4	4	3	2
	A	UL	UL	24,000	16,000	24,000	16,000	20,500	12,000	7,000

© 2015 Skidmore, Owings & Merrill LLP

SOM Research – Testing at Oregon State Univ.

© 2015 Skidmore, Owings & Merrill LLP

Strategic Plan for ICC 2021

ICC Recognition of Composite Timber Floors / Structures

- Structural testing
- Acoustic testing
- Fire testing

TABLE 503—continued
ALLOWABLE BUILDING HEIGHTS AND AREAS[a, b]

GROUP		TYPE OF CONSTRUCTION								
		TYPE I		TYPE II		TYPE III		TYPE IV	TYPE V	
		A	B	A	B	A	B	HT	A	B
	HEIGHT (feet)	UL	160	65	55	65	55	65	50	40
		STORIES(S) AREA (A)								
R-1	S	UL	11	4	4	4	4	4	3	2
	A	UL	UL	24,000	16,000	24,000	16,000	20,500	12,000	7,000
R-2	S	UL	11	4	4	4	4	4	3	2
	A	UL	UL	24,000	16,000	24,000	16,000	20,500	12,000	7,000
R-3	S	UL	11	4	4	4	4	4	3	3
	A	UL	UL	UL	UL	UL	UL	UL	UL	UL
R-4	S	UL	11	4	4	4	4	4	3	2
	A	UL	UL	24,000	16,000	24,000	16,000	20,500	12,000	7,000

© 2015 Skidmore, Owings & Merrill LLP

Strategic Plan beyond ICC 2021

ICC Recognition of Composite Timber Floors / Structures

- Structural testing
- Acoustic testing
- Fire testing
- Precedents

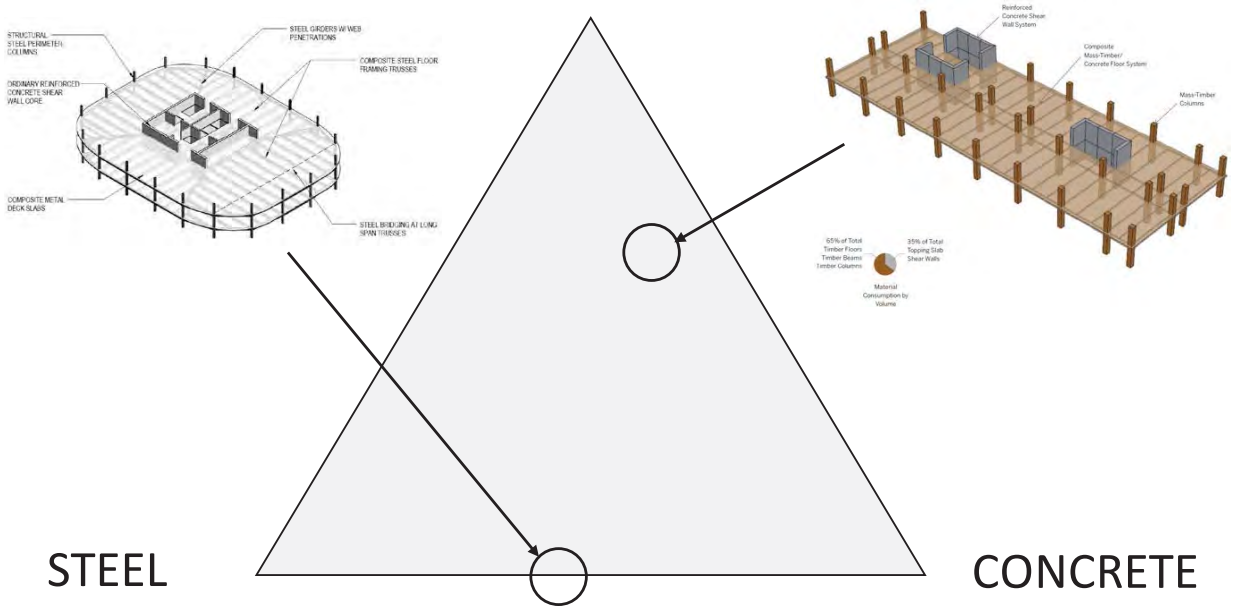
TABLE 503—continued
ALLOWABLE BUILDING HEIGHTS AND AREAS[a, b]

GROUP		TYPE OF CONSTRUCTION									
		TYPE I		TYPE II		TYPE III		TYPE IV		TYPE V	
		A	B	A	B	A	B	CT	HT	A	B
	HEIGHT (feet)	UL	160	65	55	65	55	160	65	50	40
		STORIES(S) AREA (A)									
R-1	S	UL	11	4	4	4	4	11	4	3	2
	A	UL	UL	24,000	16,000	24,000	16,000	UL	20,500	12,000	7,000
R-2	S	UL	11	4	4	4	4	11	4	3	2
	A	UL	UL	24,000	16,000	24,000	16,000	UL	20,500	12,000	7,000
R-3	S	UL	11	4	4	4	4	11	4	3	3
	A	UL	UL	UL	UL	UL	UL	UL	UL	UL	UL
R-4	S	UL	11	4	4	4	4	11	4	3	2
	A	UL	UL	24,000	16,000	24,000	16,000	UL	20,500	12,000	7,000

© 2015 Skidmore, Owings & Merrill LLP

Conclusions

TIMBER

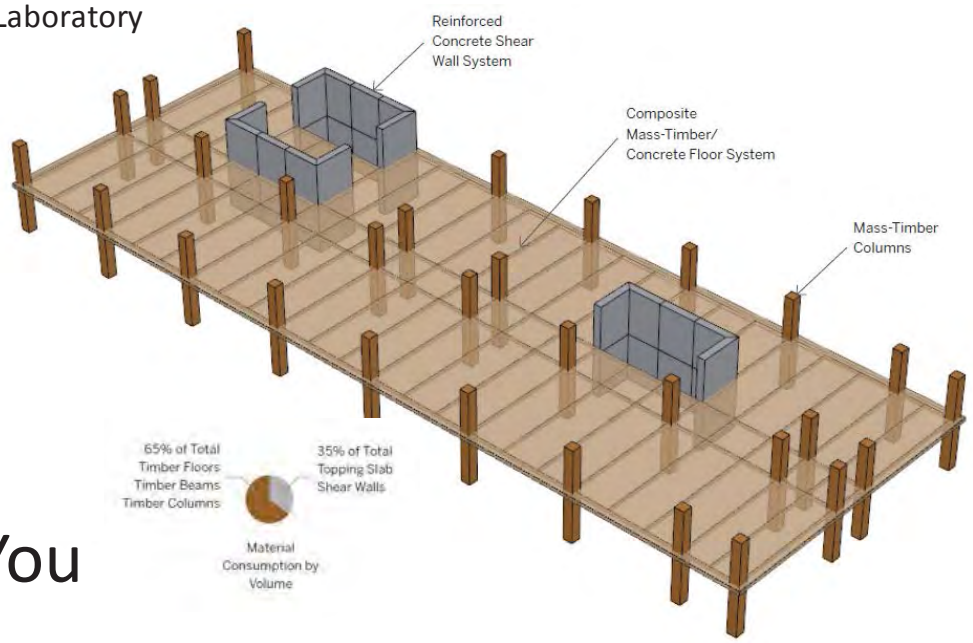


STEEL CONCRETE

© 2015 Skidmore, Owings & Merrill LLP

Timber-Concrete Composites

Mass Timber Research Workshop
November 3RD, 2015
Forest Products Laboratory



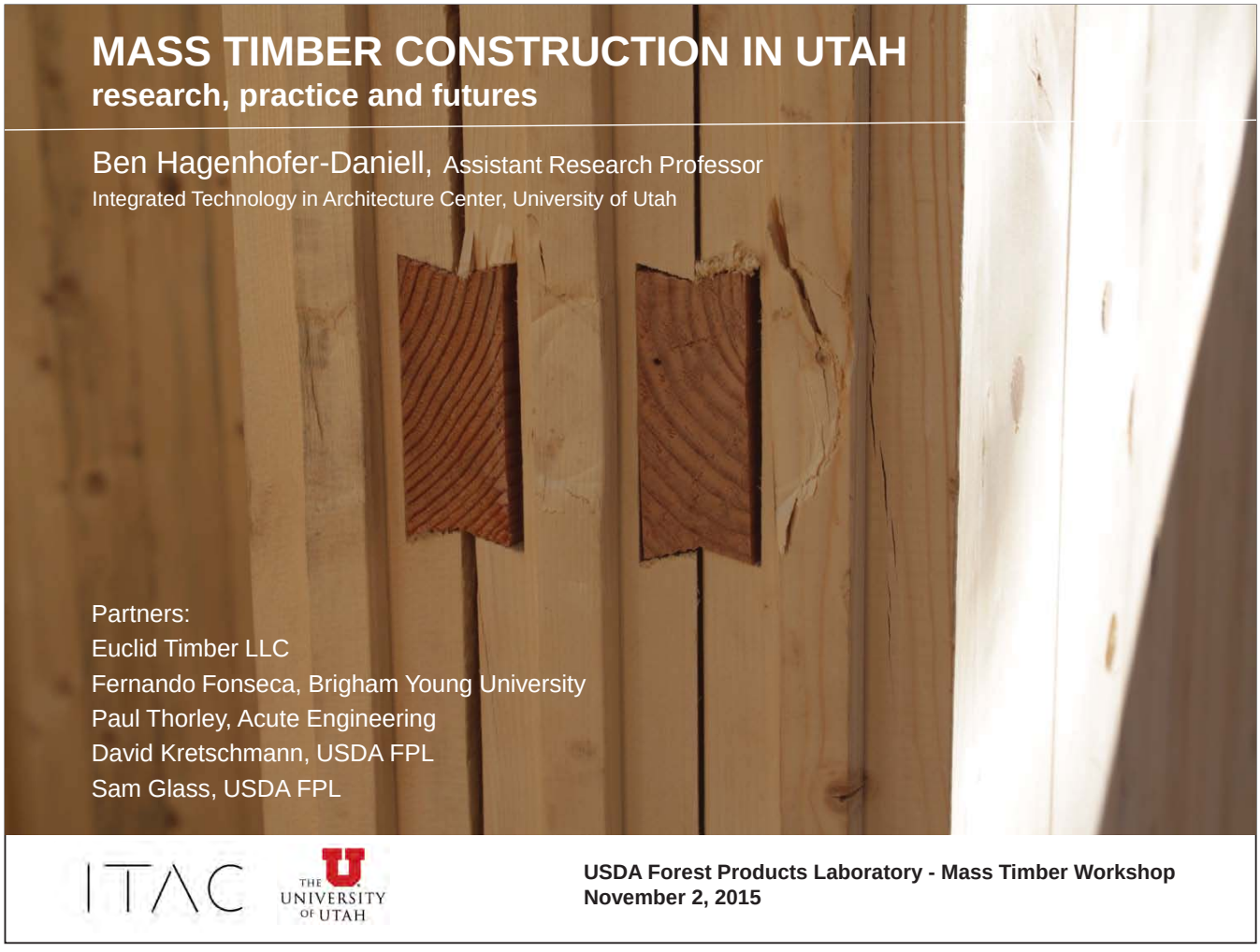
Thank You

Contact:
benton.johnson@som.com

Mass Timber Construction in Utah: Research, Practice, and Futures

Ben Hagenhoffer-Daniel, Assistant Research Professor
University of Utah, Salt Lake City, Utah

This presentation is an overview of mass timber research, development, and commercial work, using beetle-killed pine from the intermountain forests. This work is performed by an industry–university partnership between the University of Utah, Brigham Young University, and Euclid Timber LLC, a timber fabricator and general contractor in Heber, Utah. The presentation will include the following: (1) Explorations into non-glued solutions to mass timber construction through a product commercially available from Euclid Timber LLC called Interlocking Cross-Laminated Timber (ICLT). The presentation will explain research on optimizing and testing ICLT for structural and hygrothermal performance, case studies of built works utilizing ICLT, and studies into digital interoperability, dimensional stability, and economic impacts of drying for alternative non-glued mass timber products. (2) The research team has more recently been exploring transverse post-tensioned timber planar elements and the potential of cellulose fiber. (3) Finally, the presentation will reveal results of a recently released report, “Solid Timber: Process Practice Performance,” sponsored by USDA Forest Products Laboratory, FPInnovations, and the AIA that documents 17 case study mass timber projects for their cost, schedule, quality, and risk key performance indicators in comparison to traditional site-built construction.



NO-GLUE

INTERLOCKING CLT
POST-TENSIONED
TIMBER

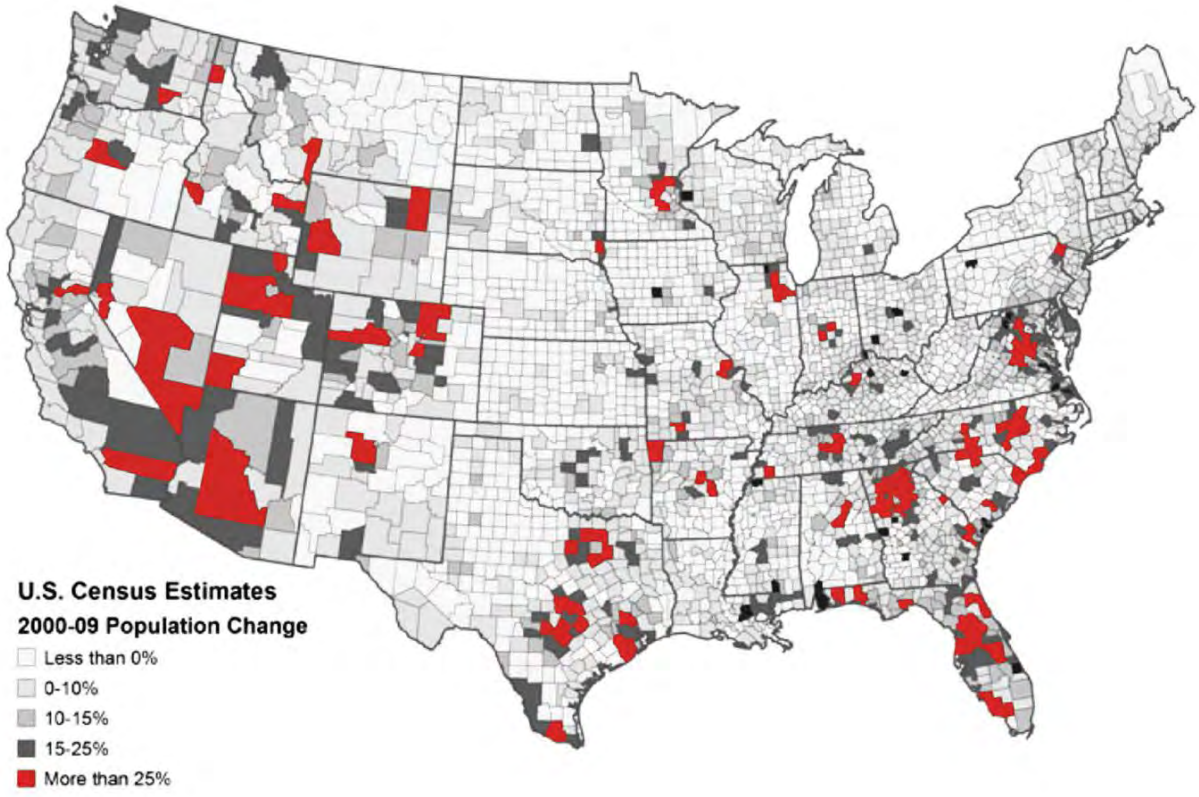
OPTIMIZATION

DIGITAL WORKFLOW

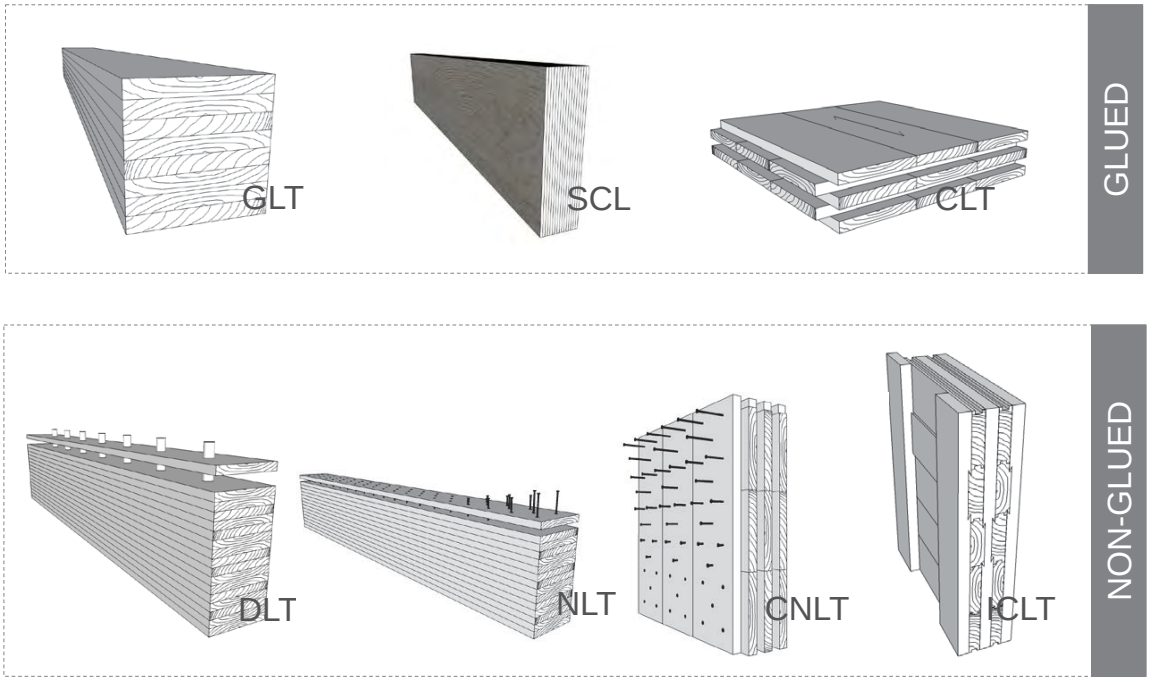
PERFORMANCE

COST/SCHEDULE

NO-GLUE



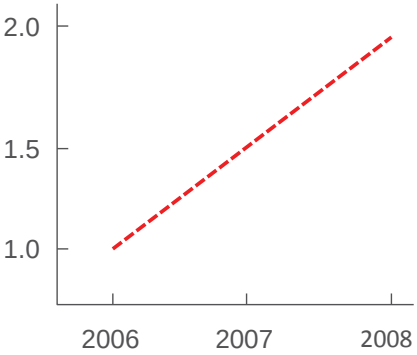
Source: U.S. Census Data 2000 – 2010

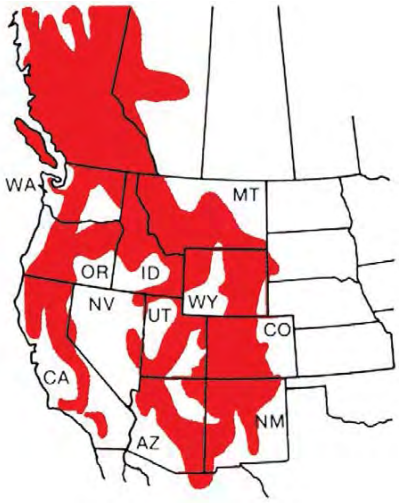


Credit: COCIS Edinburgh Napier University & ITAC UofU

=

44%





Source: Colorado State University Report No. 5.528

Area =	1,000,000 acres
Trees (50 / acre) =	50,000,000 trees
Board feet =	1695 B.F. / tree
Board feet total =	84,750,000,000 B.F.
B.F. / House =	40,000 B.F.
# of potential houses =	**2,118,750 Homes**

Adapted from DOA U.S. Forest Service Data

EUCLID

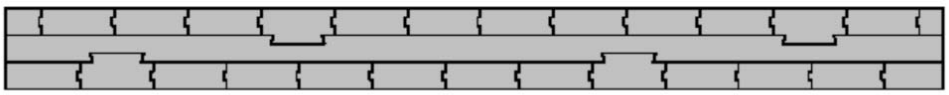
TIMBER FRAMES, L.C.

WWW.EUCLIDTF.COM

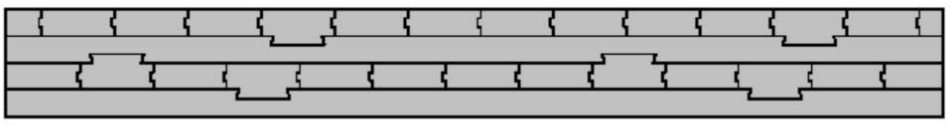
Hundegger USA

2 Ply: 5.5”

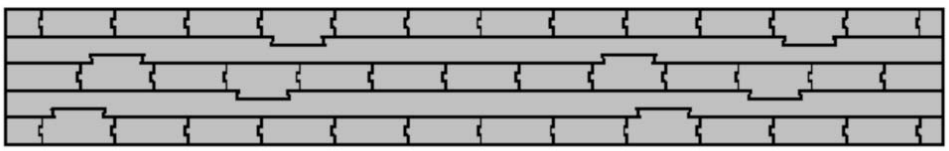
3 Ply: 8.25”



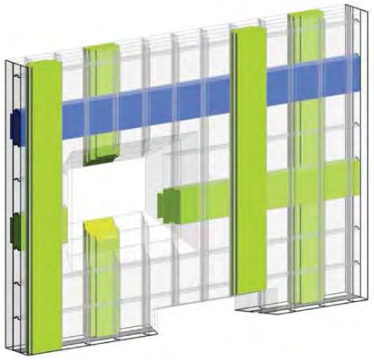
4 Ply: 11”

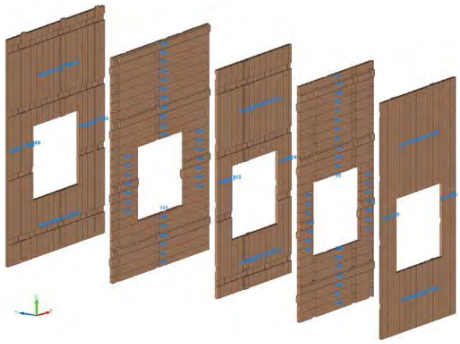


5 Ply: 13.75”

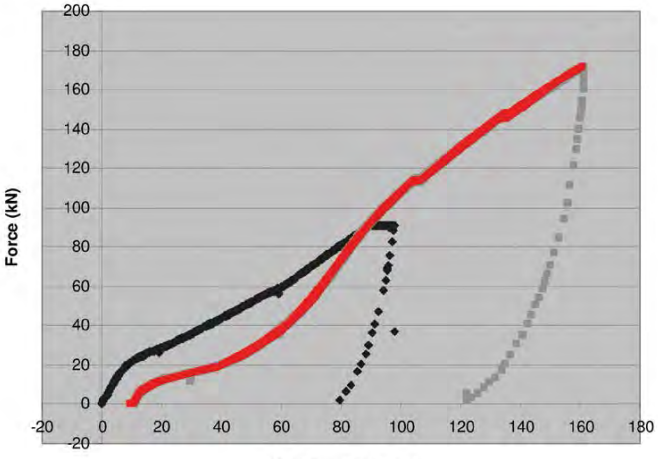


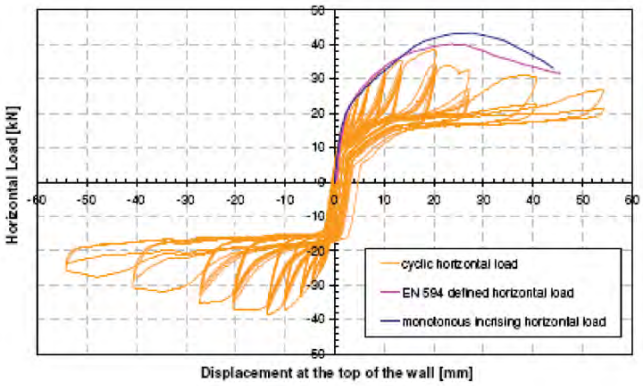
Credit: Euclid Timber





Credit: Euclid Timber



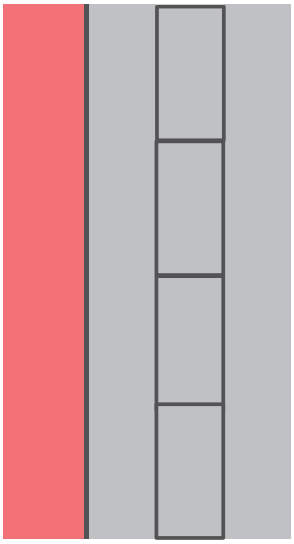


Shear wall type	P_u (kips)	δ_{ult} (in)
iCLT	38.3	5.97
glued CLT	10	1
Light frame wood	4.5	.89
ICF	34.2	2.66

Credit: Brigham Young University & Acute Engineering

3-PLY ICLT WITH EXTERIOR INSULATION

Vapor-open
Mineral wool

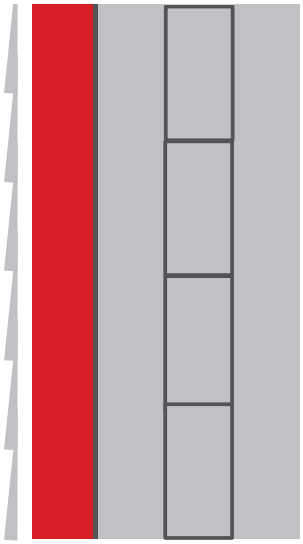


Exterior to interior:

- Composite wood siding
- Drainage cavity/ventilated air space
- R-10 insulation
- Vapor-permeable air barrier membrane
- 3-ply ICLT with no interior finish

Credit: Sam Glass, USDA Forest Products Laboratory

Vapor-tight
Extruded polystyrene



Credit: Euclid Timber

Credit: Euclid Timber

Credit: Euclid Timber

Credit: Euclid Timber & ITAC UofU

Credit: Euclid Timber & ITAC UofU

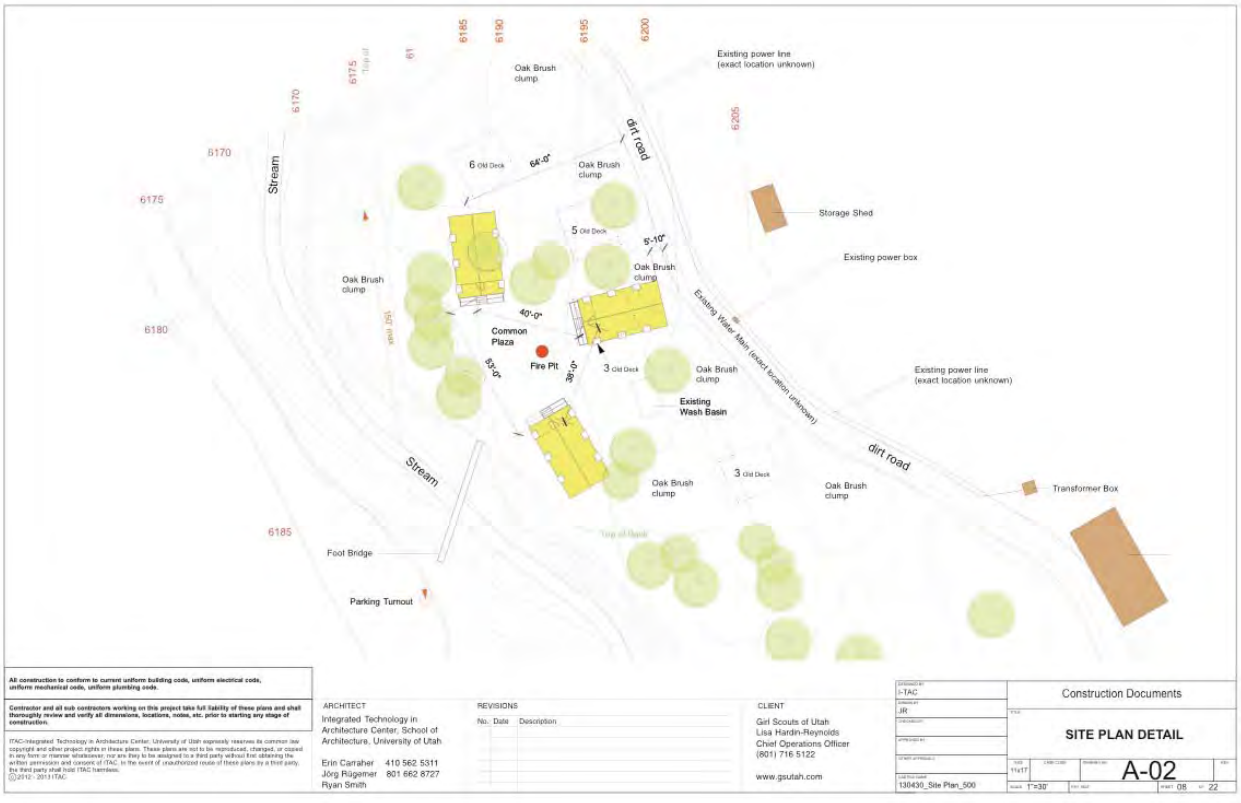
Credit: Euclid Timber & ITAC UofU

Credit: Euclid Timber & ITAC UofU

Credit: Girl Scouts of Utah & ITAC UofU

Credit: Girl Scouts of Utah & ITAC UofU

Credit: Euclid Timber & ITAC UofU



Credit: Girl Scouts of Utah, ITAC UofU, & AJR Altier

Credit: Euclid Timber, Girl Scouts of Utah, ITAC UofU

Credit: Euclid Timber, Girl Scouts of Utah, ITAC UofU

Credit: Euclid Timber, Girl Scouts of Utah, ITAC UofU

PROJECT: ARCHITECTURE

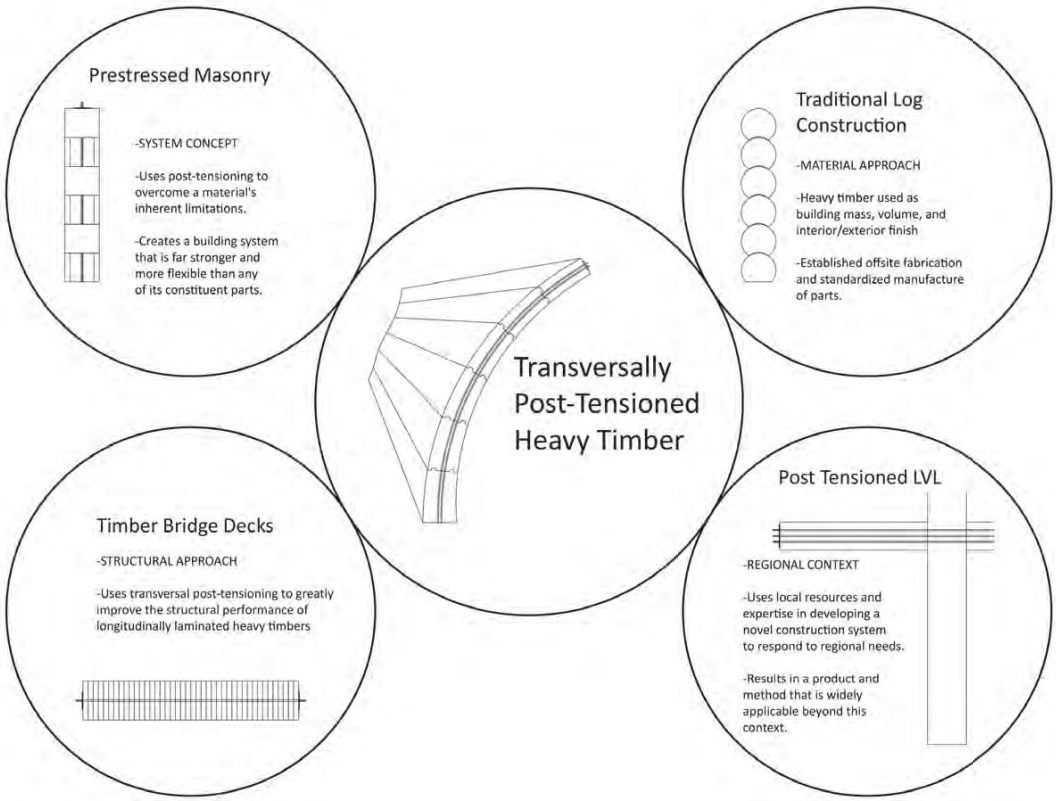
PROJECT ARCHITECTURE HAS BEEN AWARDED WITH: • 2014 DESIGN ARTS UTAH JUROR'S AWARD • 2014 ACSA DIVERSITY ACHIEVEMENT AWARD • 2014 HONORABLE MENTION AWARD • PUBLIC INTEREST DESIGN AWARD • 2014 ACSA COLLABORATIVE PRACTICE AWARD

Credit: Euclid Timber, Girl Scouts of Utah, ITAC UofU

PROJECT: ARCHITECTURE

CABIN #1 INTERIOR WITH TABLE DESIGNED BY ARCHITECTURE STUDENTS

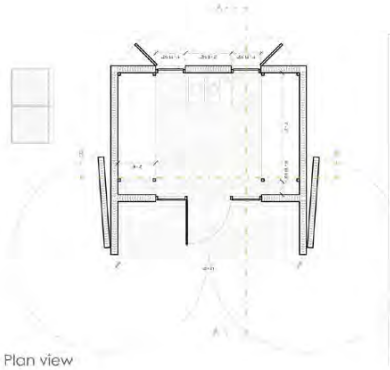
Credit: Euclid Timber, Girl Scouts of Utah, ITAC UofU



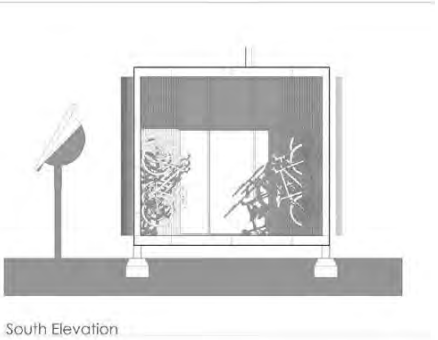
Credit: ITAC UofU

• Problem Identification

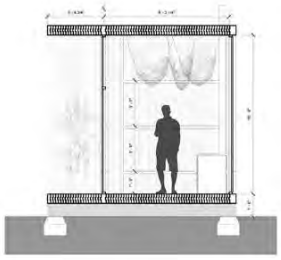
San Juan county is the poorest county in the state of Utah. It has many recreational opportunities that are not being utilized. As a result the city of Monticello is looking for any ways to develop a new trail system simillar to the Appalachian trail in North Carolina. This system would include a series of cabins along the trail that accomodate multiple adventurers.

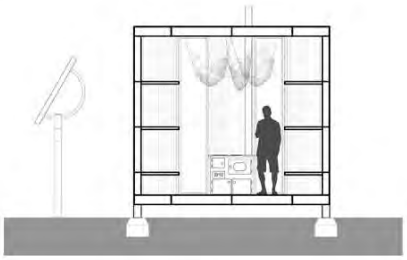


Plan view

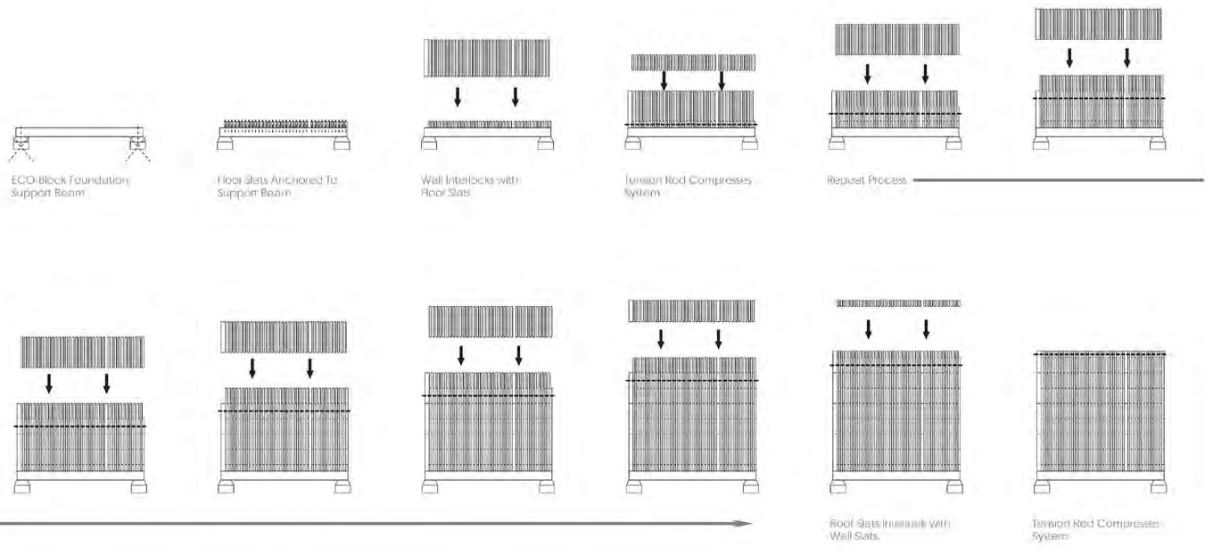


South Elevation

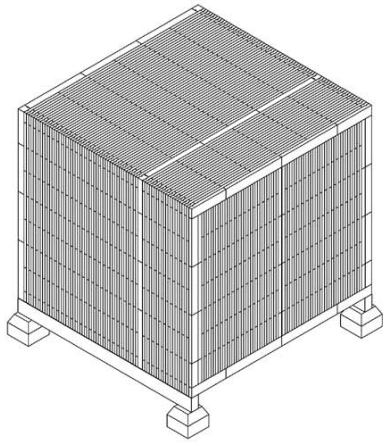




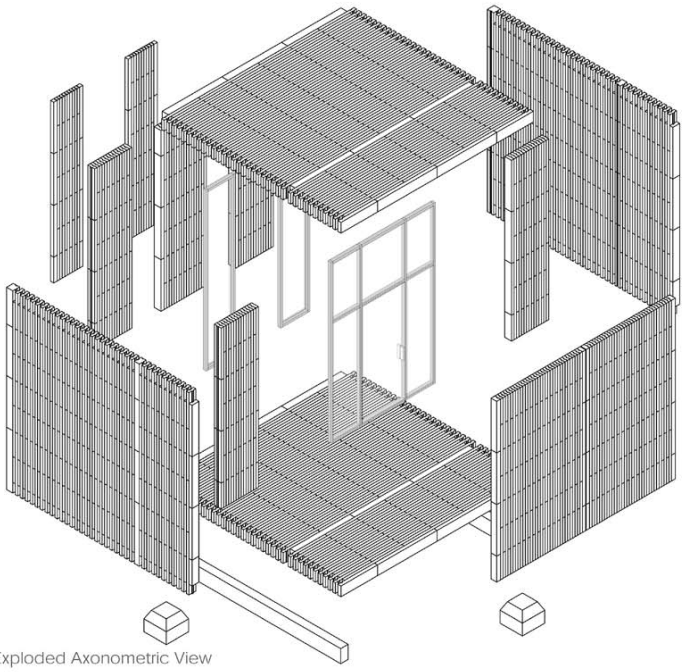
Credit: ITAC UofU



Credit: ITAC UofU

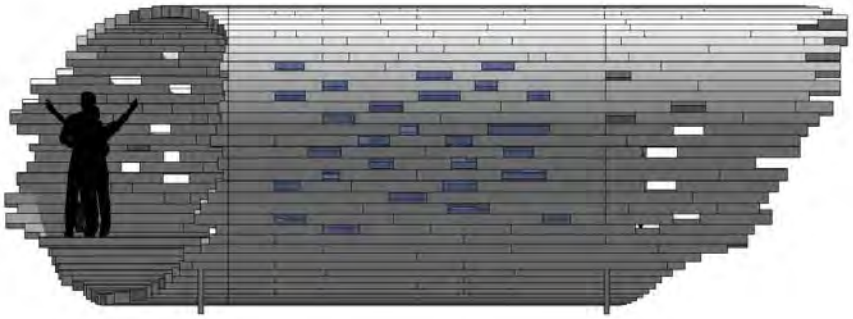


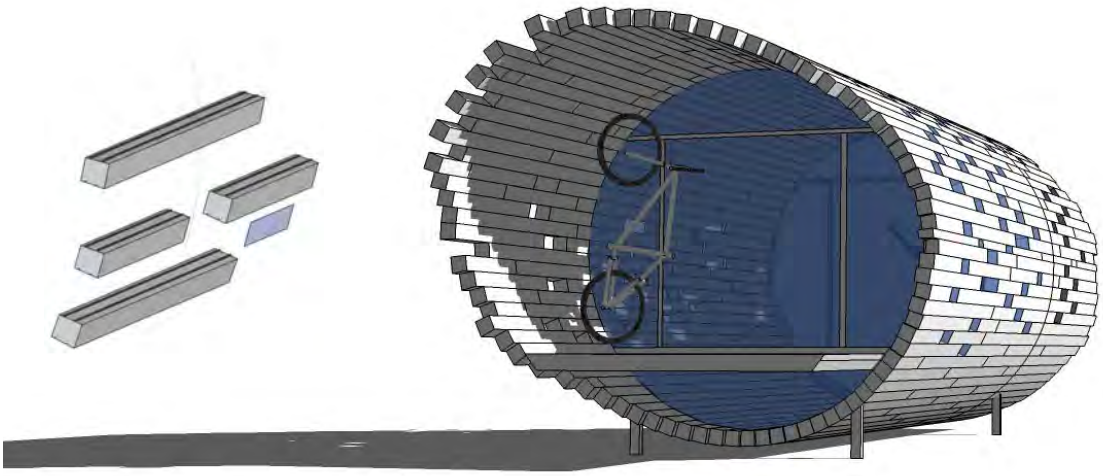
Axonometric View



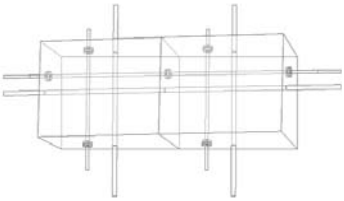
Exploded Axonometric View

Credit: ITAC UofU

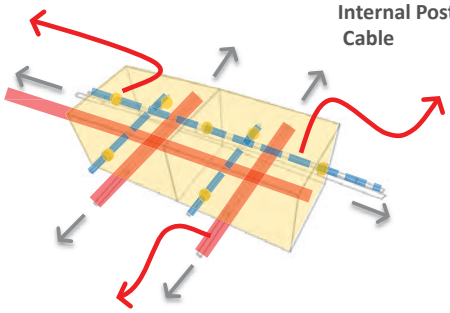




Credit: ITAC UofU

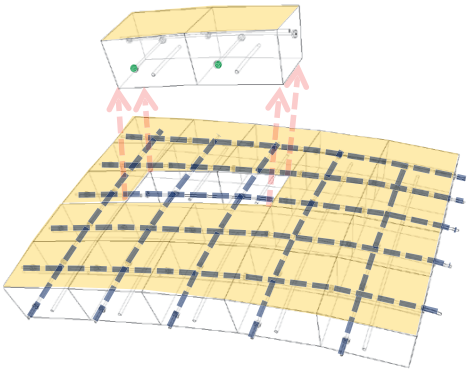


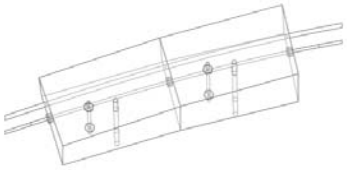
Connection Piece

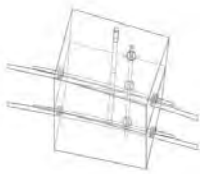


Internal Post- tension Cable

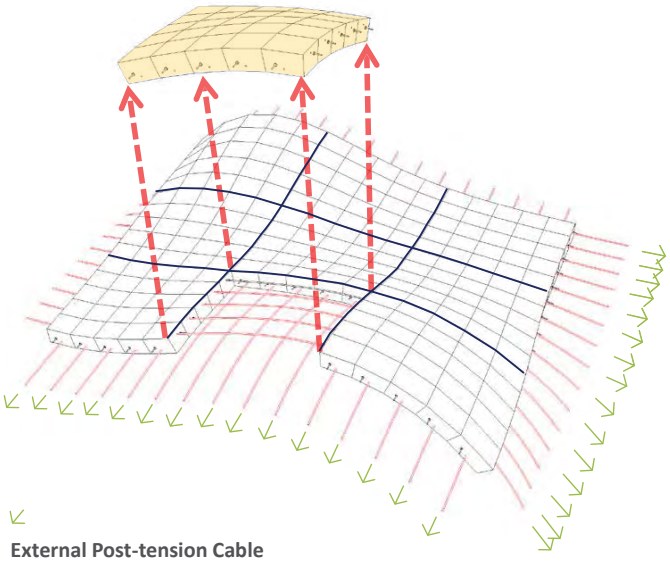
External Post-tension Cable



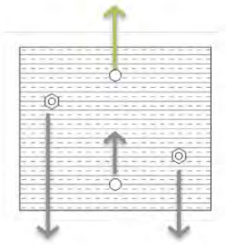


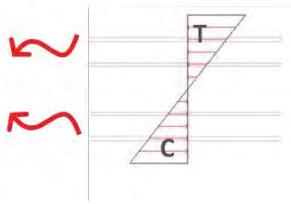


Credit: ITAC UofU

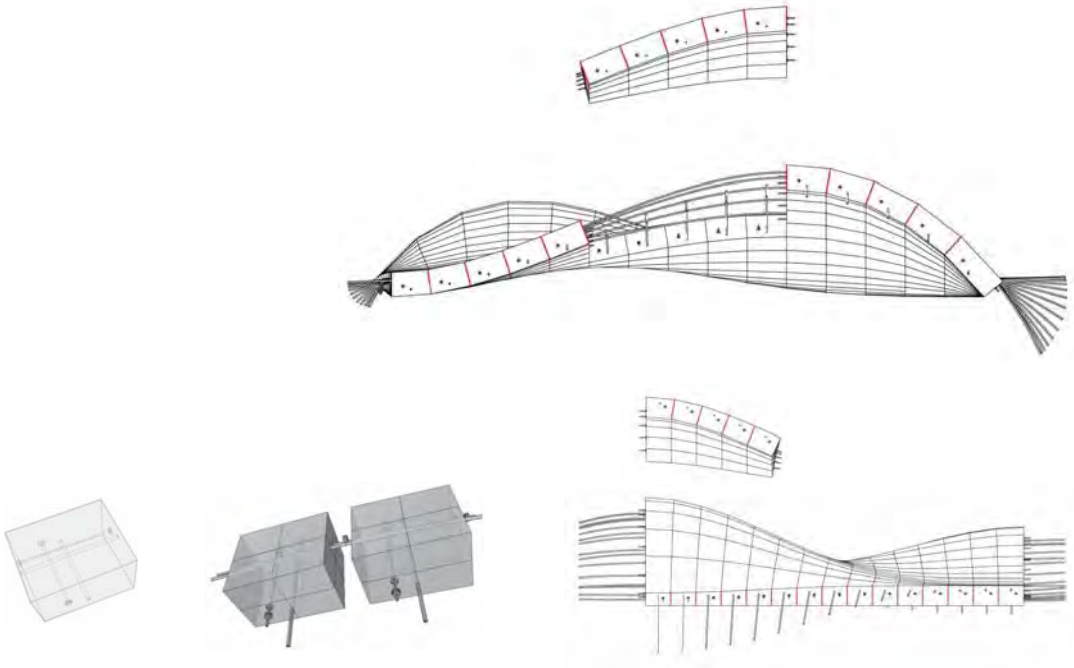


External Post-tension Cable





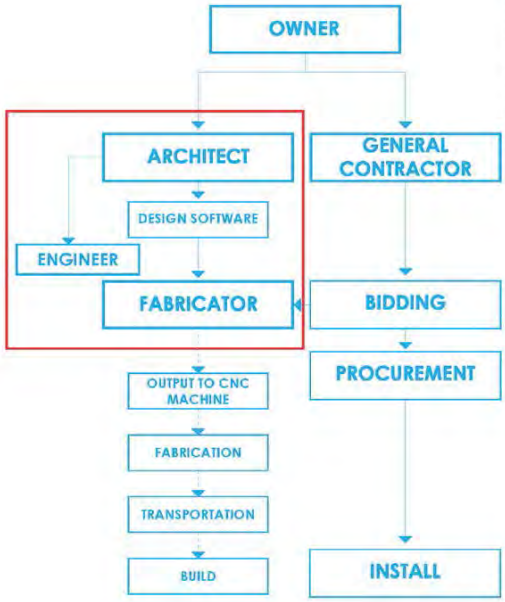
Credit: ITAC UofU



Credit: ITAC UofU

OPTIMIZATION

TIMBER WORK FLOW — I

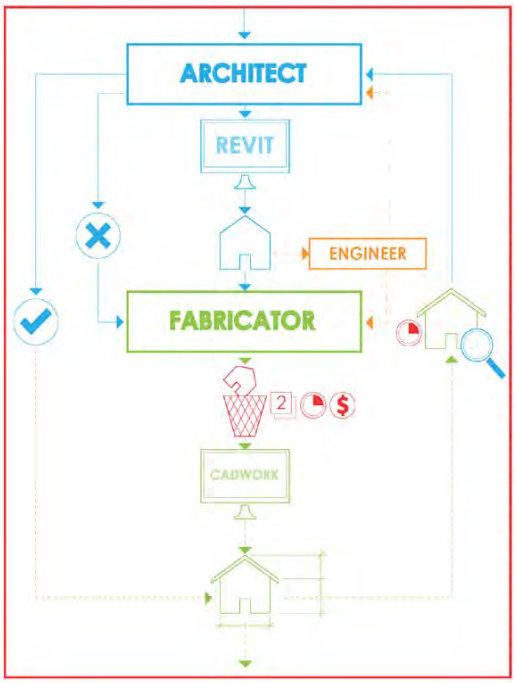


INTRO

The structure of the workflow in the timber industry will vary depending on the contract structure. These examples take a traditional contract workflow and analyze the roles of the Architect, Structural Engineer. The structure shown here is a Design Build contract.

In evaluating the workflows, 3 suggestions were formulated to overcome the barriers of interoperability.

TRADITIONAL DELIVERY — II



INTRO

This method is the most widely used throughout the industry. The architect and fabricator hardly communicate, and two seperate models are being prepared. The fabricator designs the project in their CAD/CAM software that communicates with CNC machinery. The model given to them by the architect is only used for reference.

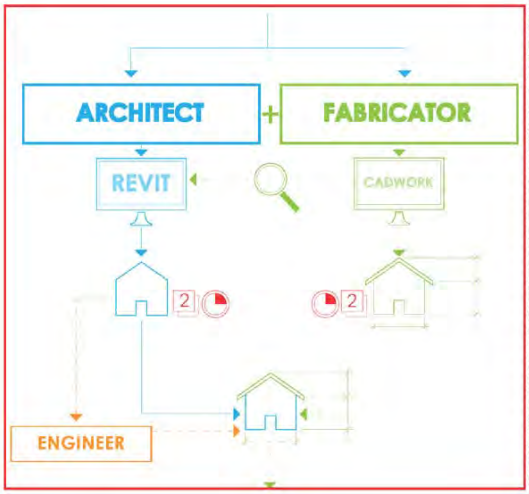
PROS
- RISK CLEARLY DELINEATED
- QUALITY ASSURANCE

CONS
- TAKES LONGER
- EXTRA FABRICATION DESIGN TIME
- MORE WORK FOR ALL PARTIES
- MORE COST TO OWNER

SYMBOLS
- EXTRA TIME
- $ EXTRA MONEY
- 2 DUPLICATE WORK

Source: ITAC UofU

EARLY ENGAGEMENT OF FABRICATOR — 1



INTRO

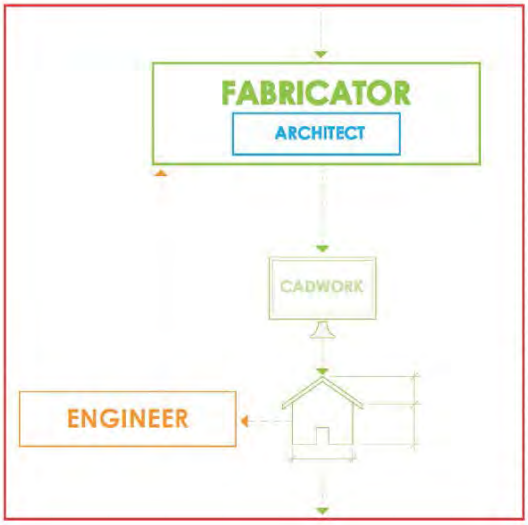
This method brings in the fabricator early, to act as a consultant to the architect. The fabricator educates the architect on how timber is used, its restrictions, and design suggestions. The fabricator simultaneously designs a model in their CAD/CAM software, using the architect's model as a guide.

PROS
- SAVES TIME
- FABRICATOR EDUCATES ARCHITECT
- NO SHOP DRAWINGS
- CONCURRENT CORRECTION/REVIEW

CONS
- TWO MODELS STILL BEING MADE
- TRY TO BALANCE DESIGN & FABRICATION

SYMBOLS
- 2 DUPLICATE WORK
- EXTRA TIME

FABRICATOR HIRES IN-HOUSE ARCHITECT — 2



INTRO

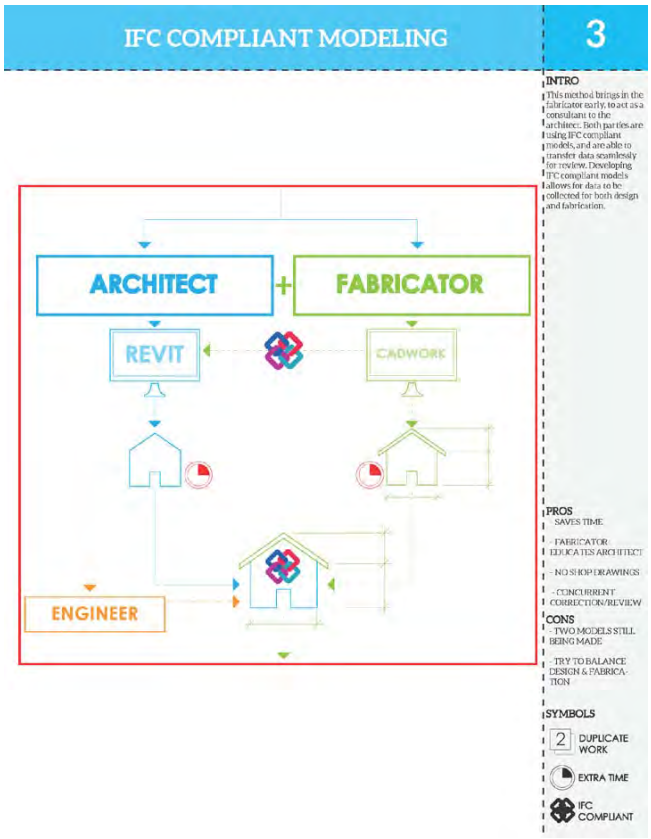
This method has an architect that works for the fabricator. The architect then designs using CAD/CAM software and not design software. The software has a lot of restrictions and does not allow for creative expression.

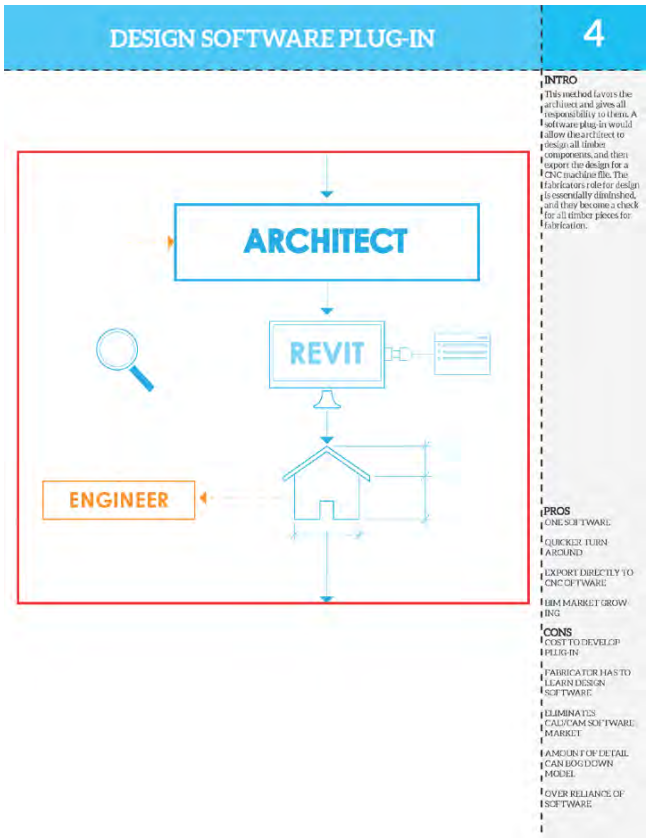
PROS
- ONLY ONE DIGITAL MODEL
- NO LOSS OF INFORMATION
- INTEGRATED DESIGN/FABRICATION PROCESS

CONS
- ARCHITECT HAS TO LEARN CAD/CAM SOFTWARE
- LIMITED DESIGN ABILITY
- FABRICATOR LED DESIGN MAY LACK HOLISTIC PERSPECTIVE
- OTHER SYSTEMS INTEGRATION MODELING LACKING

cadwork SEMA EXPERIENCE D Dietrich's hsbCAD

Source: ITAC UofU

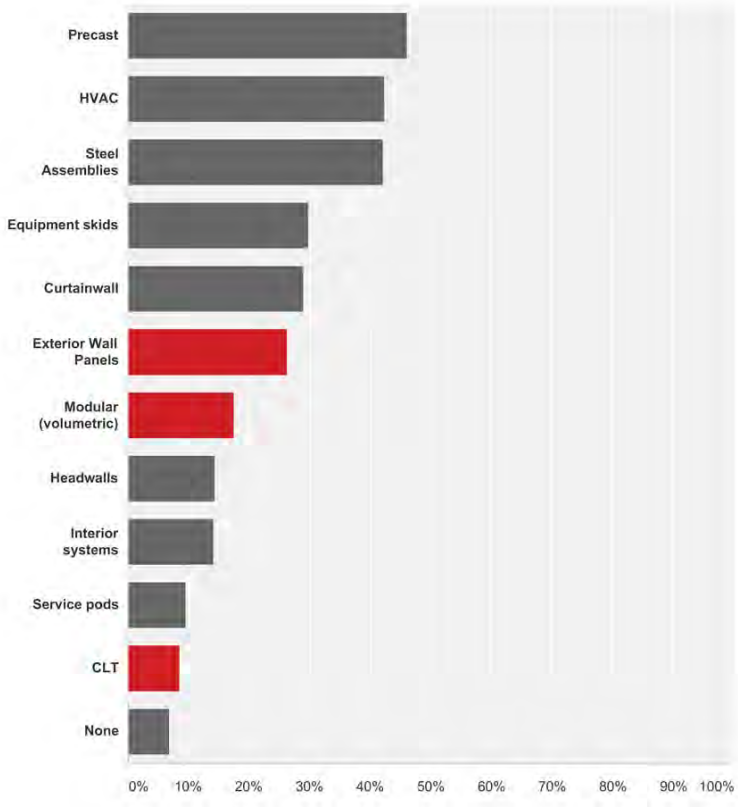


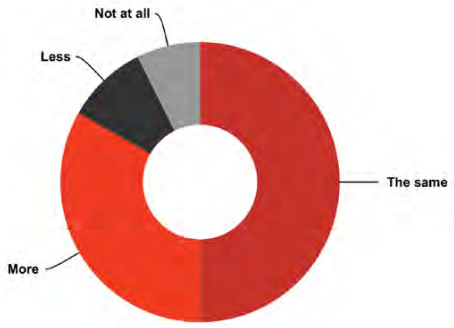


Source: ITAC UofU

PERFORMANCE

ELEMENTS USED IN LAST 12 MO?

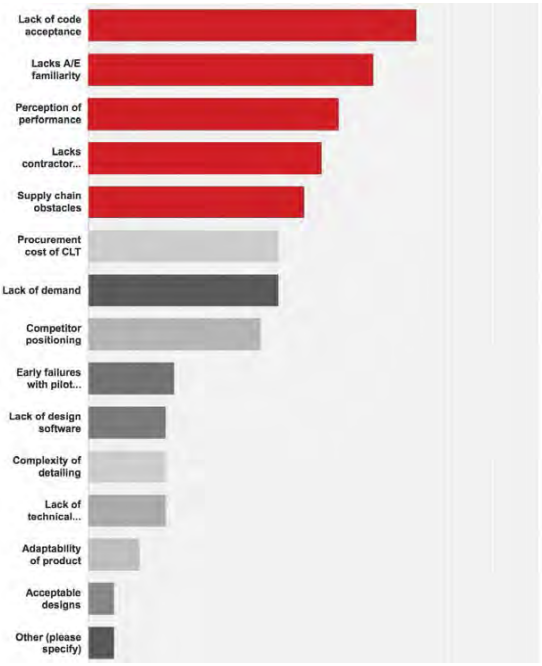




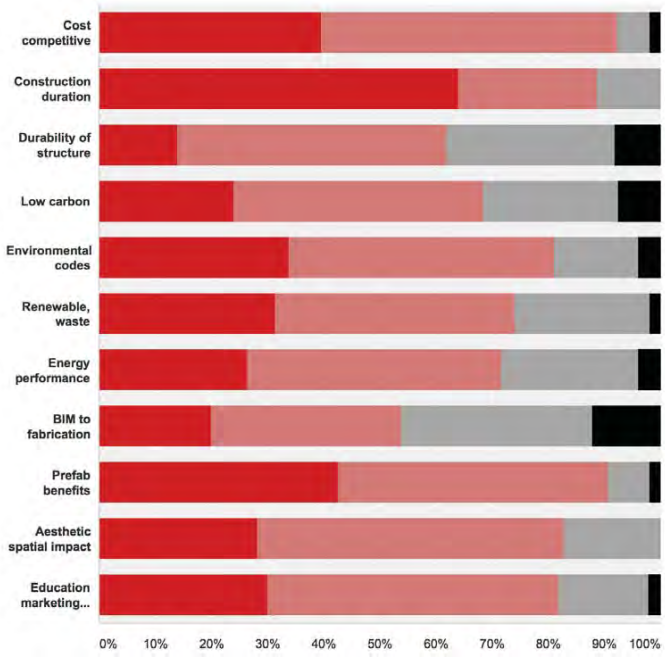
NEXT 12 MO?

Source: NIBS OSCC

BARRIERS TO UPTAKE



BENEFIT OF SOLID-TIMBER



Credit: COCIS Edinburgh Napier University & ITAC UofU

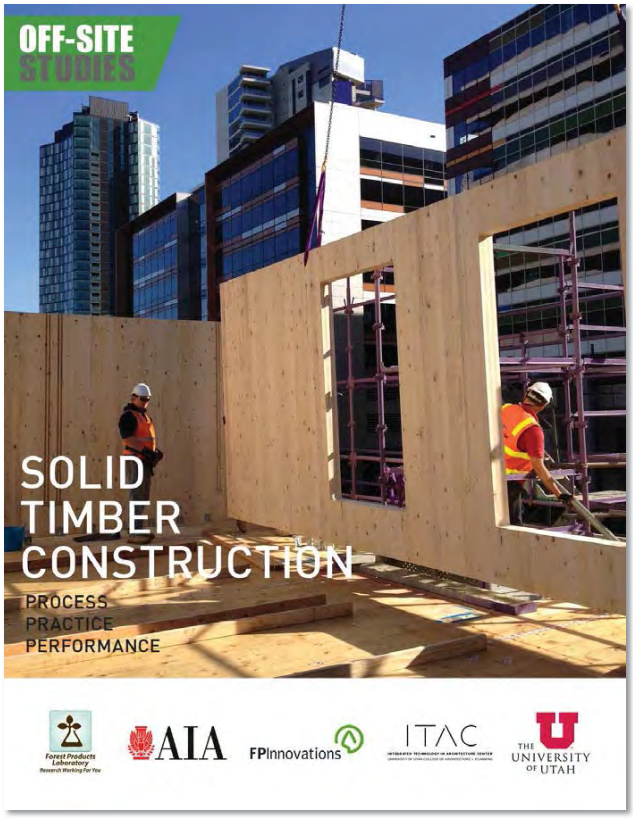


TABLE 3 - CASE STUDIES

Case studies included herein are diverse in region and context.

PROJECT	LOCATION
Bridport House	Hackney, London, UK
Bullitt Center	Seattle, WA, USA
Carlisle Lane Lofts	Waterloo, London, UK
Centre for Creative Competitive Design	Bedforshire, UK
Elkford Community Centre	Elkford, BC, Canada
Fort McMurray Airport	Fort McMurray, Canada
Forté	Melbourne, Australia
Holy Trinity Primary School	Richmond, London, UK
Massive Living	Graz, Austria
Open Academy	Norwich, UK
Smart Price House	Hamburg, Germany
SmartLIFE Centre	Cambridge, UK
Tamedia Office Building	Zurich, Switzerland
The Long Hall	Whitefish, MT, USA
UBC Earth Systems Science Building	Vancouver, Canada
UBC Okanagan Fitness & Wellness Center	Kelowna, BC, Canada
Via Cenni	Milano, Italy
Wagramerstrabe	Wien, Austria

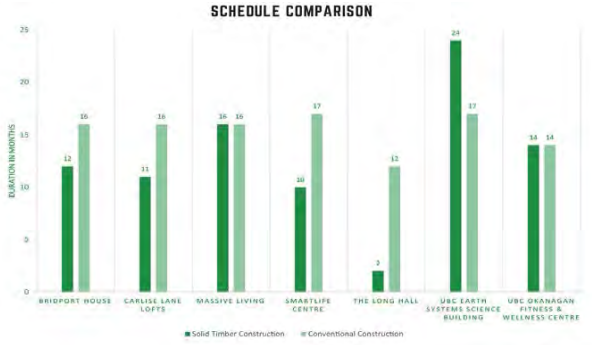


Figure 23

Schedule comparison in months analysed by Cumming Corp.

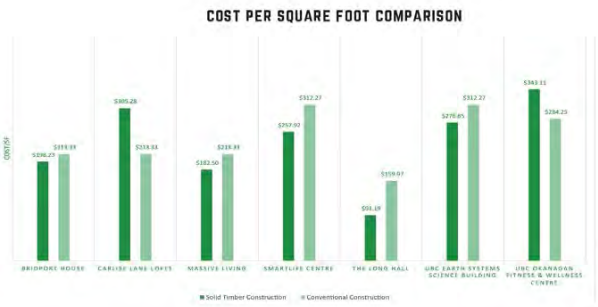


Figure 24

Cost per square-foot comparison analysed by Cumming Corp.

Figure 25

Pro-Formas include a cost reduction in terms of a 25% and 50% faster build time. The lease rate information assumes a 100% building occupancy to reflect the possible savings.

Figure 26

Pro-Formas include a cost reduction in terms of a 25% and 50% faster build time. The lease rate information assumes a 100% building occupancy to reflect the possible savings.

BRIDPORT HOUSE
HACKNEY, UK

Architect: Karakusevic Carson Architects
CLT Supplier: Stora Enso
Contractor: Willmott Dixon Housing

ABOUT
Designed as the first phase of the regeneration of the Colville Estate, Bridport House was commissioned by Hackney Council to replace an original 1950s block with 41 new homes in two joined blocks, one eight stories high and the other five stories.
All elements from the ground floor upwards are CLT – including the lift shaft. Below ground level (the piles, foundations and lift pit) is reinforced concrete.

GENERAL
HOUSING BUILDING TYPE

2011 YEAR COMPLETED
45,424 SQUARE FEET (4,220M²) (FT²)
55,726 TIMBER VOLUME (1,578M³) (FT³)
8 + 5 STORIES TALL

COST
£5.8M CONSTRUCTION COST
£1.2M CLT CONTRACT

SCHEDULE
18 MONTHS FROM START TO FINISH
12 MONTHS UNDER CONSTRUCTION
6 MONTHS FOR DESIGN
6 WEEKS IN FACTORY
14 WEEKS TO ERECT
850 MILES FROM FACTORY TO SITE

COMPARISON
7% MORE COST EFFECTIVE
$198.19* PER S.F.
25% FASTER CONSTRUCTION
Normalized to the first quarter of 2014 in US Dollars and Washington, DC

LESSONS LEARNED
The biggest acclaim for this project was the ability to double the size of the replacement structure with only a 10% increase in overall weight. A summation of the lessons learned provided by the stakeholders interviewed are outlined below:

- Front load even more of the design process to help better streamline the fabrication and construction process.
- Full BIM integration
- Allow designers and specialists to be involved through the entire project to facilitate new methods of construction to completion.

Photo Credits: Karakusevic Carson Architects & Willmot Dixon Housing

REFERENCES

- Mannewitz, Stefan. Karakusevic Carson Architects. Online survey on 8.1.14
- Cook, Steve. Willmott Dixon Housing. Online survey on 9.3.14
- Fovargue, Johnathan. Eurban. Phone interview with Gentry Griffin on 6.11.14

	BRIDPORT HOUSE	COMPARED PROJECT
CONSTRUCTION DURATION	12 MONTHS	16 MONTHS
STORIES AND CONSTRUCTION TYPE	8 STORIES WOOD	4 STORIES WOOD
SQUARE FOOTAGE	45,424	55,000
COST	$9M	$11.7M
COST/SF	$198.23	$213.33

EXTRINSIC RESEARCH

CONSTRUCTION PERFORMANCE
- COST AND SCHEDULE PERFORMANCE
- WORKER SAFETY
- CHANGE ORDER REDUCTION

SOCIAL BENEFITS
- ENVIRONMENTAL IMPACT
- ALTERNATIVE MASS TIMBER WITH LOCAL SUPPLY CHAIN
- TAX INCENTIVES

MARKETS
- REGIONS AND BUILDING TYPE COMPATABILITY
- DECISION MAKING / DEMAND MANAGEMENT
- REGULATORY PATHWAYS

PROJECT DELIVERY TOOLS
- DETAILS AND SPECIFICATION INFORMATION
- SOFTWARE TOOL DEVELOPMENT
- CONTRACTS AND PROJECT MANAGEMENT TOOLS

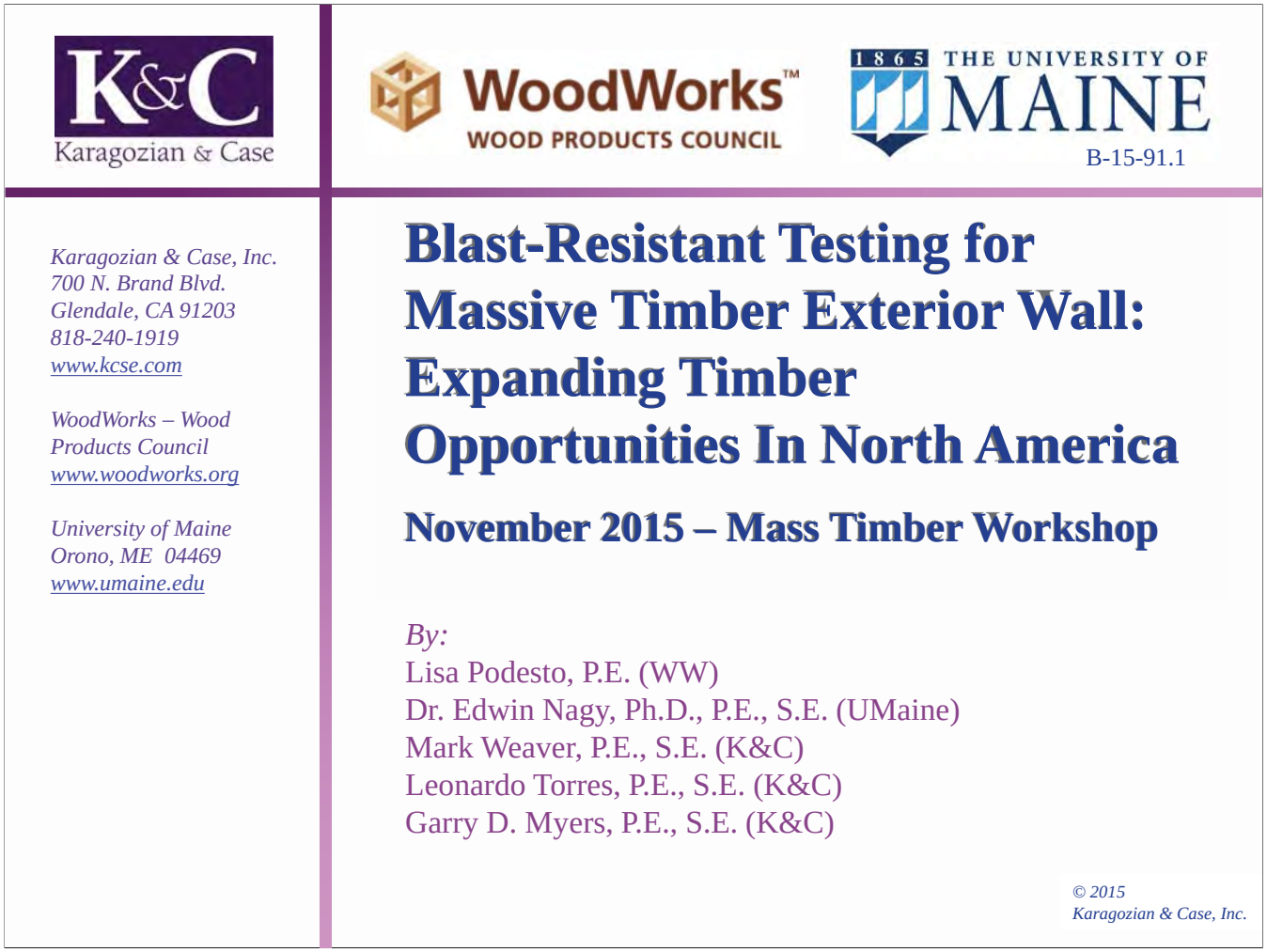
SUPPLY CHAIN DEVELOPMENT
- SALVAGE WOOD SUPPLY
- DRYING INFRASTRUCTURE

ITAC THE UNIVERSITY OF UTAH

Blast-Resistant Testing for Massive Timber Exterior Wall: Expanding Timber Opportunities in North America

Lisa Podesto, Senior Technical Director
WoodWorks, Aptos, California

This presentation will share the research plan with regard to performance of mass timber walls under blast loading. The project goal is to characterize the response of cross laminated timber (CLT) panels under blast loading and establish inelastic and ultimate response limits of CLT structural systems to gain repeatable approval for CLT construction on United States military bases where there is currently little room for wood structural solutions. As a project that recently received funding from the USDA Wood Innovation Grant program, the research is intended to support expansion of the U.S. wood products market.



Project Objectives

- Expand market opportunities for wood construction in Department of Defense and growing civilian markets requiring blast resistant structures.
- Work with the Army Corps of Engineers Protective Design Center to develop an acceptable mass timber blast resistant alternative to steel and masonry.
- Create a basis for inclusion of mass timber solution(s) in the Unified Facilities Criteria's conventional construction provisions.

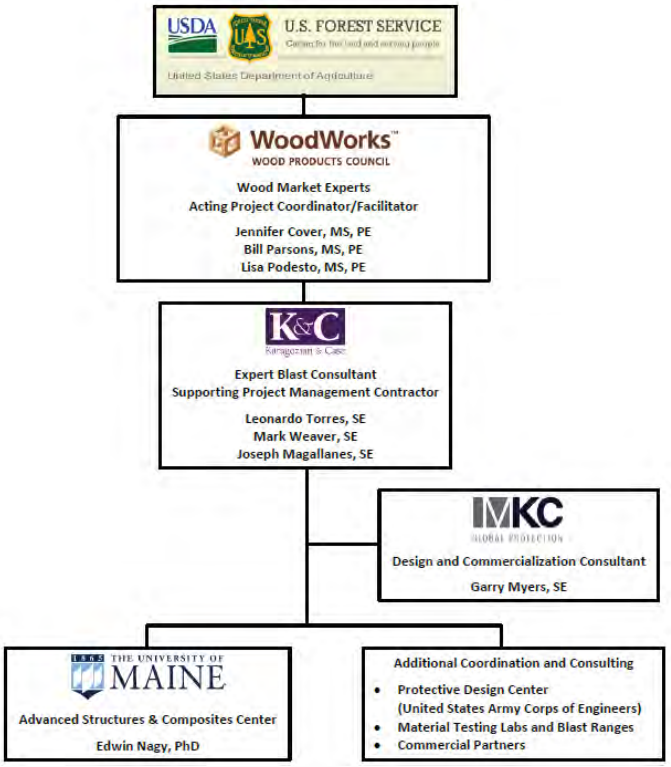
Project Deliverables

- Develop analytical methodologies to analyze CLT for blast loads. Both SDOF and high-fidelity physics-based (HFPB) FE methods will be developed.
- Conduct static and dynamic CLT testing that tests / improves developed analytical methodologies.
- Document analytical methodologies and test data in a form that could be used in blast analysis by structural engineers and potentially incorporated into SBEDS.
- Establish a foundation for characterizing material dynamic response of Nail Laminated Timber walls.

Project Overview
Approach & Organizational Chart

B-15-91
pg 4

- Conduct literature review.
- Develop preliminary SDOF analysis methodology.
- Define target conventional CLT construction.
- Create HFPB FE CLT model.
- Perform static CLT testing.
- Refine SDOF and HFPB FE analysis methodologies.
- Perform dynamic CLT testing.
- Document literature review, analysis methodologies, and testing results in report form.
- Publicize findings of effort.



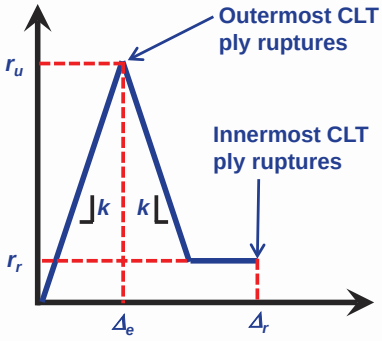
Literature Review
Overview

B-15-91
pg 5

- **Sources Sought**
  - *Published testing results that document out-of-plane response of CLT.*
  - *Case studies that document the usage of CLT in practice.*
  - *CLT standards and design aids.*
- **Conclusion**
  - *Limited published test results that documents out-of-plane response of laminated timber exposed to high-strain rates.*

Preliminary Scoping Analyses
Single Degree-of-Freedom

- **Preliminary Assumptions**
  - ***Ultimate resistance, r_u, and equivalent stiffness, k, derived using "shear analogy" method (Kreuzinger, 1999).***
    - Both flexural and shear stiffness were used to derive equivalent stiffness.
  - ***Residual resistance, r_r, derived assuming innermost ply(s) provides flexural strength.***
  - ***Assume immediate softening stiffness is equivalent to initial stiffness.***
  - ***Static increase factor (from ANSI/APA PRG 320-2012)***
    - 2.1 for out-of-plane flexure.
    - 3.15 for out-of-plane shear.
  - ***Dynamic increase factor set equal to one and $C_D = 1$***
  - ***Response limit: Ductility, $\mu = 1$ (i.e., elastic response only).***
- **All of the above assumptions will be investigated via the UMaine static testing and ideally refined based on uOttawa and PDC CLT testing.**



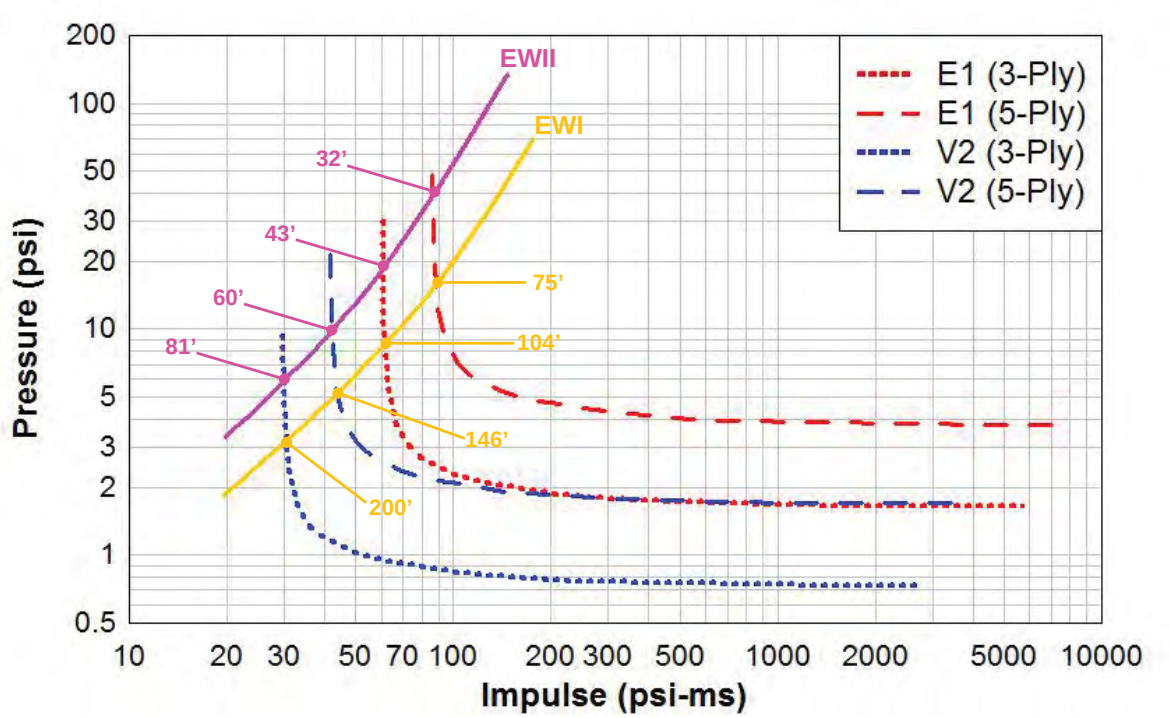
Schematic SDOF Flexural Resistance Function for 3-Ply CLT

Preliminary Scoping Analyses
Typical Grade Information

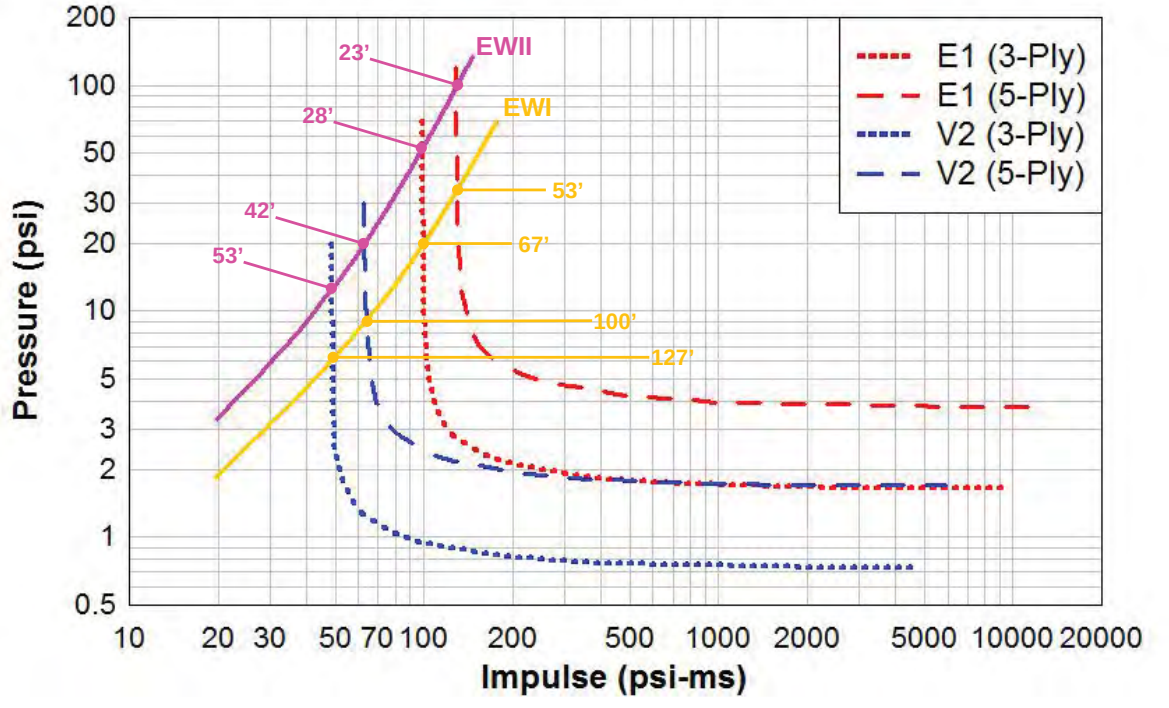
TABLE A1.
ALLOWABLE DESIGN PROPERTIES[a,b,c] FOR PRG 320 CLT (for use in the U.S.)

	Major Strength Direction						Minor Strength Direction					
CLT Grades	$F_{b,0}$ (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)
E1	1,950	1.7	1,375	1,800	135	45	500	1.2	250	650	135	45
E2	1,650	1.5	1,020	1,700	180	60	525	1.4	325	775	180	60
E3	1,200	1.2	600	1,400	110	35	350	0.9	150	475	110	35
E4	1,950	1.7	1,375	1,800	175	55	575	1.4	325	825	175	55
V1	900	1.6	575	1,350	180	60	525	1.4	325	775	180	60
V2	875	1.4	450	1,150	135	45	500	1.2	250	650	135	45
V3	975	1.6	550	1,450	175	55	575	1.4	325	825	175	55

Preliminary Scoping Analyses
Supported Weight: Wood Panel (i.e., 10 psf)



Preliminary Scoping Analyses
Supported Weight: Brick Veneer (i.e., 44 psf)



Preliminary Scoping Analyses
Proposed Conventional Construction Options

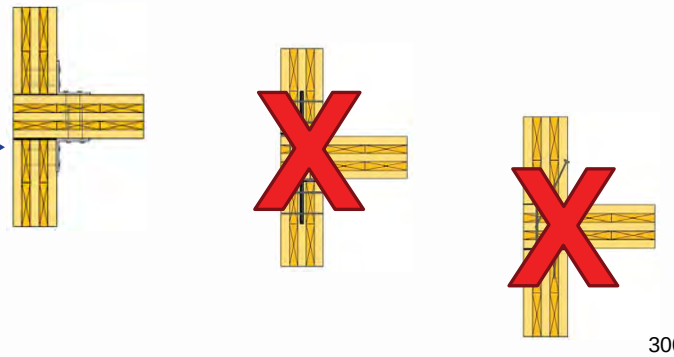
B-15-91 pg 10

Wall Type	Sections	Span	Min. Static Material Strength	EWI Standoff Distance	EWII Standoff Distance
Reinforced Concrete	≥ 6”	12’ – 20’	3,000 psi	66	**16**
CLT – Brick Veneer (44 psf)	5-ply	10’ – 14’	Grade E1	53	**23**
CLT – Brick Veneer (44 psf)	3-ply	10’ – 14’	Grade E1	67	**28**
Reinforced Masonry	8” – 12”	10’ – 14’	1,500 psi	86	**30**
CLT – Wood Panel (10 psf)	5-ply	10’ – 14’	Grade E1	75	**32**
Wood Studs – Brick Veneer	2x4 & 2x6	8’ – 10’	875 psi	105	**36**
CLT – Brick Veneer (44 psf)	5-ply	10’ – 14’	Grade V2	100	**42**
CLT – Wood Panel (10 psf)	3-ply	10’ – 14’	Grade E1	104	**43**
CLT – Brick Veneer (44 psf)	3-ply	10’ – 14’	Grade V2	127	**53**
CLT – Wood Panel (10 psf)	5-ply	10’ – 14’	Grade V2	146	**60**
Steel Studs – Brick Veneer	600S162-43; 600S162-54; 600S162-68	8’ – 12’	50,000 psi	187	**75**
CLT – Wood Panel (10 psf)	3-ply	10’ – 14’	Grade V2	200	**81**
Wood Studs – EIFS	2x4 & 2x6	8’ – 10’	875 psi	207	**86**
Steel Studs – EIFS	600S162-43; 600S162-54; 600S162-68	8’ – 12’	50,000 psi	361	**151**

Proposed Static CLT Testing
Overview

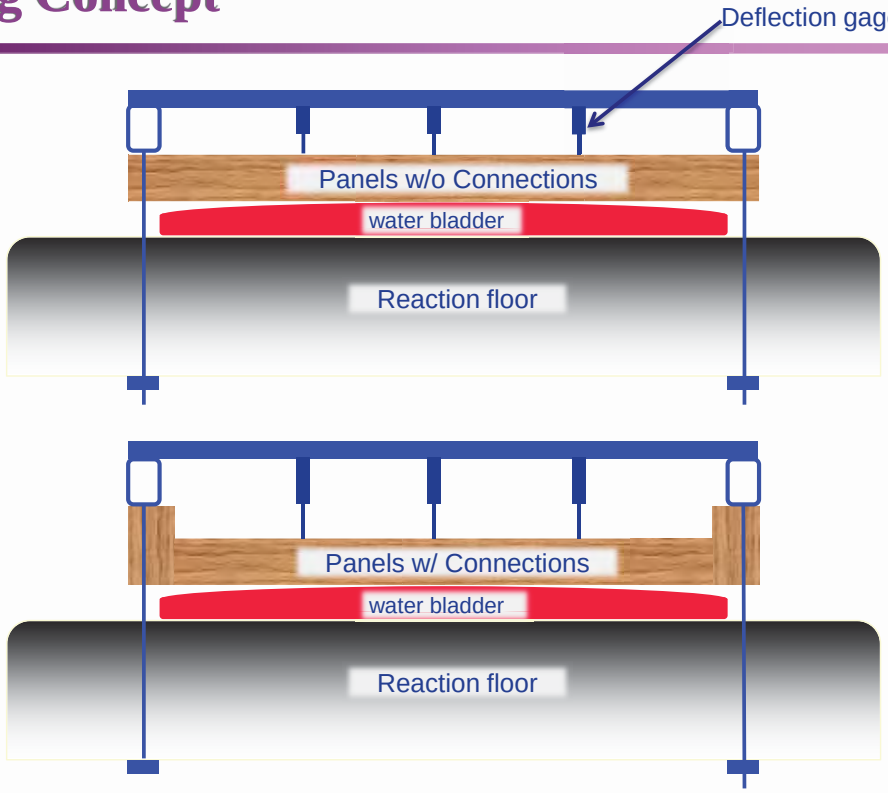
B-15-91 pg 11

- **Objective: Investigate out-of-plane behavior of CLT for different conventional connection configurations.**
- **Tests will be used to develop resistance functions for SDOF analysis.**
- **5 to 7 days of testing at University of Maine.**
- **Proposed panel: 3-ply (and/or 5-ply), two different grades, 4’x8’ specimen size.**
- **Two connection configurations to be tested (likely self-tapping screws & brackets).**
  - ***Baseline (i.e., roller supports)***
  - ***Brackets (weaker)***
  - ***Brackets (stronger)***



Proposed Static CLT Testing
Test Jig Concept

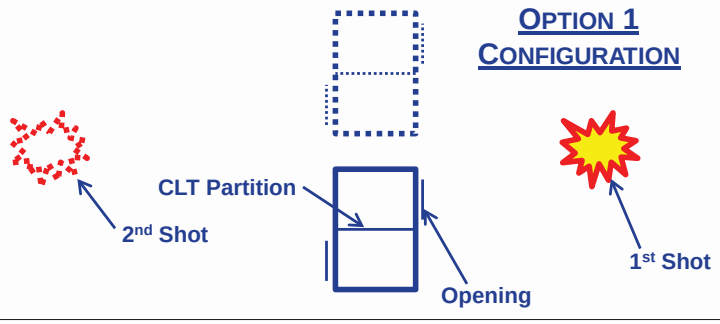
B-15-91
pg 12



Proposed CLT Dynamic Testing
Overview

B-15-91
pg 13

- **Objective**
  - ***To demonstrate the blast resistance capability of cross-laminated timber (CLT) via a live blast field full-scale test.***
  - ***To validate SDOF and HFPB FE analysis methodologies.***
- **Peak Blast Load**
  - ***EWII at 30-ft***
- **Test Configuration Options**
  - ***Option 1: One (or two) 1- to 2-story, 30'x15' two bay CLT structures.***
  - ***Option 2: (24) 4'x10' panels supported by previously constructed reaction structures. For purposes of cost, assume 3 panels are tested at a time.***



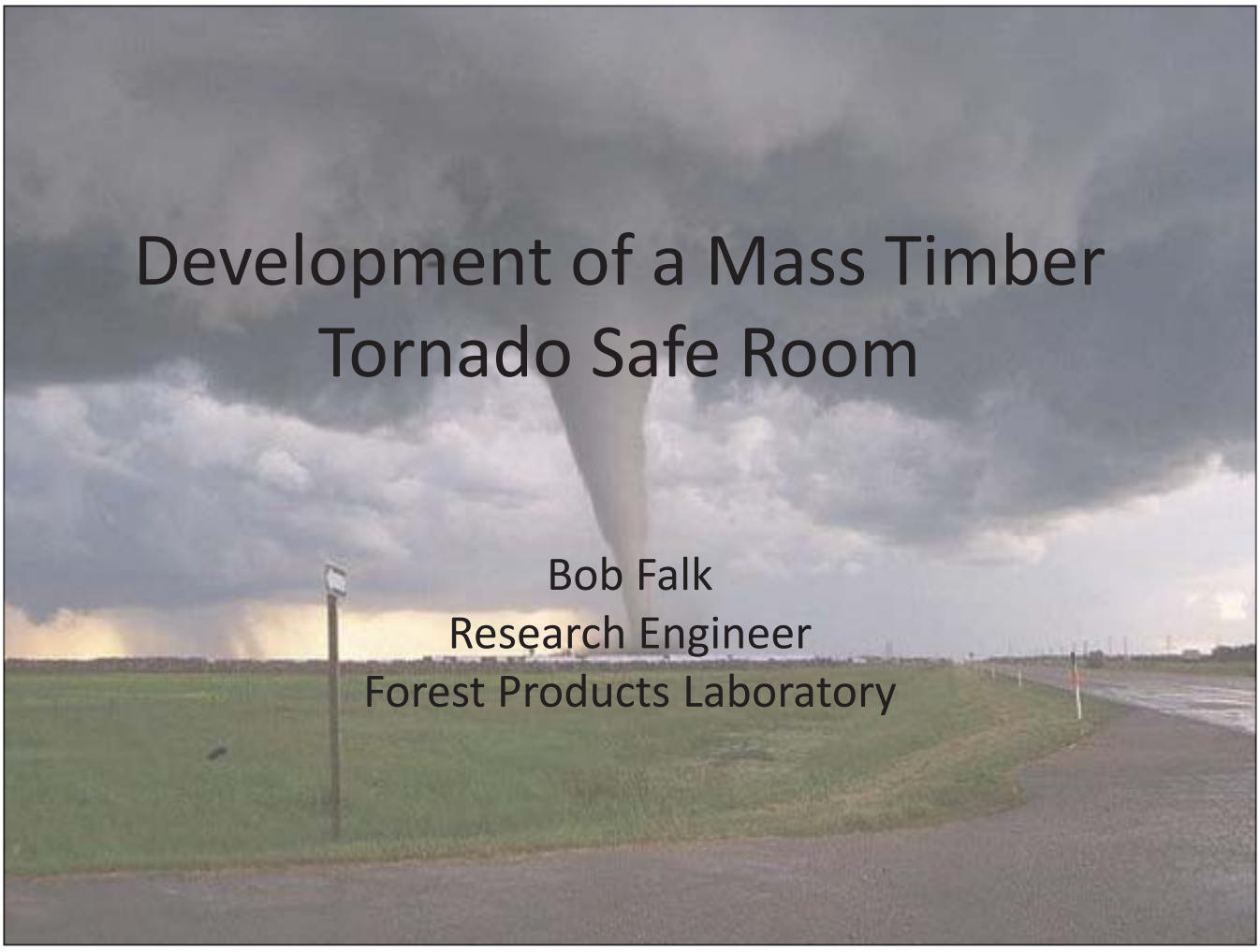
Live Blast Testing

B-15-91
pg 14

Development of a Mass Timber Tornado Safe Room

Bob Falk, Research Engineer
USDA Forest Products Laboratory, Madison, Wisconsin

This presentation will overview the development and impact testing of a tornado safe room built from mechanically laminated commodity wood products. Various wall designs were tested and indicate the effect of wood product type, fastening, adhesives, and sheathing type on impact resistance. Results of testing to develop a wood tornado safe room door will also be presented.



Objectives

- Design a residential tornado safe room from commodity wood products
  - Feasible for existing housing
  - Buildable by a DIY'er
  - Most materials available at a big box store
  - Low cost compared to existing steel and concrete safe rooms
  - Sized to serve another function and optimize material usage

Objectives (cont.)

- Perform wall and door testing to verify design for EF-5 tornado
  - Debris impact testing (2x4 @ 100mph)
  - Wind pressure testing (225 psf – 340 psf)
- Build full size room and wind load test
- Develop standard plans and guidelines for construction
- Develop a dynamic impact model to simulate wall behavior

Cooperative Effort

- FPL
  - Bob Falk, John Hermanson, Adam Senalik
- PFS Corporation (Cottage Grove, WI)
  - Deepak Shrestha

Status

- Impact test of walls panels and doors completed
- Research report on wall testing completed
- Research report on door testing in preparation
- Pressure testing initiated (in cooperation with PFS Corporation)
- Room built and wind load test setup under development
- Plans and construction guidelines to be developed
- Dynamic impact model developed and verified

For More Information

Bob Falk

rfalk@wisc.edu

(608) 231-9255

More with Less—An Overview of the First CLT Hotel in the United States

Jeff Morrow, Program Manager
Lendlease, Nashville, Tennessee

This presentation will provide an overview of the construction of the Redstone Arsenal Candlewood Suites Hotel built from cross laminated timber.

More with Less –
An Overview of the 1st CLT Hotel in the U.S.

Timber Innovations Group
2016 Mass Timber Research Workshop
November 3, 2016

lendlease

REDSTONE ARSENAL CLT PERFORMANCE COMPARISON VS. PREVIOUS METAL STUD NEW BUILD HOTELS IN PAL PORTFOLIO

The Case for CLT / Modular Construction

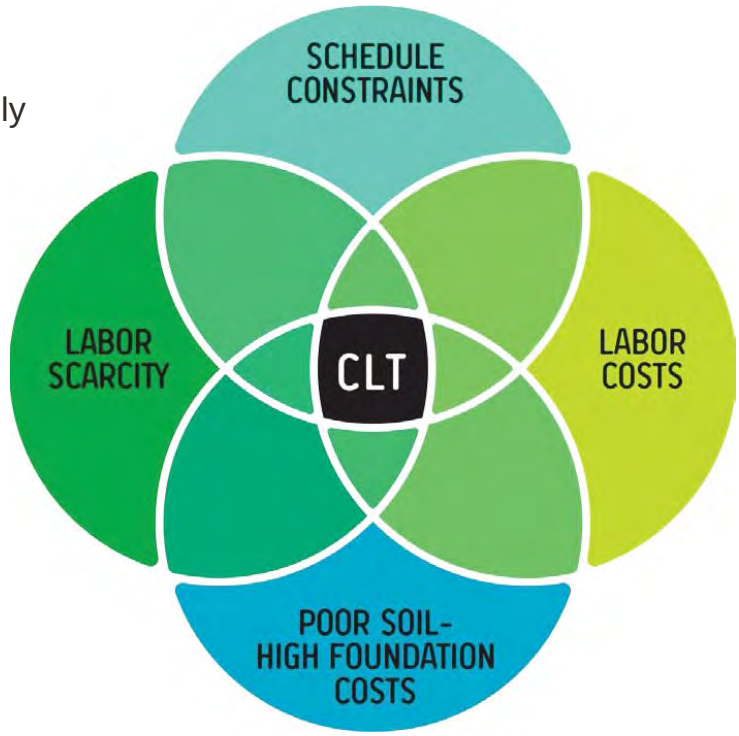
PAL PORTFOLIO	TYPICAL NEW PAL HOTEL (ACTUAL*)	REDSTONE ARSENAL (ACTUAL)	DIFFERENCE
Gross SF	54,891	62,688	+14%
Average # of Employees	18 (Peak 26)	10 (Peak 11)	-43%
Structural Duration (Days)	123	78	-37%
Structural Man Hours	14,735	8,203	-44%
Structural Production Rate/Day (SF)	460 SF/day	803 SF/day	+75%
Overall Schedule	15 months	11 months**	-27%**

** PAL New Build Hotel Historical Average*
***Forecasted completion 10/26/15*

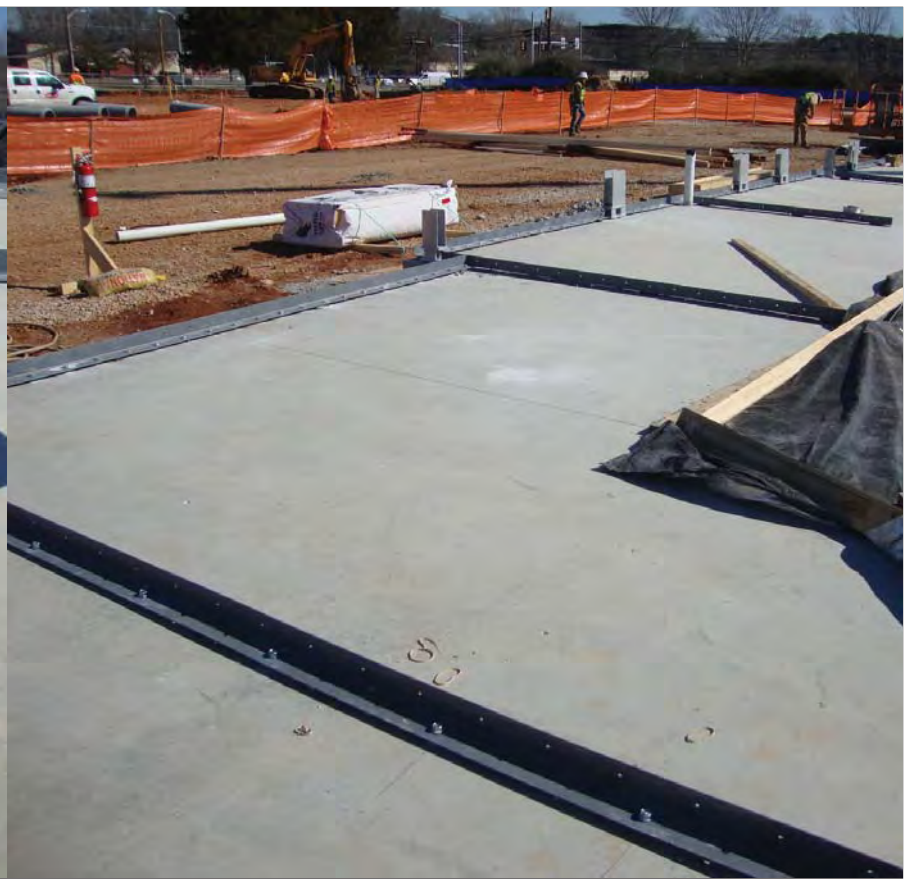
lendlease

The Sweet Spot

CLT should be strongly considered when a project experiences 3 of these 4 conditions.



lendlease



6
CraneWorks

CraneWorks
United Rentals

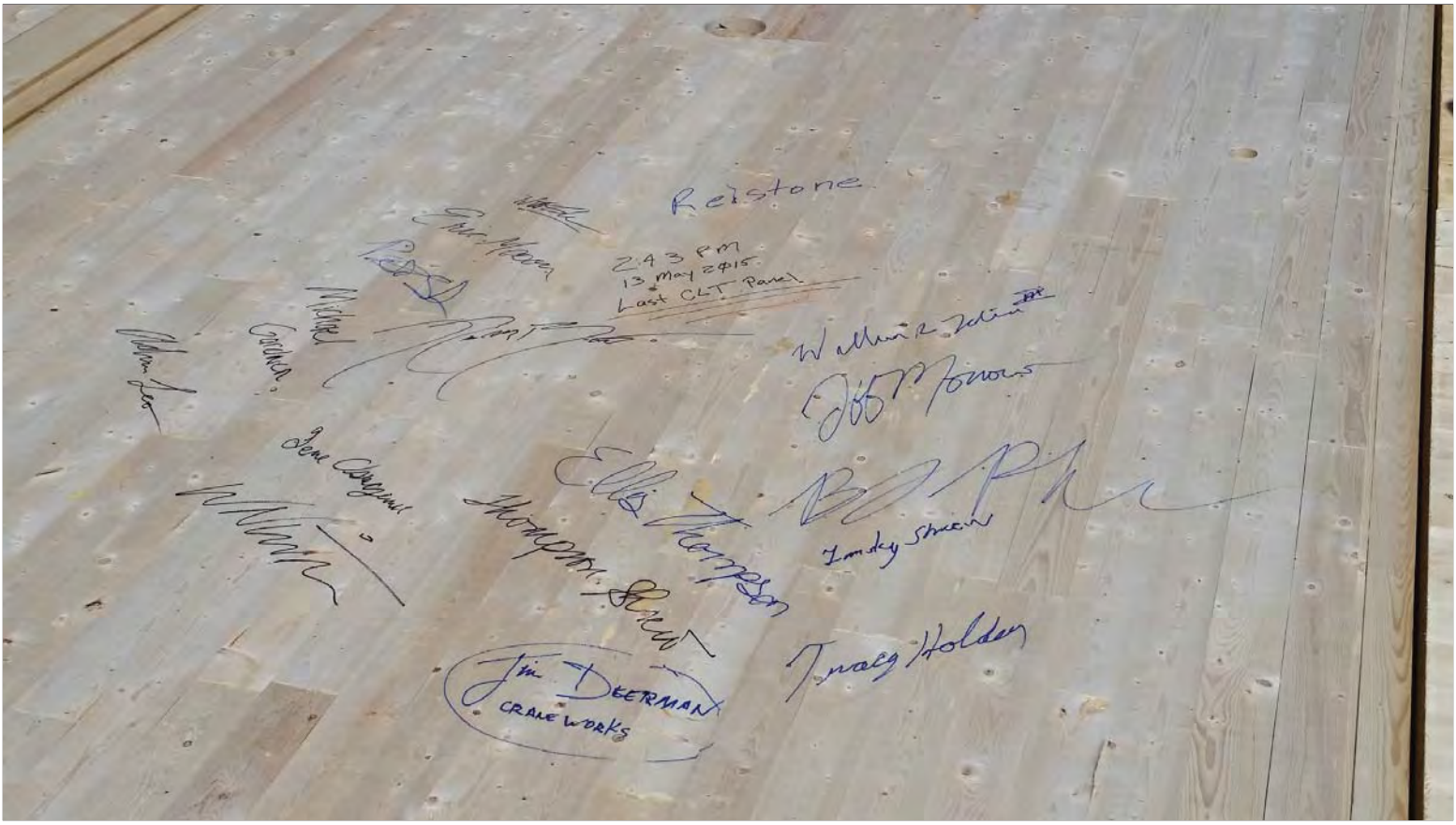
12

13

16

17

19



Economic

- 27% Faster *than Traditional Metal Stud Construction*
- Cost Neutral to Metal Stud Framing

Environmental

- 27% more energy efficient *than previous PAL New Hotels of similar size per current energy model*
- 1,656 tons carbon sequestered *(1 m3 of timber = 1 ton CO2)*

Social

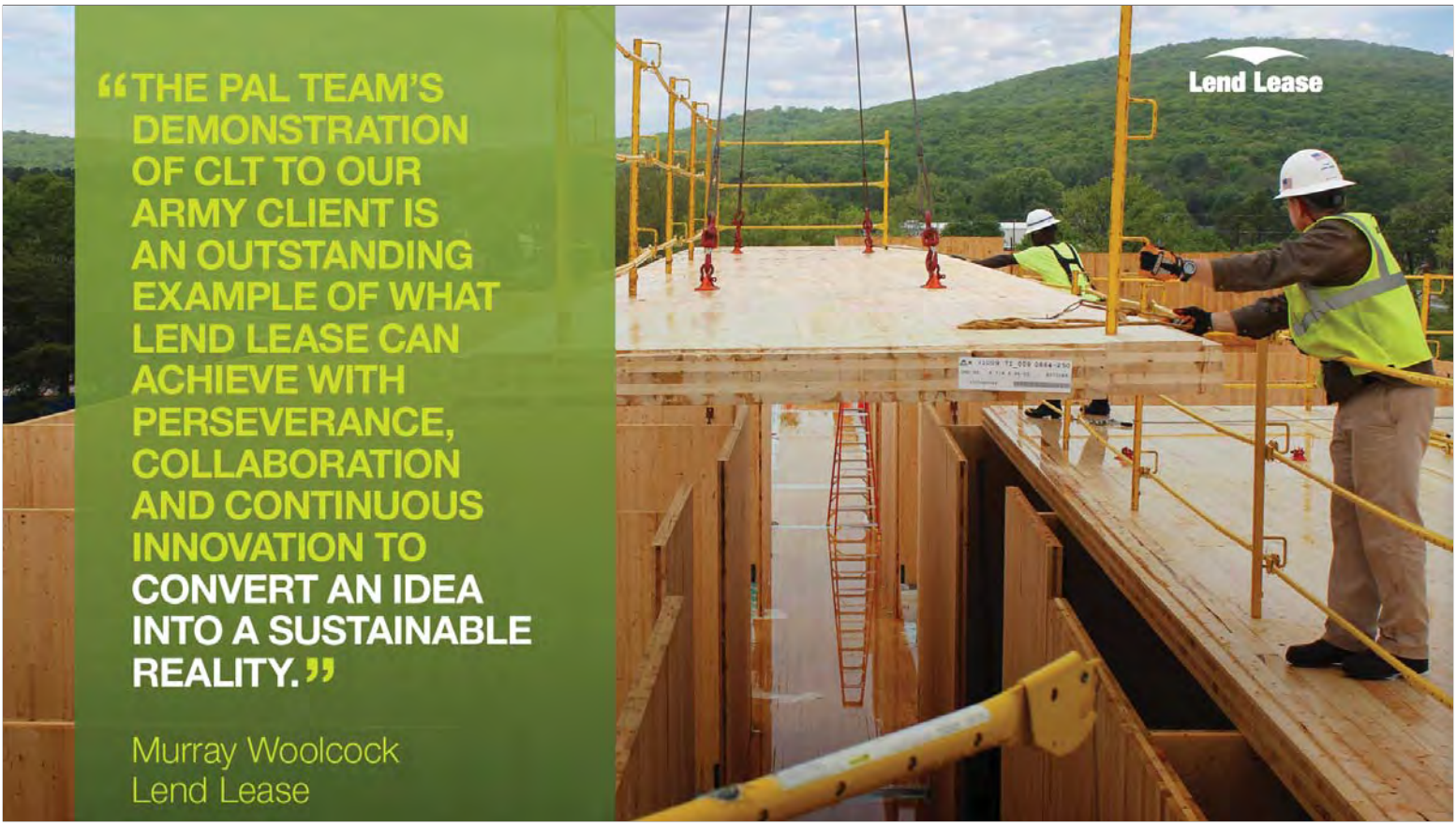
- Unemployed Veterans were upskilled in the construction trades.
- Eliminated exposure to falls for workers from elevated heights.

Smart Design Cannot Eliminate Human Error

R&D Priorities

- Testing
  - Fire (UL)
  - Force Protection / Blast Resistance
  - Seismic
    - What is the correct R-value?
  - Acoustical
  - Thermal Envelope
  - Vibration
- Regulatory/Political
  - AHJ Acceptance for taller buildings
  - Union Acceptance
  - DoL Recognition – CLT Installer

lendlease



"THE PAL TEAM'S DEMONSTRATION OF CLT TO OUR ARMY CLIENT IS AN OUTSTANDING EXAMPLE OF WHAT LEND LEASE CAN ACHIEVE WITH PERSEVERANCE, COLLABORATION AND CONTINUOUS INNOVATION TO CONVERT AN IDEA INTO A SUSTAINABLE REALITY."

Murray Woolcock
Lend Lease

THANK YOU

Keynote Presentation

Challenges of Building with Mass Timber in the United States

Robert Malczyk, Principal
Equilibrium Consulting, Vancouver, British Columbia, Canada

Equilibrium Consulting has been recently commissioned to work on two large U.S. based university projects: Integrated Design Center at UMass in Amherst Massachusetts and Peavy and AWP Research and Testing Building at Oregon State University. The purpose of this presentation is to present the wide variety of issues that we are confronted with by the design team when a project uses a mass timber solution. This presentation will list major challenges and elaborate more on the ones that can be addressed by research and development and code authorities.

Challenges List:

1. Find appropriate CLIENT.
    a. Educate the client.
    b. Develop trust.
2. Identify available GRANT – if possible.
3. Develop political support: federal, state or local
4. Find an open minded LOCAL CONSULTANT TEAM.
    a. Timber Engineer and EOR relationship – one or more structural consultants.
    b. Mechanical and Electrical
    c. Code – Fire
5. Educate client and consultant team about not code based parameters:
    a. Vibration criteria and limits.
    b. Deflections including creep and visual effects.
    c. Sound transfers.
6. Know what is currently in and what is coming up in local design CODES
7. Find appropriate PROJECT DELIVERY METHOD and scope of contracts: fabrication with or without erection.
    a. Construction Manager with open mind and willingness to change.
    b. Try DESIGN ASSIST to lower costs and get Mass Timber fabricator on design team.
8. Identify and pre-qualify SUPPLIERS and ERECTORS of Mass Timber.
    a. U.S. based
    b. Canadian
    c. EU based
9. Shop drawing coordination.
    a. Cadwork, Dietrich and AutoCad.
    b. Viewers and software education.
    c. Use of Revitt 3D by architect – liability.
10. Negotiate a CONTRACT at the right time when scope becomes clear during design assist.
    a. Develop a system to deal with extra costs and savings resulting from design assist.
        i. Volume CLT pricing

ii. Steel connection pricing for:
    1. Simple plates and bars
    2. Simple connectors – hangers
    3. Complicated geometry connectors.
    4. Patented systems.

11. Use of PATENTED SYSTEMS.
    a. Appropriate approvals and testing for:
        i. Composite Floor Systems.
        ii. Hold down systems and large capacity shear transfer systems.
12. Education and coordination with other trades on construction site.
    a. Concrete – accuracy and fit
    b. Mechanical/Electrical
    c. Finishes: steel studs and drywall.
13. Coordination with erection contractor
    a. Experience with working with wood.
    b. Shoring: timing and coordination with other trades.
    c. Erection plan.
    d. Temporary stresses – lifting points
14. INSPECTIONS;
    a. Local engineer for day to day inspections.
    b. Use of photographs.
    c. Final inspections
15. As built drawings to accommodate fabricators changes.
    a. Shop drawings versus structural drawings.
    b. 3D model as as-built
16. Maintenance plan:
    a. Inspection after one heating season.
    b. Client education when new systems introduced – Passive House.

CLT ?

EU TRAVEL
PUBLICATIONS
CONSULTANTS
SEMINARS

PRICE

SOURCES
RELIABLITY
PRELIM & FINAL
COMPARISSON

PRICING

ESTABLISHED:
CONCRETE
MASONRY
STEEL
UN-RELIABLE:
WOOD

COMPETITION

NLT
BRISCO
CONCRETE
FRAMING
LVL/LSL

CLIENT

PUBLIC
PRIVATE
DEVELOPER
RENTER

GRANTS

PILOT PROJECTS
GOVERNMENT
INDUSTRY
FEDERAL
STATE

CONTRACTOR

CM
GENERAL
DESIGN ASSIST
PAYMENTS
SCHEDULE

ERECTION

FABRICATOR
SPECIALTY
STEEL
GC

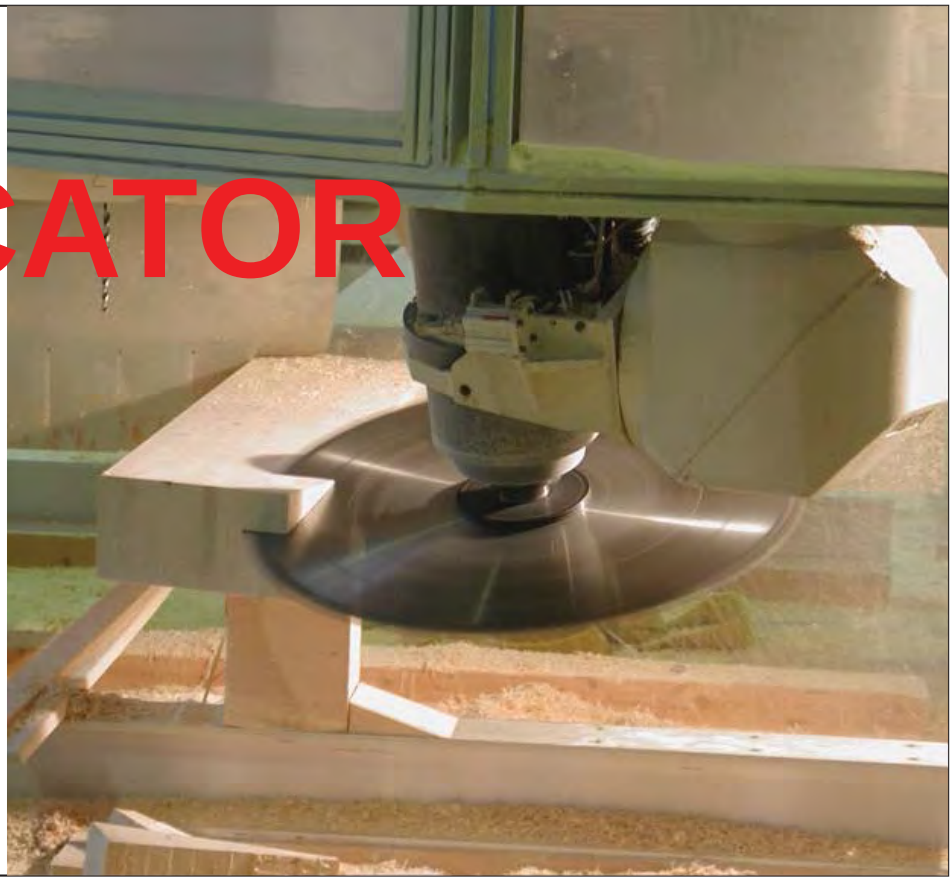
SPEED

PREFAB
EASY TRADES
FIT

PATENTED SYSTEMS

FABRICATOR

CANADA
EUROPE
USA



BUILDING CODE

UPCOMING EDITIONS
TECHNICAL APPROVALS
FOREIGN CODES
GUIDELINES
TESTING

LATERAL

R FACTORS
CONNECTIONS
BRACING + SW
WIND DRIFT

SYSTEMS

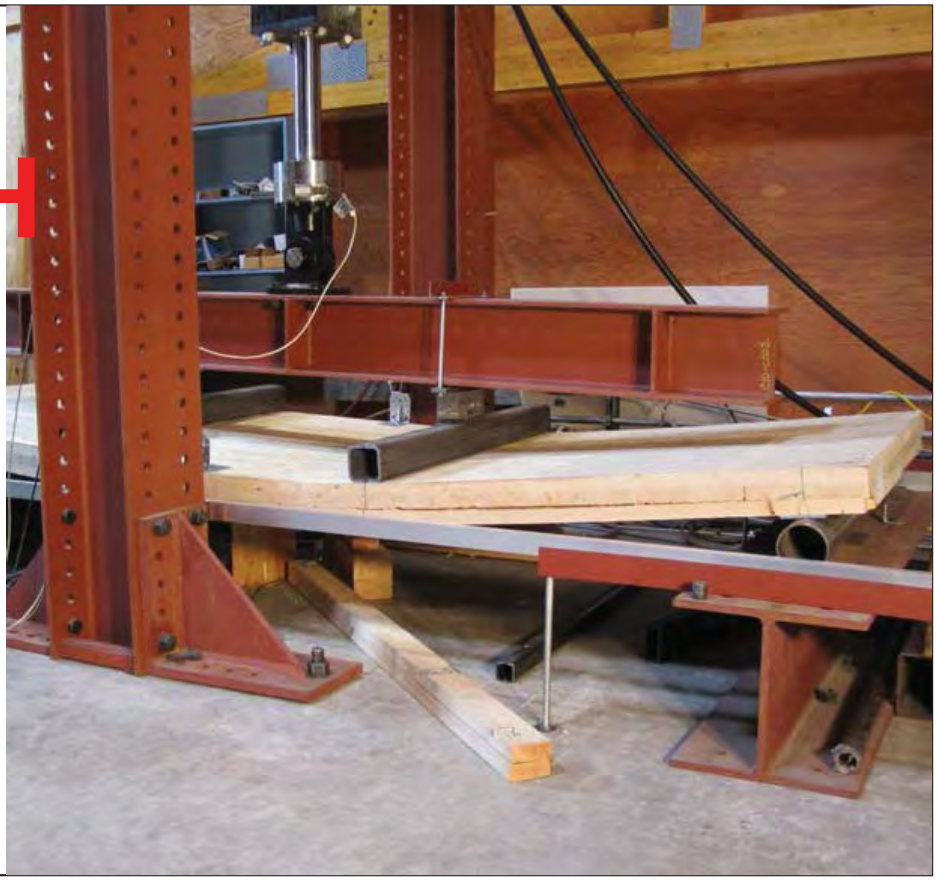
TESTING
APPROVALS
ALTERNATIVES
KNOWHOW
CODES
PRICE

TESTING

REPORTS
APPROVALS
SYSTEMS
CODES

RESEARCH

IDEAS
NEW SYSTEMS
DESIGN INFO
REPORTS
CODES



HOLD-DOWN

RIVETS
SCREWS
HSK
??

NAILS *R* US

VIBRATION

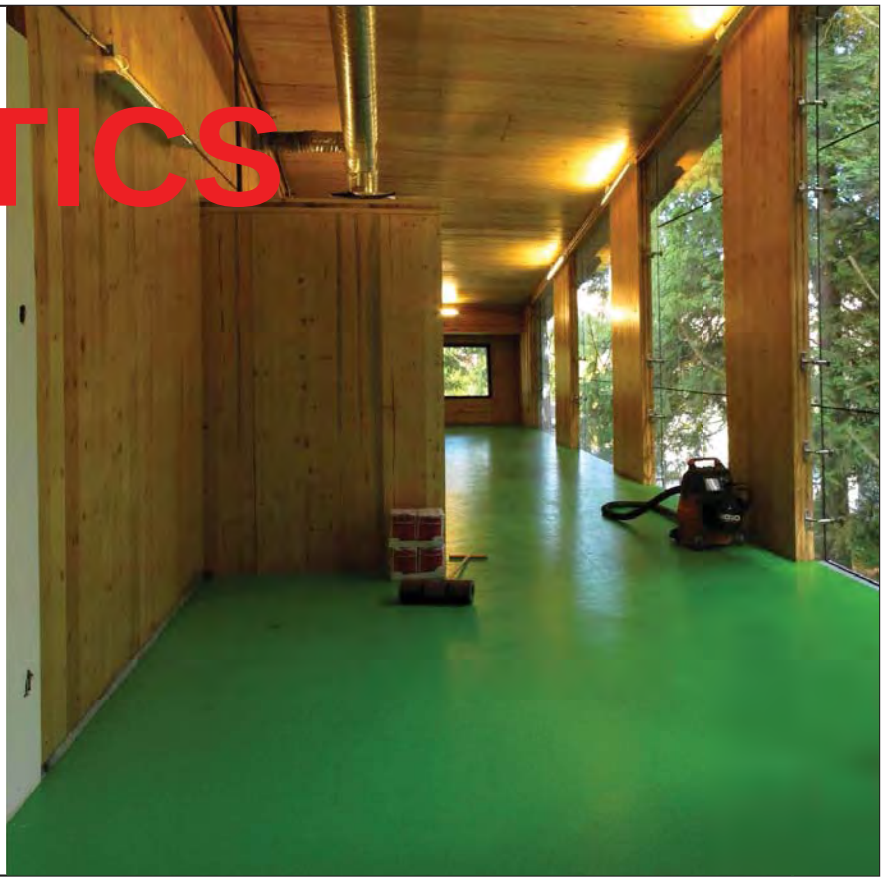
PERCEPTION
DEFLECIONS
LIMITS 8 HERZ?
TOPPING
CODE

DEFLECTION

LIMITS
ACCURACY
OVERHANGS
CREEP

ACCOUSTICS

PERCEPTION
EU SYSTEMS
TOPPINGS
PRICE
CODE



CODES

IBC 2015
O-860-16
FPINNOVATIONS
EU REPORTS
FABRICATORS

IDB AMHERST, MA

DESIGN ASSIST

CONCEPT
60% DRAWINGS
INCENTIVES
RESULTS

CHALLENGES

CLIENT
PRICING
CONSULTANTS
FABRICATOR
ERECTOR

RECEPTION
CHAMPION

Summary of Breakout Sessions

Breakout Session 1—Resistance to Lateral Loads

Doug Rammer, FPL (session moderator) and Adam Senalik, FPL (session assistant), led discussions with attendees for this session. Detailed notes recording discussion points are provided in Appendix 1. Rammer and Senalik summarized key findings of this session as follows:

Seismic Design Parameters Research

Completion of the FEMA P-695 research at Colorado State University (CSU) to develop R-factors for seismic design needs to be a high priority. Aspects of this study that are important to the future use of CLT include comparative performance of long/short walls with various aspect ratios and an analysis of the performance of connections. Is a FEMA P-795 study for connections needed, or can the results of the CSU study be extrapolated to other connection systems?

Full scale validation (3 stories to 10 stories) tests are needed to gain a better understanding of building height limitations for CLT construction. The effect of openings in CLT shear walls is another design aspect that needs to be evaluated through testing.

While most of the research focus to date has been on CLT, similar research is needed to determine design parameters for nail laminated systems.

Diaphragms

In addition to the performance of CLT as shear walls, it is critical to complete research that will quantify the diaphragm behavior of CLT systems. Full-scale diaphragm testing is needed to validate finite element models that have been developed to establish a reliable design approach. The effects of openings in CLT diaphragms needs to be studied

Also, research is needed to determine how balloon versus platform framing influences CLT diaphragm performance. Research efforts need to be expanded to other systems, such as nail laminated decks.

Resilient Seismic Systems

The rocking wall system research needs to be continued, and the effect of deformation (soft story) is important to understand. Post-tensioning could be highly beneficial, but how this will work needs to be better understood. Subassembly validation is required, plus large-scale validation followed by a fire test.

Connections

Research is needed on high-capacity connections for overturning and shear forces because these forces can be quite high in a multi-story mass timber building. Is the failure mode of pullout of nails at the base of shear walls a correct design approach, or do we need to evaluate alternative failure modes?

Deformation compatibility between lateral and gravity systems is an important consideration that needs further study.

Are glued connection systems viable, and if so, what research is needed?

Connection innovations for fire protection to achieve 1- and 2-hour fire ratings is very important and needs to be a high-priority research item to advance CLT into “tall” buildings.

More testing is needed at both connections and component levels.

Other Design Topics

A better understanding of the 3D behavior of mass timber (CLT) buildings is needed.

Advances in numerical/structural modeling of mass timber framing systems are needed. But are such models adequate for the design community? Do designers need a commercial software package, and how can this all interface with Revit/BIM?

Information availability and coordination for structural design is needed (i.e., there is a critical need for a clearing house for CLT design information).

The development of a simplified design guide needs to be considered. Related to this is the need to update the *CLT Handbook* to reflect the latest information available.

Breakout Session 2—Building Performance: Durability, Sound, Vibration, Life-Cycle Assessment (LCA)

Jim Bowyer, Dovetail Partners (session moderator), and Sam Glass, FPL (session assistant), led discussions with attendees for this session. Detailed notes recording discussion points are provided in Appendix 2. Bower and Glass summarized key findings of this session as follows:

Acoustics

Because many CLT projects to date have been multifamily apartments or condos, acoustics is a major concern and research is needed to provide designers with guidance on how to best achieve good acoustic performance using CLT assemblies. The research needs to cover a wide range of sound frequencies and construction systems.

Life-Cycle Assessment (LCA)

It was agreed that an LCA study comparing a CLT-framed building with competitive materials is needed to demonstrate the environmental benefits of using CLT. The project or projects need to be carefully selected based on reproducibility of results, having willing partners providing data sharing, and publishability.

Vibration/Creep

Vibration is a key design consideration for CLT-framed floors. Additional research is needed to better quantify floor vibrations, especially for CLT systems that span continuously from one building area to

another, such as between apartments and corridors. Many variables can impact vibration performance, such as spans, boundary conditions, and floor weight, and the impact of each of these needs to be assessed through research.

Another vibration issue that needs research is the effect of vibrations induced by wind forces on the performance of tall wood buildings. Very little is known about this phenomenon, and designers need guidance as the heights of mass timber buildings increase.

Creep in horizontal floor and roof systems due to long-term applied loads is well understood for many wood products. But little is known about creep performance of CLT panels, and research is needed to better understand this design parameter.

Durability

In accordance with PRG-320 and the IBC, CLT is limited to dry use conditions. However, it is recognized that CLT panels may be subjected to bulk water, such as during transport, on site construction delays, the possible breach of the building envelope, fire sprinkler activation, or internal plumbing leaks. Research is needed to evaluate the performance of CLT panels when subjected to exposure to bulk water.

General Building Performance

Overlap of all performance areas on a set of typical details for multiple archetypes, including fire, vibration, creep, acoustics, and the moisture/building envelope, need to be better understood.

Breakout Session 3—Fire Safety

Kuma Sumathipala, American Wood Council (session moderator), and Sam Zelinka Glass, FPL (session assistant), led discussions with attendees for this session. Detailed notes recording discussion points are provided in Appendix 3. Sumathipala and Zelinka summarized key findings of this session as follows:

ICC Height and Area Limitations

Existing ICC limitations for Type IV (Heavy Timber) come from a historical basis with numerous assumptions, and new state-of-the-art firefighting capabilities have not been accounted for. It is essentially a political issue, and the wood products industry needs to develop fire performance data that can be used to address/revise these limitations in light of new information. As a first step, the ICC has issued a public comment request to create a committee to look at Tall Wood Buildings; an ad hoc committee will be formed in early 2016 to begin discussing this. Fire performance research is needed to substantiate industry claims in support of this effort.

Alternative Means and Methods

Engineering design firms want third-party accredited test report data on assembly and component fire resistant characteristics. Preference is for manufacturers to be the source of these reports, but this is very expensive and probably not feasible. Plus, most North American labs cannot fully load a CLT wall during an E119 wall fire test. What are the alternatives for developing and providing this information?

Fire performance of mass timber structures with different degrees of exposed timber needs further study.

Adhesives

The type of adhesive used in CLT will affect performance levels due to delamination and hence multiple flashovers. Most CLT fire test data in North America is based on PUR adhesives, which is also the adhesive used in Europe. Research is needed on fire performance of CLT using a broader range of adhesives, such as the work begin done at FPL, and this effort needs to be expanded. It is desirable if this research can evaluate adhesives that are similar in manufacturing time/ease and also are formaldehyde free.

Education of Fire Service and Code Officials

Communication and education of fires service and code officials regarding fire performance of mass timber structures is a major barrier restricting growth of these building systems. How can we educate these groups efficiently about how CLT assemblies perform in fire? Would 1- or 2-hour seminars for fire service and code officials in the United States work, and if so, how would they be funded?

In Canada, demonstration projects for fire performance of elevator shafts were conducted and fire service representatives were invited to observe the tests. Two-day workshops for fire chiefs also were held.

Extensive documentation is needed to demonstrate that mass timber can offer not just “equal to” but “better than” fire performance of other competitive construction systems.

Risk Analysis

Considerations of property protection (sprinkler efficiency, redundancy), life safety, water damage, and occupant modifications to passive fire protection must be analyzed and provided to the insurance industry and fire services and code officials to bring them up to speed and favorable to mass timber construction.

Need to understand and calculate entire risk scenario and how to compare mass timber to traditional construction

Fire Resistance of Connections

There is no fire test standard for screw or bolted connections such as used with mass timber, but designer’s need 1- and 2-hour fire-rated connection information. There are some recommended 1-hour rated connections for glulam, but none have been fire tested and there are no 2-hour rated glulam connections. Does every potential connection system need to be tested, or can typical connections be tested and models be developed to expand to other systems? This can be very expensive—is it the responsibility of connector suppliers, CLT manufacturers, or others? Not having this information has the potential to limit the broader application of mass timber to tall buildings and is a high-priority research area.

Need to document existing field data that demonstrate the performance of connectors in fire situations. When failures occur at connections, what is the nature of the failure and how can we learn from it?

Breakout Session 4—Material Resources and Other Topics

Brian Brashaw, FPL (session moderator), and Xiping Wang, FPL (session assistant), led discussions for this session with attendees. Detailed notes recording discussion points are provided in Appendix 4. Brashaw and Wang summarized key findings of this session as follows:

Materials—Resources

A recurrent topic of discussion was the importance of research that will lead to optimizing the available timber resources for mass timber. Questions were posed regarding the certainty of supply to support a growing industry. The importance of evaluating use of beetle-killed timber and forest restoration materials was emphasized as well as a need to evaluate use of hardwoods and other underutilized softwood species.

Strategies are needed to bring wood resources to market and to further develop the supply chain. Certification opportunities need to be better understood as they impact the expansion of available resources, and more information is needed regarding properties of hybrid/composite systems.

Manufacturing Issues

A “tension” seems to exist between standardization of CLT products and promotion of custom products. PRG 320 provides seven standard grades (layups) but clearly supports the development of custom products by individual manufactures that support their specific available resources. As this industry evolves, this issue should become less of a point of controversy, much like the glulam industry promotes both standard and custom grades.

Optimization of manufacturing to reduce costs is important.

- The use of a wider range of lumber species and grades is needed.
- Adhesives and press cycles need to be better understood.
- Manufacturing process needs to be studied with an emphasis on issues such as workforce training, labor considerations, and optimum crew size.

Need exists to determine what is the best business model for CLT to attract additional manufacturers, (i.e., capitalization costs, inventory control, and labor force considerations).

It is important to understand what technical assistance and manufacturing support is available to current and potential new manufacturers.

Durability and Preservation

Minimal information exists related to the preservation side, such as the need for water protection and what environmentally friendly preservative treatments are available. Treatment options and their effect on material properties need to be studied.

A myriad of durability issues related to the use of composite and hybrid systems exist and need to be better understood to advance the use of these emerging technologies. Of particular interest is what happens at the interface between concrete and CLT, and studies are needed to make sure there are no concerns on long-term durability.

Moisture and Stability

Wood–moisture relationship is important for CLT, such as dimensional stability and the impact of system and manufacturing modifications.

Need to know how important it is for the materials to be kept dry during the construction process. What problems will occur if it gets wet? Needs to be addressed and solution identified.

Other Topics

More extensive marketing information is needed to expand the industry, such as green building markets, blast-resistant structures markets, and niche non-building markets.

Policy incentives, such as those associated with GSA purchasing vs. public buildings vs. private construction, all impact future markets and need to be better understood.

Deconstruction and reparability of CLT buildings need to be understood.

What trade association can best represent CLT? APA is currently certifying all N.A. production, and AWC is heavily involved with codes and standards related to CLT.

Research database is needed for mass timber. A vast amount of research has been published, and a significant need exists to have a central source of this information

Close-Out Session to Prioritize Future Research Needs

Tom Williamson, Workshop Facilitator, led a discussion with attendees to try to prioritize future mass timber research needs. Key observations were reported as follows:

Resistance to Lateral Loads

The development of CLT shear wall system R factors and design guidelines and examples for seismic performance were identified as a high priority. Current testing at Colorado State University (CSU) needs to be completed with the understanding that whatever comes of the current FEMA P-695 project will be limited based on the scope of what was able to be modeled and validated by testing and those limits will become the future barriers to CLT use.

Diaphragm testing and design guideline

a. The testing of connections and full-scale experimental diaphragm testing are needed to quantify the behavior and failure modes of CLT systems.
b. Design and modeling guidelines are needed to enable designers to use CLT and lead to the eventual standardization of design methodologies.

Whether the lateral force resisting system is a wall or a Heavy Timber Buckling Restrained Braced Frame, the diaphragm comes into play for seismic load transfer and becomes an important design consideration that needs further study. A concern exists that details of panelized CLT diaphragms may produce brittle behavior and loss of structural function in seismic overload situations and this needs to be evaluated.

The deformation compatibility between gravity framing and lateral deflections needs further evaluation.

The Heavy Timber Buckling Restrained Braced Frame (BRB) seems very promising, but a FEMA P-695 evaluation will probably be needed to prove that surrounding wood elements and construction details developing the strength of the BRB can indeed function as intended prior to a broadly accepted code/standards recognition.

Connections

a. A FEMA P-795 research study is very expensive for product manufacturers to pursue and thus may not be a viable option. Preference is for the FEMA P-695 testing at CSU to identify the establishment of performance criteria/parameters that connectors must meet so that additional costly testing does not need to be repeated.
b. Higher capacity connections and construction details for mass timber framing are needed such as for overturning and shear forces.

Building Performance

Moisture research is needed to demonstrate moisture performance of CLT and tall wood buildings during transport, construction, and operation cycles. Little is known about the effect of exposure of CLT to bulk water, and this needs further study.

Vibration research

a. Need exists for performance-based vibration design guidelines for mass-timber floors because this is a key design consideration.
b. Many variables impact vibration performance, such as spans, boundary conditions, and floor weight, and all these need to be assessed through future research.
c. Coupling vibration research with acoustics research could be beneficial.

Wind-induced vibration in tall wood buildings is another design consideration that needs evaluation from both occupant comfort and structural performance perspectives.

Overlaps of all performance areas on a set of typical details for multiple archetypes, including fire, vibration, acoustics, and moisture/building envelope, need to be better understood.

Fire Safety

Connection performance—Fire resistance ratings of connections used in HT/mass timber applications are needed, whether concealed or otherwise. It was noted that there may not be standardized testing for this, so perhaps research should help determine what that standard should look like.

Adhesives

a. It was observed that adhesive performance is a concern due to delamination and hence multiple flashover, and further study of this is needed.
b. A need exists to establish which adhesives are at least similar in manufacturing time/ease and also are formaldehyde free—from there further fire performance testing would be useful.

Communication and education regarding fire performance of mass timber structures is a major barrier restricting market growth of these building systems. How do we best share this information with fire service and code officials and the insurance industry?

Need exists to develop documented fire performance data to convince the ICC to increase heights and area limitations for Heavy Timber/mass timber construction (Type IV).

Fire performance of structures with different degrees of exposed mass timber needs further documentation.

Risk analysis/risk modeling is needed. Is there an additional fire risk associated with mass timber buildings? Probably not, but how do we prove it to the insurance industry?

Need proof that CLT/mass timber performs in a superior way from other framing systems when exposed to fire—perhaps through full-scale fire demonstration projects.

Material Resources and Other Research Topics

More information on the costing aspects of CLT is needed. Is it cost competitive, and if not, what research needs to be done to address this? As first steps, we need to do the following:

a. Develop a series of case studies with detailed cost information
b. Complete economic impact studies
c. Undertake general market research associated with costs

Better understanding of sourcing for mass timber products is needed. Gap appears to exist between the wood fiber that we “need” to use, such as beetle-killed and forest fire thinning materials, and what is accessible/economical to use.

General

A lot of time and effort goes into finding information regarding mass timber research, and a well-maintained and easy-to-access industry database is needed.

A concern was expressed as to how the wood products industry is going to train future leaders to carry these efforts forward at both the university level and the practicing professional level.

Appendix 1—Discussion Notes for Breakout Session 1, Resistance to Lateral Loads

Doug Rammer and Adam Senalik reported discussion points from attendees for this session as follows:

R-Factors for high-aspect-ratio CLT panels—how much reduction in R is based on aspect ratio, or is it something with the specific system evaluated reducing the R values. CSU test program limited aspect ratio during testing to 1:1. What will happen with aspect ratios less than one? Response is currently beyond the scope and reduction unknown.

Displacement capacity is important and is driving the R-Factor. Difficult to drive results in one direction. Results expected in December. Design provisions were present before starting, and the current study now designed to those provisions. If those provisions are changed, the project would need to be started over from scratch.

Trying to get the panel activated rather than just connections. End of first quarter, 2016, will have more results. Wind rather than R-factor will likely guide construction on East coast. Need to move away from statics and think deformed shapes as it yields better design.

How do we determine the proper design parameters to plug and chug to design a building in CLT? Do we have the R factors to design them? Seismic design is a blank area. It is not out for public release yet. Reports will be reviewed and out within the next 6 months. It will probably come out as a FPL publication and will be in public domain. Then it has to go to the building seismic safety council (BSSC) then to ASCE 7 and ultimately the I-codes for adoption and general use by designers.

National building code of Canada—is there any methodology to recommend an R value based upon height?

Is there anything available right now for R factor? *CLT Handbook* hints at R value and gives preliminary values. State of Oregon has pulled in values from ASCE 7. You can go to a municipality and show that a high seismic area has made a decision regarding R values.

How are the CSU numbers comparing to the Oregon numbers? Group in Canada said an R of 3 would be a good number. There was talk about two R's at one time. Everyone thinks it will be greater than 2.

R = 1.5 for long panels. Long brittle system. It's a business decision of best product for least cost. Low seismic performance factors probably won't have much effect.

CLT shear walls with openings are an area of interest that needs to be researched.

What do we need to know to design the connection systems? The R value testing will help guide the connection system to achieve those R values.

Balloon type framing different than mounted to slab. Platform framing—if you have ductile layers you will have large R.

Most test results show the failure mode is pullout of nails at the base of shear walls. Is there another system where we find that acceptable? Systems with axial loads on the walls; should we be providing greater support at the base of those walls?

On the Canadian projects, when will that information be made available? We need to be knowledge sharing, but when you are in the middle of the research there is nothing to yet share. As practitioners we have to protect our intellectual property. How do we get around that?

What can be shared and when depends upon the nature of the research. There is a commitment that information that is publically funded will be made available to the public. When something is 100% publically funded that information will be made available. When a private firm or nongovernment research organization is involved and they pay a percentage, then IP issues become relevant. There is an increasing incremental portion that is coming from private interest groups.

Have efforts been made to look at heat transfer? Heat transfer of lateral connection systems may be a research area. Efforts are going to be made at looking at the deformation compatibility of the connections. That is a test that is good for seismic and fire testing.

Is shake and bake testing being planned? The UCSD shake table is an option, but a burn test would have to be off the shake table. It might be possible to construct the test assembly on a movable platform that can be moved off after the shake test.

Some shake and bake tests have been conducted but the fire was in a compartment.

National Science Foundation does not mix shake and burn.

Besides fire resistance, are there CLT grading procedures after a fire event? Has anyone looked at that?

Tall wood building in Portland—Has anyone looked at sandwiching two panels together to create the larger cross sections needed.

What about flexible diaphragms? Current R value of 1.5 is based upon rigid diaphragm. For diaphragms, the connections have such a large effect; we are not certain how close the FEM equations will be. A full-scale diaphragm test is a high priority. A light frame wood diaphragm—gaps that closed versus closed gaps did not have a great difference analytically. Connections will have a large effect on the behavior of the CLT diaphragm.

We have great modelers, but we are being asked to show the models are accurate with full-sized test. Some people we are dealing with are treating CLT as dangerous systems because of the unknowns. One research need is more large-scale testing to validate the models, and there are tests being planned for full-size diaphragms.

Need exists for multistory shake table tests. Some engineers are concerned with a failure mode between walls and floors.

Should be testing the entire diaphragm and evaluating platform construction vs balloon construction. Once we have diaphragm behavior, then we extrapolate to uses in 3D.

A nail laminated platform will be difficult to test because it will likely take 500 kips.

The walls have a big effect over the chord action. Light frames don't count that, but found it has a large effect. How many buildings will have CLT walls that go the length of the diaphragm?

Where can you get information regarding connections other than nails for CLT diaphragms? If the connections are proprietary, then the vendor should have that information.

R-value and diaphragm are critical. Should we put all our resources in achieving good R-value and diaphragm information on a fast track?

Tall wood buildings—deformation of panels with regards to connections needs to be looked at. Wood gave more play and torsional effects. Is there a way to work with the connections to avoid that rather than bulk up the system?

Is there value in understanding rocking walls vs nonrocking walls?

Resilience requirements/market need. Rocking wall systems—idea of a big test. It is feasible, but is it a priority? Likely earthquake will be an event with aftershocks. How many shakes will this take before it fails? If we set up a big test, we are going to run multiple tests. So this issue would likely be addressed in a large-scale test. It should be a priority. Is there a way to do the diaphragm tests? Maybe isolate horizontal and vertical tests? How about doing two-story tests, where the diaphragm tests could be performed, to improve the models and then do the seismic tests? Could do an assembly test, then do a diaphragm test? It can be done, but everyone needs to buy in to justify that type of testing.

If post tensioning is a solution, there is a great deal of information available in the bridge area. There are small tests that can be started regarding creep and deformation. With regards to LVL there is information. There needs to be detail regarding how these systems will be used to avoid crushing.

CLT in post tensioned systems makes sense. The next progression might be prestressing, but we need answers to questions and the precast concrete industry might be a resource.

Design guides help get the technology into the community. This is what the post-tension balloon vs. platform framing testing will provide. Researchers have to publish for credit prior to widespread distribution.

Need early design guide for second tier level users for architects and engineers just starting in the area of CLT. Simpler than the *CLT Handbook*.

Is there any software for CLT? Feeling regarding models: is there more modeling needed or are people comfortable with them? Numerical modeling software. Design software. REVIT plug-in potentially. Building information modeling. Need to update CLT handbook on structural design.

Standard drawings for using CLT by architects, or protocols would be helpful.

Any need to come up with repair procedures for CLT if a building has gone through an event and some of the connections have been dislodged? All the codes are written for life safety to let the people get out.

Post-event recovery is not part of the code. Those living in the building may be willing to pay for some of the resilient systems and it would be good to anticipate that now.

Is there value in seismic retrofit to buildings? CLT has an advantage because it can be sized per application.

Connections aren't a "sexy" area. Most of the shear walls will be clad so you won't see the connections. For braces, they will be visible and can be detailed beautifully. However, it is an area of possible differentiation that could be an advantage.

General comment regarding USDA award buildings. There will be funding for testing. Is there any coordination for the testing? There was discussion for a smaller group to coordinate activities as a whole. That was partially the objective of this meeting to bring interested parties together to be that group. There have been discussion regarding the FPL or AWC leading that group, but this meeting was the first step. Canadian Wood Council is somewhat doing that in Canada. We need a similar effort in the US.

Bottom line is that some organization needs to step up and coordinate the research information related to mass timber research.

A lot of time and effort goes into finding information regarding CLT and a well-maintained, easy-to-access industry data base is needed.

Appendix 2—Discussion Notes for Breakout Session 2, Building Performance: Durability, Sound, Vibration, Life Cycle Assessment (LCA)

Jim Bowyer and Sam Glass reported discussion points from attendees for this session as follows:

LCA-related comments

LCA: what are some of the key considerations?
- Need to identify realistic projects
- Need to look at four alternative systems (in design)

What makes a good LCA project?
- Reproducible
- Willing partner, data sharing, publishable

Looking for comparative LCA study—wood, concrete, and steel-framed buildings. Question posed as to whether we can skip the comparison study and just do an LCA on CLT as a component. Response was generally "no" as we need to identify a project suitable for a comparative LCA analysis because the competition of high importance is dominantly steel, concrete, or composites, and comparative LCA is needed to provide answers needed by designers.

Look at LEED, Green Globes, and restrictions on comparative LCA—what does it mean in practice? Environmental building declaration vs. product declaration. Current work on whole-building LCA. Do we have LCA for CLT? Comparative LCA on Burnaby building (CLT vs. concrete). CLT higher fossil

impact from adhesive. One goal of LCA is to lower environmental impact at manufacturing. Need to develop EPDs on 5-year basis.

Comparative operational energy analysis needed: CLT vs. other structural systems. Passive house examples could be used.

What are the wood thermal resistance benefits? Need exists for whole building energy modeling and monitoring.

Develop actual operational cost data from Redstone CLT project vs. identical building in steel stud.

Moisture issues

Research on adhesives to provide lower environmental impact, better resistance to heat and moisture; bio-based alternatives needed.

Water vapor permeability of adhesives needs to be better understood.

Long-term research on mold on interior, decay, termites, carpenter ants, etc.—need for preservative treatment is needed? What happens at concrete–wood intersections in hybrid construction?

Preservative treatments—do they affect the performance of CLT?

Does building physics change with mass timber? E.g., types of weather barriers?

Long-term moisture effects on mass timber: potentially a huge problem; solutions for construction moisture; recommended moisture content before enclosing the building.

Design optimization for CLT building envelope performance is needed to evaluate value vs. cost.

What is the impact of wetting at CLT lamina that is not edge-glued?

What is the effect of bulk water on CLT such as wetting by sprinkler activation or plumbing leak?

Procedures for retrofitting/remediation after wetting from post-fire-sprinkler need to be investigated.

What is the impact of concrete topping over mass timber on moisture, durability; look at data on gyp-crete over OSB; do differences in adhesives come into play?

Vibration/creep-related comments

It is claimed that vibration drives CLT design; how solid is the research basis? More data needed to back up design; what can be done to optimize? Can the application of stiffeners help to increase spans?

U.S. codes don’t have objective approach for floor vibration; performance is a design choice. Need to define range of mass of floors as basis for vibration. Many guidelines: which one should the designer use? Many parameters affect performance—spans, connections, etc.

Wind-induced vibration in tall buildings: is dampening needed? At what height does it become a design issue? Interaction between building vibration and floor vibration? Monitoring on tall buildings in Canada shows it's an issue. What about tornado, hurricane? Extreme events can be designed for structurally, but how about from a vibration perspective.

How does the layout of panels in relation to partition walls affect vibration issues?

Creep performance of CLT panels: do we know what we need to know? No, and additional research is needed.

Acoustics

Anecdotal solutions. Mitigation methods differ by frequency; need to focus on critical range; low frequency; how to manipulate mass and stiffness and how does it affect fire rating?

Where should research be focused on vibration and acoustics? Sound transmission through columns; detailing between columns/floors.

Perceptions of sound differ geographically and internationally; need to develop methods that account for different expectations.

Overall building performance

What kind of building monitoring equipment is needed that is unique to mass timber to provide useful building performance information for practitioners?

Do species, grade, adhesive used to construct CLT impact sound transmission, vibration, stiffness, deflection, creep, thermal resistance? Probably, but additional testing on each building performance element is needed.

Post-occupancy interviews regarding perceptions of acoustics, vibration—research ISO method for evaluations.

Can building performance issues be addressed at manufacturing? Maybe, but it is mostly a design/system issue.

What happens at panel joints—need for flexibility for seismic, but how to treat joints for moisture, thermal, and air control. Multiple performance criteria: fire, structural, building envelope need to be further evaluated.

Foam gasketing at joints for acoustics, vibration, air sealing—are they effective and what is the cost/benefit proposition? What is the range of density to choose for specific applications?

Relation between thermal resistance (R-value) and heat capacity (thermal mass) in building energy performance important and needs to be better understood for mass timber systems.

Need to evaluate coating technologies for CLT for moisture protection and intumescent coatings for fire; effect on system cost vs. benefits derived.

How does the application of coatings during manufacture vs. on-site affect performance and costs?

Steps after CLT is constructed: how to build CLT structures for compatibility with trades with standard details for mechanical, electrical, plumbing.

Critical details for CLT based on archetypes—test for each design criterion (acoustics, vibration, fire, moisture); note differences between residential and non-res structures.

Major issue

Who is going to train next generation of designers on wood and mass timber design? Need to think strategically about research and education and training. Is there a role for the FPL similar to the FPL's Clark Heritage training program of educators in the 1970s?

Appendix 3—Discussion Notes for Breakout Session 3, Fire Safety

Kuma Sumathipala and Sam Zelinka reported discussion points from attendees for this session as follows:

Key elements of fire performance of mass timber are life safety/property protection/firefighter safety. How do we address each of these?

Sprinkler reliability claimed as 95%, but what happens if sprinklers do not activate and there is no immediate fire service response?

- For steel, allow burnout, steel regains strength as temperature drops as long as buckling temperatures are not reached and the steel has not collapsed.
- For mass timber, char develops, minimizing fire prorogation, self extinguishes and high level of residual strength retained.

Options for increasing the fire performance of mass timber systems:

- Encapsulation so that the wood doesn't burn
- Increase sprinkler reliability
- Challenge the fire service to better extinguish fires

What about having more sprinklers—is that a viable option or needed with taller mass timber buildings?

If there's a lot of water, what happens to the CLT if it gets wetted as a result of sprinkler activation (fire or accidentally)?

There is always water damage when there is a fire. Not a fire issue, but a durability/building science issue (i.e., no different than other wood-framed buildings). Steel and concrete structures are also damaged in a fire, and structures need to be rehabilitated.

How do we effectively transmit the needed information about fire performance of CLT-framed buildings to fire code officials and the insurance industry?

Do we need to conduct a shake/bake/wash test program?

Fragility model/insurance model needed to demonstrate that the fire performance of mass timber is different and superior to stick frame and other competitive framing systems.

CLT is now classified as mass timber and codified as Type IV in the 2015 IBC.

Fire performance of CLT is also addressed in Chapter 16 of the 2015 NDS.

Many code jurisdictions do not accept these code provisions and it is still up to local authorities to approve the use of mass timber.

What additional fire testing is required to gain broader building code approval for mass timber—beyond Type IV construction?

Performance-based route, without the ICC sanction. How do we achieve this on a larger scale?

ICC heights and area table needs to be addressed to permit increases for mass timber systems.

Proposal to ICC to increase heights for Type IV from 85-100 feet opposed by two groups.

- Seismic group in Portland
- Sector of the fire service

Height and Areas—political issue (not technical)

How do we get around that? Perhaps by creating an ICC committee on tall wood buildings? Public comment period on creating such a committee initiated by ICC. Maybe if that is not a possibility, set up an open (ad hoc) committee outside of ICC to propose changes.

IBC—fire protection strategies for fire-protected steel in alternative design SPFE 29 (standardized methodologies for structural steel). Can the industry (AWC/APA, etc.) create similar methodology for mass timber and get backing by SFPE/ASCE guideline for performance based design- consistent platform? Good idea, but it's probably 10–15 years off. We just don't have the technology/evidence to do this yet.

Maybe once the "showcase tall buildings" in NYC and Portland are built, this attitude will change.

What are the fire-related issues with the 11 and 12 story tall buildings in NYC and Portland? What is the strategy to get these approved?

Portland project—jurisdiction at state building code level, and they are willing to look at alternatives such as a one-off building code approval including fire protection methods by looking at the mass timber framing as a unique system.

NYC—different issue with BOs being less open to change and focused on fire performance of traditional buildings. Lots of work needed to gain this approval since NYC has own building code. Approach—alternative material (not holistic) combustibility of structure and more focused on each component of the building system

Both jurisdictions want to understand how exposed wood behaves in taller buildings.

Do we need to *demonstrate* superior fire performance of mass timber and if so how?

Stick frame constructions, wall cavities exist where fire can transfer. CLT framing essentially provides continuous fire blocking.

Each burn of a test structure costs $1M to test. What kinds of models can be used? Can we show that mass timber is safe in taller buildings?

If CLT passes a fire component test, could it be applied to the whole building?

Fire engineering community would accept modeling, but the fire service not as favorable to this approach.

It's a prescriptive code, and what happens, for example, if someone changes gypsum in the apartment versus what has been tested?

Issue—fire safety of mass timber shafts in Canadian structures. Need exists to demonstrate fire performance for CLT shafts.

How do we demonstrate fire performance of connections used in mass timber framing?

Do the fastener manufacturers have a UL test for fire performance of connectors?

Does the entire fire safety approval process need to be under UL listing?

General acceptance of the fire performance of glulam because it's been around for a long time and NDS has been around for a long time. Authorities have seen it before, and we need to achieve that for CLT.

Wood industry question—do we need to test every single CLT manufacturer's product combination? This is not what we've been doing. Then there'd be no end of testing and this is a very expensive proposition. Some disagreement exists among experts on this. Can we treat it more generically like glulam and lumber? For example, glulam char rate is applied to all. Same with lumber. CLT needs a concerted industry wide effort to achieve this. DCA-1 flame spread. Class C, Class B, etc.

Some people think every single CLT combination will need its own test report.

Wood products in general have few fire test reports and none exist for CLT. Example—wood I-joist fire related problems mostly addressed through UL testing and reports for both proprietary and typical systems.

Significant "diffusion of CLT information" and we need to optimize this education.

Need survey of tall wood buildings in Europe. What is done related to educating fire services? How much education is done at the planning stages?

Is fire resistance enough to prove property protection or do we need to do more?

Extensive discussion of risk—what is the likelihood of fully developed fire in a CLT framed structure?

Return periods—risk analyses studies needed.

Risk analysis/risk modeling needed. Is there an additional fire risk associated with mass timber buildings? Probably not, but how do we prove it?

Designing building to facilitate more rapid evacuation and improving life safety aspect is desirable but not directly related to mass timber.

Codes address this. All buildings need the same fire protection systems. Level of safety relatively the same for all building types.

Anecdotal discussion of a fire in the UK at the Nottinghamshire chemistry building (under construction). Happened before tours and it was a non-sprinklered building.

- Fire service didn't even attempt to put it out because the fire was too hot. Lithium ion battery of an electrical vehicle next to building caused fire. How can we address that since it's rare?
- Truth is that fire service did not have the right equipment to put it out: 120 kW/m^2 fire services didn't have right clothing
- Fire services don't put out fire. They just stop it spreading to neighboring structures. It's about protecting neighboring buildings once fire reaches a certain size.
- How do we address higher fuel loads with the fire service? How to we address this perception (super high intensity)?

Significant problem associated with timber buildings is that fire risk is highest during construction. Construction fires—not addressed from a code issue at all. Building fire protection is one of the last things to be installed.

May need to consider a new method of building mass timber buildings where fire protections installed during construction. Minimize risk during construction.

San Francisco now has a fire safety during construction document for wood structures.

CWC provided document on construction site safety. Water supply, etc.

AWC has construction safety document.

Could consider the approach taken with prefabricated modular buildings. Fire-stopping could be done off-site, making it safer for construction.

Based on fully involved building and fire service fighting it from the outside

What about adhesives allowed in North America vs adhesives allowed in Europe. What glues are allowed in Europe/North America and what standards are applied for acceptance. How do they perform in CLT exposed to fire?

Is there a comprehensive database on adhesive performance in CLT?

PRG 320 sets minimum adhesive standards. Most of the fire testing of CLT done in Canada with single component PUR, where delamination is observed during fire tests.

All CLT manufacturers in Europe using PUR glues.

PUR is the choice because of the ease of use. It's easy to glue up with a longer open assembly time and lends itself to CLT manufacturing. But we need to get acceptable fire performance along with the easy to work with aspect. Adhesive manufacturers can make it happen but they need to know what the performance standards are.

Some other adhesives exhibit different char layer development and fire performance is impacted. Testing program needed.

Formaldehyde-based glues perform better in fire with no delamination.

Glulam in North America has traditionally used MF/PRF adhesive but now moving towards other adhesives such as PUR adhesives. Fire performance unknown, with 20–30% difference possible.

Is FRT CLT an option and how could that impact fire rating and glues? Possibly pressure impregnate the lumber and then glue up the CLT.

Certain things need to be tested right away to help get things through alternative means and methods. Documentations. How can we make this easier?

1. Suppliers with third-party test reports but there is a gap between 1-hour ratings and 2-hour ratings. Reluctance for fire testing in wood industry, holds everything back. How can code officials accept it if the suppliers won't pay for their own test reports?
2. Glulam connections is a concern with little research to support industry recommendations. Don't have a tested 1-hour fire-rated glulam connection. No 2-hour fire-rated glulam connection exists, and this is needed for tall wood building. Suppliers need component tests.
3. Education of fire service and code acceptance officials. They need 1-hour seminars

Perception—whole building is going to burn. Engage fire service at early stage.

NJ fire where fire started in between compartments—caused whole building to burn down (300 units). 500 firefighters involved, so maybe some of them broke down compartmentalization.

Go through historical data and characterize historical failures.

How does wood compare with steel/concrete (way better), but how do we effectively communicate this information?

Need to "dumb down" technical information to YouTube level video.

Appendix 4—Discussion Notes for Breakout Session 4, Material Resources and Other Topics

Brian Brashaw and Xiping Wang reported discussion points of attendees for this session as follows:

The session was started with a review of the six topics presented the previous day.

1. CLT Supply Chain from Forest to Market, Rusty Dramm, USDA FPL
2. Timber–Concrete Composites, Benton Johnson, SOM
3. Mass Timber in Utah: Research, Practice and Futures, Ben Hagenhoffer-Daniel, University of Utah
4. Blast-Resistant Testing for Massive Timber Exterior Wall: Expanding Timber Opportunities in North America, Lisa Podesto, WoodWorks
5. Development of a Mass Timber Tornado Safe Room, Bob Falk, USDA FPL
6. More with Less—An Overview of the first CLT Hotel in the U.S., Jeff Morrow, Lendlease

Blast-resistant aspects of CLT

What is the Department of Defense (DoD) role in supporting CLT projects?

- DoD is very impressed with CLT as a potential solution to construct wood framed buildings that are safe from blasts.
- DoD has a large portfolio of buildings and is interested in pursuing strategic objectives for blast proof structures that advocate sustainability
- The DOD is currently seen as a cheer leader for CLT projects

Regarding the blast aspect, when does GSA come into play? Can FPL play a role in this effort?

If blast testing is successful, what are the next steps?

Research is needed to identify details on connection design, windows and doors. What details can we take advantage of in multi-story CLT?

Progressive collapse is important and more work is needed to develop guidelines for design.

It is also important to determine energy absorption in CLT structures as related to blast resistance.

Safe room application

The safe room is an exciting concept, but how does CLT fit into safe room research? Tests to date indicate that a four-ply CLT worked. For the market, it needs to be easy to assemble by consumers, and a hardware package is needed. A thesis on CLT shelter design is needed, and models dealing with impact and blasting at the same time are needed.

Manufacturing-related issues

From a manufacturing stand point, a number of concerns were raised that need further study:

- Supply chain: (1) quality materials needed; (2) competitive price; (3) applications such as composite-CLT may help manufacturing process; (4) inventory management, (5) resource procurement issues need to be addressed.

- Are standardized sizes and grades needed? Engineered products industry is different from the traditional lumber industry and tends to focus on proprietary custom products.
- How uniform are the materials that actually go into the CLT panels?
- Optimization of manufacturing process is needed
- Time to delivery, chain of custody needs to be better understood.
- How we manufacture CLT panels? Reengineering design lay-out, put connections in interior; make it more efficient.

Need to identify ways to increase manufacturing efficiency (manual vs. automation).

What are best business models for CLT? Do we need new business models to promote CLT to large timber companies like GP and LP?

Species issues

Supply quality of the materials vs. quality of products. Tension exists between using low-grade materials and supplying high quality products.

MSR lumber vs. visually graded? Which one is best for CLT? Does it make a difference? Both are permitted in PRG320.

Issue of custom products vs. standardized products was discussed? Should the CLT industry follow the lead of the glulam industry, which promotes both products?

Lumber supply issues

Shortage of lumber, how much is true? Industry has capacity. Market drives production. Need exists to differentiate between raw material supply and production capacity?

One of the biggest challenges is identifying material properties for design purposes.

Should we look at the economics of using thermally modified timber; a lot of interest seems to exist from the designer's perspective.

Huge resources of beetle kill and dead timber are available. Can these effectively be used to manufacture CLT? If so, what testing is needed?

Local materials, is there a better way to access local supply chain?

How do we bridge the gap between resource and CLT manufacturing? In Montana, a couple of mills in the area have resources available but need to better understand CLT manufacturing.

High priority: sourcing timber for CLT from federal and nonfederal lands. Timber supply is a big issue. 20% mortality in FS, something needs to change. FS takes long time to go through the process of salvage from dead timber. How can this be optimized?

A large supply of hardwood species also exists. Testing needed to evaluate the performance of these species in CLT.

What about Hybrid CLT? Hardwood and softwood, low grade and high grade intermixed.

ICLT system, discussion on lack of material resources.

Composite CLT/concrete systems

Where can composite CLT design best fit in?

- Design methodology: material characterization, variation
- Bridge engineering: guidance for bridge design, durability by design

Composite timber/concrete approach: acoustic and vibration control. How do we handle it?

Initial research provided guidance on vibration design; acoustics depends on mass.

Research is needed? How to track it is important consideration?

Do we need a committee on composite CLT in NDS process?

What trade association is appropriate?

Durability issue for concrete–timber composite: Interface between concrete and CLT; we need studies to make sure there are no concerns on durability issue. A pilot study has been done and is ongoing.

What can be improved in concrete-CLT composites? Depends on applications. Money saving such as reduce mass to meet seismic performance demands.

Building performance concerns

Concealed spaces in CLT construction? Fire performance? How can design details be improved so that there is no concealed space issue?

Need an approved guideline for after fire exposure: post fire inspection, reparability after fire?

Missing gap: most current work focused on architecture aspects. No information on preservation side; such as water protection, more environmental friendly preservative treatments.

Are there issues with phytosanitation? Bugs? Fungi? If so, research is needed.

Need to understand the impact of pressure treating CLT with fire-retardant or preservatives on structural performance.

Wood–moisture relationship is important for CLT. Dimensional stability. Impact of system and manufacturing modifications.

Need to know how important it is for the materials to be kept dry during the construction process? What problems will occur if it gets wet? Needs to be addressed and solution identified.

Redstone project was a good demonstration of how to deal with standing water? Panels exposed to moisture and a wet condition? Dried out in sun; did not absorb excessive water, did not swell; didn't have that issue.

Other issues

Certification work around mass timber needs to be clarified? Should it be the same as for other wood products or is a different certification system needed? APA is currently certifying all N.A. production.

CLT projects: Pricing/cost analysis, information should be shared. Labor, training, etc. saving is there. There is an advantage in on-site labor.

CLT is a viable product and is very efficient in labor. How do we translate this to the best markets?

Need to identify other applications for CLT to expand market potential.

How do we educate the labor force to ensure quality of CLT buildings?

- Steel erectors. Should we get them involved in CLT building construction?
- Barrier at DOL; unions; need DOL support to classifications; crew sizes.

Deconstruction industry: Collective industry collaboration, all players need to be involved. How to demolish CLT buildings needs study?

What types of research forums for CLT should we have?

- High on research (develop test matrix),
- Highlight project showcases
- Establish new bench marks

A lot of work published and we need to take advantage of the database in publisher; technical report; citations; etc. Use NSF system to access data

List of Attendees

Marc Alam
malam@cwc.ca
Canadian Wood Council

Dave Anderson
davea@rfpco.com
Roseburg Forest Products

David Barber
david.barber@arup.com
ARUP

Andre Barbosa
andre.barbosa@oregonstate.edu
Oregon State University

Marshall Begel
mbegel@fs.fed.us
USDA Forest Products Laboratory

Richard Bergman
rbergman@fs.fed.us
USDA Forest Products Laboratory

Butch Bernhardt
butch@wwpinstitute.org
Western Wood Preservers Institute

Todd Beyreuther
beyreuther@wsu.edu
Washington State University

Todd Black
tblack@drjlumber.com
DR Johnson

Hans-Erik Blomgren
hans-erik.blomgren@arup.com
ARUP

Keith Bourne
kjbourne@fs.fed.us
USDA Forest Products Laboratory

Jim Bowyer
jimbowyer@comcast.net
Dovetail Partners, Inc.

Brian Brashaw
bbrashaw@fs.fed.us
USDA Forest Products Laboratory

Scott Breneman
scott.breneman@woodworks.org
WoodWorks–Wood Products Council

Taylor Cabot
taylor@kaisergroupinc.com
Kaiser Group Inc.

Keith Calder
kcalder@sereca.com
Jensen Hughes Canada Ltd.

Linda Caudill
lcaudill@vt.edu
Wood-Based Composites Center

Kevin Cheung
kcheung@wwpa.org
Western Wood Products Association

Mark Clark
mark.clark@hexion.com
Hexion, Inc.

Carol Clausen
cclausen@fs.fed.us
USDA Forest Products Laboratory

Max Closen
max@my-ti-con.com
MyTiCon Timber Connectors Inc

Jennifer Cover
jennifer@woodworks.org
WoodWorks—Wood Products Council

Paul Crovella
plcrovella@esf.edu
State University of New York

Christian Dagenais
christian.dagenais@fpinnovations.ca
FPInnovations

Thang Dao
tndao@eng.ua.edu
University of Alabama

Emily Dawson
edawson@srgpartnership.com
SRG Partnership

Hannah Derrico
hkd40@msstate.edu
MSU-Sustainable Bioproducts

Mark Dietenberger
mdietenberger@fs.fed.us
USDA Forest Products Laboratory

James Dolan
jddolan@wsu.edu
Washington State University

Rusty Dramm
jdramm@fs.fed.us
USDA Forest Products Laboratory

Chris Duvall
chrisd@cplinc.com
Coughlin Porter Lundeen

Russell Edgar
russell.edgar@maine.edu
University of Maine

Omar Espinzoa
espinoza@umn.edu
University of Minnesota

James Evans
jwevans@fs.fed.us
USDA Forest Products Laboratory

Bob Falk
rfalk@wisc.edu
USDA Forest Products Laboratory

Kathryn Fernholz
katie@dovetailinc.org
Dovetail Partners

Julie Frappier
jfrappier@nordicewp.com
Nordic Structures

Charles Frihart
cfrihart@fs.fed.us
USDA Forest Products Laboratory

Bill Gareis
wgareis@ashland.com
Ashland

Sam Glass
svglass@fs.fed.us
USDA Forest Products Laboratory

Hongmei Gu
hongmeigu@fs.fed.us
USDA Forest Products Laboratory

Klas Hagberg
klas.hagberg@wspgroup.se
WSP

Ben Hagenhofer-Daniell
ben.hagenhofer.daniell@utah.edu
University of Utah

Laura Hasburgh
lehasburgh@fs.fed.us
USDA Forest Products Laboratory

Daniel Hindman
dhindman@vt.edu
Virginia Tech

Patrick Holmes
patrick.holmes@osec.usda.gov
USDA

Dan Hovanec
dan.hovanec@tecotested.com
TECO

Melissa Jenkins
melissaljenkins@fs.fed.us
USDA Forest Service

Lehong Jin
ljin@viance.net
Viance LLC

Benton Johnson
benton.johnson@som.com
Skidmore, Owings & Merrill LLP

Bevan Jones
bevan.jones@holmesfire.com
Holmes Fire

Steve Kalinosky
skalinosky@fs.fed.us
USDA Forest Products Laboratory

Steve Kelley
sskelley@ncsu.edu
North Carolina State Univ

Greg Kingsley
gkingsley@klaa.com
KL&A Inc.

Grant Kirker
gkirker@fs.fed.us
USDA Forest Products Laboratory

Dennis Krueger
dennsk@smartlam.com
SmartLam LLC

Brian Kukay
bkukay@mtech.edu
Montana Tech

Archie Landreman
archie@woodworks.org
WoodWorks

Stan Lebow
slebow@fs.fed.us
USDA Forest Products Laboratory

Cameron Lewis
cnlewis@fs.fed.us
US Forest Service

Steve Lidicker
slidicker@dci-engineers.com
DCI Engineers

Phil Line
pline@awc.org
American Wood Council

Marco Lo Ricco
mloricco@uwm.edu
University of Wisconsin–Milwaukee

Timm Locke
locke@ofri.org
Oregon Forest Resources Institute

Bobby Loper
bobby.loper@hexion.com
Hexion Inc.

Steve Lovett
lovett@softwoodlumberboard.org
Softwood Lumber Board

Robert Malczyk
rmalczyk@eqcanada.com
Equilibrium Constulting Inc.

Steve Marshall
smarshall@fs.fed.us
US Forest Service

Karen Martinson
klmartinson@fs.fed.us
USDA Forest Products Laboratory

Eric McDonnell
eric.mcdonnell@kpff.com
KPFF

M. Mohammad
mohammad.mohammad@fpinnovations.ca
FPInnovations/NRCan

Jeff Morrow
jeff.morrow@lendlease.com
Lend Lease

Eric Mucklow
eric.s.mucklow.civ@mail.mil
Headquarters, Corps of Engineers

Edwin Nagy
edwin.nagy@maine.edu
University of Maine

Mojgan Nejad
m.nejad@msstate.edu
Mississippi State University

Douglas Nyseth
scott.nyseth@stonewoodstructural.com
Stonewood Structural Engineers

Elaine Oneil
eoneil@uw.edu
CORRIM

Weichiang Pang
wpang@clemson.edu
Clemson University

Bill Parsons
bill.parsons@woodworks.org
WoodWorks

Shiling Pei
spei@mines.edu
Colorado School of Mines

Don Peterson
kari@renewableresourcesolutions.com
Renewable Resource Solutions

Ciprian Pirvu
ciprian.pirvu@fpinnovations.ca
FPInnovations

Lisa Podesto
lisa@woodworks.org
WoodWorks.

Steve Pryor
spryor@strongtie.com
Simpson Strong-Tie

Neethi Rajagopalan
nrajago3@ncsu.edu
North Carolina State University

Douglas Rammer
drammer@fs.fed.us
USDA Forest Products Laboratory

Craig Rawlings
craig@forestbusinessnetwork.com
Forest Business Network

John Redfield
jredfield@drjlumber.com
DR Johnson Lumber Co

Michael Ritter
mritter@wisc.edu
USDA Forest Products Laboratory

Thomas Robinson
Thomas@leverarchitecture.com
Lever Architecture

Bob Ross
rjross@fs.fed.us
USDA Forest Products Laboratory

Mark Rudnicki
mrudnick@mtu.edu
Michigan Technological University

Ann Sarnecki
asarnecki@fs.fed.us
USDA Forest Products Laboratory

Laurence Schimleck
laurence.schimleck@oregonstate.edu
Oregon State University

Adam Senalik
christopherasenalik@fs.fed.us
USDA Forest Products Laboratory

Doug Sheets
doug@leverarchitecture.com
Lever Architecture

Rubin Shmulsky
spf11@msstate.edu
Mississippi State University

Deepak Shrestha
dshrestha@pfscorporation.com
PFS Corporation

Nicholas Sills
nsills@structurlam.com
Structurlam

Charles Starck
charles.starck@lendlease.com
Lend Lease

Douglas Steimle
doug.steimle@schaefer-inc.com
Schaefer

Kuma Sumathipala
ksumathipala@awc.org
American Wood Council

Erik Timmons
erikt@yorkeandcurtis.com
Yorke & Curtis, Inc.

Bill Tobin
bill.tobin@lendlease.com
Lend Lease

Robert Tudhope
michelleh@smartlam.com
SmartLam, LLC

John van de Lindt
jwv@engr.colostate.edu
Colorado State University

Steve Verrill
sverrill@fs.fed.us
USDA Forest Products Laboratory

Mark Vuong
mark@udplp.com
Urban Development Partners

James Wacker
jwacker@fs.fed.us
USDA Forest Products Laboratory

Hui Wan
hw2@msstate.edu
Mississippi State University

Jasmine Wang
jwang@cwc.ca
Canadian Wood Council

Xiping Wang
xwang@fs.fed.us
USDA Forest Products Laboratory

Steve Wellenstein
stevew@uihlein-wilson.com
Uihlein-Wilson Architects

Tom Williamson
tomwilliamson@live.com
Timber Engineering LLC

Borjen Yeh
borjen.yeh@apawood.org
APA - The Engineered Wood Assn

Samuel Zelinka
szelinka@fs.fed.us
USDA Forest Products Laboratory